THE WEST ANTARCTIC ICE SHEET INITIATIVE

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level

2008 WAIS Workshop Agenda

AGENDA

Wednesday, October 8, 2008

4:00 to 6:00	Registration	Main Building
7:00 to 9:00	INFORMAL DINNER (Pizza and Drinks)	Cottage #1

Thursday, October 9, 2008

8:00	BREAKFAST	Main Building
8:00	Registration	Main Building
9:00	Welcomes and Introductions	Main Building
	***Topic #1: "Mirror, mirror, on the wall"* – Looking at the past to see forward**	
9:30	History of the grounded ice sheet in the Ross Sea sector, Antarctica, at and since the LGM [Abstract]	Hall

9:45	Swinging Gate or Saloon doors: Do we need a new model of Ross Sea deglaciation? [Abstract] [PPT (4mb)]	Ackert
10:00	Late Quaternary fluctuation of Scott Glacier in response to grounding-line retreat in the Ross Sea Embayment [Abstract] [PPT (30mb)]	Bromley
10:15	Evidence for Rapid Surface Elevation Changes Around Siple Dome During the Deglacial [Abstract] [PPT (6mb)]	Taylor
10:30	BREAK (30 min.)	
11:00	Glaciology of the Bottleneck [Abstract] [PPT (3mb)]	Hughes
11:15	Rapid Early Holocene Sea-level Rise: Laurentide or Antarctic Ice? [Abstract] [PPT (18mb)]	Cronin
11:30	Mega-scale glacial lineations beneath Rutford Ice Stream [Abstract] [PDF (33mb)]	King
11:45	Poster Introductions (30 min.)	
12:15	LUNCH (90 min.)	
1:45	ENSO Modulation of West Antarctic Climate [Abstract]	Bromwich
2:00	Megapackets and Megapseudosynclines in East Antarctica [Abstract] [PPT 36mb)]	Arcone
2:15	PANEL DISCUSSION (30 min.)	Plenary
2:45	BREAK (30 min.)	
	***Topic #2: "ANDRILL"* - A Neat Data Recovery Initiative to Learn Lots about WAIS**	

3:15	Evidence of long- and short-term responses of the West Antarctic Ice Sheet during the Plio-Pleistocene and theirimplications: ANDRILL-McMurdo Ice Shelf Project [Abstract] [PPT (64mb)]	Powell
3:30	Plio-Pleistocene evolution and variability and the West Antarctic Ice Sheet from the ANDRILL, AND-1B geological record [Abstract] [PPT (6mb)]	Naish
3:45	WAIS collapse before GIS collapse! (~1 million years ago) [Abstract] [PPT (13mb)]	Scherer
4:00	BREAK (30 min.)	
4:30	Expanding provenance constraints on Ross Embayment till to assess LGM input of ice from the WAIS [Abstract] [PPT (31mb)]	Licht
4:45	Climatic forcing of WAIS mass balance on glacial-interglacial and longer timescales [Abstract] [PPT (18mb)]	DeConto
5:00	WAIS in ANDRILL future planning [Abstract] [PPT (7mb)]	Rack
5:15	PANEL DISCUSSION (30 min.)	Plenary
5:45	BREAK (15 min.)	
6:00	DINNER	Main Building

Friday, October 10, 2008

9:00	Recent flow history of Pine Island Glacier [Abstract] [PPT (14mb)]	Scott

9:15	Dynamic glacier thinning in the Larsen B Embayment, Antarctica, 2002-2008 [Abstract] [PPT (21mb)]	Shuman
	Topic #3: "When you need a friend, I'll be there" **- How my model can help your model**	
9:30	Modeling West Antarctic Ice Sheet Growth and Retreat through the last 5 million years [Abstract] [PPT (43mb)]	Pollard
9:45	Modified Morland-MacAyeal model for ice-stream flow [Abstract] [PDF (1mb)]	Sargent
10:00	Toward a next-generation community ice sheet model: Progress and plans [Abstract] [PDF (2mb)]	Lipscomb
10:15	BREAK (45 min.)	
11:00	Cyberinfrastructure Opportunities for Antarctic Research [Abstract] [PPT (4mb)]	Lubin
11:15	Effect of Climate Cycling and Meltwater Plumbing on Ice-Sheet Grounding-Line Migration [Abstract] [PPT (7mb)]	Parizek
11:30	Hydrostatic equilibrium: a good assumption for the position of grounding lines? [Abstract] [PPT (3mb)]	Nowicki
11:45	Hydraulic Fracture along Glacier Beds by Turbulent Flow of Meltwater [Abstract] [PPT (7mb)]	Rice
12:00	Possible Mechanisms for Glacial Earthquakes [Abstract] [PPT (0.5mb)]	Tsai
12:15	LUNCH (90 min.)	
1:45	Stick/Slip Behavior of Ice Streams: Modeling Investigations [Abstract] [PDF (11mb)]	Sergienko

2:00	Simulation of glaciogenic tsunamis generated by the Wilkins Ice Shelf collapse of 2008 [Abstract] [PDF (55mb)]	MacAyeal
	***Topic #4: "Older, yes, but wiser?"* – How to improve predictions of future WAIS behavior**	
2:15	Springing Forward: The Need for Viscoelastic Ice-Flow Modeling [Abstract] [PPT (0.3mb)]	Alley
2:30	How to improve predictions of future WAIS behavior [Abstract] [PDF (4mb)]	Fastook
2:45	Reaching for the Grail: Predicting Sea-Level Contributions from Dynamic Ice Sheets for 2100 before 2100 [Abstract] [PPT (0.2mb)]	Bindschadler
3:00	BREAK (45 min.)	
3:45	PANEL DISCUSSION (30 min.)	Plenary
4:15	Report of the FRISP/WAIS Workshop September 18-20, 2008	
4:30	GUEST FEEDBACK	
5:00	WAIS business	
5:30	Adjourn	
6:00	DINNER	Main Building

Posters

Megapackets and Megapseudosynclines in East Antarctica [Abstract]	Arcone

Initial Observations and Inferences from New Field Work on Pine Island Ice Shelf [Abstract] [PPT (6mb)]	Bindschadler
Characterization of Internal layers and Basal Conditions at the WAIS Divide Drill Site using a VHF Surface Based Radar [Abstract]	Blake
Reconstructing Holocene ice-marginal fluctuations with relict algal mats at Reedy and Scott Glaciers [Abstract]	Hall
Surface elevation changes at the front of the Ross Ice Shelf; Implications for basal melt [Abstract]	Horgan
Accumulation Patterns and Basal Conditions from Radar Observations Along the US-ITASE Traverse in East Antarctica [Abstract] [PPT (14mb)]	Jacobel
Surface melt magnitude retrieval over Ross Ice Shelf, Antarctica using coupled MODIS optical and thermal satellite measurements during the 2002-03 melt season [Abstract]	Karmosky
Evaluating a model of the current dynamical state of the Antarctic ice sheet using the Parallel Ice Sheet Model [Abstract]	Khroulev
Carlson Inlet - fast or slow? [Abstract]	King
How ice shelf morphology controls the longitudinal distribution of basal melting [Abstract] [PPT (3mb)]	Little
Modeling the spatial variation of ice-sheet radar attenuation [Abstract]	MacGregor
Mapping Internal Layers Using a 12-18 GHz Plane Wave Radar [Abstract]	O'Sadnick
A New Digital Elevation Model of the West Antarctic Ice Sheet from Altimetry and Images [Abstract]	Scambos
Possible Mechanisms for Glacial Earthquakes [Abstract]	Tsai
Transient subglacial water-flow [Abstract]	Winberry

2023 WAIS Workshop

2022 WAIS Workshop

2022 Agenda

2021 WAIS Workshop

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2014 WAIS Workshop

2014 Agenda

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2013 Agenda

2012 WAIS Workshop

2012 Agenda

Previous Meetings

Swinging gate or Saloon doors: Do we need a new model of Ross Sea deglaciation?

Robert P. Ackert Jr.
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Knowledge of the history of the marine-based West Antarctic Ice Sheet (WAIS) is important due to its potential instability in the face of global warming. With an ice volume equivalent ~5m of sea level, even partial collapse could have disastrous consequences along the World's coasts. New data from the WAIS interior are stimulating reappraisal of established WAIS reconstructions and models of grounding line retreat. In particular, models that simulate stable isotope and thinning data from the Siple Dome ice core indicate that surprisingly low surface elevations (~1000 m) persisted there during the last glacial maximum (LGM)(Price et al., 2007; Waddington et al., 2005). In addition, data from near the head of the Mercer Ice Stream, close to the WAIS divide, indicate maximum ice elevations were <125 m above the present surface and occurred as late as the early Holocene. These new data challenge the traditional view of WAIS expansion in the Ross Embayment. Rather than a relatively thick ice sheet sourced largely in West Antarctica, with ice streams similar in length to those of today (Denton and Hughes, 2002), a much thinner ice sheet, with a significant contribution from East Antarctica (Licht et al., 2005) and low slope ice streams extending across the Ross Embayment (Parizek and Alley, 2004), seems more plausible.

This alternative WAIS reconstruction calls for re-examination of deglaciation models. Rather than a "swinging gate", hinged on Roosevelt Island (Figure 1a)(Conway et al., 1999), grounding line retreat may have been characterized by a calving embayment centered over the Eastern Basin in the central Ross Sea, with retreat more normal to flow lines originating from both outlet glaciers of the EAIS flowing through the Transantarctic Mountains and from Marie Byrd Land (Figure 1b). Three lines of circumstantial evidence support a "saloon door" model with early formation of a calving bay in the central Ross Sea.

First, it is consistent with broadly limiting ^{14}C dates on tills and overlying glacial marine sediment in the Ross Sea, given the inherent uncertainty in the large, poorly constrained corrections for old organic carbon. Secondly, ice recession from maximum positions on the west coast of McMurdo Sound was underway by ~14.5 ka (Hall et al., 2000) indicating that the WAIS lobe in McMurdo Sound began thinning ~4500 years prior to final deglaciation (unloading) at ~9 ka. Price et al. (2007) find thinning began at Siple dome as early as ~14 ka. Given the inherent lag in ice sheet response, it seems likely that significant thinning due to grounding line retreat began prior to 14 ka. Third, relative sea level (RSL) curves obtained from raised beaches on the Scott Coast have an exponential form, consistent with the final unloading of grounded ice occurring between 8 and 9 ka (Hall and Denton, 2000; Hall et al., 2004). However, the highest raised beaches are only ~21 m above sea level, suggest ice thickness of only ~100 m. In contrast, the actual ice thickness, as indicated by the elevation of Ross Sea drift was ~400 m. This apparent inconsistency results from the persistence of an ice shelf following retreat of the grounding line that prevented the formation of raised beaches (Hall et al., 2004; Stuiver et al., 1981). The implication is that >70 m of rebound (~300 m of thinning) occurred between 14.5 and 9 ka.

This "saloon door" style of retreat in turn has potentially large implications for the interpretations of grounding line retreat rates based existing chronologic data along the Victoria Land coast. For example, tying existing glacial chronologies to the swinging gate model, Conway et al. (1999) concluded that most of the grounding line recession from the LGM position near Coulman Island to Ross Island occurred during the early to mid Holocene, in the absence of substantial sea level or climate forcing (Figure 1a). Consequently, they inferred that grounding line retreat from Ross Island to the Siple Coast occurred even more recently, may well be ongoing, and that grounding line retreat could continue even in the absence of further external forcing. However, if ice retreat instead followed a calving bay centered in the Ross embayment (Figure 1b), deglaciation could have begun earlier, initiated by sea level and temperature forcing. The chronologic constraints utilized by Conway et al. (1999) would instead record only the final deglaciation of grounded ice that lingered along the Victoria Land and Marie Byrd Land coasts after the grounding line had passed by in the central Ross Embayment. These alternatives have significantly different implications for the sensitivity of the WAIS to climate change.

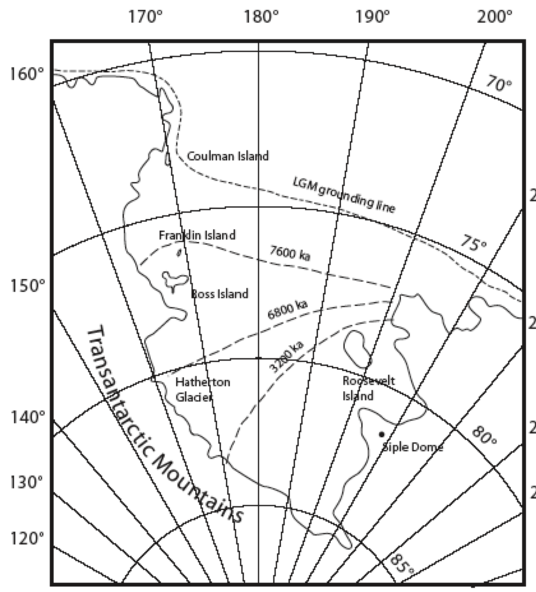

Figure 1a) Cartoon depicting the *swinging gate* mode of Ross Sea deglaciation (modified from Conway et al., 1999). The dashed line represents the location of the grounding line. Note that grounding line retreat occurs fastest along the deep troughs fronting the TAM, perhaps aided by higher ablation rates due to katabatic winds (Stuiver et al., 1981).

