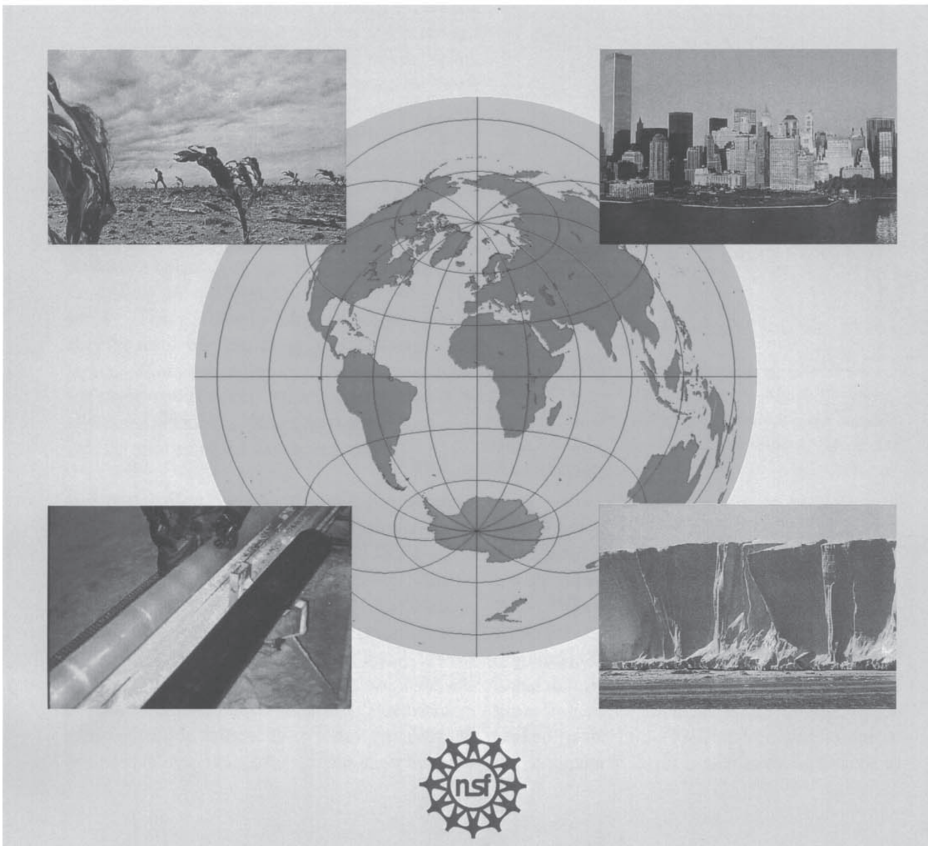
WAIS

The West Antarctic Ice Sheet Initiative

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level



2009 WAIS/FRISP WORKSHOP

(16th Annual WAIS)

September 27 - 29, 2009
Pack Forest Conference Center
Eatonville, Washington

Agenda & Abstracts

http://neptune.gsfc.nasa.gov/wais

Agenda

2009 WAIS/FRISP Workshop (16th Annual WAIS)

AGENDA

Saturday, September 26, 2009		
4:00 to 6:00	Registration	Scott Hall
7:00 to 9:00	DINNER (Pizza and Drinks)	Dining Hall
Sunday, September 27, 2009		
8:00	BREAKFAST	Dining Hall
8:00	Registration	Scott Hall
9:00	Welcomes and Introductions	Scott Hall
	Topic #1: "Shelf-Life" - How intense is the interaction of the ocean with the ice shelves and what is expected in the future?	
9:30	Using oceanographic data to calculate the melt rate at an ice shelf's base	Nicholls
9:45	Ocean circulation and water mass transformation beneath Filchner-Ronne Ice Shelf: results from a three dimensional ocean model	Makinson
10:00	Modelling Amery Ice-Shelf/Ocean Interaction	Galton-Fenzi
10:15	Overturning of the Antarctic Slope Front and ice shelf melting along the coast of Dronning Maud Land	Nost
10:30	BREAK (30 min.)	
11:00	Bathymetry beneath Pine Island Glacier revealed by Autosub3 and implications for recent ice stream evolution	Jenkins
11:15	Ocean properties beneath Pine Island Glacier revealed by Autosub3 and implications for circulation and melting	Dutrieux
11:30	Effects of waves on ice shelves	Sergienko
11:45	Seismic Studies of Glacier Calving	Walter
12:00	Poster Introductions (30 min.)	
12:30	LUNCH (90 min.)	Dining Hall
2:00	Idiosyncrasies of Measurements and Mixing in Seawater Near Freezing	McPhee
2:15	Grounding line basal melt rates determined from internal stratigraphy	Catania
2:30	Analysis of ice plains on Ross and Filchner/Ronne ice shelves using ICESat data	Brunt
2:45	Antarctic ice shelf thickness estimates derived from satellite altimetry	Griggs
3:00	A Time-Dependent Model of Pine Island Glacier Constrained by Satellite Observations	Joughin

3:15	BREAK (30 min.)	
3:45	GPS velocity from the Pine Island Glacier drainage area	Truffer
4:00	Wind Effects on Circumpolar Deep Water Intrusions on the West Antarctic Peninsula Continental Shelf	Dinniman
4:15	Marine ice in Larsen Ice Shelf	Holland, P.
4:30	Antarctic Ice Shelf Environmental Survey and Oceanographic Capability: Interdisciplinary Science Plans and Prospects	Rack
4:45	PANEL DISCUSSION (30 min.)	Plenary
5:15	BREAK (45 min.)	
6:00	DINNER	Dining Hall
7:00	Poster session (2 hr.)	
Monday, September 28, 2009		
8:00	Breakfast	Dining Hall
	Topic #2: "Answering the Call" - How are models being used to predict the future of the ice sheet and future sea level?	
9:00	Inferring Transients in Ice Flow, Ice Thickness, and Accumulation Rate from Internal Layers near the WAIS Divide ice-core site	Koutnik
9:15	The interaction of context and structural uncertainty in ice sheet modeling	Little
9:30	High-resolution simulation of the extent and flow of Antarctic Peninsula glaciers	Golledge
9:45	The failure of fracture mechanics: (Or can fracture mechanics be used to predict when melt ponds will drain?)	Bassis
10:00	Ice sheet water models: routing, timing, and pressure distribution	Carter
10:15	BREAK (30 min.)	
10:45	The Dilemma of RESOLUTION: How good MUST it be?	Fastook
11:00	Response of the Antarctic Ice Sheet to increased ice-shelf oceanic melting	Pollard
11:15	The heroic age of ice sheet modeling: Glimmer, CISM and all that	Lipscomb
11:30	SeaRISE: Addressing "How bad could it get"?	Bindschadler
11:45	The Life Cycle of Ice Streams	Hughes
12:00	PANEL DISCUSSION (30 min.)	Plenary
12:30	LUNCH (75 min.)	Dining Hall
	Topic #3: "Up & Down We Go" - Active subglacial hydrology and what it might mean for West Antarctica's future	
1:45	Basal Reflectivity and Bed Conditions Along the US-ITASE Traverse, Taylor Dome to South Pole	Jacobel
2:00	Active sub-glacial lakes beneath two more Antarctic outlet glaciers appear to cause rapid speed and elevation changes	Scambos
2:15	What are your lakes doing to my glaciers?	Smith, B.
2:30	Stability and drainage of subglacial water systems	Creyts
2:45	BREAK (30 min.)	

3:15	Progress in modeling sheet-flow outburst flooding	Rice
3:30	Of Bubbles and Bergs: Underwater Acoustics at the Ice/Ocean Boundary	Pettit
3:45	The Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) Project	Fricker
4:00	PANEL DISCUSSION (30 min.)	Plenary
4:30	BREAK (15 min.)	
	Topic #4: "Doctors with a Drill" - Where, why and when should the next deep ice core in West Antarctica be drilled?	
4:45	Modelling and measurements of vertical strain-rates under ice domes and ridges	Gillet-Chaulet
5:00	Antarctic temperature change and its relevance to future ice core drilling efforts	Steig
5:15	PANEL DISCUSSION (30 min.)	Plenary
5:45	BREAK (15 min.)	
6:00	DINNER	Dining Hall
7:00	Poster Session (2 hr.)	
Tuesday, September 29, 2009		
8:00	Breakfast	Dining Hall
	Topic #5: "Exposed!" - If the ice sheet were largely removed during the last interglacial, what would we find at the bottom of WAIS Divide or elsewhere revealing this history?	
9:00	Reconstructing past Antarctic ice flow paths using detrital zircon provenance	Schilling
9:15	Subglacial Landform Analysis and Reconstruction of Miocene Paleotopography of Marie Byrd Land	Spector
9:30	Preservation of Pliocene age surfaces beneath the WAIS: Insights from emergent nunataks in the Ohio Range	Ackert
9:45	Active-Recent Volcanism Associated With the West Antarctic Rift System Interpreted From Aerogeophysical Observations, and Possible Effects on the Stability of the West Antarctic Ice Sheet	Behrendt
10:00	AGAP: Exploring the Gamburtsev Subglacial Mountains with Aerogeophysical Surveys during the IPY	Studinger
10:15	BREAK (30 min.)	
10:45	Variation in Subglacial Roughness in West Antarctica: What does this mean for pre ice sheet sediment provenance?	Young
11:00	Pleistocene WAIS history from marine sediment cores	Scherer
11:15	A Probabilistic Assessment of the WAIS and Greenland Contributions to Sea Level during the Last Interglacial	Oppenheimer
11:30	Anisotropic basal roughness at scales close to the transition wavelength beneath upper Thwaites Glacier	MacGregor
11:45	PANEL DISCUSSION (30 min.)	Plenary
12:15	LUNCH (90 min.)	Dining Hall

	Topic #6: "Life on the Edge" - What is happening, once happened or might happen beyond the ice sheet margin that relates to the future of West Antarctica?	
1:45	Is ice mechanical heterogeneity controlling the stability of the Larsen C ice shelf?	Kulessa
2:00	Numerical model investigation of Crane Glacier response to collapse of Larsen-B Ice Shelf, Antarctic Peninsula	Campbell
2:15	Factors Regulating Post-LGM Retreat of the Pine Island and Marguerite Ice Streams	Anderson
2:30	PANEL DISCUSSION (15 min.)	
	WAIS/FRISP business	
3:00	Adjourn	
	Posters	
	West Antarctic Ice Sheet Elevations near the Ice Divide prior to the LGM	Ackert
	The Antarctic Glaciological Data Center An Archive for NSF Antarctic Program Glaciological Research	Bauer
	Decadal flow variations of Whillans and Kamb Ice Streams from high resolution GPS measurements	Beem
	Peering Beneath the Ice Sheet: AGAP Evidence for a More Dynamic East Antarctica	Bell
	A second MODIS Mosaic of Antarctica: MOA-2009	Bohlander
	Analogue modeling of water flow under ice; what can we learn?	Catania
	Geometric enhancement of the absorption of incoming insolation on complex terrain	Cathles
	Changes in the surface velocity of Thwaites Glacier from differential GPS observations	Christianson
	A comparison of geophysical observations of a Greenlandic supraglacial lake drainage using commercial instruments and a low-cost experimental alternative	Christianson
	Constraints on the Timing of the Last Deglaciation of Antarctica	Clark
	Oceanographic Observations Pertinent to the Petermann Glacier	Falkner
	Past Flow Conditions of Thwaites Glacier revealed by radar-detected internal layer patterns	Fudge
	Modeling Abrupt Change in Global Sea Level due to Ocean–Ice-sheet Interaction	Gladish
	Surface Elevation Changes at the Front of the Ross Ice Shelf; Implications for Basal Melting	Horgan
	Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers	Jenkins
	A Closer look at evidence for subglacial drainage systems in Pine Island Bay, Antarctica	Kirshner
	Using the level set method to track ice sheet boundaries	Lindsey
	Examining the slope-driven control of basal melting	Little
	Glaciology of the Bottleneck, Amery Ice Shelf	Lurie

	Limits to WAIS Predictability?	MacAyeal
	Estimating englacial radar attenuation using depth profiles of the returned power, central West Antarctica	Matsuoka
	Assessing Assessments: a sociocultural history of the West Antarctic Ice Sheet	O'Reilly
	Glaciology of the Bottleneck	Pingree
	Subglacial Landform Analysis and Reconstruction of Miocene Paleotopography of Marie Byrd Land	Spector
	Provenance Implications of Cenozoic Basalt in East Antarctica	Townsend
	Recent thinning and migration of the Western Divide, central West Antarctica	Waddington
	Initial effects of oceanic warming on a coupled ocean-ice shelf-ice stream system	Walker
	Autonomous unmanned platforms and sensors for polar research applications	Wardell
	Analyzing TAMSEIS for Seismic Events of High Temporal Regularity Beneath David Glacier in the Transantarctic Mountains	Zoet

Abstracts

(in order of presentation)

Using oceanographic data to calculate the melt rate at an ice shelf's base

Keith Nicholls, British Antarctic Survey, U.K.

To predict the response of ice shelves to climate variability we need to be able to calculate basal melt rates as a function of the oceanographic forcing on the sub-ice shelf cavity. Key processes are the transfer of heat and salt to the ice shelf base. From the limited available evidence, this appears to have been successfully parameterized for the low melt rate regime, such as beneath large areas of Ronne Ice Shelf, but a dearth of data from the rapidly melting counterpart has hindered the development and testing of such parameterizations for use on warm-sector ice shelves.

In the late 1980s several hot-water drilled access holes were made through George VI Ice Shelf, which lies between the west coast of the Antarctic Peninsula and Alexander Island. The oceanographic regime beneath the ice shelf is similar to that in the Amundsen Sea Embayment. Thermistor cables were deployed at each drill site to measure the temperature through the ice column and in the upper part of the water column; oceanographic profiles (CTD) were obtained from two of the sites at the southern end of the ice shelf. At some sites the thermistor cables were logged every hour or so for a year or more, giving an indication of variability.

We present some of these unpublished data, highlighting differences between the ice-ocean boundary layers beneath this high melt rate environment and the low melt rate environment exemplified by Ronne Ice Shelf. The results suggest that the parameterization used successfully to calculate melt rates beneath the lower melt rate areas of Ronne Ice Shelf cannot be applied in a straight-forward manner to George VI Ice Shelf. We discuss the implications for the calculation of melt rates beneath extreme melt environments such as Amundsen Sea embayment ice shelves.

Ocean circulation and water mass transformation beneath Filchner-Ronne Ice Shelf: results from a three dimensional ocean model

Keith Makinson, British Antarctic Survey, Cambridge, UK...

Ice shelves around Antarctica's coastline provide the largest interface between the Antarctic Ice Sheet and the Southern Ocean. Melting and freezing at the base of these floating extensions of the ice sheet affect ice shelf geometry and dynamics, and are therefore crucial to ice sheet evolution as well as to the generation of globally significant water masses. In the southern Weddell Sea, the annual growth and decay of sea ice over the broad continental shelf and the interaction between ice shelf and ocean, drive the ocean circulation beneath Filchner-Ronne Ice Shelf (FRIS). Ultimately, water masses entering this sub-ice shelf cavity are cooled and freshened, exiting as Ice Shelf Water that flows down the continental slope, making a significant contribution to the Weddell Sea deep and bottom waters.

Applying a modified version of the Miami Isopycnic Coordinate Ocean Model (MICOM) to the southern Weddell Sea and the cavity beneath FRIS, the model results compare well with the limited number of available observations. With the inclusion of tidal forcing and using a horizontal grid resolution of 0.35 degrees of longitude, the model indicates that the majority of the flow into the cavity occurs to the west, in Ronne Depression, while the outflow of around 0.6 Sv occurs in the east, along Filchner Ice Front. Further to the north at the continental shelf break, around 0.9 Sv spills over the Filchner Sill. Beneath FRIS, the average melting at the ice shelf base is 0.24 m/a, with melt rates close to some deep grounding lines exceeding 10 m/a, particularly around Foundation Ice Stream. With so few direct observations from this region, the model also provides useful suggestions for the ocean circulation pattern away from these locations and for the modification of dense water masses trapped within deep depressions... Such results are invaluable in guiding the efficient planning future field work.

Modelling Amery Ice-Shelf/Ocean Interaction

Ben Galton-Fenzi(1,2,3), John Hunter(2), Simon Marsland(3) and Richard Coleman(1,2,3)
1 University of Tasmania, Hobart
2 Antarctic Climate and Ecosystems CRC
3 CSIRO Marine and Atmospheric Research

The effect of climate change on the mass balance of ice shelves and bottom water formation is investigated using a terrain-following three-dimensional numerical ocean model. The Regional Ocean Modeling System was modified to simulate the thermodynamic processes beneath ice shelves, including direct basal processes and frazil ice dynamics. The Amery Ice Shelf/ocean model is forced with tides, seasonal winds and relaxation to seasonal lateral boundary climatologies. The open ocean surface fluxes are modified by an imposed climatological sea-ice cover that includes the seasonal effect of polynyas.

The circulation and basal melting and freezing show good agreement with glaciological and oceanographic observations. Strong horizontal and thermohaline ("ice-pump") circulation is primarily driven by melting and refreezing of the ice shelf interacting with High Salinity Shelf Water. The net basal melt rate is ~45 Gt year-1 (~0.7 m ice year-1), which represents 67 % of the total mass loss of the Amery Ice Shelf. The total amount of refreezing is ~5.3 Gt year-1, of which 70 % is due to frazil accretion. The seasonal variability of the basal melt/freeze (up to +-1 m ice year-1) within 100 km of the open ocean is the same magnitude as the area-averaged melt rates. The annual averaged bottom water formation rates are ~1 Sv to the west of the Amery, in the vicinity of Cape Darnley.

The Amery Ice Shelf/ocean model is used to investigate the sensitivity of the basal melt/freeze and bottom water formation to the inclusion of various physical mechanisms and changes in forcing. Direct comparison with glaciological observations shows that ice-shelf models that include frazil processes improve the simulated pattern of marine ice accretion. Simulations without ice-shelf/ocean thermodynamic processes overestimate bottom water formation by up to 2.8 times as much as simulations with ice-shelf/ocean thermodynamic processes, due to the missing buoyant freshwater from the melting ice shelf. Climate change sensitivity studies suggest that an ocean warming of 1 degree C above present day temperatures can potentially remove the Amery Ice Shelf in ~700 years, solely due to increased basal melting, and can also lead to a significant decrease in the formation of bottom water. This research contributes to understanding how interaction between ice shelves and various forcing mechanisms can lead to changes in basal melt/freeze and dense water formation, which has major implications for the stability of ice shelves, sea level rise, and the salt budget of the global oceans.

Overturning of the Antarctic Slope Front and ice shelf melting along the coast of Dronning Maud Land

Ole Anders
Norwegian Polar Institute
Polar Environmental center, Tromso, Norway, 9296

Out of 19 elephant seals that were equipped with CTD data loggers on the Bouvet Island in January 2008, eight reached the Antarctic coast. These eight seals collected hydrographic data from the Dronning Maud Land coastal zone between 25W and 45E covering the period from February through October 2008. During this period the seals collected more that 2000 profiles of temperature and salinity within the coastal zone, which we define as the area with bottom depth less than 2000m. The hydrographic data has been used to explore the properties of the water masses south of the Antarctic slope front. These water masses are directly interacting with ice shelves, and temperature and circulation of these water masses determine the ice shelf melting in the region. The data suggests that the Antarctic Slope Front is an effective barrier preventing the Warm Deep Water (WDW) to flow directly on to the continental shelf, as the warmest temperatures observed south of the ASF is about -1.6 °C. However, WDW is still the most important heat source of the shelf water masses. The low temperatures observed is a result of strong mixing with shelf water as WDW crosses the ASF. From February to October the water masses south of the ASF are gradually getting more saline. The salinity increase cannot be explained by sea ice formation alone. Overturning of the ASF with accompanied inflow of modified WDW onto the continental shelf is an important process leading to the salinity increase. ISW is observed flowing out from the main sill between the Fimbul Ice Shelf cavity and the open ocean. No other locations of ISW outflow is observed, suggesting that the Fimbul outflow is unique for the region. We will discuss estimates on ice shelf melting based on the observed salinity increase and inflow of WDW.