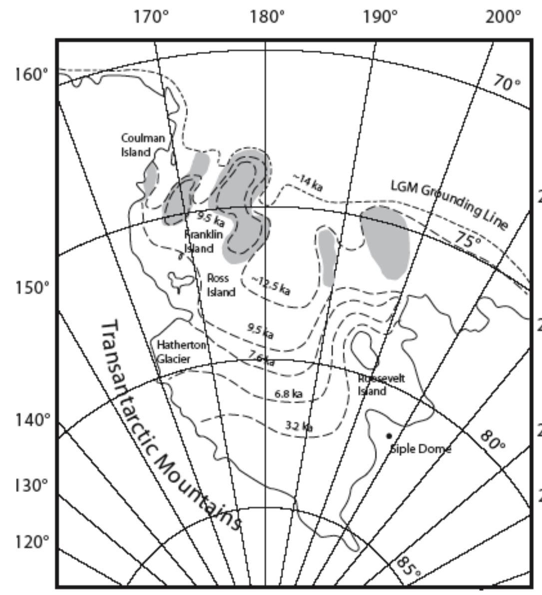

Figure 1b) Cartoon depicting the *saloon door* mode of Ross Sea deglaciation suggested by interior WAIS elevation data, and composition of Ross Sea sediments. The LGM and ~12.5 ka grounding line positions (dashed line) are based on the mapping in the Ross Sea that indicates streaming ice in troughs and divergent flow from banks (Shipp et al., 1999). Shallow banks marked in gray.

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Hall, B.R., Baroni, C., and Denton, G.H., 2004, Holocene relative sea-level history of the Southern Victoria Land Coast, Antarctica: Global and Planetary Change, v. 42, p. 241-263.

Licht, K.J., Lederer, J.R., and Swope, J.R., 2005, Provenance of LGM glacial till (sand fraction) across the Ross Embayment, Antarctica: Quaternary Science Reviews, v. 24, p. 1499-1520.

Parizek, B.R., and Alley, R.B., 2004, Ice Thickness and isostatic imbalances in the Ross Embayment, West Antarctica: model results: Global and Planetary Change, v. 42, p. 265-278.

Price, S.F., Comway, H., and Waddington, E.D., 2007, Evidence for late Pleistocene thinning of Siple Dome: Journal of Geophysical Research, v. 112, p. F03021.

Shipp, S., Anderson, J.B., and Domack, E.W., 1999, Late Pleistocene/Holocene Retreat of the West Antarctic Ice-sheet System in the Ross Sea: Geological Society of America Bulletin, v. 111, p. 1486-1516.

Waddington, E.D., Conway, H., J., S.E., Alley, R.B., Brook, E.J., Taylor, K.C., and White, J.W.C., 2005, Decoding the Dipstick: Thickness of Siple Dome, West Antarctica, at the Last Glacial Maximum: Geology, v. 33, p. 281-284.

Springing Forward: The Need for Viscoelastic Ice-Flow Modeling

R.B. Alley, S. Anandakrishnan, R.T. Walker, B.R. Parizek, T.K. Dupont and D. Pollard

We argue that viscoelastic ice-flow modeling is essential to allow inversion for the basal "flow law" required for accurate prediction of large and rapid ice-sheet changes.

Despite the importance of deformation within ice, rapid ice-flow changes appear to occur primarily at the bed. And despite a great amount of empirical, theoretical, and modeling effort, we are not especially close to a "flow law" (or more properly, a collection of flow laws) relating basal velocity to basal shear stress, a prerequisite for successful predictive ice-flow modeling. Such a flow law must include the nature of the bed (bumpy bedrock versus soft till, for example) and the responses of the various bed types to changing stress. Comparison of ice-flow velocities at different places with similar basal shear stresses suggests that the nature of the bed can have order(s)-of-magnitude effects on flow speed, and comparison of flow velocities at a place over time similarly suggests that plausible changes in stress can cause order(s)-of-magnitude changes in velocity.

Inversions from the surface-velocity field following MacAyeal, Joughin and others can produce maps of basal drag and basal velocity, but cannot be used to learn a flow law without high-spatial-resolution data on the bed character (frozen/thawed, hard bedrock/till/lake, etc.) to allow comparison of flow over similar beds with different stresses. Appropriate geophysical techniques allow bed characterization, and are essential in moving forward, but realistically cannot be applied across widespread regions quickly.

The best hope for learning the basal flow law may be to relate variations in stress and velocity over time at a range of sites, with sufficient geophysical investigation to demonstrate that the velocity changes arise from the stress changes and not from changes in the basal character; treating this as a perturbation from the surface-velocity inversions would be especially productive. However, stress variations averaged over multi-year intervals are almost always too slow to be useful; the ice sheet would have to do potentially scary things to create a large enough range of stresses for a successful calculation. Far better is to use the natural stress variations provided by tides, iceberg-calving events, glacial earthquakes, meltwater-drainage events, and other nonsteadiness in the glacial system. These can be monitored using continuous GPS, or in other ways. The main difficulty in applying this technique is that the forcings are generally fast enough that the responses include elastic as well as "viscous" elements, and existing flow models generally do not incorporate elastic flow. We are investigating viscoelastic ice-flow modeling; a real advance in this field seems necessary to enable predictive ice-flow modeling.

Megapackets and Megapseudosynclines in East Antarctica

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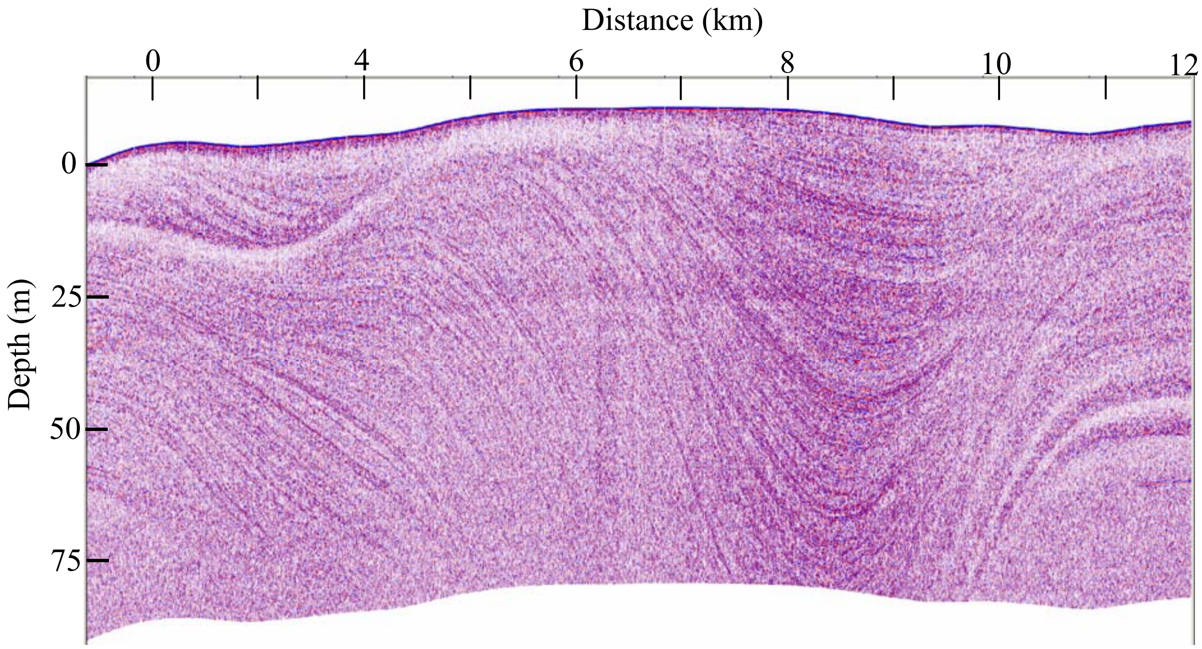
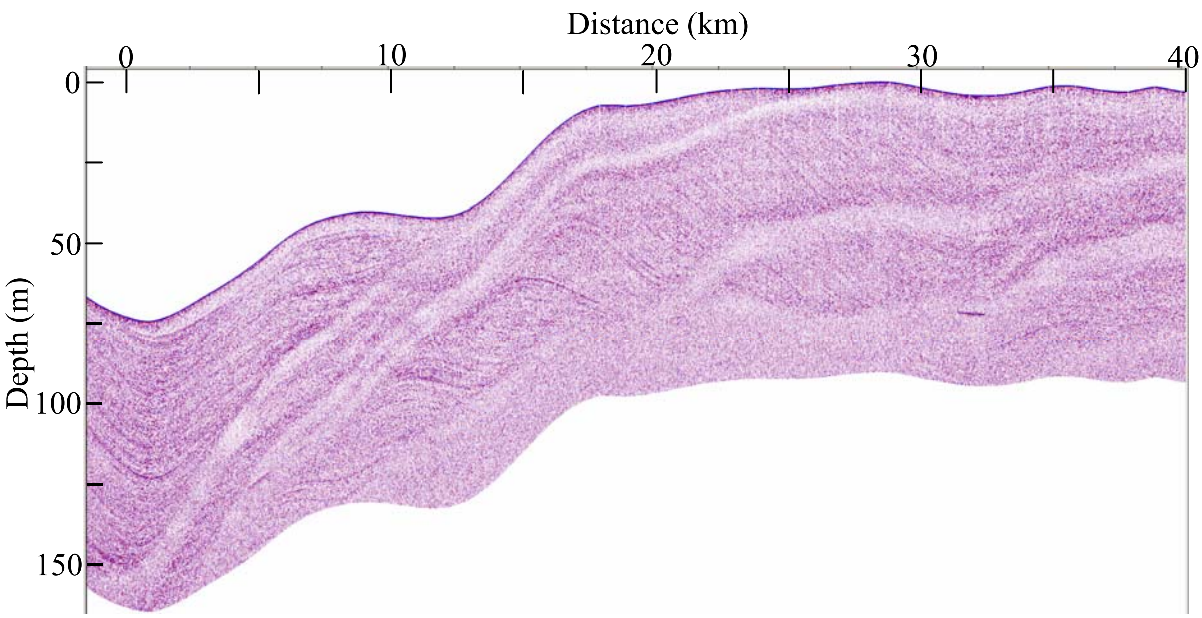
We have used GPR to profile sequential packet formation east of the megadunes region, both on a smaller scale north of Byrd Glacier, and on a much larger, megapacket scale south of it. Packets presently refer to the 8–15 m thick prograding beds sandwiched between 1–4 m thick metamorphic layers previously profiled with GPR in the megadunes region. The metamorphic layers generally grow under glazed surfaces of zero accumulation and are then buried by progradation. Much larger megapackets occur along a 530 km southerly transect, obtained during the 2007 US ITASE program, that started at latitude 81.7 degrees, far west of the Transantarctic Mountains. The first 130 km of this transect was orthogonal to ice flow, along an eastern fringe of the megadunes area, and parallel to dunelike ridges. Along this segment our 90-m deep 200-MHz profile reveals metamorphic layers, one of which may extend 140 km, and an absence of well defined progaded packets, as expected for the transect orientation. For the next 400 km south the transect diverged east from the megadunes to a maximum distance of 220 km. In contrast with the 2–6 km megadune wavelengths and their 8 m maximum amplitudes, along this segment hills are spaced 10 to 30 km, local elevation differences up to 40 m, and packets containing prograding stratigraphy originate from the south-facing windward slopes. Our 4 MHz profile suggests bedrock controls this surface topography. The 200 MHz profile shows sequential metamorphic layers up to 60 km long, with a few clear horizons from buried glaze. In contrast to megadune region packet dimensions, one of several megapackets contains 25 km of prograding beds up to 50 m thick and associated with metamorphic layers up to 15 m thick. Equally spectacular along the entire transect are megapseudosynclines (formed from deposition and not deformation) well over 100 m thick and from which progradation extends north. These features depress and override metamorphic layers. The 4 MHz profile reveals even larger megapackets, including one 250 m thick that reaches more than 1000 m deep, and a 70 km metamorphic unconformity that dips over 200 m. Glaze, underlain by metamorphism, appears to cover about 46% of the entire transect. By 86 degrees latitude, at 530 km, the metamorphic layers fade, and simple layering forms after another 200 km. The 25 km length of progaded deposits must represent extremely high deposition rates, given its concentration at windward faces. The megapseudosynclines should be ideal core sites to obtain deposition history because they lack metamorphic layers. Clearly, packet stratigraphy extends well beyond the megadunes area.



A megapseudosyncline profiled with 200-MHz GPR at the eastern edge of the megadunes area, 81.7° latitude. It is a pseudosyncline because the fold is caused by deposition and not by compression. The bottom of the pseudofold hinge projects to over 150 m deep. The feature is migrating over layers of metamorphosed firn (white streaks) that grew under glazed surfaces.



A megapacket, consisting of prograded beds over 25 km long sandwiched between metamorphic layers. The thickness of these sections is about 90 m.

Initial Observations and Inferences from New Field Work on Pine Island Ice Shelf

Robert Bindschadler, NASA Goddard Space Flight Center

David Holland, New York University

David Vaughan, British Antarctic Survey

Patricia Vornberger, SAIC at NASA GSFC

A new field program has begun on the ice shelf fed by the Pine Island Glacier, West Antarctica. This glacier is experiencing dramatic thinning, acceleration, and retreat. The spatial pattern of change suggests the cause is related to interaction between the ice shelf underside and warm water from the Southern Ocean. Recent airborne geophysical data, satellite altimetry and optical imagery have been analyzed to both plan the field research and to formulate an initial interpretation of the ocean-ice interaction. Significant new acceleration has been documented and new satellite data identify rapid changes that suggest a highly dynamic and spatially variable sub-shelf environment. Field observations to be conducted in the coming seasons will measure profiles of ice thickness and water cavity depth, and basal melt rates. Automatic weather station and GPS data, along with webcam photographs will be transmitted daily from the ice shelf. Our report will include the most recent conditions from the ice shelf.

Reaching for the Grail: Predicting Sea-Level Contributions from Dynamic Ice Sheets for 2100 before 2100

Robert Bindschadler, NASA Goddard Space Flight Center

One outcome of the recent Los Alamos workshop on "Building a next-generation community ice sheet model" was a set of self-selected focus groups intended to help inform the central activity of an improved community ice-sheet model. Because the use of such an improved ice-sheet model in a coupled global climate model framework is expected to take a number of years, one of these focus groups is attempting to improve the quantification of this century's ice-sheet contributions to sea level in anticipation of the next IPCC report. This group is rapidly coming to consensus on an overall strategy with a timetable that will meet the 2013 publication date of the next IPCC report. Presently, the strategy involves three basic types of models: whole ice sheet; ice-stream/ice-shelf; and ice-shelf/ocean. Multiple models of each type are available by the many participating investigators and the group is now determining a set of simple common experiments to run. More extreme scenarios, such as rapid removal of all ice shelves are taken as the starting point to help set the upper bound of possible behavior and ice mass loss by 2100. Model results will be compared to help separate real physical sensitivities of the modeled systems from model-dependent artifacts. Subsequent links between model types, i.e., runs that apply the insight of ice-shelf/ocean models to ice-stream/ice-shelf models, and of ice-stream/ice-shelf models to whole ice sheet models are hoped for before results must be published.

Characterization of Internal layers and Basal Conditions at the WAIS Divide Drill Site using a VHF Surface Based Radar

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Ice thickness, deep internal layers some more than 3 km and the ice-bed interface around the West Antarctic Ice Sheet (WAIS) divide deep drill site have all been mapped simultaneously at a fine resolution with an ultra-wideband, very high frequency (120 to 300 MHz) ground based radar. The radar was built by the Center for the Remote Sensing of Ice Sheets (CReSIS) as part of the Polar Radar for Ice Sheet Measurements (PRISM) project with the main goal of developing and testing surface-operated radars to measure ice thickness and determine bedrock conditions in Antarctica and Greenland. The system was fine-tuned in the field to a center frequency of 150 MHz with a bandwidth of 20 MHz to produce greater sensitivity, thus achieving a resolution of 8.45 m. The survey covered a 30 km by 8 km area with 1-km line spacing along a polar stereographic grid that overlapped both the drill site and the WAIS divide.

The surface based radar had eight receive antenna elements in a linear array as well as two transmit antennas. Synthetic Aperture Radar (SAR) processing was done to increase the SNR and enhance the basal returns and bring out some of the deeper layers. With the higher SNR the basal returns are nearly continuous and therefore the ice thickness was able to be estimated and a digital elevation map (DEM) of the base of the ice sheet was created.

Major findings to date:

1) Nearly continuous internal layers are observed as deep as 2800 m, as much as 500 m below the deepest previously mapped layers in this region.
2) Internal layers have been detected to within 350 m of the bed, covering about 90% of the ice thickness.
3) Ice thickness varies between 3100 m and 3550 m over the grid and is about 3500 m at the drill site.
4) Basal returns are nearly continuous along gridlines and vary by more than 30 dB, indicating both wet (slippery) and frozen bed conditions.

The data will aid rigorous interpretations of the WAIS Divide ice core (impurity records and depth/age scale) and the morphology and evolution of the region (mean annual accumulation rates, spatial extent, divide migration and volcanism). Fine-resolution information on deep internal layers, ice thickness/bed elevation and basal conditions will help unlock glacial, climate change and sea-level histories by constraining both forward and inverse two and three dimensional dynamic ice flow models. Echograms, ice thickness, bed elevation maps and the processed data are available on the CReSIS website:
https://www.cresis.ku.edu/research/data/antarctic_data.html

Late Quaternary fluctuation of Scott Glacier in response to grounding-line retreat in the Ross Sea Embayment

Gordon R. M. Bromley and Brenda L. Hall, University of Maine
John O. Stone and Howard Conway, University of Washington

Thickening of the WAIS during the last glacial maximum (LGM) dramatically influenced the flow of East Antarctic outlet glaciers draining through the Transantarctic Mountains into the Ross Sea Embayment, instigating significant changes in both surface elevation and profile. Subsequent recession of the Ross Sea grounding line removed this effect, causing outlet glaciers to thin and steepen. Today, only Reedy Glacier (86ºS) remains connected to the WAIS. Dating of glacial deposits adjacent to the outlet glaciers has enabled researchers to reconstruct the broad pattern of Ross Sea deglaciation during the Holocene. This is an important step in identifying the mechanism that triggered ice recession in this sector of the WAIS and has implications for the future stability of the ice sheet. However, the most recent behaviour of the WAIS grounding line in the Ross Sea, since the isolation of Hatherton Glacier at ~7 Ka BP, remains poorly understood and prevents us from determining whether the grounding line has stabilised on the Siple Coast or whether the WAIS continues to retreat.

During the 2003-4 and 2004-5 field seasons, we mapped glacial deposits alongside Reedy Glacier and sampled former ice limits for surface-exposure dating. Exposure ages from nunataks at the confluence with Mercer Ice Stream show that the bulk of post-LGM thinning at Reedy Glacier was complete by 3.8 Ka BP. Only minor thinning (<30 m) has occurred over the last two millennia, but whether this marks the end of deglaciation or localised reorganisation of glacier flow is unclear. To further constrain the most recent behaviour of the Ross Sea grounding line, we are continuing our glacial geologic investigation at neighbouring Scott Glacier.

Scott Glacier is the last major outlet glacier of the EAIS draining into the Ross Sea north of the grounding line. Large nunataks (the Karo Hills) are located above the shear margin of Scott Glacier at its confluence with the Ross Ice Shelf. We are mapping and sampling glacial deposits at the Karo Hills and elsewhere at Scott Glacier in order to accurately constrain the timing of the LGM and Holocene deglaciation. Coupled with the Reedy Glacier record, we anticipate that these data will provide strong constraints on the past few thousand years of Ross Sea grounding-line retreat. In particular, the Scott Glacier record will help establish whether grounding-line recession in the southern Ross Sea has ended or whether it is ongoing. Additionally, unlike at Reedy Glacier, the Karo Hills nunataks are high enough for their summits to have remained ice-free during the LGM. Therefore, the distribution of glacial deposits at the mouth of Scott Glacier will provide valuable geologic constraint of the surface elevation of the WAIS during the LGM.

ENSO Modulation of West Antarctic Climate

Ryan L. Fogt[1] and David H. Bromwich[2]

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According to research conducted in the so-called modern satellite era (post 1978), the El Nino-Southern Oscillation phenomenon has variable impacts on the climate of West Antarctica. The super El Nino of 1997-1998 (1982-1983) was strongly (weakly) manifested in West Antarctica. This followed from a decadal variability in the coupling between ENSO (monitored by the Southern Oscillation Index) and the Southern Hemisphere Annular Mode (SAM), most pronounced in austral spring. Further examination of this nonlinear coupling is well motivated by the finding that variable ENSO modulation is manifested in the new deep ice core from central West Antarctica (Eric Steig, personal communication, 2008).

To provide context for the above evaluation, the SAM has been seasonally reconstructed using principal component regression of surface pressure observations from Antarctica, the Southern Ocean, and the mid-latitude land masses. Prior to 1957 when surface pressure readings were not available in most parts of Antarctica, the reconstructions primarily depend on the mid-latitude pressure observations and the mid-latitude signature of the SAM. Reconstructions from 1865 were derived for summer and autumn, and from 1905 in winter and spring. Using these reconstructions, the relationship between ENSO and SAM is found to be quite variable in the historical record, and that periods similar to the 1990s when the two were strongly coupled have occurred in the past.

Rapid Early Holocene Sea-level Rise: Laurentide or Antarctic Ice?

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Maximum rates of glacio-eustatic sea-level rise (SLR) reached 50 mm/yr during the last deglaciation, >16 mm/yr during the last interglacial period, and 7-15 mm/yr during the early Holocene. These rapid rates, which were 3 to > 10 times the current rate of SLR, are ultimately caused by changes in orbital insolation and poorly understood ocean-climate-ice sheet interactions. Understanding the contribution of northern hemisphere and Antarctic ice sheet to past periods of rapid SLR yields clues about possible future rates for Greenland and Antarctic ice. We will discuss sea level change between 10 and 7 ka, which includes the largest climate anomaly of the Holocene interglacial - the 8.2 ka (thousand years ago) cooling event. The 8.2 ka event was a complex multi-century period of atmospheric cooling and reduced deep ocean circulation followed by an abrupt, large-scale warming ~ 7.9 ka when meridional overturning circulation (MOC) in the North Atlantic strengthened. The most likely trigger was abrupt discharge of 163,000 km^3 of freshwater from glacial lake Agassiz-Ojibway through Hudson Strait ~8.4-8.3 ka, which slowed MOC and contributed ~ 0.2 to 1.0 m of sea-level equivalent. Coral reef and coastal stratigraphic records indicate that early Holocene sea level rose a total of ~16 m between 9 and 7.0 ka, concentrated in several pulses about 8.9 ka, 8.0 ka and 7.6 ka when rates exceeded 7-15 mm/yr. Glacial lake water accounts for < 1 m sea-level equivalent, so most early Holocene SLR came from melting ice sheets. Evidence combined from sediment core tidal marsh record from Chesapeake Bay, North American glacial geology, and deep-sea foraminiferal oxygen isotopes suggest a pattern of early Holocene SLR characterized by alternating contributions from the remaining Laurentide Ice Sheet and unknown parts of the Antarctic Ice Sheet. Interhemispheric phasing of northern and southern hemisphere millennial climate variability is embodied in the "bipolar see-saw" hypothesis, which invokes changes in the strength of deep-ocean circulation as a mechanism. This hypothesis can be tested by correlating intervals of rapid SLR and with Antarctic and Laurentide ice-sheet history at multi-centennial timescales.