Bathymetry beneath Pine Island Glacier revealed by Autosub3 and implications for recent ice stream evolution

Adrian Jenkins1, Pierre Dutrieux1, Steve McPhail2, James Perrett2, Andy Webb2 and Dave White2 and Stan Jacobs3

1 British Antarctic Survey, Natural Environment Research Council, Cambridge, UK.
2 National Oceanography Centre, Southampton, UK.
3 Lamont-Doherty Earth Observatory of Columbia University, New York, USA.

The Antarctic ice sheet, which represents the largest of all potential contributors to sea level rise, appears to be losing mass at a rate that has accelerated over recent decades. Ice loss is focussed in a number of key drainage basins where dynamical changes in the outlet glaciers have led to increased discharge. Some of the most significant changes have been observed on Pine Island Glacier, where thinning, acceleration and grounding line retreat have all been observed, primarily through satellite remote sensing. Even during the relatively short satellite record, rates of change have been observed to increase.

Between 20th and 30th January 2009 the Natural Environment Research Council's autonomous underwater vehicle, Autosub3, was deployed on six sorties into the ocean cavity beneath Pine Island Glacier. Total track length was 887 km (taking 167 hours) of which 510 km (taking 94 hours) were beneath the glacier. One of the main aims was to map both the seabed beneath and the underside of the glacier.

Among the instruments carried by Autosub-3 were a multi-beam echosounder that could be configured to look up or down, and two Acoustic Doppler Current Profilers (ADCP's): an upward-looking 300 kHz instrument and a downward-looking 150 kHz instrument, providing a record of ice draft and seabed depth along the vehicle track. The ADCP data reveal an apparently continuous ridge with an undulating crest that extends across the cavity about 30km in from the current ice front. Swath soundings indicate that this ridge was a former grounding line, while satellite imagery from the early 1970's hints that Pine Island Glacier might still have been in contact with the ridge at that time. These findings suggest that the changes observed by satellite over the past two decades are the continuation of a longer period of grounding line retreat.

Ocean properties beneath Pine Island Glacier revealed by Autosub3 and implications for circulation and melting

Pierre Dutrieux1,, Adrian Jenkins1, Stan Jacobs2, Steve McPhail3, James Perrett3, Andy Webb3 and Dave White3*

1British Antarctic Survey, Natural Environment Research Council, Cambridge, UK.
2Lamont-Doherty Earth Observatory of Columbia University, New York, USA.
3National Oceanography Centre, Southampton, UK.

The Antarctic ice sheet, which represents the largest of all potential contributors to sea level rise, appears to be losing mass at a rate that has accelerated over recent decades. The synchronous response of several independent glaciers, coupled with the observation that thinning is most rapid over their floating termini, is generally taken as an indicator that the changes have been driven from the ocean. The deeper parts of the Amundsen Sea continental shelf are flooded by Circumpolar Deep Water (CDW) with a temperature around 1ºC, which potentially drives rapid melting of the floating ice.
Between 20th and 30th January 2009 the Natural Environment Research Council's autonomous underwater vehicle, Autosub-3, was deployed on six sorties into the ocean cavity beneath Pine Island Glacier, totaling a track length of 510 km (taking 94 hours) in this previously unexplored environment. Some specific aims were to investigate how CDW flows beneath Pine Island Glacier and determines its melt rate.

Among the instruments carried by Autosub-3 were a Seabird CTD, with dual conductivity and temperature sensors plus a dissolved oxygen sensor and a transmissometer, and two Acoustic Doppler Current Profilers (ADCP's) providing a record of seabed depth and ice draft along the vehicle track. The ADCP data reveal an apparently continuous ridge that extends across the cavity about 30km in from the current ice front. This topographic feature blocks CDW inflow from the inner cavity and impacts the degree to which it mixes with the cooler melt water outflow. Melt water concentration derived from temperature, salinity and oxygen measurements traces the path of the outflow. High melt water concentration always corresponds to high light attenuation indicating the presence of suspended matter.

Effects of waves on ice shelves

Olga Sergienko

AOS Program, Princeton University
201 Forrestal Road
Princeton, NJ, 08540

Floating glaciers, ice shelves and ice tongues are in constant interaction with ocean. Traditionally, this interaction is considered in terms of the ocean thermodynamic effects - melting/refreezing on the floating ice base. This study focuses on mechanical effects of the ocean waves on ice shelves and floating glaciers. Effects of the long waves (wavelength is much larger than the water depth at the ice front) on the ice-shelf stress regime are investigated numerically and analytically. Magnitudes of the stresses induced by the ocean waves are in order of 10-15% of other glaciological stresses.

Seismic Studies of Glacier Calving

F. Walter(1), S. O'Neel(2), Jeremy Bassis(3), Helen Fricker(1), W.T. Pfeffer(4)

(1) Scripps Institution of Oceanography, University of California San Diego, La Jolla CA USA
(2) USGS AK Science Center, Anchorage AK USA
(3) Geological Sciences, University of Michigan, Ann Arbor MI USA
(4) Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder CO USA

In order to better constrain glacier and ice sheet mass balance changes as a response to global climate changes, a large number of glaciological studies have been centered around the phenomenon of iceberg calving. However, to this point calving is still poorly understood and has therefore not been included in ice flow models used to predict large-scale mass balance changes. Fracture propagation, failure mechanism and the role of the proglacial melange are some of the factors whose role in the calving process have to be clarified in order to derive a physically-based quantitative description of calving. Observations from a variety of calving environments are needed as local conditions like the effective water pressure and stretching rates near the glacier's terminus affect the calving rate and style. In this context, seismic measurements are a valuable tool to monitor and characterize glacier calving.

The seismic signals associated with glacier dynamics show a large variety of characteristics. Related to very big calving events, 'glacial earthquakes' can have a moment magnitude of up to 5 and are thus detectable on global seismic networks. On the other hand, material fractures inside glacier ice emit much weaker signals, which can only be detected on or near the glacier. Whereas the seismograms of individual tensile crack openings inside a glacier are of very short duration (<0.1 seconds), calving events can produce seismic waveforms that can last for several minutes. Recent studies have furthermore revealed the presence of seismic tremors most likely emitted by scraping icebergs inside the melange in the proglacial fjord. These observations reflect that large numbers of individual migrating and connecting fracturing events occur during the detachment of icebergs. Here we present seismic records from a variety of calving environments such as an Alaskan tidewater glacier, an Alpine mountain glacier and Antarctic ice shelves. The seismic signatures elucidate differences and similarities in calving styles and thus contribute to a better understanding of calving mechanisms.

Idiosyncrasies of Measurements and Mixing in Seawater Near Freezing

Miles McPhee

McPhee Research Company
Naches Wa

Supercooling associated with pressure effects on the freezing temperature appears to be an important feature of ice shelf/ocean interaction, capable of significant mass redistribution as water circulates in the shelf cavity, and also providing supercooled water in the ocean beyond the terminus. While describing property exchanges between floating ice shelves and the underlying ocean has traditionally utilized parameterizations and models obtained from observations under drifting sea ice, guidance from measurements in supercooled conditions is rare. This results partly from the fact that supercooling is seldom observed under pack ice, but also from the difficulty of measuring in an environment where instruments provide attractive nucleation sites.

During a study of air-ice-ocean interaction under fast ice in Freemansundet, Svalbard, with strong tidal forcing in water near freezing, we observed the following unexpected behavior in three different conductivity measuring instruments deployed at different depths in nearby locations. During maximum current velocities but at different times, the three C sensors would show sudden drops in conductivity that would persist for 30-60 minutes, then just as suddenly revert to values near those observed before the event. Considered in isolation, the drops were "believable" in the sense that salinity (calculated from temperature and conductivity) would differ by less than one practical salinity unit (psu) from the apparent ambient level, and similarly the inferred supercooling would be less than about 0.2 kelvins. However, from several lines of reasoning, we believe that although the events did signal the presence of supercooled water, the actual change is salinity was minor, hence the magnitude of supercooling was also much smaller. Although perhaps just a curiosity, we believe these events are significant, both because of their implications for properly measuring characteristics of supercooled water, and also providing insight into mixing processes involving different water masses near their respective freezing temperatures.

From the perspective of instrument response, our interpretation of the conductivity drop events is that as a front in salinity (density) structure was advected back and forth past our instruments in a strong tidal flow (~2 kt), supercooled water embedded within the front nucleated a thin layer of ice on the electrode elements that changed the geometry of the sensor enough to modify the conductivity reading. As the front passed, the thin ice film was melted (or eroded) by water that was not supercooled and the cell geometry returned to normal. The implication is that in similar circumstances, our usual instruments for measuring conductivity may be susceptible to nucleation in a way that does not make the reading nonsensical.

From a scientific perspective, a more intriguing aspect of the Freemansundet measurements is that they suggest a process whereby a sharp horizontal front in salinity is sheared under a solid surface (fast ice), leading to vertical mixing of the two water types. Since density depends almost exclusively on salinity, the direction of flow is important for determining the stability of the near surface water column and mixing efficiency. This is apparent in our stress measurements. If the mixing was *conservative* (i.e., salt and heat mixed at the same rate), then no supercooling would occur. Instead, the presence of transient supercooling implies that heat is mixed out of the fresher (slightly warmer) water type faster than salt is mixed in. This apparent double-diffusive mechanism for producing supercooling in a highly turbulent flow, has not to our knowledge been considered before, and may be important in areas where frontal structures exist, including under ice shelves.

Grounding line basal melt rates determined from internal stratigraphy

G. Catania, Institute for Geophysics, University of Texas, Austin TX 78758
C. Hulbe, Geology Department, Portland State University, Portland OR
H. Conway, Dept. of Earth and Space Sciences, Univ. of Wash., Seattle, WA 98195

We use ice-penetrating radar data across the grounding line of Siple Dome and Roosevelt Island, Antarctica to measure the spatial pattern and magnitude of sub-ice shelf melting at these locations. Layers are typically (although, not always) downwarped at the grounding line, likely due to basal melting from warm sub-ice shelf waters coming into contact with the base of the ice sheet. Downwarping occurs over a limited region of up to five kilometers downstream of the grounding line indicating that the pattern of melt may be much more focused than previously assumed. Further, localized downwarping indicates a temporal shift in the melt pattern; either the magnitude of the peak melt rate, the location of the grounding line and/or the shape of the melt pattern shifted at some point in the past. We also find that the pattern of basal melting is not spatially uniform -even over short distances. This heterogeneity may reflect small differences in the shape of the ice shelf cavity since the spatial distribution of melting is sensitive to the sub-ice shelf slope. When compared to melt rates obtained from modeling of sub-ice shelf circulation we find that our peak melt rates obtained from layer analysis agree with the model results around Siple Dome, but not for Roosevelt Island where we find much larger melt rates than expected.

Analysis of ice plains on Ross and Filchner/Ronne ice shelves using ICESat data

Kelly M. Brunt, Helen A. Fricker, Laurie Padman*

We use laser altimeter data from the Ice, Cloud, and land Elevation Satellite (ICESat) to map the grounding zones of ice shelves in Antarctica. Ice flexure in the grounding zone occurs as the ice shelf responds to ocean height changes due primarily to tides. The landward and seaward limits of this flexure region, which define the grounding zone, can be detected through ICESat repeat-track analysis since each satellite pass is acquired at a different tidal phase. Using this method, we have currently mapped the major Antarctic ice shelves (Amery, Filchner/Ronne, and Ross) and the Antarctic Peninsula (the Larsen ice shelves and the Wilkins Ice Shelf). Through the course of this endeavor, we have identified and mapped a number of ice plains, or regions of lightly grounded ice, on the Ross and Filchner/Ronne ice shelves. This was accomplished through analysis of altimetry profiles and comparison of ICESat grounding line estimates with others based on either digital elevation models or satellite imagery. We present some of the unique signatures of these features in ICESat data.

Antarctic ice shelf thickness estimates derived from satellite altimetry

J.A. Griggs and J.L. Bamber

Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, UK.

Ice shelf thickness is an important boundary condition for ice sheet and sub shelf cavity ocean modelling and is needed to improve mapping of all the ice shelves in Antarctica. It is also required near the grounding line to calculate the ice fluxes required to determine ice sheet mass balance. In this approach, the accuracy of the ice thickness is one of the constraining parameters on the uncertainty in the estimate. Ice thickness is also required to calculate the sub-shelf mass balance and bottom melting rates based on the principles of conservation of mass.

Ice thicknesses can be determined from in situ radio echo sounding measurements but these data provide, in general, rather sparse spatial coverage. Ice thickness can also be estimated from the surface elevation of floating ice if it is assumed to be in hydrostatic equilibrium, an assumption which we will discuss in the presentation. Satellite altimetry has dramatically increased the accuracy and coverage of elevation data and the capability to infer the ice thickness of all Antarctic ice shelves now exists.

We present a satellite retrieval of the ice thickness for all Antarctic ice shelves mainly using the ERS-1 geodetic phase data from 1994-5 supplemented by GLAS data for regions where ERS-1 data are not available. Surface elevations derived from these instruments are interpolated onto regular grids using krigging and converted to ice thicknesses using a modelled firn density correction. We focus particularly on Larsen C as a case study for concerted validation effort. This is our worse case scenario shelf due to its northerly location meaning lower data densities and its melting surface as melting is not included in our modelled firn density correction. Validation for Larsen C suggests that ice thickness can be determined with an accuracy of -0.22 ± 36.7 m. The random error determined is equivalent to about 13% of the mean ice shelf thickness.

A Time-Dependent Model of Pine Island Glacier Constrained by Satellite Observations

Ian Joughin and Ben Smith

Several studies have demonstrated that Pine Island Glacier should speedup as its ice shelf thins and ungrounds. Here we conduct similar experiments, but constrained by time series of velocity and recently derived grounding-line estimates. We begin by using inverse methods to infer the ice stream's basal shear stress in 1996, when a large ice plain existed just above the grounding line. Since 1996, the grounding line has retreated by more than 20 km in places, leaving behind a grounded "island" where the ice plain once existed. We force our model by reducing the bed resistance linearly with time in the region between the 1996 and 2009 grounding line positions, which produces velocity increases that agree well with the observed values. We experiment with a number of sliding parameterizations, including linear-viscous, power-law, and plastic models. The results show that for the plastic bed and some n=3 cases, thinning propagates far more rapidly inland than it does for the linear-viscous model used in earlier studies. After physically reasonable adjustment of the model parameters, we are able to reproduce the magnitude and the pattern of thinning along the entire length of the ice stream.

GPS velocity from the Pine Island Glacier drainage area

Truffer, Bindschadler

Pine Island Glacier is one of the glaciers draining the marine West Antarctic Ice Sheet and is believed to be particularly vulnerable to change. A series of velocity observations derived from remote sensing show that the glacier continues to accelerate. Here we present results from GPS observations at a location near the main glacier. The data spans two summer seasons with interruptions in winter due to power problems. A time series analysis show that there is a small seasonal variation in flow. Since surface melting is not believed to be a factor here, the variation could be related to previously suggested seasonal variations in melting near the grounding line, which also appears to be manifested in the sub-iceshelf topography.

Wind Effects on Circumpolar Deep Water Intrusions on the West Antarctic Peninsula Continental Shelf

Michael S. Dinniman and John M. Klinck
Center for Coastal Physical Oceanography, Old Dominion University

Relatively warm Circumpolar Deep Water (CDW) can be found near the continental shelf break around most of Antarctica. Advection of this warm water across the continental shelf to the base of floating ice shelves is thought to be a critical source of heat for basal melting in some locations. Changes in either the temperature or quantity of CDW moving onto the continental shelf have been proposed as a possible mechanism for increases in the basal melt rate of the ice shelves in some areas. Along the west Antarctic Peninsula (WAP), the southern boundary of the Antarctic Circumpolar Current (ACC) is adjacent to the shelf break which is relatively close to several ice shelves, allowing the effects of cross-shelf break transport of CDW to have a rapid impact on the basal melting of the nearby ice shelves.

A high resolution (4 km) regional ocean/sea-ice/ice shelf model of the west Antarctic Peninsula coastal ocean is used to examine the mechanisms of CDW intrusions onto the continental shelf. In the WAP, the previous view (based on broad scale hydrographic surveys) was that there were 4-6 intrusions per year in the Marguerite Bay area. However, mooring data in Marguerite Trough, the major pathway for CDW intrusions into Marguerite Bay, shows a much higher intrusion frequency of approximately 4 intrusions per month with the typical duration being 1-3 days (Moffat et al., 2009). Examining fluxes of not only heat, but a simulated "dye" representing oceanic CDW, shows that the model has about 2 intrusions per month in Marguerite Trough with an average duration of 1-4 days. The model solutions have a significant correlation between the along shelf break wind stress and the cross shelf break dye flux through Marguerite Trough suggesting that intrusions are at least partially related to short duration wind events.

The effects of possible changes in the winds on the CDW transport and basal melt have also been examined. Instead of performing full climate downscaling simulations, simplified simulations were run where the winds were scaled by constant (stronger or weaker) factors. One additional simulation was run with an increased ACC transport, forced by increased temperature and salinity gradients in the ACC fronts on the model lateral open boundaries. Increases in winds and ACC transport led to increases in the amount of CDW advected onto the continental shelf. However, these did not necessarily lead to increased CDW flux underneath the nearby ice shelves and the basal melt underneath George VI Ice Shelf actually decreased with increased wind strength.

Marine Ice in Larsen Ice Shelf

Paul R. Holland, Hugh F. J. Corr, David G. Vaughan, Adrian Jenkins, and Pedro Skvarca

It is argued that Larsen Ice Shelf contains marine ice formed by oceanic freezing and other mechanisms. Missing basal returns in airborne radar soundings and observations of a smooth and healed surface coincide downstream of regions where an ocean model predicts freezing. Visible imagery suggests that marine ice currently stabilizes Larsen C Ice Shelf and implicates failure of marine flow bands in the 2002 Larsen B Ice Shelf collapse. Ocean modeling indicates that any regime change towards the incursion of warmer Modified Weddell Deep Water into the Larsen C cavity could curtail basal freezing and its stabilizing influence.

Antarctic Ice Shelf Environmental Survey and Oceanographic Capability: Interdisciplinary Science Plans and Prospects.

F.R. Rack(1), R. Zook(2), J. McManis(3), D. Blythe(1), D. Harwood(1), K. Speer(4) and T. Stanton(5)

(1)ANDRILL Science Management Office, 126 Bessey Hall, University of Nebraska-Lincoln, Lincoln, NE 68588-0341 (email: frack2@unl.edu; 402-472-4785)
(2)Moss Landing Marine Laboratories, 8272 Moss Landing Road, Moss Landing, CA 95039
(3)Engineering & Science Research Support Facility, College of Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588-0511
(4)Department of Oceanography, Florida State University, Tallahassee, FL 32306-4320
(5)Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943

We have proposed the development of an Antarctic Ice Shelf Environmental Survey and Oceanographic Capability (AISESOC, pronounced "icey sock"), which would provide access through the ice shelf to environments in the Ross Sea, and potentially other ice shelf regions around Antarctica. If funded, the AISESOC will support current and future ANDRILL (ANtarctic geological DRILLing) survey and drilling projects as well as providing a community-based, multidisciplinary environmental survey capability.