Climatic forcing of WAIS mass balance on glacial-interglacial and longer timescales

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The numerical modeling effort associated with the ANDRILL program is using a hierarchy of models to explore the climatic and glacial evolution of Antarctica on Cenozoic timescales. Modeling work over the past several years has concentrated on the development of a combined ice sheet-shelf model, the adaptation of a Regional Climate Model to the Antarctic region, GCM-ice sheet coupling, and the development of asynchronous coupling techniques allowing long time-continuous climate-ice sheet simulations on orbital and longer timescales. To complement recent findings by the ANDRILL field program, simulations to date have concentrated on the Plio-Pleistocene, and in particular on Marine Isotope Stage 31 (~1.07 Ma); a super-interglacial interval when the Ross Embayment appears to have been ice-free and WAIS was partially or completely collapsed. Here, we show results from GCM, RCM, and coupled AOGCM model simulations exploring the potential range of surface mass balance forcing and oceanic, sub-ice-shelf melt in response to MIS31 orbits and interglacial greenhouse gas concentrations. The climate model output is used to drive an ice sheet-shelf model and the results are compared with 5-myr time-continuous sheet-shelf simulations forced by parameterized climate and sub-ice melt deduced from orbital solutions and deep-sea-core $d^{18}O$. Our climate model results reinforce the conclusions of the parameterized 5-myr ice sheet-shelf simulations, and point to the overriding importance of sub-ice melt to Ross Ice Shelf and WAIS variability on these timescales. However, more explicit, high-resolution ocean modeling of West Antarctic embayments and continental shelf flow may be needed to directly address the potential impact of increasing ocean heat content in past and future scenarios of WAIS retreat.

How to improve predictions of future WAIS behavior

James Fastook

Modeling ice sheets has proceeded from

1. the very simplest parabolic profiles of the perfectly plastic approximation, a 1-D, steady-state solution where the driving stress is exactly balanced by a uniform basal yield stress;

2. on to the elliptical profiles, where a uniform accumulation rate is assumed, again a 1-D steady-state solution, but now the basal stress varies along the flowline;

3. to the shallow-ice approximation, a 1-D flowline or 2-D map-plane, time-dependent models, where only the basal stress is included and is assumed to equal the driving stress;

4. to the "shelfy-flow" models which are ad hoc adaptations of Morland's ice shelf equations, a 1-D or 2-D time-dependent solutions with only longitudinal stresses and an added basal resistance term;

5. to the current full-momentum solvers, true 3-D, time-dependent solutions where all stresses are presumably accounted for.

All of these treatments have in common the requirement that the modeler must specify some parameter that characterizes the coupling of the ice sheet with the bed. For the parabolic profiles it is the yield stress. For elliptical profiles and the shallow-ice approximation it is the ice hardness in the Flow Law and the lubrication factor in the Sliding Law. For shelfy flow it is again the ice hardness and also the basal resistance term For full-momentum it is the explicit basal boundary condition, either a Dirichlet-style specified velocity (zero for no sliding, non-zero for sliding) or a Neumann-style applied stress (the basal resistance, analogous to the term in the shelfy flow).

In modeling the interior of an ice sheet where sliding does not occur, parabolic, elliptical, and shallow-ice do a reasonable job of reproducing ice sheet behavior. Only shallow-ice is time-dependent, and since we are concerned with "predictions," this is a necessary capability. In all three of these, however, a "fitting" process is required to "tune" the model. Early shallow-ice models specified the ice hardness in the Flow Law, but thermo-mechanical coupled models eliminated the need to specify ice hardness, as it could be calculated from the temperature field within the ice sheet. A new parameter, the flow-enhancement parameter, emerged to allow us to still "tune" the model. This new parameter, while an improvement over the old " specification" of ice hardness, is necessary to have the model adequately describe the present configuration. As with other parameters in the model, the flow enhancement factor accounts for something we don't understand (impurity content, etc.). We have mentioned the lubrication factor, a parameter within the Sliding Law that basically serves to turn on and off sliding and to determine its magnitude. We have a clear picture that this depends in some way on the presence and amount of water at the bed, but sliding's actual coupling with the water field is uncertain (as well as being complicated by different kinds of sliding, hard-bed vs. deformable sediment, etc.)

An additional factor to consider in our search for improved predictions, is that we need a good starting point from which to project into the future. We are not starting from a simple steady-state ice sheet, but instead from one that has undergone significant changes in the not too distant past. Most geological reconstructions of the ice sheet have the Ross Sea beneath the current ice shelf fully grounded, possibly out to the continental shelf, with the major retreat occurring relatively late. With such a recent major change in the ice sheet configuration, major features such as the internal temperature field and the distribution of water at the bed will have preserved in them transient features reflective of the retreat history. Both internal temperature and basal water have a strong impact on the ice sheet's dynamic behavior, and hence must be well characterized in order to have a good starting point for a predictive model. The easiest way to accommodate this is to run the model for a glacial cycle capturing the endpoint as initial conditions for the predictive run. One problem with this approach is that the known history of the ice sheet is relatively short, and not unambiguously understood. The expanded extent of the ice sheet, the timing at which it stood at that larger configuration, the increase in the volume, as well as the important timing of the recent collapse are all controversial questions. Another problem of course involves which climate "proxy" to use to drive the ice sheet through it cycle, and how to couple that proxy to the controlling mechanisms.

The point here is that expecting higher-order models to solve all our problems is naive. We need a clearer understanding of the physical processes involved, or at least an adequate and versatile parameterization of said process that can be tuned to match the current configuration. Included in this of course is the recognition that we are dealing with a time-dependent creature, one whose current configuration (the starting point for our predictions) contains transients reflecting recent past behavior, which must be well characterized.

Reconstructing Holocene ice-marginal fluctuations with relict algal mats at Reedy and Scott Glaciers

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We report here the existence of relict lacustrine algal mats in sheltered valleys alongside Reedy and Scott Glaciers (~86^{o} S). These algae once grew in ice-marginal ponds dammed in favorable locations alongside the expanded glaciers. The samples occur as much as 100 m above the present-day ponds and 90 m above present ice level. In order for these ice-marginal ponds to have formed, Reedy and Scott Glaciers must have been thicker than at present.

Radiocarbon dating of algal remains from both Reedy and Scott Glaciers indicate that all samples are from the Holocene and were deposited soon after initial recession from the last glacial maximum position. Those samples from Polygon Spur (Reedy Glacier) date between 2000-8800 ^{14}C yr B.P., whereas those from Mt. Walshe (Scott Glacier) are 1600-7200 ^{14}C yr old. The two records show evidence of thinning ice throughout the mid-Holocene, with ice reaching close to its present location by at least 2000 years ago, if not earlier. The dates, along with glacial geologic mapping, also suggest a stillstand or minor readvance in ice retreat between ~4000-6000 ^{14}C yr B.P.

History of the grounded ice sheet in the Ross Sea sector, Antarctica, at and since the LGM

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The behavior of the Antarctic Ice Sheet, especially the marine-based West Antarctic Ice Sheet (WAIS), remains a significant unresolved problem in predicting future sea-level change. In addressing this issue, the history of the ice sheet is an important guide to its present stability and likely evolution. In particular, the timing and style of deglaciation from the last glacial maximum (LGM) position on the continental shelf is critical for understanding the mechanisms, including sea-level fluctuations, oceanic temperature variations, and ice dynamics that control ice-sheet behavior.

Here, we review the history of the Ross Sea sector of Antarctica, which is one of the areas of greatest ice-volume change during the LGM and subsequent deglaciation. During the LGM, the Siple Coast grounding line of the WAIS advanced across the sea floor, merged with expanded East Antarctic outlet glaciers, and terminated near the continental shelf edge. The thickness of this ice sheet in the central interior remains uncertain, but along the TAMS front, the surface elevation was ~700 m a.s.l. on Ross Island and more than 1000 m a.s.l. in the southern and central TAMS. Gradual ice-sheet thinning was initiated as early as about 15,000 years B.P., with ice levels remaining high until after about 12,000 yrs B.P. Grounding-line retreat lagged thinning. Relative sea-level data show grounding-line recession along the northern Victoria Land coast at ~8000 yr B.P. and a period of rapid retreat between 7000-8000 yr B.P., during which ice receded as far south as Hatherton Glacier. Retreat continued past Roosevelt Island in the eastern Ross Sea at ~3000 years B.P., leading to an initial suggestion that deglaciation from the LGM position could be ongoing.

Our present work focuses on two East Antarctic outlet glaciers in the interior Ross Embayment. Reedy Glacier currently flows into the WAIS, whereas Scott Glacier enters the Ross Ice Shelf north of the Siple Coast grounding line. At the LGM, the level and behavior of both glaciers were affected by the ice sheet in the Ross Sea. Both glaciers thickened substantially in their lower reaches near the coast, while remaining relatively unchanged at the East Antarctic ice plateau. The resulting longitudinal surface profiles were flatter than exist today. Exposure ages of erratics indicate that Reedy Glacier started thinning sometime after 15,000 years B.P., with most surface-level drop occurring after 9000 years B.P. Exposure ages from the mouth of Scott Glacier indicate that the Ross Sea grounding line reached that glacier ~2000 years ago and has retreated only 30-40 km since that time. These new data suggest that Holocene retreat in the Ross Sea sector may have slowed and that the present grounding line may be approaching relative stability.

Antarctica has been suggested as a potential source for deglacial sea-level pulses, such as meltwater pulse 1A. However, the total amount of excess ice available from Antarctica and the time at which it was released into the ocean are generally not compatible with such hypotheses. Our data indicate that most of the thinning and nearly all of the grounding-line retreat in the Ross Sea sector occurred after meltwater pulse 1A. Thus, ice from the Ross Sea sector could not have contributed substantially to this event.

Surface elevation changes at the front of the Ross Ice Shelf; Implications for basal melt

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Spatial and temporal elevation changes at the calving front of the Ross Ice Shelf (RIS) are examined using GLAS ICESat laser altimetry data. Elevation profiles show a spatial trend of decreasing elevation towards the calving front, while temporal changes over a 3-4 year timeline demonstrate ongoing lowering of surface elevations. The constraint of hydrostatic equilibrium, along with assumptions regarding spreading-rate, accumulation rate, and firn-depth, allow basal melting to be quantified. Estimated melt-rate increases exponentially towards the front. Using a best-fitting exponential function for melt rate, preliminary findings indicate that melt within the front 50 km of the ice shelf is responsible for almost half of the total melt produced beneath the RIS.

Glaciology of the Bottleneck

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The Bottleneck (60 W to 135 W, 86 S) is the narrow neck joining grounded portions of the East and West Antarctic Ice Sheets. In two wide gaps in the Transantarctic Mountains, separated by Thiel Mountains, ice up to 2500 m high and 3000 m thick spans the Bottleneck, with East Antarctic ice drained by Foundation Ice Stream into Filchner-Ronne Ice Shelf and by Mercer Ice Stream into Ross Ice Shelf. These ice shelves formed after gravitatonal collapse of the West Antarctic Ice Sheet beginning 6000 years ago to create large embayments in the Weddell Sea and Ross Sea. During collapse ice entered these embayments from three sides, east, west, and south, and left from one side, north. Today, ice leaves the remaining West Antarctic Ice Sheet from three sides, east, west, and north, and enters from one side, south. That entrance is the Bottleneck. It seems possible, therefore, that the remaining third of the ice sheet can collapse much faster than first two thirds, in 1000 years or perhaps much sooner.

Collapse of the remaining third of the grounded West Antarctic Ice Sheet would produce a similar large embayment in the Amundsen Sea, with collapse already having begun to form Pine Island Bay, which would widen toward the Bottleneck as downdrawn retreat of Pine Island Glacier and Thwaites Glacier continues. Retreat could continue through the Bottleneck into East Antarctica, with Pine Island Glacier and Foundation Ice Steam joining to pass east of Thiel Mountains and Thwaites Glacier and Mercer Ice Stream joining to pass west of Thiel Mountains. This would expose the heart of the East Antarctic Ice Sheet to rapid gravitational collapse, just as the heart of the Laurentide Ice Sheet collapsed 8000 years ago after a downdrawn ice stream retreated up Hudson Strait into Hudson Bay.

Two sectors of the East Antarctic Ice Sheet have already been downdrawn by major ice streams. At the grounding line of Byrd Glacier with Ross Ice Shelf, East Antarctic ice is 1000 m lower today than formerly. At the grounding line of Lambert Glacier with Amery Ice Shelf, East Antarctic ice is 3000 m lower. Both ice streams have drainage basins in East Antarctica that are as large as the remaining grounded West Antarctic Ice Sheet. Ongoing gravitational collapse of the West Antarctic Ice Sheet "pulls the plug" in the Bottleneck and opens a flood of East Antarctic ice into a new Amundsen Sea Embayment that may dwarf the 5 to 6 meters of sea level now locked up in West Antarctica.

Accumulation Patterns and Basal Conditions from Radar Observations Along the US-ITASE Traverse in East Antarctica

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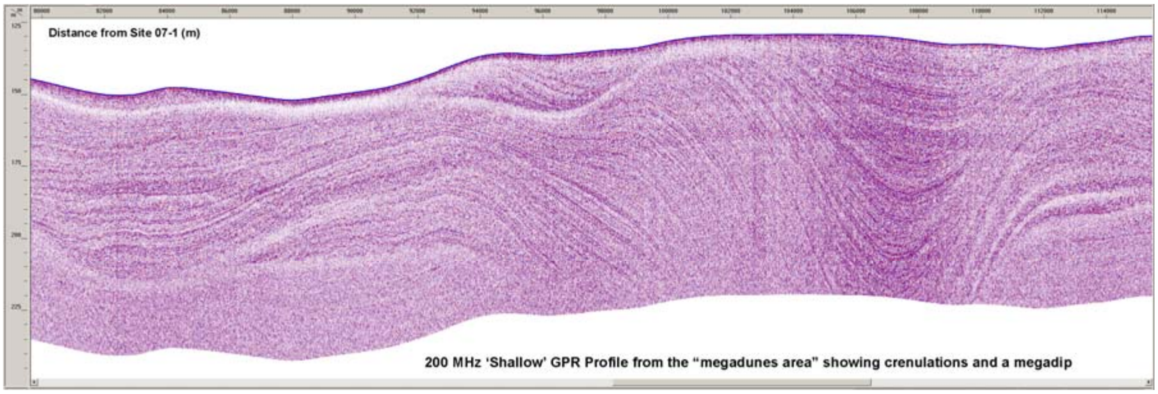
We present short-pulse radio echo reflection profiles recorded along a largely cross-flow transect during the 2006-08 US-ITASE traverse from Taylor Dome to South Pole. We used a 200-MHz system to focus on firn strata within the upper 100 meters and a 4-MHz system to focus on englacial strata, as well as the bed. Within the catchment area of Byrd Glacier, unusual cross-cutting englacial horizons suggest changing accumulation patterns possibly caused by long term wind shifts. Profiles recorded by both systems from south of the Byrd catchment area to Titan Dome are conspicuously characterized by buried megadunal type stratigraphy, consistent with the traverse being downflow from the apparent eastern edge of the modern megadunes region. The 200-MHz profiles reveal buried and partially buried foreset beds extending over 20 km in length, and in packets up to 50 m thick that are sandwiched between 4–8 m thick unstratified layers up to 35 km long. These beds are antidunal deposits, and the unstratified layers are glazed, zero accumulation zones of extreme, long term metamorphism. One packet projects to well over 100 m thick, and several intersect the surface so that they are active. The deeper, 4-MHz profiles show apparent foreset beds to 1000 m depth, up to 200 m thick and all with strata dipping to the south, consistent with near surface profiles. These impressive features, both near the surface and at depth, apparently show the concentrated way snow accumulates in the megadunes area. If these beds formed during high accumulation Holocene warming periods, then we need to understand how they could be interleaved with features characteristic of zero accumulation. The 4-MHz detection of deep foreset beds must be made possible by volcanic high conductivity layers, which suggests that these beds contain datable layers.

We have also plotted the power received from some 300,000 bed echoes versus ice thickness along the traverse. We use these data to estimate the average 4-MHz signal absorption rate within the ice, which allows us to calculate bed reflectivity and interpret basal properties. The results suggest many areas of thawed basal conditions, generally thought to be rare in East Antarctica. They also depict bed reflectivity at several candidate subglacial lake sites based on satellite imagery and reveal at least one possibly new subglacial lake.



200 MHz ‘Shallow’ GPR Profile from the “megadunes area” showing crenulations and a megadip

Surface melt magnitude retrieval over Ross Ice Shelf, Antarctica using coupled MODIS optical and thermal satellite measurements during the 2002-03 melt season

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Ice shelf stability is of crucial importance in the Antarctic because shelves serve as buttresses to glacial ice advancing from the Antarctic Ice Sheet. Surface melt has been increasing over recent years, especially over the Antarctic Peninsula, contributing to disintegration of shelves such as Larsen. Unfortunately, we are not realistically able to quantify surface snowmelt from ground-based methods because there is sparse coverage in automatic weather stations. Satellite based assessments of melt from passive microwave systems are limited in that they only provide an indication of melt occurrence and have coarse resolution. Though this is useful in tracking the duration of melt, melt amount of magnitude is still unknown. Coupled optical/thermal surface measurements from MODIS were calibrated by estimates of liquid water fraction (LWF) in the upper 1cm of the firn derived from a one-dimensional thermal snowmelt model (SNTHERM). SNTHERM was forced by hourly meteorological data from automatic weather station data at reference sites spanning a range of melt conditions across the Ross Ice Shelf during a particularly intense melt season. Melt intensities or LWF were derived for satellite composite periods covering the Antarctic summer months at a 4km resolution over the entire Ross Ice Shelf, ranging from 0-2% LWF in early December to areas along the coast with upwards of 10% LWF during the time of peak surface melt. Spatial and temporal variations in the amount of surface melt are seen to be related to both katabatic wind strength and wind shifts due to the progression of cyclones along the circumpolar vortex. A future application of surface melt mapping using this empirical retrieval model is to determine melt magnitude over other Antarctic Ice Shelves, such as Larsen, where surface melt has been well documented in contributing to the disintegration of the ice shelf.

Evaluating a model of the current dynamical state of the Antarctic ice sheet using the Parallel Ice Sheet Model

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We present a complete Antarctic ice sheet, stream and shelf model, and show that there is a close match of model output to observed surface velocities. The model is high resolution, with the entire ice sheet resolved on a 10 km grid. This resolution, and the immediate prospect of higher resolution, is possible because the Parallel Ice Sheet Model ("PISM"; www.pism-docs.org), an open source code, is used with hundreds of processors. The model is a shallow hybrid which includes ice stream and ice shelf flow based on the shallow shelf approximation and a plastic model for the subglacial till (Bueler and Brown, 2008; Schoof, 2006). A distributed map of till friction angle, in combination with a pore water pressure model, determines the till yield stress. The model is prognostic and thermomechanically coupled.

It is initialized by time-stepping through a paleoclimate history of several ice age cycles. Initialization uses publicly-available data including BEDMAP geometry, surface temperature from (Comiso, 2000), net surface mass balance from (Vaughan and others, 1999), and geothermal flux from (Shapiro and Ritzwoller, 2004). Critically, till friction angle is a function of the bed elevation instead of inverse modeling of surface velocities, for instance. This reinterprets an idea used by Huybrechts and de Wolde (1999) in a shallow ice approximation model, but in our using membrane stress balance model. Our reinterpretation is effective in generating ice streamflow distributed appropriately throughout WAIS. The result is a qualitative and quantitative fit to observed surface velocities. We measure the difference relative to interferometry-derived data from the Modified Antarctic Mapping Mission (Jezek, 2003). We also "zoom in" and compare to RIGGS velocities for the Ross Ice Shelf, and we compare other model outputs to observations. To obtain optimal fit we adjust only three scalar parameters. A parameter study is given. The evaluation of the model done here is a preamble to inverse modeling using these data and prognostic determination of sea level rise using the model coupled to a GCM.

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Carlson Inlet – fast or slow?

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I conducted a ground-based radar survey of Carlson Inlet and Rutford Ice Stream, West Antarctica to determine the internal ice stratigraphy and flow history. Rutford Ice Stream has a fast-flow signature and most of Carlson Inlet has a slow-flow signature. I used radar layer tracing and 1D modelling to estimate the age of the ice. I conclude that most of the ice in Carlson Inlet has been stagnant throughout much of the Holocene and that there has not been any flow switching between Carlson Inlet and Rutford Ice Stream during that time period. A narrow region near the margin of Carlson Inlet changed from fast to slow flow, possibly related to changes in subglacial water distribution.

Mega-scale glacial lineations beneath Rutford Ice Stream

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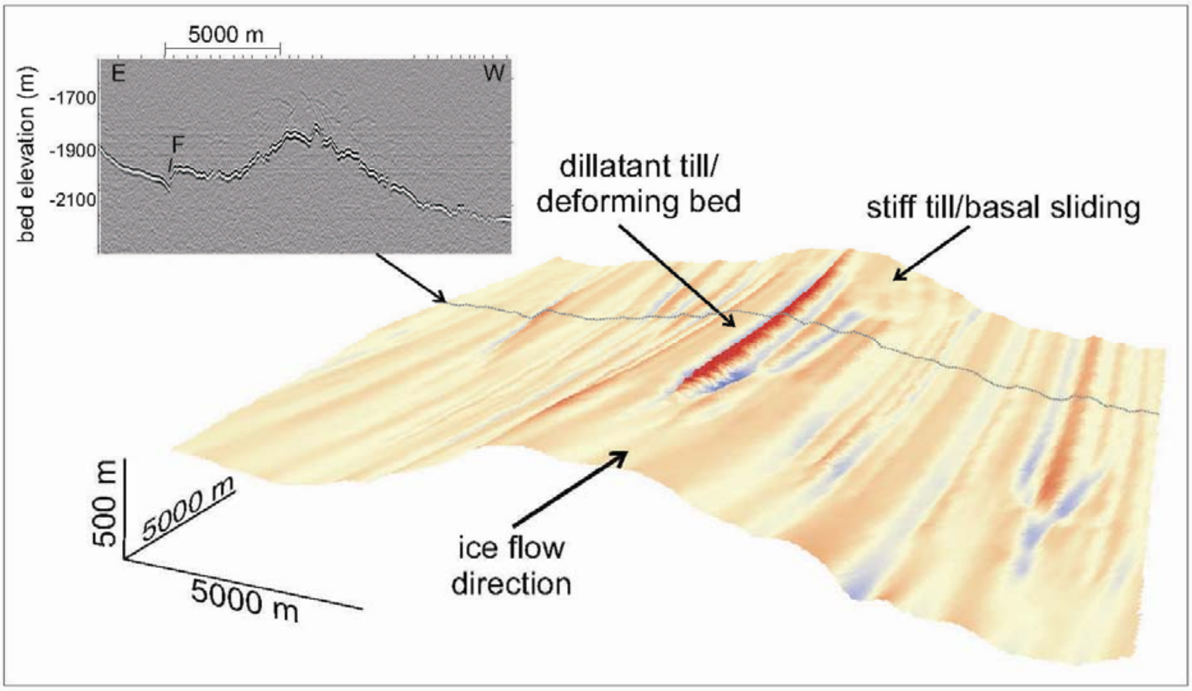
I used a 3 MHz ground-based radar to map the spatial distribution of deforming sediment beneath the fast-flowing (*c.* 375 m/a) part of Rutford Ice Stream. The sediment is organised into streamlined bed forms with high elongation and exceptional parallel conformity. The forms are identical to mega-scale glacial lineations (MSGL) described from polar continental shelves and the former bed of the Laurentide Ice Sheet. The sedimentary system here is known from repeated seismic surveys to be very dynamic with both erosion and deposition of substantial quantities of sediment over a 13 year period. These data prove the hypothesis that MSGL are formed beneath ice streams and provide control on process models of bed form evolution.



Expanding provenance constraints on Ross Embayment till to assess LGM input of ice from the WAIS

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Sand petrography of till from Reedy Glacier and till from the base of Whillans and Kamb ice streams in West Antarctica revealed similar mineral and rock types indicating that sediment fill in the West Antarctic basin beneath the Whillans and Kamb Ice Streams was eroded from the southern Transantarctic Mountains. However the Reedy glacier samples contain higher proportions of feldspar and less quartz than the WAIS samples. When compared to the Ross Sea samples, the central Ross Sea till composition aligns more closely with Reedy Glacier samples than West Antarctic samples (Kramer, 2008) suggesting the mixing line of East and West Antarctic ice at 180° in the central Ross Sea (from Licht et al., 2005) may represent the maximum extent of the WAIS in the Ross Sea during the LGM. Further work is needed to determine whether a signature of West Antarctic rocks can be identified in the sub-ice stream tills.

We have expanded our till provenance studies in the Ross Embayment to include U-Th-Pb detrital zircon age distributions as an additional fingerprinting tool. In a preliminary study, three replicate samples collected from the Lonewolf Nunatak at the head of Byrd Glacier are dominated by ages that fall between 564-583 Ma with a few older groups (i.e., 1000 Ma and 2730 Ma) common to at least two of the three samples. However, no ages are reported younger than about 450 Ma (Palmer, 2008). Several samples were analyzed from the Ross Sea floor to try to identify whether that zircon age distribution signature could be traced downstream. The zircon age distribution at site ELT27-14 in the west-central Ross Sea is statistically similar at the 95% confidence interval using the K-S test (Palmer 2008). A core from the east-central Ross Sea (east of 180˚), NBP-07-39, shows a very different zircon age distribution, with a zircon age population is dominated by grains of 100Ma. Rocks of this age have never been identified in East Antarctica and suggest a West Antarctic source. Therefore, this major difference in age populations between these two sites in interpreted to represent a boundary between the East and West Antarctic ice sheets. To further test this observation from the detrital zircon data, we will compare the U-Th-Pb detrital zircon fingerprint of samples collected from beneath West Antarctic ice streams and till from additional samples from the East Antarctic plateau to LGM-age till from across the Ross Sea floor.