Ice shelves isolate the seafloor beneath them from sunlight and primary productivity, alter water motion from waves and currents, and prevent gas exchange between surface ocean waters and the atmosphere. Ice shelves also play a role in regulating global sea level by buttressing the ice sheets that feed into them. Understanding the role of heat transport to the base of the ice shelf by currents and determining the rate of change in ice shelf thickness are two critical parameters for understanding past and future ice shelf/ice sheet dynamics. Understanding the transport of nutrients under the ice shelf and their influence on benthic ecology and diversity is another important question that should be addressed to quantify change in these remote ecosystems. Linking the known Ross Sea oceanographic system to the unknowns under the Ross Ice Shelf is a highly significant and desirable goal that will be advanced through the deployment of AISESOC.

AISESOC is conceived as an integrated "instrument package" (comprising six modules), including: (1) the development of a deep-water, modular, small-diameter, Remotely Operated Vehicle (ROV), topside winch system and maintenance van (i.e., a deep-water enhancement of the existing SCINI ROV (300 m water depth limit) to enable operations in combined ice shelf and water depth thicknesses of up to 1200 m); (2) a mobile hot water ice drilling system (designed to make 30 cm in diameter access holes through the 300 to 500 m-thick regions of the ice shelf) that can also be used in a stand-alone mode for specific projects; (3) mobile environmental laboratories (with power, plumbing, environmental systems, and instrumentation appropriate to their functions); (4) an oceanographic instrument pool (i.e., current meters, thermistors, CTDs, water samplers, profilers, etc.) and supporting deployment equipment (A-frame and winches); (5) two tractors (traverse heavy equipment, e.g., Caterpillar Challengers or Case IH articulated quad trac tractors) that will tow the modules across the ice shelf to specific site locations; and (6) mobile camp facilities to support 10-16 people.

The drilling strategies being explored for the ANDRILL Coulman High (CH) Project, either POGO-style (offset) drilling or borehole re-entry, each require the use of a deep-water ROV to provide observations, mapping, and/or advanced capabilities requiring a gripper, such as attaching lines or guiding tools, or sampling the benthic biology, water and sediments. The mechanics of re-entry operations are complex and will require the ability to access the sea riser and the re-entry cone during re-connection operations. The Deep-SCINI ROV will be designed to carry out "lightweight" tasks, such as triggering equipment on the seafloor, aligning logging tools for bore hole re-entry, and transferring light guide lines. Preliminary field site surveys at the CH sites are scheduled in 2010 to investigate the sub-ice cavity with the existing SCINI ROV, to deploy current moorings, and begin to develop and test procedures for sub-ice shelf deployments of longer-duration and deeper depths during ANDRILL Coulman High sediment drilling.

The Deep-SCINI ROV system will be supported by a hot water drill (HWD) system that melts (~30 cm in diameter) access holes through an ice shelf up to 500 m thick. The proposed HWD will be used to augment the existing ANDRILL HWD system during drilling operations requiring ROV support, as well as providing a mobile, independent capability for interdisciplinary surveys across the Ross Sea that require integrated hot water drilling, ROV operations, and deployment of oceanographic sensors. Mobile laboratories that can be reconfigured to support science requirements will be combined with mobile logistics infrastructure (camp/kitchen/sleeping quarters) and heavy equipment to tow these modules. This integrated environmental survey capability is intended to be capable of conducting benthic (photographic and multi-beam sonar imaging/mapping) surveys of the seafloor beneath the ice shelf, make water column measurements, and perform discrete sampling at the seafloor, augmented by the deployment of oceanographic instrument arrays (oceanographic moorings and ice-tethered profilers) to conduct both short- and long-term time series observations.

The proposed AISESOC modules are aligned with the scoping requirements of the ANDRILL CH Project and those of the WISSARD project, both of which are being planned for presumed field operations between 2012-2016 based on proposed schedules. The development of the AISESOC would provide significant risk mitigation for these large, complex projects that require traverse and other capabilities. Oceanographic instrument deployments using the AISESOC, combined with modeling efforts using the data generated by these installations, would contribute to an improved understanding of the sub-ice shelf environment and support long-term observatory science as part of a Southern Ocean Observatory System (SOOS). The availability of year-around data from the sub-ice cavity, from time series measurements and discrete observations of critical parameters, will lead to improvements in our understanding of Ross Sea oceanographic, biological and ecological processes, which in turn will improve our understanding of these environments and allow data to be incorporated into a wide variety of models.

Figure 1. Ross Ice Shelf thickness in meters overlain on LIMA imagery.

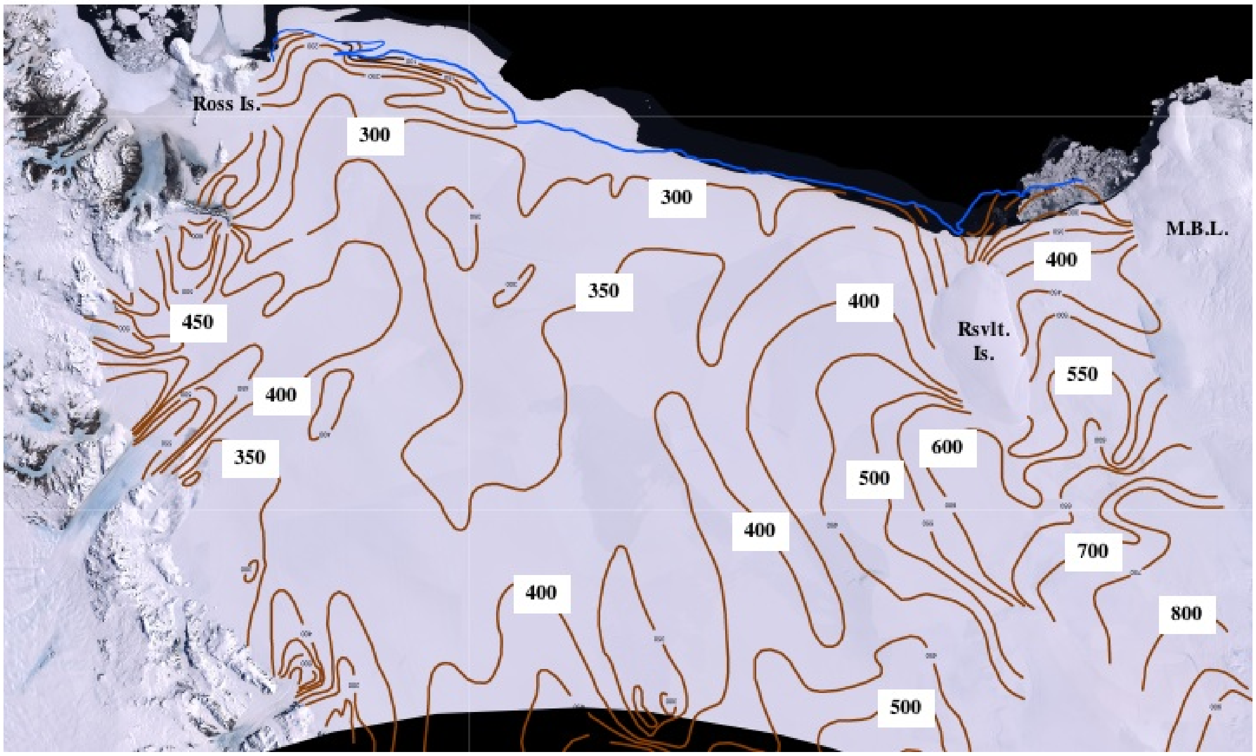
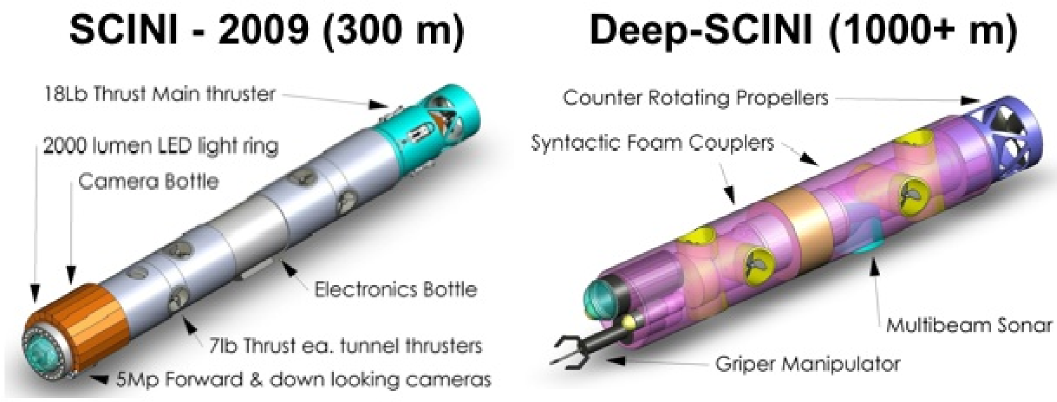


Figure 2. SCINI-2009 and Deep-SCINI remotely operated vehicle schematics.



Inferring Transients in Ice Flow, Ice Thickness, and Accumulation Rate from Internal Layers near the WAIS Divide ice-core site

Michelle Koutnik[1], Ed Waddington[1], Howard Conway[1], Tom Neumann[2], and Steve Price[3]

[1]*Department of Earth and Space Sciences, University of Washington, Seattle, WA*
[2]*NASA Goddard Space Flight Center, Greenbelt, MD*
[3]*Fluid Dynamics Group, Los Alamos National Laboratory, Los Alamos, NM*

Ice-sheet internal layers preserve information about how the ice sheet responded to past spatial and temporal changes in accumulation rate and ice dynamics, and present-day internal-layer shapes observed by radar are the most accessible remaining record of this past information. To infer transients in ice flow, ice-sheet thickness, and accumulation rate from the shapes of internal layers, we solve an inverse problem. While some details of these histories can be recovered from ice cores, ice cores represent conditions at only a single point. However, our approach is more robust in combination with ice-core data. If internal layers are dated, for example by an intersecting ice core, then radar-observed internal layers provide both spatial and temporal information. We apply our new inverse approach near the WAIS Divide ice core.

Each layer represents a past surface of a particular age that has been subsequently buried by accumulation and also modified by ice flow; the process of internal-layer formation can be described with an ice-flow forward model. Deeper layers contain information from further in the past, making them highly valuable. However, deep layers have also likely been subjected to greater spatial and temporal gradients in strain rate and accumulation, making them more difficult to decipher. Our goal in solving this inverse problem is to find the smoothest set of model parameters (e.g. accumulation-rate history) that will explain the data (e.g. internal-layer shapes). We match predictions of observable quantities made with our forward algorithm to the measured values at an expected tolerance while, in this case, finding a spatially smooth accumulation pattern and a parameter set that is consistent with physically characteristic values of the parameters.

The spatial and temporal histories of ice-sheet flow and of accumulation are necessary to recreate ice-volume and sea-level histories. In addition, understanding large-scale evolution of ice sheets over long timescales is critical in order to properly interpret ice-core chemistry and to properly date an ice core, especially in portions of the core where annual-layer counting is no longer reliable. For example, we can infer the accumulation rate at the location and time where each piece of ice in the ice core originated on the ice surface to convert chemical concentrations into fluxes from the atmosphere, or we can infer temporal changes in accumulation and ice thickness at one location on the surface to test GCM simulations of past climate. These spatial and temporal histories are necessary to properly date the ice core with occluded gases because Δage at pore closeoff depends on accumulation rate. We also examine the sensitivity of our approach to infer the individual imprint of ice-divide migration and of accumulation-rate variations on internal-layer architecture.

The interaction of context and structural uncertainty in ice sheet modeling

Christopher M. Little
Princeton University, Department of Geosciences

Michael Oppenheimer
Department of Geosciences and Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton NJ

Jessica O'Reilly
Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton NJ and Department of History and Science Studies Program, University of California, San Diego

As indicated by this session's title, there is a call (scream?) to improve glaciological models for the purposes of century-scale sea level rise (SLR) prediction. Fully characterizing the uncertainty associated with these predictions is a daunting, and essentially impossible, task. Yet the effort is worthwhile, because policy tools employed in SLR assessment may differ depending on the nature and magnitude of model uncertainty. For policy makers, methodologies to cope with pervasive structural uncertainty may include imprecise probabilities [Kreigler et al. 2009], scenario-based [Betz 2007], and "robust" approaches [Lempert et al., 2004]; these policy tools may in turn influence the choice of scientific models used in risk assessment.

One existing typology [Walker et al., 2003] employs three criteria to characterize uncertainty in model-based risk assessment: its location, level, and nature. In this presentation, we suggest how SLR projections derived from glaciological models might be characterized by this typology, highlighting uncertainty introduced in the bounds of the analysis ("context uncertainty"). Historically, subjective bounds have resulted in the ignorance of key processes or have focused attention on regions that may be less vulnerable to rapid ice loss.

Context and model uncertainty often exhibit tradeoffs that hinder uncertainty analysis and aggregation. This interaction mandates that both end users (policymakers) and model developers (scientists) recognize the assumptions and boundaries of an assessment. It also implies that any one modeling framework is likely to be limited. Model hierarchies similar to those employed in climate assessment may offer a path forward, yet there remain difficulties in developing appropriate "reduced" ice sheet models.

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High-resolution simulation of the extent and flow of Antarctic Peninsula glaciers

Nicholas Golledge[1], Jeremy Everest[2], Alun Hubbard[3], Phil Leat[4], Joanne Johnson[4]

[1]Antarctic Research Centre, Victoria University of Wellington, Wellington 6140, New Zealand
[2]British Geological Survey, West Mains Road, Edinburgh, EH9 3LA, United Kingdom
[3]Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, United Kingdom
[4]British Antarctic Survey, Madingly Road, Cambridge, United Kingdom

Steig et al (2009) identified the Antarctic Peninsula as one of the fastest warming regions on Earth over recent decades. Changes to glacier systems consequent on atmospheric and oceanic temperature perturbations will best be understood through combined interpretation of high-resolution ice sheet modelling, remotely-gathered, and field-based empirical data. We outline an incipient research program which aims to use high-resolution numerical glacier modelling to interpret geological proxy evidence concerning recession of Peninsula glaciers through the last Termination. Assuming this can be achieved with realistic model physics and forcing conditions, our aim is to use the validated model to assess glacier sensitivities to predicted future environmental changes.

The failure of fracture mechanics: (Or can fracture mechanics be used to predict when melt ponds will drain?)

Jeremy Bassis

One of the discoveries in glaciology over the past decades with far reaching consequences is the realization that melt water can accumulate in ponds or lakes on the surface of ice sheets and ice shelves and then suddenly drain all the way to the ice sheet (or shelf) base. Although these sporadic drainage events have little influence on the mass balance of ice sheets, they can have profound consequences for the dynamics of the ice sheet/shelf. For instance, the explosive disintegration of Antarctic Peninsula ice shelves has been blamed, at least in part, on the increased fragmentation of the ice caused by the hydrofracturing events that preceded melt lake drainage. Linear elastic fracture mechanics (LEFM) provides the theoretical framework which has long been invoked to explain how melt water assisted fractures can penetrate through up to one kilometer of sub-freezing ice. In the most common interpretation of LEFM, the availability of melt water is the primary limiting factor in explaining when fractures will propagate through the entire ice thickness. However, if melt water truly limits when a lake drains one would expect some threshold size beyond which lakes cannot exist.

Instead, observations indicate that the size distribution of surficial lakes on Greenland follows an exponential distribution, where nearly all of the measured lakes have sufficient melt water volume that they ought to drain (by LEFM standards). The question we ask is why don't these lakes drain? In this presentation we argue that fracture is a random process and that the exponential size distribution of observed lakes can be explained using extreme value statistical. In this theory, the probability that a lake will drain is determined from the probability that a lake intersects with a pre-existing fracture. To make predictions using this theory we also need to know something about the size distribution of fractures. We explore a class of statistical thermodynamic models of fracture of disordered media as a means of making quantitative predictions of surficial drainage events.

Under very general assumptions, we show that this approach can explain the exponential distribution of melt lake sizes.

Ice sheet water models: routing, timing, and pressure distribution

Sasha P. Carter (spcarter@ucsd.edu)[1], Helen A Fricker (hafricker@ucsd.edu)[1], William H. Lipscomb (lipscomb@lanl.gov)[2], Stephan H. Price (sprice@lanl.gov)[2]
Jesse Johnson (jesse.johnson@mso.umt.edu)[3]
Donald D. Blankenship (blank@ig.utexas.edu)[4]

(1) Institute of Geophysics and Planetary Physics (IGPP), Scripps institution of Oceanography, University of California at San Diego, mail code 0225
9500 Gilman Drive, La Jolla, CA 92093
(2) Los Alamos National Laboratory, Group T-3, Mail Stop B216, Los Alamos, NM 87545
(3) Department of Computer Science, Social Science Building, Room 417, The University of Montana, Missoula, MT 59812-5256
(4) University of Texas at Austin John A and Katherine G Jackson School of Geosciences Institute for Geophysics, J.J. Pickle Research Campus, Bldg. 196; 10100 Burnet Road (R2200), Austin, TX 78758-4445

Ice sheet basal hydrology and its relation to basal sliding continues to constitute a source of significant uncertainty in ice sheet modeling. Most basal water models currently employed construct the hydraulic head surface; the sum of the basal elevation and the normalized water pressure, assuming water pressure is equal to overburden pressure everywhere. Although this assumption of zero effective pressure is valid for the centers of large subglacial lakes, it implies an absence of basal traction anywhere water is present while producing a water distribution in which most basal water is confined to narrow channels one grid cell across, and consequently unable to support widespread the basal sliding observed in major ice streams. Given that effective pressure tends to increase with water depth, the initial concentration of water in narrow channels predicted by current models will tend to spread laterally if effective pressure is taken into consideration. Here we explore an iterative algorithm to obtain more realistic predictions of water sheet thickness, velocity and effective pressure, in the context of the GLIMMER CISM Ice sheet model and its application to the Siple Coast region.

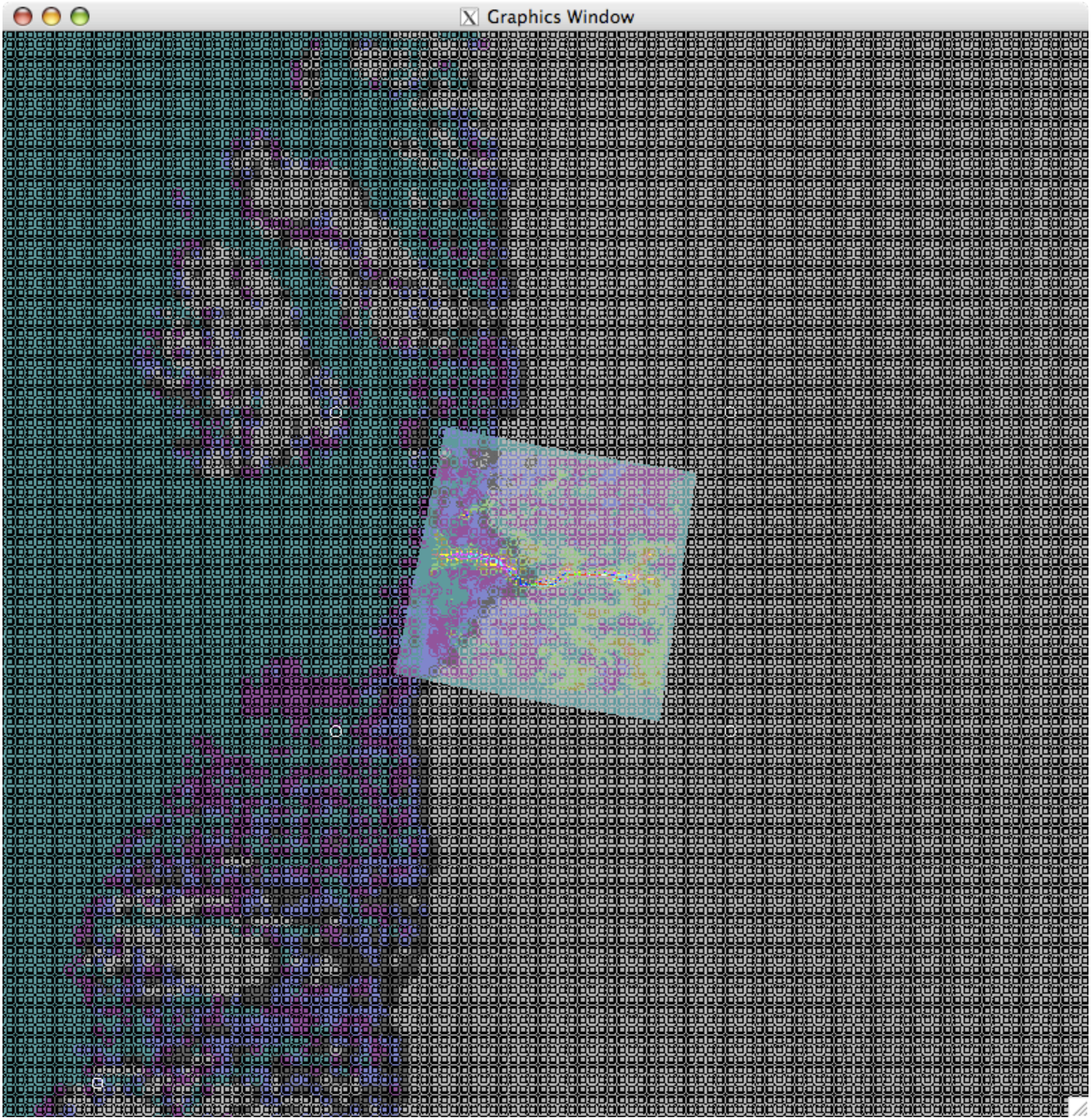
The Dilemma of RESOLUTION: How Good is Good Enough: A Case Study from Greenland

James Fastook,
Climate Change Institute & Computer Science, University of Maine

Many of the whole-icesheet modelers involved with SeaRISE are attempting to predict the response of the Greenland and Antarctic Ice Sheets to projected climate change, and as such are using a database of the present icesheets' configurations provided by Jesse Johnson (http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment). These datasets include surface elevation, thickness, bedrock elevation, and other critical boundary conditions required by the icesheet models. Both Greenland and Antarctica are provided at 5 km resolution.