Toward a next-generation community ice sheet model: Progress and plans

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The ice sheet modeling community is under increasing pressure to make credible predictions of 21st century sea level rise. There is general agreement on the need for next-generation models with higher-order dynamics, improved subglacial hydrology and basal physics, finer grid resolution, coupling to atmosphere and ocean GCMs, and realistic treatments of sub-shelf melting, iceberg calving, and grounding line migration. No such model exists, although many of the required elements are being developed. Time is limited if we are to make a meaningful contribution to the next IPCC assessment report, AR5, which is scheduled for release in 2013. Model development must be largely complete by 2010 and results submitted for publication by 2011 to meet IPCC deadlines. Since the ice sheet modeling community is relatively small, it is essential that we coordinate our efforts.

Responding to this need, a workshop entitled "Building a next-generation community ice sheet model" was held at Los Alamos National Laboratory in August 2008. The goal of the workshop was to create a detailed plan for developing a community ice sheet model, or CISM, suitable for sea level prediction. CISM will be the ice sheet component of the U.S. Community Climate System Model (CCSM) and will be openly available to the glaciology and climate communities for both standalone and coupled experiments. Workshop participants agreed on a software development strategy and identified physical processes that should be included in CISM in time for AR5. The dynamical core will initially consist of modules from the existing GLIMMER model, modified so that they can be called from other high-level drivers. Software infrastructure will be based on the POP and CICE models, which serve as the ocean and sea ice components of CCSM. Modules for generic functions such as coupling, I/O, and MPI communication can be adapted from POP and CICE with minimal effort. During the next year the ice flow model will be upgraded to a higher-order model with a unified treatment of stresses. Standard datasets will be developed for forcing, initialization, verification, and validation. Improved parameterizations of ice sheet hydrology, grounding line migration, and iceberg calving will be tested in process-scale models and implemented in CISM. Focus groups have been formed to coordinate the development of software, datasets, and new parameterizations and to design strategies for sea-level assessment. We welcome participation from others in the glaciology and ice sheet modeling communities.

How ice shelf morphology controls the longitudinal distribution of basal melting

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Satellite observations indicate that basal melting rates are spatially variable and strongly enhanced near grounding lines (e.g. Joughin and Padman 2003; Rignot and Steffen 2008). Ice-ocean modeling studies retain this pattern even with highly idealized topography and forcing (Holland, Jenkins et al. 2008), suggesting that large-scale ice shelf morphology may underlie longitudinal gradients in melting rate. Simulations performed using 3-D ocean models (Little et al. FRISP 2008) indicate that steep slopes drive entrainment of heat into the oceanic mixed layer, and that heat advected from these regions is a non-negligible component of the mixed layer heat budget. Here, a 1-D analytical model is used to explore how these factors influence the distribution of melting. When values for (highly uncertain) entrainment and boundary layer heat transfer velocities are specified, the simple model compares favorably with 3-D numerical results along the longitudinal axis of the ice shelf. In both models, melting rates are driven by the product of thermal forcing and flow speed; high temperatures in steep regions increase the spatial correlation of these properties near the ice-ocean interface and shift melting towards the grounding line. An intensification of cavity-wide melting rates driven by steeper ice shelves (the "basal slope feedback") suggests an instability in the coupled ice-ocean system, however, ice dynamics may mute this effect (e.g. Walker and Holland 2007).

Simple ice shelf-ocean models allow ice sheet responses to be explored at a high spatial resolution for a large parameter space. Adding a morphology-dependent distribution of basal melting will likely improve their ability to assess the basal slope feedback and the more general role of basal melting in ice shelf stability.

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Cyberinfrastructure Opportunities for Antarctic Research

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New resources are available to the WAIS research community through the NSF Office of Cyberinfrastructure (OCI). The advancement of our understanding in glaciology and high latitude climate change is becoming increasingly dependent on the most modern and capable computational resources. In addition, Antarctic field data sets are invaluable records of ever-changing phenomena, and their proper curation and interoperability among researchers is vital. This talk will review the three overlapping components of OCI - high performance computing, virtual organizations, and data interaction and visualization - and will review new funding opportunities including Cyber-enabled Discovery and Innovation (CDI), Virtual Organizations as Socio-technical Systems (VOSS), and DataNet Partners. This talk will explain how other geophysical science communities have recently been successful with proposals to these programs, and will also cover the NSF pre-proposal process which is frequently used by OCI and elsewhere in the foundation.

Simulation of glaciogenic tsunamis generated by the Wilkins Ice Shelf collapse of 2008

Douglas MacAyeal, University of Chicago

The 28-29 February, 2008, break-up of a part of the Wilkins Ice Shelf, Antarctica, exemplifies the now-familiar pattern of "explosive" ice-shelf break-up thought to be a consequence of environmental warming in the Antarctic Peninsula region. Key aspects of this "explosive pattern" to be explained by theories of ice-shelf dynamics include:

- The abrupt, near simultaneous onset of iceberg calving across a large-scale stretch of ice front
- High outward drift velocity (~0.3 m/s) of a leading "phalanx" of tabular icebergs that formerly comprised the seaward edge of the ice shelf prior to the break-up
- Efficient "surface coverage" of the ocean surface between the intact ice shelf and the leading phalanx of tabular icebergs by small icebergs, capsized icebergs and dismembered tabular icebergs (small irregular pieces)
- Extremely large gravitational potential energy conversion rates, e.g., up to 3 x 10^{10} W, by the "inverted submarine landslide" process over short periods of time (e.g., hours to days) in the absence of significant ice deformation
- The apparent lack of proximal iceberg-calving triggers (e.g., strong atmospheric storms in the local environment) at the time of break-up onset
- The capacity for enabling conditions (e.g., presence of melt-water induced "hydrostatic fracture") to make possible multiple break-up events (e.g., a second pulse of the Wilkins Ice Shelf break-up in late May, 2008) distributed through various seasons.

I examine the basic dynamic features of ice-shelf/ocean-wave interaction (including ice-shelf sources of ocean waves) that may explain the above aspects of the explosive ice-shelf disintegration process. Ice-shelf generated surface-gravity waves and flexural-gravity waves associated with initial calving at an arbitrary "seed location" produce stress perturbations capable of stimulating calving on the entire ice front. Waves generated by parting detachment rifts, iceberg capsize and break-up stimulate the "inverted submarine landslide" process, whereby ice shelf of thickness H_i is converted to a field of iceberg rubble of thickness $H_f<H_i$. Gravitational potential energy released by this conversion is primarily dissipated by surface gravity wave radiation through the ice rubble in the region of ocean surface located between the advancing phalanx of tabular icebergs and the active calving front of the still-intact ice shelf. I conclude by describing how field research and remote sensing can be used to test the various conjectures about ice-shelf/wave interaction that appear to be at play during ice-shelf disintegration.

Modeling the spatial variation of ice-sheet radar attenuation

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Knowledge of the spatial variation of ice-sheet attenuation rates is poor but is needed to accurately infer englacial and basal properties from ice-penetrating radar data. Radar-attenuation rates depend on the spatial variation of temperature and soluble impurity concentrations (in Antarctica, primarily acid and sea-salt chloride).

Because temperature and impurity-concentration data are measured only at the surface or in ice cores or boreholes, models of their spatial variation are required to predict attenuation rates in ice sheets. Here we evaluate several methods for modeling the spatial variation of attenuation rates, using an example of their application along a flowline that crosses through the Vostok ice core in East Antarctica. We use radar-layer depths and temperature and velocity outputs from a thermomechanical ice-sheet model to extend impurity-concentration and borehole-temperature data from Vostok along the flowline. The simplest possible model is a uniform, depth-averaged attenuation rate everywhere along the flowline, the next model uses spatially-varying temperatures and uniform impurity concentrations, and subsequent models use radar-layer depths the ice-sheetmodel outputs to also estimate the spatial variation of impurity concentrations, along with spatially-varying temperatures. We find that models that include the spatial variation of temperature can have large differences in roundtrip attenuation (> 10 dB) compared to models that simply use a uniform attenuation-rate field. Models with progressive improvements for modeling the spatial variation of impurity concentrations introduce only small (< 3 dB) changes in the roundtrip attenuation.

This work shows that an attenuation-rate model tied to an ice-core site can be satisfactorily extended spatially using available radar-layer depths and a temperature model.

Plio-Pleistocene evolution and variability and the West Antarctic Ice Sheet from the ANDRILL, AND-1B geological record

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While the West Antarctic Ice Sheet (WAIS) is considered to be vulnerable to future anthropogenic warming, projections of its likely behavior are hampered by a limited understanding of past variations and the main forcing mechanisms. Here we present a new proximal Plio-Pleistocene climate record constructed from the upper 600m of a sediment core (AND-1B) recovered from beneath the northwest corner of the Ross Ice Shelf by the ANDRILL program. More than forty, well-dated, sedimentary cycles in the core link ice extent to orbital-scale climate cycles dominated by obliquity during the Pliocene and Early Pleistocene - a 100,000 year-duration cycle dominates the Middle and Late Pleistocene. Our data provide the first direct evidence for an oscillating marine-based ice sheet in Ross Embayment, which periodically contracted onto terrestrial Antarctica when planetary temperatures were up to ~3°C warmer than today and atmospheric *p*CO_2 likely no higher than 400 ppm. We describe significant change in thermal regime of the ice sheet coincident with a global cooling trend between 3 and 2.5 million years ago, evident in oxygen isotope records and associated with the onset of northern hemisphere glaciations. During this time the ephemeral WAIS and the coastal margins of the East Antarctic Ice Sheet (EAIS) cooled towards their present polar state, expanding and developing more permanent marine termini and ice shelves. Further expansion occurred across the Mid-Pleistocene Climate Transition. Thereafter, extensive ice shelves rather than open marine conditions, dominated the Ross Embayment during interglacial periods.

Hydrostatic equilibrium: a good assumption for the position of grounding lines?

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Accurate determination of the position of the grounding line remains one of the challenges faced by current marine ice sheet models. Traditionally, the grounding line has been prescribed by a floatation condition (hydrostatic equilibrium) or from a migration rate based upon differentiation of the floatation condition. More recently, a boundary layer theory for marine ice sheets proposed by Schoof (2007), suggest that in the case of rapidly sliding ice sheets, grounding line migration rate should be replaced by a flux condition at the grounding line. Considering the situation where shearing in the grounded ice becomes important, Nowicki and Wingham (2008) used contact conditions to show that the floatation condition is not always appropriate, as it can result in steady state solutions that are not physically acceptable.

Nowicki and Wingham drew their conclusions from the results of a full Stokes finite element numerical model, which also solves for the position of free surfaces (air-ice and air-water interfaces). The grounding line and sea level are fixed, but the mass flux at the grounding line is varied. Once a steady state solution is reached, it is checked that (i) the compressive normal stress at the base of the grounded ice exceeds the equivalent water pressure, and (ii) the shelf lower surface does not get into contact with the bedrock. Violation of either of these two contact conditions would result in grounding line migration.

In this presentation we repeat these experiments, but with a non- linear ice rheology. We also look at the effect of different basal sliding law, and compare the numerical mass fluxes at the grounding line with Schoof's analytical expression. Following the theme of this session, we aim to show how these results can be of use for marine ice sheet models that do not solve the full Stokes equations.

Mapping Internal Layers Using a 12-18 GHz Plane Wave Radar

Megan O'Sadnick

Understanding trends in accumulation is necessary when determining the mass balance of both the Greenland and Antarctica ice sheets. In the past, a 500-2000 MHz FMCW radar has been employed in order to efficiently and accurately measure annual accumulation over a distance. Recently a higher frequency plane wave radar of 12-18 GHz was developed with the aim of detecting subannual layers as fine as three centimeters formed by individual accumulation events. Data obtained from the 12-18 GHz radar used at the Summit Greenland camp in 2005 and WAIS Divide camp in 2006 was processed to create images depicting layers present within the top five meters of the ice sheet. A comparison to other accumulation data gathered from snow pits and stake measurements was made to confirm the accuracy of the radar. Several layers were traced from images created from the 12-18 GHz radar data in order to obtain measurements of their depth. The measurements were analyzed to examine the continuity of the layers as well as the variability in accumulation between two layers. By analyzing the continuity and variability of subannual layers, a better understanding of the accumulation processes present on the ice sheets can be gained.