We have seen from previous work that an accurate representation of the bed is essential if models are to produce reasonable results. As we look at the response of the icesheets to projected climate change, we wonder how good our resolution must be, especially in the fast-flow areas of the ice streams, many of which are topographically controlled.

CRESIS has provided us with a very high-resolution representation of the bed in the Jakobshavn catchment area (Figure 1), and we show the results of 1) using this high-resolution dataset at a degraded resolution comparable to the whole-icesheet dataset provided by Jesse Johnson, and 2) using progressively higher resolutions to more accurately capture the deep channel in which the Jakobshavn Ice Stream flows (Figure 2). This is done using the embedded-model feature of UMISM, whereby a higher-resolution, small-domain model (the ice stream) is run inside a lower-resolution, broader-domain model (the whole icesheet).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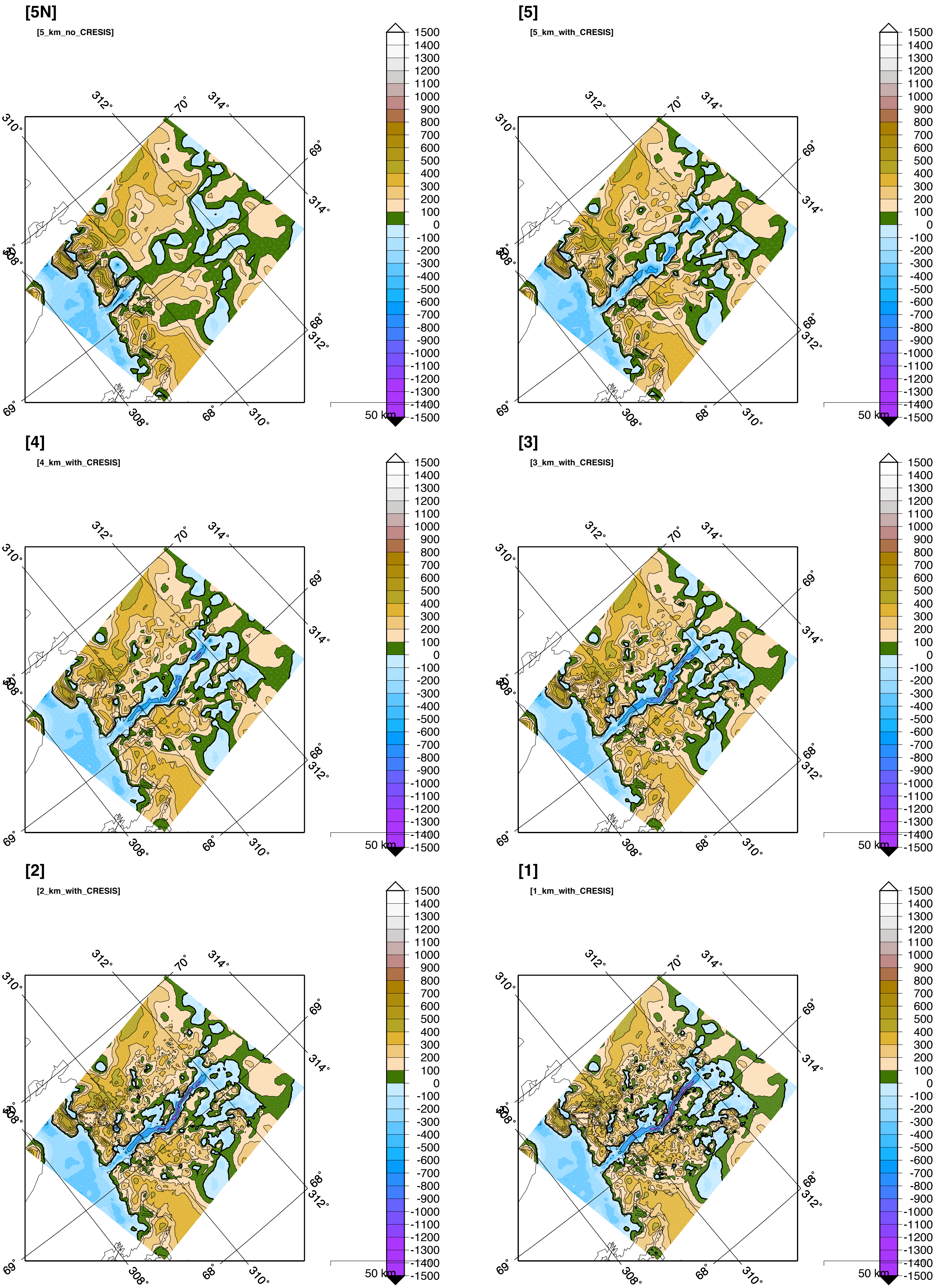

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Response of the Antarctic Ice Sheet to increased ice-shelf oceanic melting

David Pollard (1) and Robert M. DeConto (2)

(1) Earth and Environmental Systems Institute, Pennsylvania State University, University Park, Pennsylvania 16802
(2) Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003

A numerical ice sheet-shelf model is used to simulate the large-scale response of the Antarctic Ice Sheet to prescribed future increases in oceanic melting at the base of floating ice shelves. The model is driven forward in time starting from modern conditions, with either step-function or time-dependent perturbations in parameterized sub-ice oceanic melt rates that crudely represent possible ranges due to future anthropogenic warming.

In some runs, changes to Antarctic precipitation and surface melt are also simply prescribed. It is found that with melt rates under the interiors of large shelves increased to ~2 m/y or more (from modern 0.1 m/y), drastic grounding line retreat in the Ross, Ronne and Pine Island/Thwaites embayments leads to collapse of nearly all marine West Antarctic ice. The time scale of collapse depends on the magnitude of oceanic melt: ~1500 years for 2 m/y, and ~300 years for “infinite” melt (no floating ice). The WAIS collapse causes ~3 m of global sea-level rise. However, the net Antarctic contribution is modified by expected future changes in surface mass balance, especially increased East Antarctic snowfall which significantly reduces the net sea-level rise. In simulations with time-dependent forcing peaking at 2200 AD and then decaying exponentially to represent the natural uptake of anthropogenic CO_2, WAIS still largely collapses for peak oceanic melt rates of ~4 m/y or more, and the re-growth of WAIS towards its modern state is delayed by the CO_2 tail and takes longer than 20,000 years.

The heroic age of ice sheet modeling: Glimmer, CISM and all that

William Lipscomb and Stephen Price, Los Alamos National Laboratory
Jesse Johnson and Tim Bocek, University of Montana
Tony Payne, University of Bristol

Ice sheet models are evolving quickly, as a result of increased interest (and funding) from government agencies, as well as growing collaborations in the glaciology, applied math, and climate modeling communities. Several state-of-the-art ice sheet models are now openly available, including the Parallel Ice Sheet Model (PISM), SICOPOLIS, and Glimmer, the Community Ice Sheet Model (Glimmer-CISM). We are part of a U.S./U.K. group that is developing Glimmer-CISM (http://developer.berlios.de/projects/glimmer-cism/). A developmental version of this model now includes two "first-order" dynamical cores (e.g., Pattyn 2003): one developed by Tony Payne and Steve Price (in prep.), and the other by Tim Bocek, Jesse Johnson, and Frank Pattyn (in prep.). Many collaborators are working on improved parameterizations of key physical processes such as surface melting, basal water transport, iceberg calving, sub-shelf melting, and grounding-line migration. These improvements will be implemented and tested in Glimmer-CISM during the next one to two years. Glimmer-CISM will be used for IPCC simulations with at least two global climate models: the Community Climate System Model and the Hadley Centre model.

We will show some recent Glimmer-CISM results obtained with the new first-order schemes. Given the complexity of the field equations and boundary conditions, much work has focused on model diagnostics, including the ISMIP-HOM intercomparison tests (Pattyn et al. 2008) and the EISMINT-Ross experiment (MacAyeal et al. 1996). Results from these tests give us confidence that the initial large-scale runs for the Greenland ice sheet are valid with respect to the modeled ice dynamics.

The current Glimmer-CISM code is serial. A parallel version, which is needed to run the first-order schemes at higher resolution, is under development. A new DOE program, "Computational science research for ice sheet modeling," is supporting several projects whose aim is to develop efficient, scalable ice-sheet models (both first-order and full-Stokes) on adaptive grids using modern solver techniques (e.g., Newton-Krylov). If these projects are successful, ice sheet models will soon be among the most sophisticated climate model components. Scientific simulations that are impossible today will become routine. As in other heroic ages—such as the heroic age of Antarctic exploration a century ago—there will be setbacks as well as successes, but the journey is sure to be interesting.

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SeaRISE: Addressing “How bad could sea-level rise get”?

Robert Bindschadler

WAIS began under the moniker of SeaRISE (Sea-level Response to Ice Sheet Evolution) thanks to Barclay Kamb suggestion.   While the name was soon changed (thanks to those who remain nameless at NSF), the primary objective of predicting the future contribution of the West Antarctic ice sheet to future sea level remained. And so it remains today.

Recent observations of rapid ice loss in Greenland and other parts of Antarctica have expanded the concern about where increased contributions to sea level might originate and at the same time heightened concern that we might be witnessing the opening stages of dramatic acceleration. Acknowledging the observations of rapid ice-sheet changes, the IPCC-AR4 stated that the “…understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise.” Through workshops and conversations, a coordinated effort, recycling the name SeaRISE, has emerged that seeks to address this weakness in ice sheet models on a schedule to inform the next IPCC Assessment Report. SeaRISE’s goal is to provide quantitative, upper bound estimates of ice sheet contributions to sea level for the 21^{st} and 22^{nd} century. Confidence in these estimates will be gained by applying many independent models to a common set of climate and boundary condition scenarios to reduce unrealistic characteristics of any single model from affecting the predictions.

The first experiments are intentionally extreme in their physical realism to help determine the upper bound of possible future ice sheet response. Subsequent experiments representing more likely scenarios will then be run to help lower the upper bound. All models will quantify their calculated ice sheet responses relative to a control run of the same model generated either by holding modern climate fixed in the future or by using AR4 predictions of future climate. This “normalization” process will help minimize unrealistic aspects of any single model and attempt to further isolate the impact of the difference in forcing between the experiment and the control runs.

SeaRISE includes regional models as well as whole ice sheet models. The interactions are expected to be two-way: regional models will be used to help provide more reasonable forcings for selected whole ice sheet model experiments and whole ice sheet models will be used to define boundary fields that will enable regional models to refine the predicted responses of particularly dynamic areas. Another anticipated benefit is that the results of this effort will help inform the implementation of dynamic land ice into a fully coupled CCSM.

The Life Cycle of Ice Streams

T. Hughes
Department of Earth Sciences and Climate Change Institute
University of Maine, Orono, ME 04469

Ice streams have life cycles that proceed through inception, growth, mature, declining, and terminal stages controlled by basal buoyancy factor ϕ_B equal to the product of ice-bed uncoupling factor ϕ beneath ice streams and ice-shelf unbuttressing factor ϕ_O beyond ice streams, where ϕ_B, ϕ, and ϕ_O all decrease from one to zero as resistance to gravitational motion of ice increases. Table 1 shows how ϕ_B decreases as ϕ decreases with increased ice-bed coupling in stages 1 through 5 and ϕ_O decreases with increased ice-shelf buttressing in stages A through E. Any path can be taken from 1A to 5E, including temporary reversals, with an ice stream shutting down for either full coupling ($\phi = 0$) or full buttressing ($\phi_O = 0$). At stage 5E, a marine ice sheet has been downdrawn close to sea level, its ice streams have shut down, and its ice shelves are vulnerable to catastrophic disintegration, with calving bays migrating up stagnant ice streams to carve out the collapsed accumulation zone of the ice sheet, removing the ice sheet from Earth's climate system and opening the possibility for rapid climate change. For the West Antarctic Ice Sheet, ice streams entering Ross and Ronne-Filchner Ice Shelves are in stages 4D, 4E, and 5D, and in Pine Island Bay, Pine Island Glacier is in stage 2B and Thwaites Glacier is in stage 2A.

***Table 1**: A Life-Cycle Classification for Ice Streams, modified from Hughes (1992).*

↓Increasing ice-bed coupling	*Stages in life cycle*					*Stage*	*ϕ_B during life cycle*				
	1A	1B	1C	1D	1E	Inception	1	3/4	1/2	1/4	0
	2A	2B	2C	2D	2E	Growth	3/4	9/16	3/8	3/16	0
	3A	3B	3C	3D	3E	Mature	1/2	3/8	1/4	1/8	0
	4A	4B	4C	4D	4E	Declining	1/4	3/16	1/8	1/16	0
	5A	5B	5C	5D	5E	Terminal	0	0	0	0	0
Increasing ice-shelf buttressing→											

Basal buoyancy factor $\phi_B = \phi\,\phi_O$ decreases from 1A to 5E defined as:

Increasing ice-bed coupling beneath an ice stream

1. No coupling along entire length ($\phi = 1$).
2. Coupling slowly increasing upstream.
3. Coupling steadily increasing upstream.
4. Coupling rapidly increasing upstream.
5. Full coupling along entire length ($\phi = 0$).

Increasing ice-shelf buttressing beyond the ice stream

A. No ice shelf or a freely floating ice shelf ($\phi_O = 1$).
B. Weak buttressing by a confined and pinned ice shelf.
C. Moderate buttressing by a confined and pinned ice shelf.
D. Strong buttressing by a confined and pinned ice shelf.
E. Full buttressing by a fully confined ice shelf or an ice lobe ($\phi_O = 0$).

Basal Reflectivity and Bed Conditions Along the US-ITASE Traverse, Taylor Dome to South Pole

Bob Jacobel, Bern Youngblood, Jeff Stamp, Karl Lapo,
Jacki Werner, Jessica Olson and Brian Welch

St. Olaf College Department of Physics
Northfield, MN 55057

In 2006-2008 we recorded low-frequency ground-based radar data along the 1700 km US-ITASE traverse from Taylor Dome to South Pole. Recording one (stacked) trace every 3.5 m produced over 464,000 samples of the power returned from the bed, enabling a detailed study of changes in basal reflectivity along the traverse. Internal stratigraphy was also well depicted by the radar throughout the traverse, often to within meters of the bed at over 2.5 kilometers depth. Bed echo power values were corrected for geometric spreading losses and dielectric attenuation in order to derive values of basal reflectivity. Three methods were used to develop a model of dielectric attenuation. A first-order calculation based on the average decrease of basal echo power with depth for the entire data set gave a value of 8.6 db/km for depth-averaged one-way attenuation. A refinement of this technique based on the fall-off in power returned from internal reflectors at all depths was used to compute measurements of attenuation as a function of distance along the traverse. The values from this method were in general agreement with the above, yielding slightly lower attenuation in the colder ice toward South Pole and slightly higher values near Taylor Dome. The trend in these results is in accord with simple calculations based on the measured temperature profiles at these two locations. Values of attenuation near Taylor Dome are also confirmed by comparing the decrease in received power from single versus double reflections from the bed recorded there.

Using these measured values for dielectric attenuation, we mapped basal reflectivity along the length of the traverse (figure below). Our results show several areas of high reflectivity which are likely zones of localized basal melt, as well as other larger-scale regions where the bed is more highly reflective, indicating thawed conditions. Based on bed topography, some of the kilometer-scale bright features are likely to be subglacial lakes, including one within 25 km of South Pole Station. In contrast, the traverse passed over at least three areas where subglacial lakes have been indicated by changes in surface elevation seen in satellite imagery that do *not* today show high reflectivity. Larger-scale areas of thawed bed, including one near the north margin of the Byrd catchment, appear to have dynamic significance and are associated with areas of higher ice flow speed as shown by correspondence with InSAR and balance velocities.

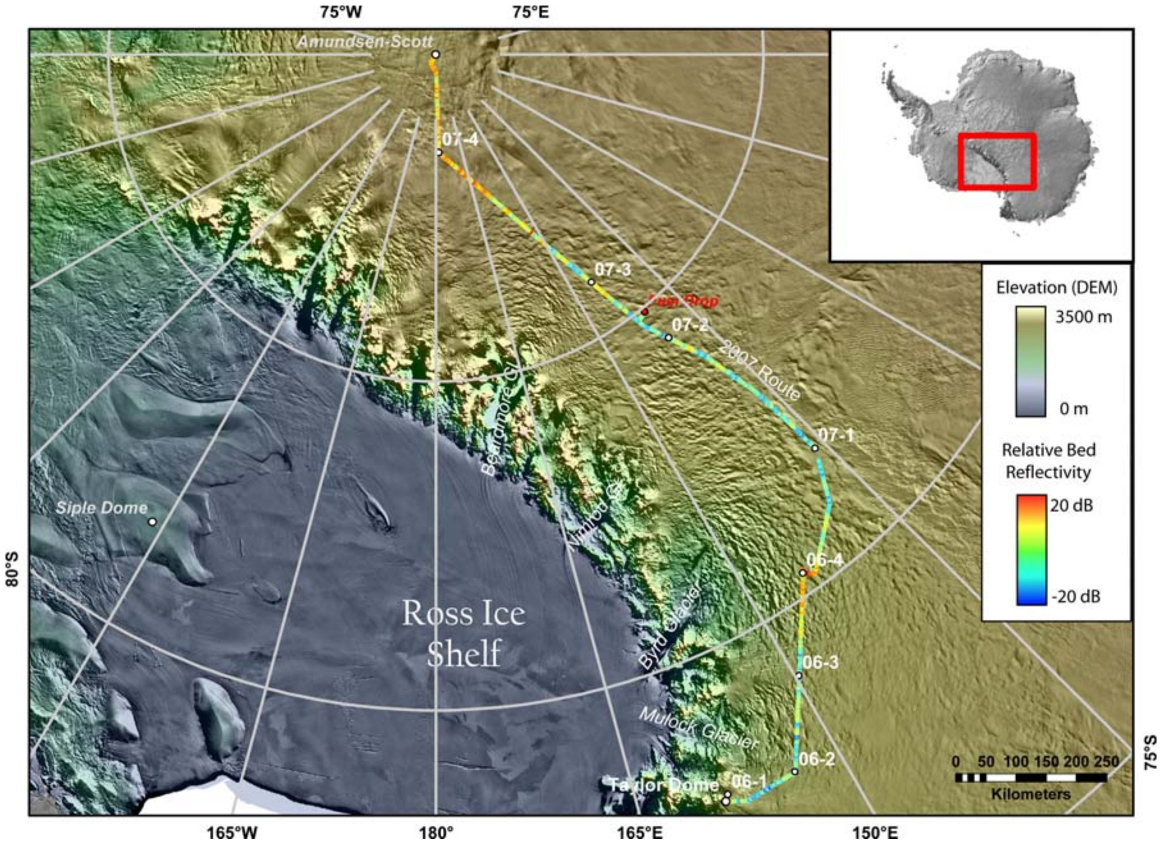

Figure 1. US-ITASE traverse, Taylor Dome to South Pole showing values of basal reflectivity, dB scale. Warmer colors correspond to areas with thawed bed conditions including small subglacial lakes and regions of enhanced flow.

Active sub-glacial lakes beneath two more Antarctic outlet glaciers appear to cause rapid speed and elevation changes

T. Scambos, C. Shuman, H. Fricker, E. Berthier

Recent studies have shown that sub-glacial lake activity can have a significant local effect on the flow speed of major outlet glaciers on the great ice sheets (e.g., Byrd Glacier: L. Stearns et al., 2008 Nature Geoscience). Here we present two additional cases where sub-glacial drainage and re-fill appears to be causing significant changes in ice flow speed. However, the two outlet glaciers discussed here show different responses to lake drainage.

MacAyeal Ice Stream in the Siple Coast region of West Antarctica has been shown to contain several active sub-glacial lakes (H. Fricker et al., 2007 Science, and H. Fricker et al. in prep.). ICESat repeat profiles and MODIS image differencing allows us to determine the fill-drain status of the lakes. We have examined the largest lake, near the grounding line area, for flow speed changes during fill and drain cycles with several ASTER images. Ice velocity mapping using ASTER image pairs spanning periods when the lake is drained show flow speeds up to 40 m/yr slower than when the lake is filled. We infer that flow speed decreased as a result of increased basal resistance (from zero to non-zero as the ice encountered the basal sediments). The scale of the slowdown is similar to modeled results on nearby ice streams (Sergienko et al., 2007, Geophys. Res. Lett.).

Crane Glacier in the Antarctic Peninsula has shown a remarkable increase in speed and decrease in elevation since the break-up of the Larsen B Ice Shelf in 2002. However, during the period November 2004 to November 2005, a portion of the lower glacier showed a sudden, localized increase in the rate of lowering, exceeding 100 m/year for a few months.

The glacier accelerated at a greater rate during and after this period (as determined by a series of satellite image pairs ending with Formosat-2 images in 2008 and 2009), and the surface character of the lower glacier changed significantly to a highly fractured serac field.

Examination of the Crane Glacier fjord bathymetry by multi-beam sonar in regions now exposed due to ice shelf and glacier retreat shows a series of enclosed over-deepened basins. This suggests that a series of sub-glacial lakes existed in the lower trunk prior to ice shelf disintegration. The region of the large Crane elevation change is still ice-covered and therefore unmapped for bathymetry, but may represent an additional lacusterine basin. Changing ice surface slope in the years before the sudden drawdown can be inferred to have significantly changed the sub-glacial pressure field. In the Crane Glacier case, acceleration during drainage may be driven by the large further increase in along-flow surface slope caused by drainage.

What are your lakes doing to my glaciers?

Ben Smith and Ian Joughin

The discovery of numerous active subglacial lakes beneath the Antarctic ice sheet, which exchange water between one another and with other subglacial aquifers, suggests that lake activity may produce large, if temporary, variations in outlet glacier ice velocities, and thus variations in ice discharge into the oceans. This process was observed in 2007 in Byrd glacier, where the discharge of around 1.4 km3 of lake water into the aquifer beneath the glacier resulted in a mean 10% increase in discharge over the course of a year. There are, however, few other examples of simultaneous altimetry and ice speed measurements that would show whether this is the typical glacier response to lake drainage. Here, I present preliminary ice speed variation measurements for Cook and Lambert glaciers. These glaciers are each downstream of large active lakes that discharged 2.7 and 0.8 km3 of water in 2007-08 and 2004-07 respectively. Lambert glacier shows no large variation in ice speed in any of the image pairs examined, and while Cook glacier shows small variations, these may be explained in part by changes in the floating ice around the outlet. Although feature-tracking data from 2009 may yet show significant variations in Cook glacier, it seems likely that neither glacier has responded as strongly as did Byrd glacier, to floods of a similar magnitude. We will discuss the role of basal geometry and substrate in determining the sensitivity of ice speed to subglacial floods, and how this determines the aggregate sensitivity of Antarctic ice discharge to these floods.

Stability and drainage of subglacial water systems

Timothy T. Creyts1 and Christian G. Schoof2

1 Earth and Planetary Science, University of California, Berkeley, California, USA 94720, Phone: 510-847-4304, Fax: 510-643-9980, Email: tcreyts@berkeley.edu
2 Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4, Phone: 604-822-3063, Fax: 604-822-6047, Email: cschoof@eos.ubc.ca

Subglacial drainage plays an important role in controlling dynamics between the overlying ice and underlying bed. Deeper and spatially distributed water systems favor decoupling of ice and bed and enhance slip rates along this interface. Shallow or coalescent water systems favor strong coupling and lower slip rates along the bed. In this work, we examine the effects of subglacial water drainage resulting from spatially distributed water sheets. In our model, the weight of overlying ice is supported by both water pressure and various sizes of bed protrusions that penetrate the water sheet. Each of the various sizes bears a different magnitude of the overlying ice based on a linear stress recursion that balances forces at the bed. Previous results [e.g., ?] have shown that water depth can be a multi-valued function of both effective pressure (ice overburden minus water pressure) that drives sheet closure and hydraulic gradient that drives water flow. Curvature and structure of this multi-valued water depth function depend on the protrusion size distribution. Switches between different branches of the water depth relationship correspond to either the establishment or shutdown of a ‘connected’ (or efficient) drainage system. We build upon and extend previous work to show how along-path discharge affects water depth and switches from one state to another. We conclude by relating state behavior to subglacial conditions beneath Antarctica.

Progress in modeling sheet-flow outburst flooding

James R. Rice and Victor C. Tsai

Meltwater generated at the surface and base of glaciers and ice sheets is known to have a large impact on how ice masses behave dynamically, but much is still unknown about the physical processes responsible for how this meltwater drains out of the glacier. For example, little attention has been paid to short-timescale processes like turbulent hydraulic fracture, which is likely an important mechanism by which drainage channels initially form when water pressures are high. In recent work (Tsai and Rice [Fall AGU, 2008; JGR subm., 2009]), we have constructed a model of this turbulent hydraulic fracture process in which over-pressurized water is assumed to flow turbulently through a crack, leading to crack growth. However, one important limitation of this prior work is that it only strictly applies in the limit of short crack length 2L compared to glacier height H, whereas relevant observations of supraglacial lake drainage, jokulhlaups and sub-glacial lake-to-lake transport episodes do not fall in this regime. Here, we improve somewhat upon this model by explicitly accounting for a nearby free surface. We accomplish this by applying the approach of Erdogan et al. [Meth. Anal. Sol. Crack Prob., 1973] to numerically calculate elastic displacements consistent with crack pressure distribution for a crack near a free surface, and use these results as before to simultaneously satisfy the governing fluid, elastic and fracture equations. Our results are analogous to the zero fracture toughness results of Zhang et al. [Int. J. Numer. Anal. Meth. Geomech., 2005], but applied to the case of turbulent flow rather than laminar flow of a Newtonian viscous fluid. Our new results clarify the importance of the free surface and potentially explain discrepancies between our previous modeling results and observations of supraglacial lake drainage by Das et al. [Science, 2008]. However, the numerical challenges increase as 2L becomes comparable to or much larger than H. We hope to ultimately develop simpler analyses for that range which make use of (visco) elastic plate theory at positions along the uplifted ice sheet that are remote from the fracturing front. This approach may also be of interest for tidal interactions with the ice-shelf grounding line location.

Of Bubbles and Bergs: Underwater Acoustics at the Ice/Ocean Boundary

Erin Pettit
(Dept of Geology and Geophysics, University of Alaska Fairbanks, Fairbanks, AK 99775)

Jeff Nystuen
(Applied Physics Laboratory, University of Washington, Seattle WA 98195)
Shad O'Neel (U.S. Geological Survey, Anchorage, AK 99508)

Passive underwater acoustics have revolutionized many fields including marine biology and physical oceanography, but have only recently been applied to explore glacier ice/ocean interactions. Sources of sound near glacier and ice-sheet margins include calving events and ice shelf rifting events, iceberg motion and collision, glacier ice melting, ocean surface-ice-cover conditions, ocean wave action (including seiches), rain and snow, and subglacial discharge. We present preliminary results from a study of the frequency characteristics of sound within tidewater glacier fjords in Alaska and a discussion of the potential similarities and differences with West Antarctic ice/ocean boundaries.

We find that the ambient sound in the audible range (above 20Hz) a tidewater glacier fjord is dominated by sound produced by the formation of bubbles in the water from the melting of glacier ice (primarily ice bergs of all sizes) containing pressurized cavities within the ice (bubbles in the ice). The release of the pressurized air creates a bubble within the water with a surface that initially oscillates and transmits acoustic energy until the bubble surface reaches equilibrium with the surrounding water. The frequency of the sound produced depends on the diameter of the bubble, small bubbles oscillate at higher frequencies than large bubbles. We find that the bubbles produced from melting ice in the fjord of the Yahtse Glacier in Icy Bay, Alaska produces sound with a peak from 1-3kHz. The acoustic energy produced is a function of the percent of ice covering the water surface, with even a small percentage of ice cover producing an ambient noise environment that is significantly louder than most oceanic environments. In particular, it is significantly louder than environments with sea ice cover, which lack pressurized cavities within the ice.

Wave action due to the impact of an iceberg after calving and the resulting seiche also create bubble clusters with particular frequency content. We find that interaction of the seiche waves with the glacier terminus and with icebergs and shorelines creates generally higher frequency signals (5 to 30kHz) than stationary melting glacier ice. The magnitude and frequency content of the seiche acoustic energy varies through time with a pattern that can be related to models of seiche wave amplitude.

The ice/ocean boundaries in West Antarctica consist of both floating ice shelves (primarily) and grounded marine-terminating glaciers (primarily on the Antarctic Peninsula). Our results suggest that monitoring these environments for surface conditions (distinguishing among melting ice bergs, sea ice, wind, and rain, for example), waves impacting on ice shelves, calving events, and other processes at the ice/ocean boundary may be possible with a small array of moored hydrophones.

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The Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) Project

Helen Amanda Fricker
Associate Professor
Scripps Institution of Oceanography
La Jolla, California, USA

WISSARD is an NSF-funded project which involves 14 PIs at 8 institutions that will use an interdisciplinary science approach to study the subglacial environment of the Whillans Ice Stream in West Antarctica. It is split into three sub-projects: LISSARD (Lake and Ice Stream Subglacial Access Research Drilling); RAGES (Robotic Access to Grounding-zones for Exploration and Science); and GBASE (GeomicroBiology of Antarctic Subglacial Environments). LISSARD focuses on investigating the role of active subglacial lakes in controlling temporal variability of ice stream dynamics and mass balance. RAGES concentrates on stability of ice stream grounding zones which may be perturbed by increased thermal ocean forcing, filling/draining cycles of subglacial lakes, and/or internal ice stream dynamics. GBASE addresses metabolic and phylogenetic diversity, and associated biogeochemical transformations in subglacial lake and grounding zone environments. These sub-projects are connected scientifically through common interest in coupled fluxes of ice, subglacial sediments, nutrients and water, as well as by the common need to characterize and quantify physical, chemical and biological processes operating subglacially. The project will focus on the lower Whillans Ice Stream, where three hydrologically connected subglacial environments that lie within close geographical proximity can be accessed: a subglacial lake (Lake Whillans); wet subglacial sediments including the grounding-zone wedge; and the sub-ice-shelf cavity. Direct sampling will yield seminal information on the glaciological, geological and microbial dynamics of these environments and test the overarching hypothesis that active hydrological systems connect various subglacial environments and exert major control on ice sheet dynamics, geochemistry, metabolic and phylogenetic diversity, and biogeochemical transformations of major nutrients within glacial environments.

Modelling and measurements of vertical strain-rates under ice domes and ridges.

Gillet-Chaulet F., Hindmarsh R. C. A. , Corr H. F. J., King E. C. and Mulvaney R.
(British Antarctic Survey, GB).

Ice domes and ridges are generally preferred drilling sites. In the vicinity of domes or ridges full-Stokes or higher order models have to be used instead to model the flow of ice in these areas. In particular, just underneath a dome, due to vanishing deviatoric stresses with depth, a non-linear Glen's rheology implies a highly viscous ice area. This area of highly viscous ice under the dome affects the vertical velocity profile of the ice which changes from the dome to the flank. As a consequence of this change, isochrones exhibit anticlines just under domes or sharp ridges. Such anticlines are visible on many radargrams, and are referred to as Raymond bumps.

The Raymond effect gives valuable information about ice rheology as it affects the vertical velocity profiles under the dome. The non occurrence of Raymond bumps in the central part of ice sheets is still matter of debate as low values of the Glen index, less than 2 and possibly close to 1, have been reported for this areas.

Hitherto modelling studies of dimensional applications have been for plane flow, but ice domes are rarely perfectly elongated or axisymmetric; often it seems that they are the meeting points of three ice divide ridges, or triple junctions and in such areas 3D effects can't be neglected.

We use Elmer, a finite element code which solve the 3 dimensional Stokes equations to study the Raymond effect as a function of the along-ridge flow. The Raymond effect is at its strongest when the along-ridge slope is null and weakens when the along ridge slope increases. The shape of the ridge is related with the strength of the Raymond effect. We also use Elmer to model the flow of ice under triple junctions. If a three-fold symmetry in the forcing is applied, the axisymmetric dome breaks up into three ridges subtending angles of 120 degrees. The along-ridge slope increases very quickly over a distance of one to two ice thicknesses. The Raymond effect is at its strongest at the dome, and weakens initially as one moves away from the divide along the ridges, but operates at distances many times the ice thickness from the dome. A set of experiments where the forcing was not exactly three-fold symmetric caused the triple junction to evolve into an elongated curved ridge. Modelled surface topography and internal layers are compared with data from Summit Greenland, Fletcher Ice Rise (Antarctica) and Thyssenhöhe (Berkner Island-Antarctica).

A phase sensitive radar has been used to measure precisely the vertical strain-rate displacement of internal layers between two visits in Greenland and in Fuchs Ice Rise (Antarctica). Profiles of the vertical strain-rate across the ice divides near the summit of the greenlandic ice cap, across the divide near the NEEM camp and across the divide of the Fuchs Ice Rise have been obtained. Variations of the surface vertical strain-rate across the divides are interpreted using the results of the numerical experiments.

These studies will give us a better understanding of the ice rheology at low strain-rates under ridges and domes and will allow us to chose the best emplacements for the next drilling.

Antarctic temperature change and its relevance to future ice core drilling efforts

Eric J. Steig
Department of Earth and Space Sciences, University of Washington, Seattle, WA

Despite the fascinating diversity of glaciological flow conditions in Antarctica, glaciologists generally treat Antarctic climate as monochromatic; it is common, for example, to use a single time series, such as the East Antarctic Vostok ice core record, as the driver of Antarctic climate boundary conditions for ice sheet models (e.g. Huybrechts, 2002), even when the focus of the research is West Antarctica (e.g. Steig et al., 2001; Pollard and DeConto, 2009). To some extent, this is justified the tendency of climate variability towards greater spatially uniformity on longer timescales. However, modern observations show that Antarctic climate is much more complex, and this complexity is expressed at least on the century (and perhaps much longer) timescales relevant to ice dynamics, particularly in regions of fast flow.

Recent observations of surface, near-surface, and tropospheric temperature change serve as a useful framework for understanding Antarctic climate dynamics. The Antarctic Peninsula is well known to have warmed substantially through most of the 20th century (and surface warming in this region is an important component in the recent loss of ice shelves there) (e.g. Vaughan et al., 2003). There is now abundant evidence that continental West Antarctica has also warmed significantly during at least the last 50 years, both at the surface and throughout the troposphere (Steig et al., 2009; Sherwood et al., 2008). In East Antarctica during the same time period, most regions have either changed little or have cooled. Several independent lines of evidence (both from ice cores and boreholes temperature records) indicate that both West and East Antarctica –like the Peninsula -- have warmed on average during the 20th century. While this general warming trend is probably attributable to greenhouse gas forcing, this is probably not primary from the direct radiative effect (i.e. it doesn't merely local radiative forcing changes). Instead, the response of the atmospheric circulation patterns to the pattern of sea surface warming at lower latitudes, and resulting changes in regional Antarctic circulation probably dominate. In particular, recent West Antarctic and western Antarctic Peninsula warming reflect the combination of enhanced warm air advection from the north due to a spin-up of the low pressure systems in the Amundsen and Bellingshausen seas; the influence of wind stress of the sea ice distribution tends to further enhance this warming. Changes in the vertical temperature profile over the ice sheet, due to the depletion of stratospheric ozone, also clearly plays a role (Thompson and Solomon, 2002), though in this author's view this is probably less important than popularly thought (after all, ozone changes did not become significant until the late 1970s).

Capturing the complexity of climate variability should be one of the primary goals for future ice core drilling efforts in Antarctica. It remains an open question to what extent our understanding of recent climate variability in the Antarctic applies on longer timescales. Existing Antarctic ice core records do not fully answer this question, in part because it has, to date, been too difficult to tease out the competing influences of elevation, circulation, and temperature on the various ice core climate proxies. However, it appears increasingly unlikely that differences between the Holocene records from Siple Dome, Byrd, Taylor Dome and the recently-completed Talos Dome record, on the one hand, and the records from the high East Antarctic plateau, can be explained simply with ice elevation changes. (Most of the evidence now points to an "ENSO-like" pattern of variability as the best explanation.) I suggest that additional ice cores in West Antarctica (or 'downstream' in East Antarctica – e.g. at Hercules Dome) should remain a priority, even after the WAIS Divide record is complete.

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Reconstructing past Antarctic ice flow paths using detrital zircon provenance

A.J. Schilling and K. J. Licht**

** Department of Earth Sciences, Indiana University Purdue University Indianapolis*

Detrital zircons were extracted from East Antarctica (EA), West Antarctica (WA) and Ross Sea tills (Fig. 1). U-Pb age distributions from 1,465 zircons provide new information on the subglacial geology of Antarctica, as well as assisting in the reconstruction of Last Glacial Maximum (LGM) ice flow paths. Statistical analyses using the Kolmogorov-Smirnov (K-S test) reveal that EA and WA age distributions are distinct at a P-value <0.05. This makes it possible to trace the unique signatures from EA and WA into the Ross Sea.

WA ice streams, Kamb, Bindshadler, and Whillans, all contain Ross age (550-500 Ma) and Grenville age (1100-1000 Ma) populations. Kamb and Bindshadler contain a young zircon age population ~100 Ma, whereas Whillans Ice Streams is missing the ~100 Ma age populations, but contains a ~230 Ma age population.