Effect of Climate Cycling and Meltwater Plumbing on Ice-Sheet Grounding-Line Migration

B.R. Parizek, R.B. Alley, T.K. Dupont, R.T. Walker, and S. Anandakrishnan

Ice-shelf response to climate cycling introduces hysteretic behavior in outlet glaciers, with the evolution of meltwater drainage networks enhancing this effect. The 2002 collapse of the Larsen B Ice Shelf (one of the floating extensions formed from glaciers flowing off the Antarctic Peninsula into the Weddell Sea) followed several years of shelf-thinning, accelerated flow, and ultimately the atypical warmth of the 2001-02 summer melt season with mean monthly temperatures rising to 4oC and meltwater production up three-fold to ~40 cm/yr (Shepherd et al., 2003; Rignot et al., 2004; van den Broeke, 2005; Vieli et al., 2006; van Lipzig et al., 2008). Yet, for at least the past half century, ice shelves along the margins of the Greenland Ice Sheet have been exposed to summer mean temperatures that hover in the 3-11oC range and melt rates that can exceed 250 cm/yr (Box et al., 2006; Vinther et al., 2006; Hanna et al., 2008; Joughin et al., 2008).

We suggest that this paradox can be explained by the advection of englacial meltwater channels that develop upglacier (Zwally et al., 2002; Das et al., 2008), thereby limiting meltwater ponding within crevasses and subsequent ice-shelf failure that is likely primed by surface and basal melting, years of thinning, as well as shear-margin weakening (Rott et al., 1998; Scambos et al., 2000; MacAyeal et al., 2003; Scambos et al., 2004; Vieli et al., 2007). Ultimately, the rapid loss and delayed establishment of ice-shelf buttressing of glacier flow amidst climate cycling leads to an asymmetric response in outlet glacier dynamics with implications for the future of the Larsen ice shelves as well as the hysteretic behavior of ice sheets.

Modeling West Antarctic Ice Sheet Growth and Retreat through the last 5 million years

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The West Antarctic Ice Sheet, grounded mostly below sea level and fringed by floating ice shelves, is considered to be vulnerable to future anthropogenic warming. However, projections of its future behavior are hampered by limited understanding of past variations and the main forcing mechanisms. Here a combined ice sheet-shelf model with imposed grounding-line fluxes following C. Schoof (J. Geophys. Res., 2007) is used to simulate Antarctic variations over the last 5 million years. We argue that oceanic melting below ice shelves is an important long-term forcing, controlled mainly by far-field influences that can be correlated with deep-sea-core d18O records. Model West Antarctic configurations range between full glacial extents with grounding lines near the continental shelf break, intermediate states similar to modern, and brief collapses to isolated ice caps on small West Antarctic islands.

Transitions between these states can be relatively rapid, taking one to several thousand years. Several aspects of our simulation agree with a sediment record recently recovered beneath the Ross Ice Shelf by ANDRILL (MIS AND-1B core), including a long-term trend from more frequently collapsed to more glaciated states, and brief but dramatic collapses at Marine Isotope Stage 31 (~1 Ma) and other super-interglacials. Higher-resolution nested simulations over the Ross Embayment resolve Siple Coast ice streams, Transantarctic outlet glaciers, and details of shelf flow. Correlations between modeled local conditions near the AND-1B core site and the overall West Antarctic state are examined, along with implications for the AND-1B lithologic record.

Evidence of long- and short-term responses of the West Antarctic Ice Sheet during the Plio-Pleistocene and their implications: ANDRILL-McMurdo Ice Shelf Project

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Response of ice sheets, especially the West Antarctic Ice Sheet (WAIS), is recognized as a significant unknown in predicting future consequences of global warming. Deeper-time data from 1284m of a sediment core drilled on the NW corner of the Ross Ice Shelf (RIS) are used to assess prior WAIS dynamics and its responses to past climate changes. The core shows WAIS changed from a cold ice sheet less than 13Ma, to being warmer with significant channelized subglacial meltwater prior to ca.7.5Ma, when during interglacials, local rivers flowed to McMurdo Sound. Between 53Ma meltwater decreased and interglacial periods were cooler with diatoms dominating rather than local meltwater. WAIS was dynamic ca.7.5-3Ma with its grounding and calving lines retreating past Ross Island in interglacials; occasionally iceberg calving was absent when termini were mostly terrestrial. Subglacial sediment deformation occurred to ca.10m depth, and glacial advance facies are locally preserved, indicating little erosion occurred during some advances and are used to indicate the ice sheet advance was probably rapid and definitely short-lived. Glacial to interglacial facies transitions are also locally condensed, often lacking retreat packages, and suggest ice sheet retreat was rapid as a response to some past warming events. Volumes of sub-ice-sheet meltwater during glacials and local interglacial meltwater declined through to ca.0.8Ma indicating WAIS was cooling. However, it remained more dynamic than after ca.0.8Ma when it reached its present cold state, inferred from thicker diamictite packages and thin to absent interglacial mudstones.

WAIS in ANDRILL Future Planning

Frank R. Rack, David Harwood, Steve Fischbein (ANDRILL Science Management Office, 126 Bessey Hall, University of Nebraska-Lincoln, Lincoln, NE 68588-0341; 402-472-4785; frack2@unl.edu) and ANDRILL Science Committee (ASC) Members.

ANDRILL (ANtarctic geological DRILLing) is a multinational program with the objectives to recover stratigraphic intervals for use in interpreting Antarctica's climatic, glacial and tectonic history over the past 50 million years (m.y.), at varying scales of age resolution (0.1 to 100 thousand years [k.y.]). The key motivation for ANDRILL relates to poor understanding of the complex role of the Antarctic cryosphere (ice sheets, ice shelves and sea-ice) in the past and future global climate system. Understanding the history of ice volume variation and associated physical changes in the Antarctic region is critical for assessing the interaction of ice sheets with the ocean, atmosphere, lithosphere and biosphere. Determining the scale and rapidity of changes affecting large ice masses is of vital importance because (i) ice-volume variations lead to changing sea levels, (ii) ice sheets influence sea-ice distribution, Earth's albedo, and latitudinal climate gradients, and (iii) ice shelves generate cold bottom-waters that ventilate the world's oceans. General circulation models (GCMs) indicate that the Polar Regions are the most sensitive to climatic warming, thus the projected global rise in temperature of 1.4 to 5.8˚C by 2010 (Intergovernmental Panel on Climate Change, [IPCC], 2001) is likely to be even greater in the Antarctic, with a probable effect on the Antarctic cryosphere. The future success of ANDRILL depends on establishing strong linkages with communities studying the behavior and significant processes exhibited by the West Antarctic Ice Sheet (WAIS) and surrounding ocean in order to understand the past and future behavior and history of the Antarctic cryosphere.

Fully understanding the role of Antarctic drivers on global climate variability requires a fundamental knowledge of Antarctic cryospheric evolution, not only in recent times, which is plainly vital, but also for earlier Antarctic history when global temperatures and atmospheric pCO2 were similar to conditions that might well be reached by the end of this century. High-quality sedimentary archives that record past ice sheet behavior have become available recently from the two ANDRILL projects, namely the McMurdo Ice Shelf (MIS) and Southern McMurdo Sound (SMS) projects. These build upon the prior successes of the Cape Roberts Project (CRP), and from ODP legs 178 and 188 to the Antarctic Peninsula and Prydz Bay, respectively. Although of excellent quality, these archives are too few in number to allow comprehensive understanding of Antarctica's influence on global climate. In June 2008 ANDRILL submitted a proposal to NSF's Office of Polar Programs and began discussions among the existing international partners to drill two sites on the Coulman High (CH) to initiate the first project of the Ross Embayment Portfolio (REP). The CH project will be accomplished by moving 125 km northeast of McMurdo Station, out of the Victoria Land Basin, to an area that has been densely surveyed using multichannel marine seismic reflection techniques at the C-19 giant iceberg calving site over CH. Two sites are proposed as part of the CH project to recover over 2 km of core (1200 m-thick sediment sequence at each site) that represents a unique archive of the paleoenvironmental and tectonic evolution in the Ross Embayment. By drilling at CH we seek to discover the Cenozoic history of West Antarctica.

Through the CH project, ANDRILL proposes to develop a capability to operate from a fast moving ice shelf platform (~700 m/year lateral movement, or roughly 2 m/day) using offset holes accomplished either by coring and fast-drilling, or by re-entry into a single borehole. Demonstrating this capability will put the Ross Ice Shelf, and other Antarctic ice shelves (e.g., Ronne-Filchner, Amery) within ANDRILL's reach. These technical and engineering objectives will be complemented by process studies conducted through the ice shelf to understand tidal currents that can impact the drilling operations (e.g., through the deployment of oceanographic moorings and pilot long-term observatory installations), as well as observations of benthic processes that contribute to a basic understanding of the sub-ice shelf environment (e.g., through field surveys using ROVs and surface sampling).

Several pre-drilling surveys must be performed for the CH project to determine conditions at the drill site and along the traverse route, and for final determination of the most robust drilling strategy. Pre-drilling, over-ice surveys will include: (1) airborne and surface radar mapping of sub-ice crevassing and topography; (2) LIDAR altimetry of the ice surface; (3) deployment of oceanographic current/tidal moorings; (4) verification of ice margin migration rates; (5) site meteorology; and (6) acquisition and processing of seismic reflection crossing lines at each drill site to augment the existing marine survey coverage. The project plan critical path includes (1) refining the initial technical research/design and (2) executing the bulk of the ice shelf-based site survey requirements in the field season following authorization to proceed (3) traversing the major equipment to the CH site; and (4) drilling in the two subsequent field seasons (ideally from 2011 to 2013).

In addition to the proposed CH project, ANDRILL completed an over-ice seismic survey in Granite Harbor within the Mackay Sea Valley (MSV) in 2007, and is currently conducting a seismic survey at Offshore New Harbor (ONH) to identify future potential drill sites. Other surveys are planned across the Ross Embayment to identify future potential sites where high quality geologic sequences could be recovered by drilling. Concerted planning efforts are underway to identify promising targets where glaciological and geological processes combine to preserve records of the evolution of the Antarctic cryosphere and interactions with the Southern Ocean that impact global thermohaline circulation, sea level and climate. A key strength of the ANDRILL approach is the ability to consistently obtain high-quality core while achieving extremely high core recovery in the targeted section (e.g., proximal glacial and glacimarine sedimentary rocks). We hope to continue this successful approach, pioneer new technological capabilities in more challenging environments, engage other scientific communities in these investigations - which will likely include modern process studies, and expand the pool of involved scientists, engineers, students, technicians and educators involved in ANDRILL.

Hydraulic Fracture along Glacier Beds by Turbulent Flow of Meltwater

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The problem of hydraulic fracture has been studied extensively, with focus ranging from enhanced hydrocarbon flow to boreholes, to water-driven glacial cracking, to magma eruption through Earth's crust. Although some of this work has addressed fast-flowing fracture, the work applied to glaciers has, so far, focused either on static or relatively long timescale conditions. However, glaciological observations suggest that the fluid-induced fracture process may occur quickly, possibly driven by turbulently flowing water during crack growth. Here, we take the approximation of a fully turbulent flow into an elastic ice medium with small fracture toughness to derive an approximate expression for the crack-tip speed. We accomplish this by first showing that a Manning channel model for wall resistance to turbulent flow leads to the same mathematical structure as for resistance to laminar flow of a power-law viscous fluid. We then make use of the asymptotic crack solution for that case by Desroches et al. [Proc. R. Soc. Lond. A, 1994], and finally estimate the pressure scale appropriate for a finite crack. Comparison of this estimated solution with an exact self-similar solution of Adachi and Detournay [Int. J. Numer. Anal. Meth. Geomech., 2002] validates the approximation. To apply this model, we use parameter values thought appropriate for a basal crack driven by the rapid drainage of a surface meltwater lake near the margin of the Greenland Ice Sheet (Das et al. [Science, 2008]). Thus, we take a maximum excess crack inlet pressure of 0.9 MPa, corresponding to neglect of any hydraulic head loss in flow from the glacier surface to crack entry at the bed, a horizontal basal crack length of 1 km, and a wall roughness scale for flow resistance of 10 mm, and hence estimate a crack-tip speed of about 8 m/s. Loss of ten percent of the surface head on descent to the bed would reduce that speed by slightly more than ten percent. Making various plate theory and linear elastic fracture mechanics approximations perhaps relevant to this setting, we additionally model both vertical and horizontal surface displacements and find rough agreement with the meter-scale displacements observed through GPS by Das et al. [Science, 2008].