All samples collected at the head and middle of major EA outlet glaciers contain grains whose age of formation is consistent with the Ross Orogeny and all samples showed small age populations scattered throughout the Proterozoic. The most noteworthy peaks occur from the Permian through the Triassic. EA outlet glacier samples, Beardmore Glacier (BG), Davis Nunatak (DN), Bates Nunatak (BN), and Cloudmaker (CM) (all where Beacon Group rocks have been mapped) match age populations from previously dated Beacon samples of ~240-270 Ma (Elliot and Fanning, 2008). This suggests that the signature from the Beacon Supergroup may be identifiable. These outlet samples are a representation of material being transported into the TAM. The fingerprint of each outlet glacier will be altered as it crosses the TAM, resulting in the addition of Ross age material. Three anomalously young zircons (19.4± 0.9, 25± 0.9 and 23.1± 0.5) were found at the head of the Scott Glacier from Mt. Howe (MH).

All of the Ross Sea samples contain age populations consistent with the Ross Orogeny, however the samples show spatial variability in the age distribution of the Mesozoic grains. The Central Eastern and Eastern Ross Sea has a ~100 Ma population which is consistent with the age populations seen at Kamb and Bindshadler Ice Streams. This suggests that the ice flow of the West Antarctic Ice Sheet (WAIS) was confined to the region during the Last Glacial Maximum (LGM).

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Subglacial Landform Analysis and Reconstruction of Miocene Paleotopography of Marie Byrd Land

Perry Spector[1,2], Christine Siddoway[1], and Paul Morin[2]
[1]Department of Geology, Colorado College, Colorado Springs, Colorado 80903
[2]The Antarctic Geospatial Information Center, University of Minnesota, Minneapolis, MN 55455

Analysis of sub-ice bed topography datasets from Marie Byrd Land (ASE05, WMB (SOAR), BEDMAP1_plus), undertaken as part of the international Antarctic paleotopography, or ANTscape, program (www.antscape.org), reveals subglacial landforms that may have implications for ice sheet history, ice dynamics, and determination of isostatic responses of the crust of Marie Byrd Land (MBL) since the onset of continental glaciation. These include subglacial volcanoes, alpine glacier valleys upon elevated topography of volcanos, and a flexural moat around the Executive Committee Range volcanic field (Fig. 1). Observations from the geophysical datasets are augmented by the Landsat Image Mosaic of Antarctica (LIMA) and high resolution commercial imagery held by the Antarctic Geospatial Information Center (AGIC).

Whereas the WAIS initiated at *ca.* 34 Ma *(DeConto et al., 2007, Pollard and DeConto, 2003)*, the volcanoes in the MBL volcanic province are 17 Ma to present (Mt Petras and Reynolds, excepted). Thus, central MBL volcanoes were not present to serve as high elevation sites for ice cap nucleation during the early history of the WAIS. During and after formation, the 2000+m volcanoes would have affected precipitation patterns and been sites of volcano-thermal perturbations that promoted warm-based glaciation, conducive to glacial erosion and development of alpine glacier valleys during times of reduced ice sheet extent. Such considerations, arising from study of bedrock geology and landforms, are the basis for our effort to reconstruct the Early Miocene (*ca.* 21 Ma) paleotopography of Marie Byrd Land through inferring subglacial bedrock response to surficial processes. Our results will be integrated into paleotopographic reconstructions of Antarctica that are being prepared by ANTscape for 6 time intervals (spanning 92 Ma to present) that have paleoclimate and tectonic significance. The geospatial data for the reconstructions of past landscapes are intended for use as inputs for future ice sheet-ice shelf models and for visualizations of Antarctic paleogeography and paleoenvironments.

Cross-sectional profiles of ASE05 and BEDMAP1_plus bed topography data show a pronounced narrow downwarp, bordered by a broad bulge, on the north and south margins of the Executive Committee Range (Fig.2). Sequential topographic profiles at 5 km spacing show that the features are laterally continuous for >40 km and systematic in geometry, suggesting that there is a volcanic moat formed from elastic response of the lithosphere to the lithostatic load of the Executive Committee range. Therefore, our paleotopography reconstruction for pre- Early Miocene time must both remove volcano elevation and allow isostatic rebound from volcano load (subaerial and shallow crustal components) and ice sheet.

Qualitative observations of bed topography of the Executive Committee Range reveals the presence of narrow, steep-walled valleys that we postulate were formed by alpine glacier erosion at a time when WAIS was of reduced extent and the Executive Committee Range hosted alpine glaciers in an environment similar to the present-day Southern Alps of New Zealand. The five major volcanoes of the Executive Committee Range are younger than 14 Ma (LeMasurier and Rocchi, 2005; Smellie et al., 1990), and so provide a maximum age constraint on a time when warm-based ice retreated to the upper elevations of the volcanoes. The finding of warm-based glacial erosion features formed at high elevations at a time after the mid-Miocene climate transition – when there was a change to hyper arid climate and onset of cold-based mode of Antarctic glaciation (Jamieson and Sugden, 2008) – is a possible indication that basal thermal conditions were elevated in the vicinity of the volcanoes.

Following the mid-Miocene climate transition, Antarctica entered an arid period when extensive areas of the ice sheets became cold-based. Warm-based glacial erosion became focused within preexisting drainages at low elevation, leading to development of deeply incised outlet glacier troughs (Jamieson and Sugden, 2008). Therefore, our paleotopography reconstruction restores post-Miocene incision by outlet glaciers and ice streams. Restoration of the changes in elevation due to volcano construction and glacial incision results in an Early Miocene subdued landscape with ~1100 m of topographic relief (Fig. 3), which we will use for calculation of isostatic corrections for removal of volcanic rock and ice. Our ongoing work assesses structural inheritance and the possibility that fault reactivation may be linked to glacial erosion-induced exhumation, tectonic influences, and fluvial or glacio-fluvial processes.

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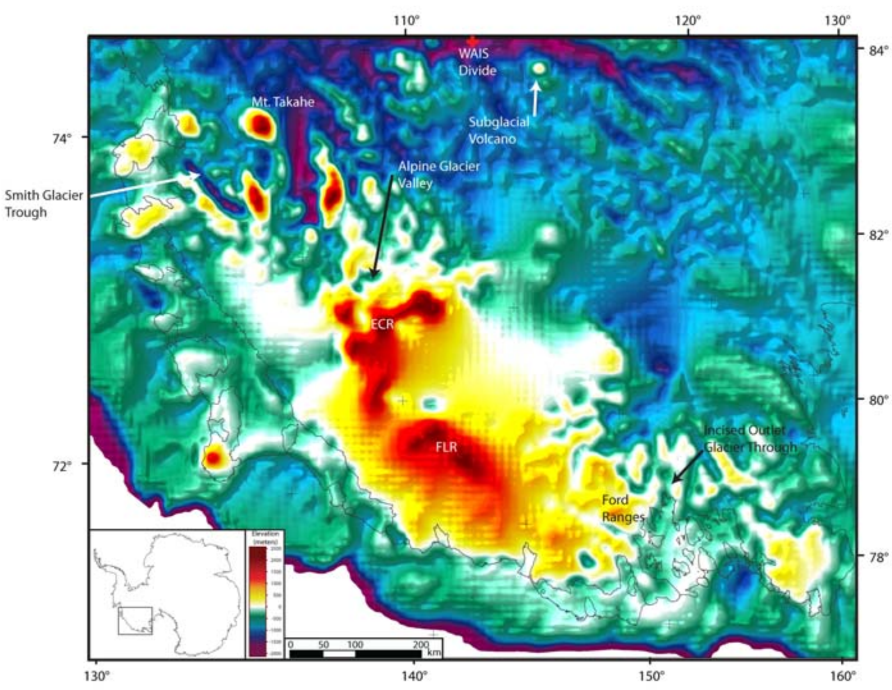

Figure 1. Shaded relief DEM of subglacial topography of Marie Byrd Land and location map for features under study, from BEDMAP1_plus (http://websrv.cs.umt.edu/isis/index.php/Present_Day_Antarctica).

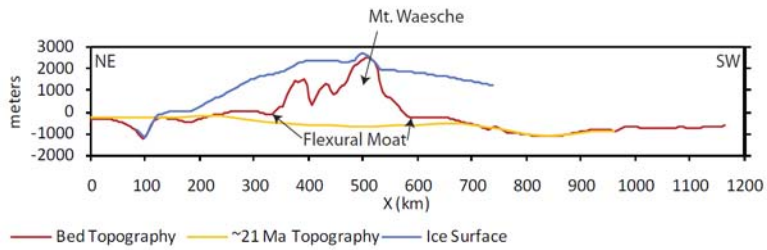

Figure 2. Profile of bed topography (BEDMAP1_plus, 2009), ice surface topography (ASE05), and reconstructed Early Miocene (21 Ma) topography across the Executive Committee Range, MBL. The feature inferred to be a "moat," or circumferential depression around the volcanic field, has topographic relief of ~450 m.

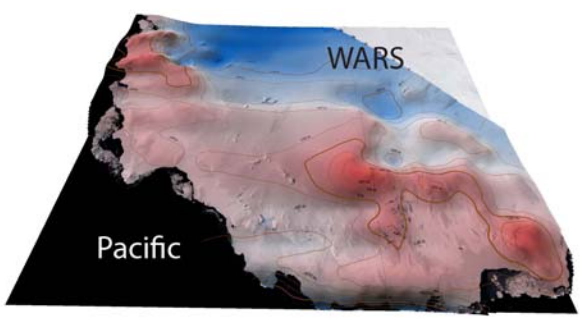

Figure 3. Oblique perspective view to SE of the reconstructed Early Miocene (*ca.* 21 Ma) landscape of Marie Byrd Land, rendered in Fledermaus (ivs3d.com). For purposes of geographic location, the Landsat Image Mosaic of Antarctica (LIMA) is incorporated in the visualization. Broad regions that are at depths <-1000 m correspond to extended (subsided) crust of the West Antarctic rift system.

Preservation of Pliocene age surfaces beneath the WAIS: Insights from emergent nunataks in the Ohio Range

Robert P. Ackert Jr., Sujoy Mukhopadhyay
Department of Earth and Planetary Science, Harvard University, Cambridge, MA 02138

Harold W. Borns, Aaron E. Putnam
Climate Change Institute, University of Maine, Orono, ME, 04469

The granitic bedrock forming the Ohio Range Escarpment and adjacent Bennett and Tuning Nunataks is typically cavernously weathered with pits ranging from a few cm to > 100 cm. The rock remaining between pits often forms delicate structures only several cm thick (tafoni). Cosmogenic ^{21}Ne and ^{10}Be concentrations indicate that the weathered bedrock surfaces are at least 4 million years old with average erosion rates of 15-35 cm /Ma on surfaces between pits. However, exposure ages of erratics on the escarpment 125 m above the present WAIS surface (~1500 m) indicates that the nunataks were buried by the WAIS 10,000 years ago (Ackert et al., 2007).

Ice temperatures at these relatively shallow depths would be well below freezing, and the WAIS remained cold-based. Consequently, glacial erosion has been minimal, generally restricted to breakage of only the most delicate weathering structures. Tuning Nunatak is located in an area with higher ice velocities as indicated by crevasses and steeper surface slopes. There, limited quarrying of horizontally jointed bedrock has locally removed up to 1 m of rock and produced a few glacial scratches. Paired ^{21}Ne and ^{10}Be data indicate that the duration of ice cover was limited. Samples of bedrock from three nunataks fall within the zone of simple exposure on ^{21}Ne/^{10}Be vs. ^{10}Be plots indicating that unsupported decay of ^{10}Be (half life = 1.5 Myr) was minimal, and no recent burial event exceeded 50, 000 years.

Wind scoops (areas of enhanced ablation) surround the Bennett Nunataks and expose cavernously weathered rock at the base of the nunataks, 40 m below the level of the surrounding WAIS surface. Presumably, the weathered bedrock extends below the WAIS surface to the average trimline elevation during the Pliocene. Ice sheet models suggest that the northern flank of the Transantarctic Mountains near the Ohio Range remained ice-covered during WAIS collapse events with average ice elevations several hundred meters below present, and that the "collapse state" was the usual WAIS configuration 3-5 Ma (Pollard and DeConto, 2009). In principle, paired ^{21}Ne and ^{10}Be from bedrock samples beneath the WAIS could be used to map ancient trimlines and test models of WAIS history. We speculate that bedrock samples from beneath the WAIS in the Ohio Range would show progressively increasing disequilibrium between stable and radioactive cosmogenic nuclides with depth as the integrated duration of Pleistocene ice cover increases, assuming ice temperatures remained below the pressure melting point. Below depths where glacial erosion occurs, stable cosmogenic nuclide concentrations in bedrock will decrease and evidence for past exposure will be lost.

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Active-Recent Volcanism Associated With the West Antarctic Rift System Interpreted From Aerogeophysical Observations, and Possible Effects on the Stability of the West Antarctic Ice Sheet (WAIS)

John C. Behrendt

INSTAAAR, University of Colorado at Boulder
and
USGS Denver

Observations from an oversnow traverse in 1957-58 during the International Geophysical Year and >10,000 km of widely spaced airborne magnetic profiles acquired over the West Antarctic Ice Sheet (WAIS) in the early 1960s, indicated numerous high-amplitude, shallow-source, magnetic anomalies over a very extensive area of the presently known West Antarctic rift system interpreted as caused by subglacial volcanic rocks. These early aeromagnetic surveys later combined with radar ice sounding in 1978-79 and 1990-97 defined this area as >500,000 km^2. These anomalies range from 100->1000 nT as observed ~1 km over the 2-3 km thick moving ice. Behrendt et al, (2005) interpreted these anomalies as indicating >1000 "volcanic centers." requiring high remanent magnetizations in the present field direction. Detailed aeromagnetic and radar ice sounding surveys since 1990 have shown that >80% of these anomaly sources at the bed of the WAIS have been modified by the moving ice into which they were injected requiring a younger age than the WAIS (about 25 Ma). Behrendt et al., (1994; 2007) conservatively estimated >1 x 10^6 km^3 volume of volcanic sources to account for the area of the "volcanic center" anomalies and suggested the presence of a large igneous province (LIP) if this volume was intruded within a time interval of 1-10 m.y.

Mt Erebus, (<1 Ma) Mt. Melbourne, (<0.26 Ma), and Mt. Takahae (<0.1 Ma) are examples of exposed active volcanoes in the WAIS area, but the great volume of volcanic centers is buried beneath the WAIS. If only a very small percentage of these >1000 volcanic magnetic-anomaly sources are active today, or in the recent past, in the drainage area of the WAIS, subglacial volcanism may have a significant effect on the dynamics of the WAIS. Interpreted active subglacial volcanism is revealed by aerogeophysical data reported by Blankenship et al., (1993), and Corr and Vaughan, (2008), who raised the question of possible volcanic effects on the regime of the WAIS. Vogel and Tulaczyk (2006) argued that subglacial volcanism may play a "crucial roll" in WAIS stability, In my presentation I will review the geophysical evidence acquired from the IGY to the IPY, and conclude that even if there is a very low probability, future effects on the stability of the WAIS should not be ignored, as the rapid changes observed in the past 20 years resulting from global warming, could be accelerated by volcanism.

AGAP: Exploring the Gamburtsev Subglacial Mountains with Aerogeophysical Surveys during the IPY

Michael Studinger[1], Robin Bell[1], Fausto Ferraccioli[2], Detlef Damaske[3], Carol Finn[4], David Braaten[5], Mark Fahnestock[6], Tom Jordan[2], Hugh Corr[2], Stefan Elieff[7], Carl Robinson[2], Nick Frearson [1,2], Dan Geue[7], Chris McMinn[5], Beth Burton[4], Felix Goldmann[3], Adrienne Block[1], Martin Bates[7], Kathryn Rose[2]

[1]Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA
e-mail: mstuding@ldeo.columbia.edu, +1 845 365 8598
[2]British Antarctic Survey, Cambrigde, United Kingdom
[3]Federal Institute for Geosciences and Natural Resources, Hannover, Germany
[4]United States Geological Survey, Denver, USA
[5]Center for Remote Sensing of Ice Sheets, The University of Kansas, Lawrence, Kansas, USA
[6]Complex Systems Research Center, University of New Hampshire, Durham,NH, USA
[7]Sander Geophysics Ltd., Ottawa, Canada

Exploring the history of the East Antarctic Ice Sheet and lithospheric structure of the Gamburtsev Subglacial Mountains have been primary goals of the International Polar Year. Scientists from seven nations have launched a flagship program to explore a major mountain range buried by a large continental ice sheet and bounded by numerous subglacial lakes. The AGAP umbrella is a multi-national, multi-disciplinary effort and includes aerogeophysics, passive seismology, traverse programs and will be complimented by future ice core and bedrock drilling. We have acquired a major new airborne data set including: gravity; magnetics; ice thickness; SAR images of the ice-bed interface; near-surface and deep internal layers; and ice surface elevation. In total, more than 120,000 km of aerogeophysical data have been acquired from two remote field camps during the 2008/09 field season. Our team will address four fundamental questions: 1) What role does topography play in the nucleation of continental ice sheets? 2) How are major elevated continental massifs formed within intraplate settings but without a straightforward plate tectonic mechanism? 3) How do tectonic processes control the formation, distribution, and stability of subglacial lakes? 4) Where is the oldest climate record in the Antarctic ice sheet? The AGAP education and outreach plans are closely linked to larger IPY education and outreach initiatives leveraging the excitement of "uncovering" a phantom mountain range, larger than the Alps but virtually unexplored since they were discovered during the International Geophysical Year in 1958.

Variation in Subglacial Roughness in West Antarctica: What does this mean for pre ice sheet sediment provenance?

Young, D. A., D.D. Blankenship, S.D. Kempf, J.B. Desantos,
M. Williams, and J. W. Holt

The WAIS displays asymmetries in its glaciology that in part may relate to the regional distribution of subglacial sediments. The current distribution of these sediments may in turn reflect erosional controls due to the current ice sheet, as well as inheritance from pre glacial geological processes, including the accommodation space from rifting, distance to paleohighs that may be sediment sources, and the location of the paleocoastline. We assess the comparative distribution likely sediments using radar imaging of subglacial structures, quantitative measurements of roughness at high spacial resolution, and potential fields methods, constrained with published results of basal shear stress and compared with new hypothesis for the evolution of the paleotopography of the WAIS.

Pleistocene WAIS history from marine sediment cores

Reed Scherer, Northern Illinois University

The ANDRILL McMurdo Ice Shelf core made abundantly clear that the WAIS had a complex history characterized by repeated cycles of advance and collapse throughout the Pliocene. Interglacials dominated, and most of these were notably or significantly warmer than present. During Pliocene interglacials the Ross Embayment was characterized by notably warmer than present conditions with little sea ice, based on interpretation of diatom assemblages that define pelagic-dominated water masses.

The Pleistocene history of the WAIS is less well defined and probably more complex. It is now clear that the WAIS collapsed during the early Pleistocene interglacial Marine Isotope 31, with response of the ice sheet directly in phase with precession-paced insolation changes. A relatively brief interval of extremely high insolation at 1.08 Ma ago would have directly affected summer sea ice and year-round sea surface temperatures. Modeling of MIS-31 by DeConto & Pollard successfully reproduces the WAIS response inferred from high resolution sediment records, including collapse in phase with precession-paced insolation changes. Ross Ice Shelf collapse and subsequent WAIS retreat were triggered from ice shelf thinning from below. Their model does not show significant circumantarctic continental surface melt, but seasonal melt pond formation on the ice shelf surface is possible, which might have offered the potential for the melt-pond formation → draining → freezing → crack propagation mechanism that ultimately triggered the catastrophic collapse of the Larsen-B ice shelf in 2002. The DeConto & Pollard model included late Pleistocene collapse events as well (e.g., MIS-7), but these events are not as well documented in sediment core records or sea level proxies.

So, did the WAIS collapse multiple times through the Pleistocene? The recalculation of WAIS sea level equivalent by Bamber et al. (2009) (3.3 M as opposed to the frequently quoted 5-6m) makes it clear that it may be extremely difficult to identify all past WAIS collapse events by interpretation of sea level proxies. Proximal sedimentary records that reflect continuous sedimentation through the Pleistocene remain the best way to interpret past WAIS behavior for the last 1 Ma. Such records have been elusive, but some new cores have been recovered that are promising, and future Antarctic drilling may fill in the gaps.

A Probabilistic Assessment of the WAIS and Greenland Contributions to Sea Level during the Last Interglacial

Robert E. Kopp (1,2), Michael Oppenheimer (1,2), Frederik J. Simons (2), Jerry X. Mitrovica(3), Adam C. Maloof (2)

(1) Woodrow Wilson School of Public & International Affairs and
(2) Department of Geosciences, Princeton University, Princeton, NJ 08544
(3) Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138

The Last Interglacial (LIG) stage, also known as the Eemian, is a partial analog for the near-future Earth under low-end global warming scenarios. Ice core data indicate that, during the LIG, Arctic and Antarctic temperatures were 3-5ºC warmer than today, comparable to the Arctic warming expected to accompany 1-2ºC of global warming. While the global mean temperature anomaly is uncertain, sea-surface temperatures in the equatorial Pacific and Atlantic were about 2ºC warmer than pre-Industrial levels. These warmer temperatures may have been the product of changes in orbital forcing.

Numerous data suggest that LIG sea level was a few meters higher than at present; based on a small set of data, the Intergovernmental Panel on Climate Change 2007 assessment report estimated 4 to 6 m above modern sea level. Greenland ice core evidence has been interpreted by some as suggesting that the extent of the Greenland Ice Sheet was significantly reduced, a possible cause of higher sea levels, but this evidence remains contested. Identifying the sources, if any, of meltwater contributing to elevated sea level can help constrain the hazard posed by future ice sheet melt.

The patterns of local sea level rise produced by ice sheet melt depend upon the meltwater source. Melting ice sheets cause changes in the position of the sea surface (the geoid), the deformation of the lithosphere, the orientation of Earth's spin axis, and the position of shorelines, as well as triggering a long-term isostatic response from the mantle. The resulting geographical patterns raise the prospect of fingerprinting meltwater sources, though also complicate the task of reconstructing global sea level from local indicators. In order to place better constraints on global sea level and make a first attempt at identifying Last Integlacial meltwater sources, we have constructed a database of LIG sea level indicators from 42 geographically-widespread localities and developed a novel statistical approach for their analysis. Our approach couples Gaussian process regression of spatio-temporal variability in sea level and ice sheet volume with Markov Chain Monte Carlo simulation of geochronological uncertainty.

Our results indicate a 95% probability that global sea level peaked during the Last Interglacial above 6.6 m, a 67% probability that it exceeded 8.0 m, and only a 33% probability that it exceeded 9.4 m. Because the current methodology requires us to approximate the bounded probability distribution for ice sheet volumes with Gaussian distributions, inferences about ice sheet volumes must be viewed cautiously. We can, however, say with 95% confidence that both Northern Hemisphere and Southern Hemisphere ice volumes reached levels 2.5 m equivalent sea level smaller than today, though not necessarily at the same time. Within the uncertainties of our projections, we can make no significant statement about which ice sheet shrunk to a greater extent.

The current version of our statistical model employs a prior distribution for individual ice sheet volumes that, like the prior distribution for sea level, is a function of time. The next version of the model will instead employ a prior distribution for ice sheet volumes that is a function of global sea level. As a consequence, it should be better able to account for bounds on ice sheet volumes (e.g., that it is impossible for the Greenland Ice Sheet to be less than about 7 m equivalent sea level smaller than today) and thus improve our ability to attribute meltwater sources.

Anisotropic basal roughness at scales close to the transition wavelength beneath upper Thwaites Glacier

Joseph A. MacGregor 1, Rebecca Boon 1, Sridhar Anandakrishnan 1, Richard B. Alley 1, Anthony M. Hoch 2 and I. Joughin 3

1 Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA
2 Center for Remote Sensing of Ice Sheets, University of Kansas, Lawrence, Kansas, USA
3 Polar Science Center, Applied Physics Lab, University of Washington, Seattle, Washington, USA

Thwaites Glacier is a large, fast-moving and rapidly changing glacier in the Amundsen Sea catchment of West Antarctica. Recent ice-flow models suggest that its basal conditions exert a strong influence upon its ice-flow patterns and that they vary significantly across the glacier. To clarify the relationship between its basal conditions and its flow, we are conducting ground-based geophysical studies (radar, seismic and GPS) along a central flowline of the glacier. Here we present preliminary results from 150-MHz ice-penetrating radar data collected during the 2008-9 Antarctic field season within an area of upper Thwaites Glacier approximately 37 km long (longitudinal to flow) and 14 km wide (transverse to flow) that crosses onto a transverse “ridge” in the inferred basal shear stress. There are several longitudinal ridges in the basal topography and a transverse step ~ 10 km upstream of the ridge in the modeled basal shear stress. The basal echo intensities along the transverse lines are significantly lower than those along the longitudinal lines, and this difference is consistent with the radar-wavelength-scale (1.1 m) roughness inferred from the basal topography. For presently glaciated beds, anisotropy in the basal roughness at this length scale has not been previously observed, and it is close to the predicted transition wavelength (~0.5-1 m), where regelation and creep around obstacles are of equal importance in basal sliding and where erosion should peak. Within our study area, longitudinal bumps whose wavelength is similar to the transition wavelength are less than half the height of transverse bumps at the same wavelength, which implies that the bed is preferentially eroded in the longitudinal direction. This inference is consistent with previous observations of deglaciated bedrock near alpine glaciers. We also find that the spatial variation in the basal roughness anisotropy is correlated with the spatial variation in modeled basal shear stress; areas of low modeled basal shear stress, which implies that the bed is softer/weaker, have larger basal roughness differences. Finally, the radar-observed roughness differences are consistent with acoustic basal reflectivity differences inferred from reflection-seismic data, and we will soon compare the radar results with the basal lithologies inferred from amplitude-versus-offset seismic data collected along two widely separated transverse lines. These observations provide clues regarding the small-scale controls on basal sliding and their relationship to the large-scale ice-flow patterns of a major Antarctic glacier.

Is ice mechanical heterogeneity controlling the stability of the Larsen C ice shelf?

Bernd Kulessa[1], Edward King[2], Brian Barrett[3], Daniela Jansen[1], Adrian Luckman[1], Peter Sammonds[4], Matt King[5]

[1]Swansea Glaciology Group, School of the Environment and Society, Swansea University, SA2 8PP, UK, b.kulessa@swansea.ac.uk
[2]Physical Sciences Division, British Antarctic Survey, Cambridge, CB3 0ET, UK
[3]Zetica Ltd, Long Hanborough, UK
[4]Department of Earth Sciences, University College London, WC1E 6BT, UK
[5]School of Civil Engineering and Geosciences, Newcastle University, UK

We want to understand why rift tips align along certain flowstripes on many Antarctic ice shelves, and what implications this has for ice-shelf stability. Such flowstripes were noted in several publications over the last three decades, and several speculative inferences regarding their origin and potential implications for ice-shelf mechanics have been brought forward. The southeastern sector of the Larsen C ice shelf is a prominent example of frequent rift generation at the Kenyon Peninsula, and subsequent rapid northward propagation (up to ~ 23 km/yr). Propagation halts abruptly when the rift tip encounters a thin flowstripe that originates downflow of the Joerg Peninsula, separating two glaciers discharging into the ice shelf. Modelling experiments of Holland et al (2009) were consistent with oceanic freezing in this area, suggesting that mechanically softer ice could make up significant proportion of the flowstripe, reducing stress intensities along it and ultimately acting to halt rift propagation in the ice-shelf's south-eastern sector. Notwithstanding, Holland et al. (2009) could not exclude the possibility that mechanisms other than oceanic freezing generated the flowstripe mechanical anomaly.

We have collected a range of seismic and ground-penetrating radar (GPR) data in both flowstripe and surrounding glacier-derived ice in this sector. These include multi-component, azimuthal common-midpoint (CMP) seismic reflection, azimuthal CMP and skidoo-towed constant-offset (CO) GPR data at 50 MHz. These data confirm that anomalous ice is indeed present in the lower half of the flowstripe, appearing geometrically as two 'lobes', as predicted by Holland et al.'s (2009) model. The interface between the overlying meteoric ice and this anomalous ice appears 'fuzzy' in the CO-GPR data, and creates distinct reflections in our seismic data. In this presentation we analyse these GPR and seismic signals in detail, and suggest possible physical origins and implications for the formation of this anomalous ice. We present detailed seismic and GPR azimuthal velocity-depth profiles through the firn, meteoric ice and the anomalous ice, and interpret these data in terms of ice anisotropy and density. We further comment on the possibility of deriving ice-shelf temperature profiles from joint seismic and GR derived velocity profiles. Indeed, we find that GPR and seismically derived density profiles for the firn layer (with a firn-ice transition at ~ 45 m) are distinctly different, which had previously been noted at other Antarctic survey sites. We revisit Doake's (1984) joint GPR and seismic analyses of average ice-shelf densities to understand the origin, and the glaciological and mechanical implications, of these differences. Finally, we synthesize all available information and attempt to answer the question in the title of this presentation.

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NUMERICAL MODEL INVESTIGATION OF CRANE GLACIER RESPONSE TO COLLAPSE OF LARSEN B ICE SHELF, ANTARCTIC PENINSULA'

Adam J. Campbell

Dept. of Earth and Space Sciences
University of Washington, Box 351310
Seattle, WA 98195
campbead@u.washington.edu

Several outlet glaciers in the Larsen B ice shelf embayment experienced sudden sped up and front retreat as a result of the ice shelf disintegration in March of 2002. Glaciers in the Larsen B embayment have responded different to ice shelf disintegration. Crane Glacier stands out among the fast responding glaciers for its dramatic increase in speed, from ~500 m/a to ~1500 m/a in its downstream reach, large surface lowering, and front retreat. Between March 2002 and early 2005, the glacier's calving front retreated by about 11.5 km to a location at which it has remained since that time. In order to investigate the physical processes that control the reaction of Crane Glacier to ice shelf disintegration, a flowline model has been developed. The model solves for the full momentum balance along the flowline using the finite element method and allows for basal sliding using a Budd type sliding relation. Model parameters are tuned to reproduce observation of surface velocity prior to ice shelf disintegration. Model can be applied diagnostically to examine instantaneous changes in boundary conditions.

The instantaneous model response of the glacier to ice shelf removal produces surface velocities and thinning rates that agree well with observations of the glacier immediately post collapse. When the front position is modified to represent the steady position reached in 2005, the model again produces velocities similar to those observed on the glacier. A typical tidewater calving criterion can be used to predict the steady position toward which the front retreated.

Ice shelf removal produces a small change in vertical shearing. This change in shearing is amplified by the basal sliding relation to produce a large velocity response. The pattern of glacier front retreat can be explained by a tidewater calving instability. These conclusions underscore the importance of basal sliding parameterizations in understanding observed changes in ice sheet outlet glaciers and modeling their future behavior. Correct representation of iceberg calving is also important.

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Factors Regulating Post-LGM Retreat of the Pine Island and Marguerite Ice Streams

John B. Anderson

Ongoing research focuses on the timing of ice sheet retreat from Pine Island Bay and Marguerite Bay and on those factors that regulated retreat. Among the controls on grounding line retreat are seafloor bathymetry and geology, ice sheet thickness and profile, sea-level rise, climate, subglacial meltwater undermining and incursion of warm deep water onto the shelf. Marguerite Bay shares a number of similarities to Pine Island Bay, but its ice stream has completely vanished. We have a much better record of glacial retreat from Marguerite Bay, in addition to better seismic, swath bathymetry and core coverage, so its retreat history is better constrained and, therefore, the factors that regulated ice stream retreat are better known. There is also a well established climate history for the Antarctic Peninsula region.

During the LGM, the Marguerite Ice Stream (MIS) extended to the shelf break (O'Cofaigh et al., 2005; Heroy and Anderson, 2008). Initial retreat (14 cal yrs BP) of the ice sheet from the landward sloping, relatively low relief continental shelf was influenced by sea-level rise with punctuated retreat at ~14,000 cal yrs BP associated an episode of rapid sea level rise (MWP 1a) (Heroy and Anderson, 2008). The grounding line was situated near the mouth of the bay at 12,000 cal yrs BP and remained their, pinned by islands and rugged bedrock topography, until ~10,000 cal yrs BP. Rapid retreat from the bay occurred just prior to ~10,000 cal yrs BP and the bay was virtually ice free by ~9,000 years BP. This rapid retreat of ice from the bay was associated with a period of climatic warming (Mid-Holocene Climate Optimum) that began at about this time on the western side of the peninsula (Allen et al., in press; Michalchuk et al., in press). Other factors that may have contributed to retreat of the ice stream from Marguerite Bay include incursion of warm deep water (Allen et al., in press) and undermining by subglacial meltwater (Anderson and Oakes-Fretwell, 2009). Ongoing research focuses on obtaining better age constraints on grounding line retreat and on constraining the timing of warm deep water incursion onto the shelf and into the bay and on the role of subglacial meltwater in controlling grounding line retreat.

Swath bathymetry data are still sparse on the outer shelf offshore of Pine Island Bay, so the extent of the LGM grounding line and paleo-ice stream is still poorly constrained. In addition, few radiocarbon dates have been acquired from the area so the timing of grounding line retreat is poorly established. What we do know is that the ice sheet was grounded within the bay during the LGM, that it retreated from by ~10,000 cal yrs BP (Lowe and Anderson, 2004a) and that there is a subglacial meltwater drainage system within the bay, very similar to the one that exists in Marguerite Bay (Lowe and Anderson, 2004b). An upcoming cruise aboard the Swedish Ice Breaker Oden (February 2010) is aimed at addressing several important questions regarding the glacial history of the region and the mechanisms that contributed to grounding line retreat.

Posters

(alphabetical by first author)

West Antarctic Ice Sheet Elevations near the Ice Divide prior to the LGM

Robert P. Ackert Jr., Sujoy Mukhopadhyay
Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138

Harold W. Borns, Aaron E. Putnam
Climate Change Institute, University of Maine, Orono, ME, 04496

Mark D. Kurz
Woods Hole Oceanographic Institution, Woods Hole, MA 02543

David Pollard
Earth and Environmental Systems Institute
Pennsylvania State University, University Park, PA 16802

Robert M. DeConto
Department of Geosciences, University of Massachusetts, Amherst, MA 01003

The surface elevation history of the West Antarctic Ice Sheet (WAIS) prior to the last glacial maximum (LGM) is largely unknown. Knowledge of the timing and extent of past WAIS elevation changes provides insight to the WAIS response to sea level and climate forcing. The history of WAIS elevation changes also provides crucial constraints for dynamic ice sheet models necessary to predict the future behavior of the WAIS. Surface exposure ages of glacial erratics near the WAIS divide at Mt. Waesche in Marie Byrd Land (MBL), and at the Ohio Range in the Transantarctic Mountains, range from ~6 ka to > 400 ka without a dependence on elevation. At both locations, maximum ice elevations recorded by moraines or erratics were reached ~10 ka (Ackert et al., 2007; Ackert et al., 1999).

However, most exposure ages are older than the LGM and cluster around ~45 ka and ~75 ka (Figure 1a). Similar exposure age distributions obtained from ice-cored moraines on the WAIS in the Ohio Range indicate that the exposure ages relate to emergence of debris in the ablation zones. We infer that local WAIS elevations, flow patterns and ablation areas have remained similar to those at present for at least ~100 kyr. Tephra layers as old as 117±7 ka at Mt. Waesche indicate similar relative WAIS stability in MBL (Dunbar et al., 1998). The presence of a few exposure ages spanning the last interglacial within the ice-cored debris at both sites suggests that ice elevations and ice flow regimes were not significantly different during the last interglacial. Such limited changes in ice elevation and flow regime would seem inconsistent with a complete WAIS collapse.

The intervals round 45 and 75 ka are roughly synchronous with obliquity-driven isolation maximums, warmer Antarctic temperatures and with exposure ages of alpine moraine boulders in the Ohio Range. These intervals likely correspond to pulses in the debris flux and higher accumulation rates. A combined ice sheet/ice shelf model driven by marine $\delta^{18}O$ predicts that

WAIS elevations near the Ohio Range have varied only ~150 m over the last glacial cycle (Pollard and DeConto, 2009). In the model simulation, relative high stands occurred ~50 and ~80 ka with maximum ice elevation reached ~10 ka (Figure 1b). The lag between modeled ice sheet high stands and peaks in the exposure age distribution suggests that debris flux into the ablation zone is maximized during down draw of the WAIS surface. The general correspondence between the model results and observations at the Ohio Range and Mt. Waesche supports the conclusion that interior WAIS elevation changes were limited to ~150 m during the last glacial cycle and are controlled primarily by accumulation rates (temperature) rather than the aerial ice sheet extent (sea level).

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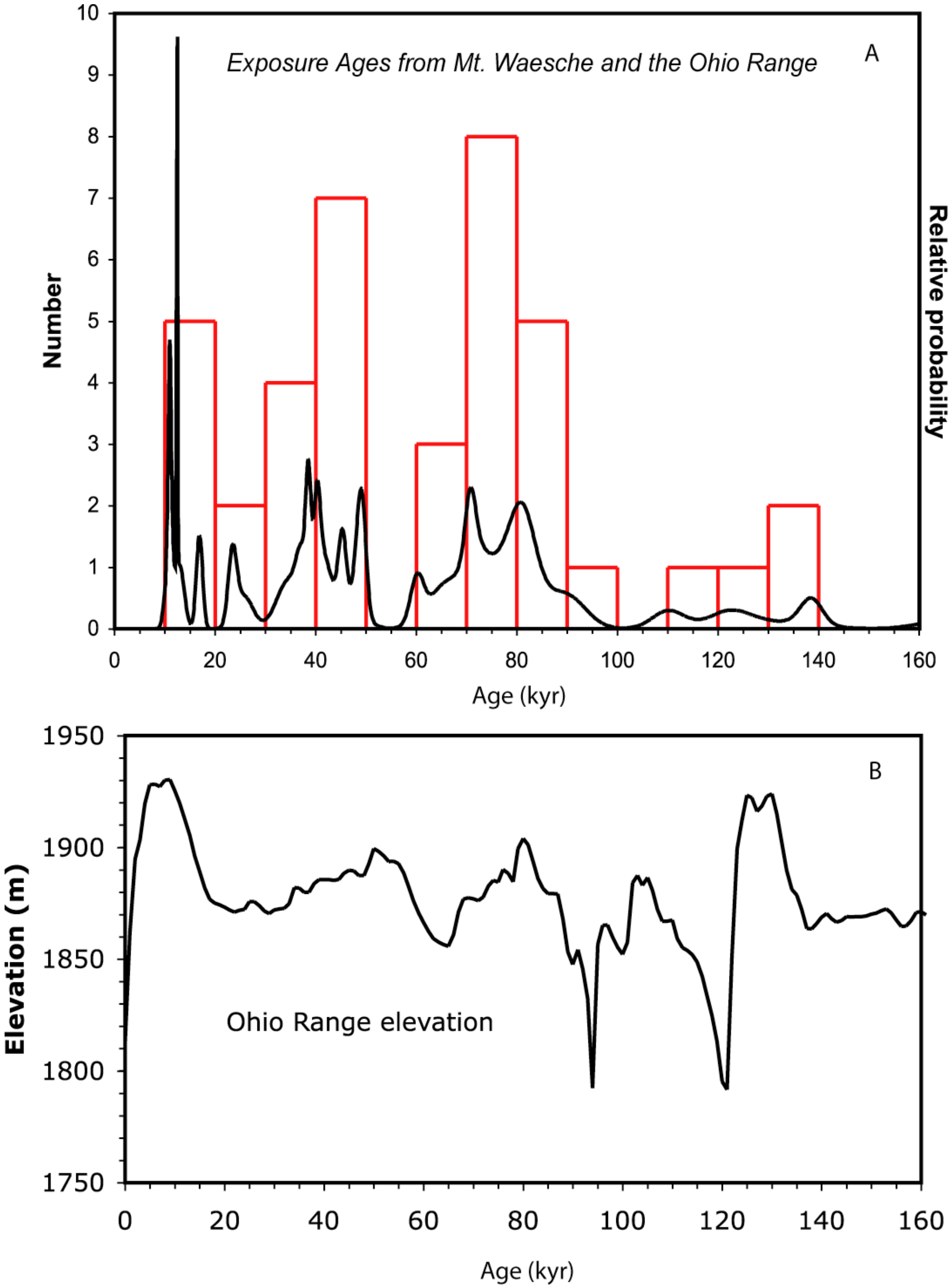
Figure 1. A) Histogram and probability density function (PDF) of surface exposure ages of erratics and moraine boulders from the Ohio Range and Mt Waesche. The exposure ages cluster in the intervals 40-50 ka and 70-80 ka. B) Modeled WAIS elevation at the grid point nearest the Ohio Range from 160 ka to the present. Output is from WAIS model presented in Pollard and DeConto (2009). The relative highstands that occur ~50 and ~80 ka correspond to peaks in the PDF of exposure ages, suggesting pulses of debris coincided with the highstands.