Modified Morland-MacAyeal model for ice-stream flow

Aitbala Sargent and James Fastook

Higher-order models have been a goal of ice sheet modelers as they have attempted to leave behind the limitations of the shallow-ice approximation. SIA is appropriate for the interior slow moving regions of the ice sheet, but due to the fact that all stresses except basal drag are neglected means that SIA fails in the transition zone in streams as the grounding line is approached. Many are approaching this with attempts at so-called "full-momentum" solvers, ie. formulations that neglect no stresses. This approach, however, is computationally very expensive.

The SIA for interior ice, and the Morland Equations for the ice shelf flow [Morland, 1987] both reduce the scale of the problem by integrating out the vertical dimension, taking advantage of the fact that the vertical dimension is very different from the two horizontal dimensions. In the case of SIA, it is the fact that the stress distribution in the vertical can be approximated as varying linearly from zero at the ice surface to the driving stress at the bed, and a mass-conserving velocity profile obtained through the flow law. In the case of the Morland Equations, a uniform velocity with depth and the zero basal drag can be used to remove the vertical coordinate from the formulation. Doing so reduces the scale of the problem for a 100X100 km region modeled with 2 km resolution in x and y and 10 layers in the vertical from 300,000 degrees of freedom to 20,000.

The Morland Equations apply specifically to ice shelf physics, but they have been successfully applied to the transition zone in ice streams with a modification whereby a basal drag of arbitrary magnitude is added to the momentum-source term in the Morland formulation [MacAyeal, 1989; Hulbe, 1998]. While this approach does yield reasonable results, the fact that the addition of this stress after the fact, violates the assumptions that go into the original integration of the vertical dimension, and hence is not self-consistent.

We present a formulation for the diagnostic equation that follows the original Morland derivation closely [MacAyeal, 1997], but include at the outset an explicit term for the basal drag. This self-consistent formulation, coupled with a prognostic equation for mass conservation and solved using the Finite Element Method, is tested for a number of simplified geometries where longitudinal stresses are comparable to the basal drag. The ultimate goal is to include this as an "embedded" higher-order component within an SIA model of the entire ice sheet [Fastook and Sargent, 2004; Fastook, 2007].

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A New Digital Elevation Model of the West Antarctic Ice Sheet from Altimetry and Images

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An image-enhanced digital elevation map has been generated using a combination of a recent satellite altimetry-based DEM combining radar and laser altimetry and a series of cloud-cleared MODIS Band 1 images. The images provide additional surface slope information via shape-from-shading methods. The slope-to-brightness relationship for the images is generated by comparison of low-pass filtered versions of the scenes with the slope from the satellite altimetry data set in the image's sunward direction. Comparison with airborne laser altimetry suggests that the image-enhanced DEM has an acccuracy of ±2 meters over the majority of the ice sheet. A further enhancement is planned using two-dimensional wavelet integration of the image-derived slope field to create the elevation grid.

WAIS collapse before GIS collapse! (~1 million years ago)

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Kawamura et al. (*Nature*, 448, 912-916, 2007) showed that "orbital-scale Antarctic climate change lags Northern Hemisphere insolation by a few millennia, and that the increases in Antarctic temperature and atmospheric carbon dioxide concentration during the last four terminations occurred within the rising phase of Northern Hemisphere summer insolation." However, recent studies of Antarctic records of Marine Isotope Stage 31 (MIS-31, 1.08 – 1.06 Ma ago), including Scherer et al. (GRL, L03505, 2008) and new results from ANDRILL – McMurdo Ice Shelf Project (AND-1B), show that Antarctic warming, RIS collapse, and WAIS retreat led NH interglacial warmth by ~7 ka. SH and subsequent NH warmth and ice sheet response coincided with unusually high precession-paced insolation peaks at both poles (1.079 and 1.072 Ma, respectively). During MIS-31, Southern Ocean and Antarctic surface waters were warmer than today with very limited sea ice, and probably warmer than that at any time in the last ca. 2.5 Ma.

Typical Pleistocene interglacials are characterized by a “sawtooth” pattern, reflecting stepwise ice sheet growth and rapid deglaciation. However, the benthic oxygen isotope record of MIS-31 includes a two-stepped rise (lightening) consistent with early WAIS collapse prior to the global $\delta^{18}O$ and eustatic peak.

This study shows a direct (and in phase) sensitivity of ice shelves and sensitive ice sheets to insolation forcing. The response seen in the geologic record has been simulated by the Pollard/DeConto coupled GCM/ice sheet model (Nature, in review). The remaining question is, what does this teach us about the sensitivity of the modern WAIS and GIS to ongoing warming driven by atmospheric CO_2, rather than insolation.

Recent flow history of Pine Island Glacier

Julian Scott, Rob Bingham and Andy Smith
British Antarctic Survey

During the austral summer seasons of 2006/2007 and 2007/2008 the British Antarctic Survey undertook extensive fieldwork on Pine Island Glacier (PIG) spending more than 150 days in total on the ground. This was the first major ground based study of this ice stream. We previously showed GPS measurements that revealed the extent of the current acceleration as greater than 170 km inland from the grounding line. Now we have extensive radar measurements using 500 MHz and 25 MHz GPR along with those from the BAS deep look radar system (DELORES) at around 1 MHz. In particular we have radar measurements along the central flowline of PIG, which reveal aspects of flow that have not been previously demonstrated by airborne radar systems.

Flow changes significantly as PIG emerges from the deeper trough around 140 km upstream from the grounding line. Upstream of this point it is possible to identify features in the radar layers that have been consistently present for at least 200 years B.P. An accumulation high just downstream of this point cannot be tracked for the same length of time by using simple velocity models. This could be linked to a change in the flow of the ice stream.

With further modelling it may be possible to put upper and lower limits on the average velocity of the ice stream over the last two centuries. This will help to put into context the current changes being observed and enable us to make better estimates of the future behaviour of PIG.

Stick/Slip Behavior of Ice Streams: Modeling Investigations

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A puzzling phenomena of ice-stream flow is the stick/slip motion displayed by Whillans Ice Stream. To investigate the origin and implications of this phenomena, a simple mechanical model widely used in seismology to study origins of earthquakes is used to examine how periodic tidal forcing and spatial variability in basal friction leads to the cyclic stick/slip motion in an ice stream. Spatially variable friction has a strong influence on the velocity amplitude and periodicity of slip events. Periodic forcing designed to mimic ocean tides near the grounding line of the ice stream can pace the periodicity of slip events (e.g., determine the fundamental periodicity of a doublet of slip events occurring once per tidal cycle), however intrinsic properties of the mechanical system (e.g., as determined by friction parameters) determine whether aftershock slip events follow the fundamental slip event triggered by external tidal forcing during each cycle. By analogy with mechanical stick/slip oscillators that display onset of stick-slip cycling from uniform slip as the speed of motion reduces, a slowing ice-stream exhibiting gradual increase in basal friction is likely to enter a transitional phase of behavior when steady flow gives way to stick/slip flow prior to complete shut-down of the ice stream.

Dynamic Glacier Thinning in the Larsen B Embayment, Antarctica, 2002-2008

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Altimetry data derived from thirteen ICESat operational periods and two long-range aircraft ATM missions acquired between November 2002 and March 2008 quantify significant elevation changes for a glacier flowing into the now-collapsed section of the Larsen B Ice Shelf. Where ICESat's Track 0129 crosses the Crane Glacier, about 12 km from the March 17, 2002 ice edge, little to no elevation change occurred between November 26, 2002 and October 30, 2003 despite an ~11 km retreat in the ice edge location just down fjord; this is due to inland ice moving downstream rapidly to maintain the floating glacier terminus. However, between Oct. 30, 2003 and March 2, 2004, >70 m of elevation lowering occurred at this point, what was a >5 km wide and ~600 m thick glacier became a fjord. The Crane's ice front retreated another ~8 km inland in less than a year and has held a relatively stable position near this point since late 2004 (~65.33°S 297.66°E). However, the combined elevation time series from ICESat and ATM indicates the surface height of the lower Crane Glacier where it was crossed by ICESat Track 0018, about 24 km inland from the March 17, 2002 ice edge, lowered >150 m between November 26, 2002 and March 18, 2007. At this location, an average >40 cm/day elevation loss was observed over ~3 months in late 2004 - early 2005 as the glacier responded dynamically to the collapse. More than 50 km inland, the Crane has shown distinct elevation changes since mid-2006 with >20 m elevation lowering where Track 0390 crosses the upper Crane tributaries. In contrast to the Crane, other glaciers show changes but without clear trends. The nearby but smaller Melville Glacier that also flows into the Larsen B embayment shows >8 m elevation lowering close to its terminus but little change farther inland and similar patterns are observed over the Flask and Leppard Glaciers at the points where the ATM and ICESat data intersect. These latter two glaciers are similar in width and thickness to the Crane (before its dynamic thinning) but are still buttressed by a remnant of the Larsen B Ice Shelf. Bedrock elevations in all cases were derived from available KU/CReSIS radar profiles. The available altimetry data are too limited to resolve seasonal elevation changes associated with velocity variations. These results support early suggestions that ice shelves play a strong role in regulating the dynamics of large outlet glaciers. Although the majority of the mass contributions from the Crane may have already occurred and are a small portion of total sea level rise, its history shows that significant ice mass loss will occur along outlet glaciers with beds well below sea level if their buttressing ice shelves collapse.

Evidence for Rapid Surface Elevation Changes Around Siple Dome During the Deglacial

Ken Taylor, Richard Alley, Ed Brook, Howard Conway, Jeff Severinghaus, Paul Mayewski, Jim White

Unlike other deep Antarctic ice cores that were purposely drilled at locations where the influence of ice flow on the record would be minimized, the Siple Dome core is strongly influenced by changes in ice flow because it was collected on an ice ridge that separates two active ice streams. The Siple Dome core was collected 200 km away from the Byrd core site, which is not directly influenced by ice streams.

Comparison of the Siple Dome records to the Byrd and other records shows there were two episodes of rapid temperature changes (15 ka BP and 22 ka BP) at the summit of Siple Dome which did not occur at other locations. These local elevations changes are interpreted to be the result of surface elevations changes on the summit of Siple Dome and the surrounding ice streams. Changes in air flow and katabatic winds caused by the changes in the surface topography may have amplified the local temperature change. The two episodes are thought to be decreases in surface elevation on order of many hundreds of meters in a few hundred years.

The following causes are being considered to explain the rapid changes in surface elevation, but none of them are entirely satisfactory.

1) A break up of the portion of the Ross Ice Shelf between Roosevelt Island and the Siple Coast caused by ocean warming.
2) An ice stream surge event similar to what is happening now on some ice streams but with a larger amplitude and shorter duration.
3) Rapid discharge of a sub glacial water system
4) Sea level rise

Despite the uncertainty in the physical process that caused the rapid surface elevation changes at Siple Dome, the core shows the Siple Coast of WAIS responded with large and abruptly local changes to the gradual changes in forcing of last deglacial.

Possible Mechanisms for Glacial Earthquakes

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The large glacial earthquakes reported on by Ekstrom et al. (2003, 2006) and Tsai and Ekstrom (2007) have previously been evaluated in terms of their seismic characteristics. Here we take constraints such as known glacial ice properties, outlet glacier size, calving style, and meltwater variability to construct a self-consistent physical model of the glacial earthquake process. We find two classes of models are able to satisfy most observational constraints, one caused by lost basal resistance coupled to viscoelastic deformation and one caused by non-equilibrium calving, such as having large icebergs capsize into the glacier front. The non-equilibrium calving model currently has much stronger support and we present a mechanical model for how such iceberg capsizing could occur.
This model builds upon the equilibrium model of MacAyeal et al. (2003), allowing for hydrostatic pressure from the surrounding water, a contact force of the iceberg against the glacier front, and an optional second contact force on the opposite side to account for a mechanically competent iceberg melange or other added mass effects. In contrast to the MacAyeal model, we allow for accelerations and solve the dynamical system of equations given various initial conditions. With proper choice of parameters such as iceberg dimensions and initial conditions, these models reproduce all available glacial earthquake observational constraints, including earthquake amplitudes and timescales and recent visual observations.

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Transient subglacial water-flow

Paul Winberry, Central Washington University

Strong nonsteadiness occurs in the subglacial water system and may influence ice–stream dynamics. We present observations of harmonic glacial tremors beneath MacAyeal Ice Stream, Antarctica (MIS). Each tremor event has sustained arrival of 3 Hz energy for over 10 minutes, during which the source location migrates. The duration, monochromatic nature, and movement indicate that the source mechanism is transient flow in the subglacial water system resulting from the discharge from a small subglacial lake.