Exposure Ages from Mt. Waesche and the Ohio Range
A
Number
Relative probability
Age (kyr)
B
Ohio Range elevation
Elevation (m)
Age (kyr)

The Antarctic Glaciological Data Center: An Archive for NSF Antarctic Program Glaciological Research

Rob Bauer

Antarctic Glaciological Data Center, University of Colorado
CIRES 449 UCB, Boulder, CO 80309

The National Science Foundation's Office of Polar Programs (OPP) funds the U.S. Antarctic Glaciological Data Center (AGDC) at the National Snow and Ice Data Center (NSIDC) to archive and distribute Antarctic glaciological and cryospheric system data collected by the U.S. Antarctic Program.

The archive is designed to provide access to Antarctic data sets over the long term, thereby making them available for comparison with future data: a critical component of change detection studies. By facilitating broad data access, the center promotes interdisciplinary scientific research.

AGDC provides data management for the National Science Foundation's Antarctic Glaciology Program and related cryospheric science investigations. Data archived at AGDC include ice velocity, firn temperature, shallow ice core measurements, geochemical composition of ice cores, snow pit data, and satellite images of ice shelves. AGDC now holds data contributed by over 120 principal investigators, whose research spans a broad variety of glaciological topics.

Have you submitted your data? The NSF OPP's policy is that principal investigators submit their data as soon as possible, but no later than two years after the data are collected. This poster features some of the new PI data sets archived at AGDC, and explains how researchers can submit their data.

Decadal flow variations of Whillans and Kamb Ice Streams from high resolution GPS measurements

Lucas Beem and Slawek Tulaczyk

The ice streams of West Antarctica may undergo cyclical changes in behavior due to time variant basal conditions. The Whillans and Kamb Ice Streams offer a comparison between two ice streams at different phases within this cycle. Each may be an analogue for future or past behavior of the other.

The Global Positioning System produces high resolution velocities and strain rates of the ice surface. Repeat surveys of velocity profiles and strain grids on the Kamb Ice Stream have occurred periodically between 1980 and 2007. Coupled with remote sensing of ice surface topography from IceSAT and airborne LiDAR an evolution of the Kamb Ice Stream over the last decade and beyond is possible.

For the Whillans Ice Stream, a network of currently deployed continuous GPS stations examine the influence of subglacial Lake Whillans on the surrounding ice motion. The GPS measurements show that the lake has been filling, from near a low stand, for the last two years. A draining of the lake has yet to be observed.

Whether each of these ice streams truly behaves as the other is yet to be seen, but observed changes allow for inferences about the changing and dominate resistive stresses controlling glacial flow.

The results of these surveys show the Kamb ice stream remains within a consistent pattern of deceleration and thickening for the time period investigated, despite modest increases in driving stress. This suggests continued basal strengthening. The Whillans Ice Stream likewise continues to decelerate, but at an increasing rate. The influence of a filling subglacial lake may have limited effect on the temporal and spatial patterns of ice movement.

Peering Beneath the Ice Sheet: AGAP Evidence for a More Dynamic East Antarctica

Robin Bell[1], Michael Studinger[1], Fausto Ferraccioli[2], Detlef Damaske[3], Carol Finn[4], David Braaten[5], Mark Fahnestock[6], Tom Jordan[2], Hugh Corr[2], Stefan Elieff[7], Nick Frearson [1], Adrienne Block[1], Kathryn Rose[2]

[1]Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA
e-mail: robinb@ldeo.columbia.edu, +1 845 365 8827
[2]British Antarctic Survey, Cambrigde, United Kingdom
[3]Federal Institute for Geosciences and Natural Resources, Hannover, Germany
[4]United States Geological Survey, Denver, USA
[5]Center for Remote Sensing of Ice Sheets, The University of Kansas, Lawrence, Kansas, USA
[6]Complex Systems Research Center, University of New Hampshire, Durham, NH, USA
[7]Sander Geophysics Ltd., Ottawa, Canada

Exploring the history of the East Antarctic Ice Sheet and lithospheric structure of the Gamburtsev Subglacial Mountains were primary goals of the International Polar Year. Scientists from seven nations have launched a flagship program (AGAP) to explore the Gamburtsev Subglacial Mountains buried by the East Antarctic ice sheet and bounded by numerous subglacial lakes. The AGAP umbrella is a multi-national, multi-disciplinary effort and includes aerogeophysics, passive seismology, traverse programs and will be complimented by future ice core and bedrock drilling. A major new airborne data set including gravity; magnetics; ice thickness; SAR images of the ice-bed interface; near-surface and deep internal layers; and ice surface elevation is providing insights into a more dynamic East Antarctica. More than 120,000 km of aerogeophysical data have been acquired from two remote field camps during the 2008/09 field season. AGAP effort was designed to address four fundamental questions: 1) What role does topography play in the nucleation of continental ice sheets? 2) How are major elevated continental massifs formed within intraplate settings but without a straightforward plate tectonic mechanism? 3) How do tectonic processes control the formation, distribution, and stability of subglacial lakes? 4) Where is the oldest climate record in the Antarctic ice sheet? Preliminary results point towards a more dynamic East Antarctic ice sheet and a more complex tectonic evolution for East Antarctica.

A second MODIS Mosaic of Antarctica: MOA-2009

J. Bohlander, T. Haran, and T. Scambos

We are assembling a new resolution-enhanced MODIS mosaic of the Antarctic continent, using a series of images from both Terra and Aqua. The mosaic will be built from images acquired between November 20, 2008 and February 28, 2009. Image selection, de-striping, precise geolocation, cloud masking, image edge feathering, filtering, and image stacking will be conducted in an identical fashion to the previous mosaic (detailed in Scambos et al., 2007). As before, the final image resolution will be 125m, and a grain-size mosaic will be prepared as well as a surface feature image map.

We will present preliminary views of the partially assembled mosaic and some test areas of image differencing. We anticipate that comparison of the two mosaics (when completed) will reveal changes in the ice extent and coastline, for example where large calving events have occurred in the interim between the two mosaics. Image differencing of the mosaics may also reveal sub-glacial lake activity, ongoing flow direction changes on ice shelves, dune movement, and new crevassing. We will also attempt to map ice velocity in heavily-crevassed outlet glaciers and ice shelves continent-wide using the two mosaics (with an expected accuracy of better than +/- 50 m/yr).

Analogue modeling of water flow under ice; what can we learn?

G. Catania, Institute for Geophysics, University of Texas, Austin TX 78758
J. Buttles, Dept. of Geology, University of Texas, Austin TX 78705
D. Mohrig, Dept. of Geology, University of Texas, Austin TX 78705

Analogue models have been used extensively in the Earth sciences to improve understanding of natural processes. We report on preliminary experiments to understand the nature of, and impacts from, water flow under ice. To simulate ice flow we use polydimethyl-siloxane (PDMS) – a liquid polymer used extensively in the tectonics community. PDMS is a transparent, non-toxic material with a specific weight similar to that of ice. Additionally, the viscosity of PDMS is well-suited to ice flow studies as it is strain-rate dependent. The polymer is loaded into a 4’x6’ plastic box which is coated with a water-based lubricant across much of the width of the box to reduce friction between the polymer and the plexiglas base. Water is injected at the interface between the polymer and the plastic box through a set of tubes that distribute the water supply across the upstream end at a constant discharge.

We measure horizontal surface displacements by tracking several bright stickers placed on the surface of the polymer through a sequence of images that make up each experimental run. Coincident water discharge and channel pattern measurements are made to correlate changes in discharge to changes in channel geometry and surface motion. The channelized area is observed by injecting dark blue dye into the water.
Of particular interest is the response of the channel system to discharge pulses. To observe this we change discharge into the flume from ~70 cm3/s to 550 cm3/s which reflects a ~8-fold increase in discharge and represents the typical diurnal fluctuation in discharge observed for alpine glaciers due to increased surface melt.

Future experiments to be conducted include experimenting with larger discharge pulses representing extreme events such as supraglacial lake drainage, changes to the shape of the bed to represent water flow around obstacles and into depressions. We also wish to understand how ice sheet surface elevation changes correspond with ponding and subsequent release of subglacial water. Finally, we will repeat experiments with a sediment layer to understand the differences in channel patterns for hard-bedded versus soft-bedded glaciers.

Geometric enhancement of the absorption of incoming insolation on complex terrain

Mac Cathles

The surface of ice sheets and ice shelves are far from flat. Rivulets, crevasses and ponds sculpt the surface of ice in an ablation zone creating surface roughness on multiple scales. These surface features reflect energy towards other portions of the surface, and cast shadows, creating a tug-of-war between the shadows which exacerbate surface roughness, and multiple reflections and absorption which acts to minimize surface features. We developed a numerical model which expands on the pioneering work of Pfeffer and Bretherton, 1987, who examined the ability of V-shaped crevasses to trap solar energy more efficiently than a flat ice surface. Our methodology extends this previous work to arbitrary, 2-dimensional surface feature geometries. Our numerical model calculates the distribution of absorbed energy for surfaces and includes multiple reflections and shadows from both direct and reflected light sources. Insolation is only part of the surface energy budget of an ice-shelf or ice-sheet, but we focus exclusively on this aspect of the surface energy flux in this study because other energy fluxes may not share the strong dependence on surface geometry associated with absorption of insolation. This may mean that meter to kilometer scale surface features in ice ablation zones evolve according to ice-sheet surface 'optics', the radiative details of complex, multiply illuminated terrain.

Changes in the surface velocity of Thwaites Glacier from differential GPS observations

Knut Christianson, Huw Horgan, Sridhar Anandakrishnan

Thwaites Glacier (TG), which together with Pine Island Glacier (PIG) drains ~5% of the West Antarctic Ice Sheet (WAIS), epitomizes the class of overdeepened ocean-terminating glaciers that would be at risk under a Weertman style retreat scenario, where grounding line retreat of a marine glacier is hypothesized to lead to thickening of ice at the grounding line and result in greater ice flux to the ocean from the higher driving stress creating additional grounding line retreat, and thus a positive feedback. This inherent sensitivity of TG to grounding line retreat is exacerbated by its discharge into a deep embayment with relatively warm water and high accumulation rates, which suggest heightened sensitivity to oceanic influences and synoptic scale meteorology, respectively. Here we present results of a ground-based differential GPS study during the 2007-2008 (17 stations) and 2008-2009 (16 stations) austral summers, where stations were deployed along the 2 central flowlines and on one transverse-to-flow line. Stations were located between 60 km and 335 km from the grounding line and sampled ice velocities from ~65 m/a to ~660 m/a. 9 stations were co-located during both austral summer deployments. 8 of the 9 co-located stations show velocity increases ranging from ~1-1.6%. The only station not exhibiting a velocity increase is located farthest from the grounding line (~335 km) and advected into a zone of slightly lower velocity as indicated by interferometric synthetic aperture radar (InSAR) data. Horizontal advection can only account for velocity magnitude changes ranging from 0.004-0.25%; thus, our observations indicate an acceleration along both central flowlines. Our results also show that TG is continuing to widen in agreement with InSAR observations. These data suggest that TG has not reached a new steady-state, but is continuing to respond to forcing, the source of which cannot be identified from this study alone.

A comparison of geophysical observations of a Greenlandic supraglacial lake drainage using commercial instruments and a low-cost experimental alternative

Peter Burkett, Bruce Long, Knut Christianson, Randy Justin, Don Voigt, Sridhar Anandakrishnan

Supraglacial lake drainages have the potential to be a driver of ice flow acceleration in a long-term retreat scenario of the Greenland Ice Sheet (GIS) if the hypothesized enhanced basal lubrication resulting from the supraglacial drainages is extensive enough in area and volume to affect a substantial portion of the margin of GIS. From late-May to early-August 2009, we instrumented a supraglacial lake in the vicinity of Jakobshavn Isbrae, Greenland with commercial broadband seismometers, high-frequency 3-component Y28 geophones (4.5 Hz eigenfrequency), and differential GPS stations (L1/L2 receivers). In addition to the commercial products, we also deployed a combined microphone, 3-channel seismic data (equipped with Y28 geophones for this deployment), and L1 GPS instrument, christened geoPebbles, developed at the Pennsylvania State University for approximately 1/10 of the cost a single commercial component. MODIS imagery indicates that the drainage of a supraglacial lake within 5 km of 2 stations occurred on June 17, 2009. The supraglacial lake drainage was coincident with an ~0.4 m uplift of the glacier in ~2 hours, an ~0.4 m excursion to the north in ~2 hours, and a more subtle acceleration to the west (the predominant ice flow direction in this area) followed by a gradual return to the average ice velocity preceding the supraglacial lake drainage. The seismometers also reveal ~24-36 hours of heightened seismic activity. In this first field test, the geoPebble data show good agreement with the commercial instruments and thus geoPebbles have the potential to allow more extensive GPS and seismic observations in Greenland and Antarctica. Here we present not only initial observations of a supraglacial lake drainage, but also illustrate the field potential of geoPebbles in polar research.

Constraints on the Timing of the Last Deglaciation of Antarctica

Clark, P.U., Department of Geosciences, Oregon State University, Corvallis, OR 97331
Carlson, A.E., Department of Geology and Geophysics, University of Wisconsin, Madison, WI

We summarize published terrestrial cosmogenic nuclide (TCN) and ^{14}C ages from Antarctica to constrain the timing of the last deglaciation. The only direct constraints on deglaciation of the East Antarctic Ice Sheet (EAIS) come from TCN ages, but because these are based on single boulders, they are subject to large uncertainties. After screening published single-boulder TCN ages for obvious uncertainties related to erosion or cosmogenic nuclide inheritance, we conclude that all but two of the remaining TCN ages indicate deglaciation of the EAIS was underway between 13 and 15 ^{10}Be ka, with younger ages possibly indicating subsequent ice-sheet thinning. Deglaciation of the Antarctic Peninsula is poorly constrained by five single-boulder TCN ages as being well underway by ~10 ^{10}Be ka. Radiocarbon ages on organic matter in marine sediments from west of the peninsula suggest that deglaciation from the maximum extent on the continental shelf may have begun as early as 19 ka, but the large uncertainties associated with bulk marine ages from Antarctica preclude an accurate assessment of this timing. The oldest TCN age constraining deglaciation of the WAIS is 14.4 ± 1.5 ^{10}Be ka, but like all other TCN ages from Antarctica, this age is for a single boulder. Most of our information on the chronology of the Antarctic ice sheet comes from the extensive radiocarbon dating from the Ross Sea sector of the WAIS, particularly that from Taylor Valley. The ^{14}C age on the oldest delta that formed in this glacial lake in Taylor Valley (28.25-28.77 cal ka; QL1708) provides a limiting minimum age for the local last glacial maximum (LLGM), whereas the ^{14}C age on the youngest reworked marine shells in glacial deposits (28.80-29.39 cal ka; TO1980) provides a limiting maximum age for the LLGM. We use the maximum range defined by these two ^{14}C ages (28.25-29.39 cal ka) as the uncertainty for the onset of the LLGM.

We use several lines of evidence from dating of the Taylor Valley geomorphic record to identify termination of the LLGM in the Ross Sea. (1) The youngest ^{14}C age (14.7-15.1 cal ka; AA-20667) constraining the time of the LLGM ice margin at the Hjorth Hill moraine provides a limiting maximum age for retreat from the moraine. (2) Two ^{14}C ages on algae that grew in a glacial lake that formed following ice-margin retreat from the Hjorth Hill moraine provide limiting minimum ages for this retreat (14.8-15.2 cal ka; AA-13576, and 14.9-15.2 cal ka; AA17342). (3) The glacial lake in Taylor Valley permanently dropped below ~80 m after 13.9-14.7 cal ka (AA-17314) (^{14}C age on youngest high-elevation delta) and before 13.9-14.1 cal ka (QL1707) (^{14}C age on oldest low-level delta after permanent drop). (4) Lacustrine deposits occur in a stream exposure cut into the moraine deposited by the LLGM ice margin on the floor of Taylor Valley, with a ^{14}C age requiring deglaciation from the moraine before 14.3-14.8 cal ka (AA17333). (5) Glaciolacustrine sediments containing dropstones occur along the distal side of the valley-floor threshold moraine, indicating that the ice margin was at the moraine. The youngest ^{14}C age from this unit (13.6-14.7 cal ka; QL-1794) provides a limiting maximum age for retreat from the moraine. Given these dating constraints, we assign an error for the termination of the LLGM (13.9-15.2 cal ka) based on the youngest limiting maximum ^{14}C age for ice-margin retreat (13.9-14.7 cal ka (AA-17314) and the oldest limiting minimum ^{14}C age for ice-margin retreat (14.9-15.2 cal ka; AA-17342).

Oceanographic Observations Pertinent to the Petermann Glacier

Kelly K. Falkner1, Andreas Muenchow2, Humfrey Melling3 and Helen Johnson4

1 College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon
2 College of Marine and Earth Studies, University of Delaware, Newark, Delaware
3 Institute of Ocean Science, Department of Fisheries & Oceans, Sidney BC, Canada
4 Department of Earth Sciences, University of Oxford, Oxford, United Kingdom

A 2003 Icebreaker Healy mission in August of 2003 that was part of the Canadian Archipelago Throughflow Study (CATS) program allowed the first in a series of four opportunistic ocean sampling efforts in the vicinity of the floating tongue of the Petermann Glacier in northern Greenland. Our most recent sampling effort was just completed in August 2009. Measurements include bottom mapping, CTD profiles, ADCP measurements and chemical tracer hydrography. This poster summarizes our findings to date.

Our bathymetric measurements establish that the 70 km long about 15 km wide glacial tongue floats over a 1000-m deep, near vertically walled fjord. The fjord basin is separated from the adjacent 800-m deep Hall Basin in Nares Strait by a sill depth of 480-m. It has been established by others that Petermann Glacier is grounded at about 600 m below sea level. Others have concluded from indirect evidence that ocean driven melting concentrated in front of the grounding line is the dominant loss term in the mass balance of this glacier. We have observed freshwater plumes emanating seaward from the underside of the seaward end of the glacial tongue. These plumes are relatively small in scale (near surface and less than a km in width) and correspond to the scale of undulations mapped in recent radar studies by others. We also have observed fluxes of relatively warm (1 ˚C) salty water into the fjord at the sill below about 100 meters. Chemical evidence shows that waters below sill depth within the fjord are renewed more slowly than in the adjacent Hall Basin (timescale on the order a few decades) but not so slowly that oxygen contents are more than 20% depleted from saturation. Rigorous melting flux estimations based on ocean measurements would require better spatial and temporal scale sampling than we have achieved to date.

Past Flow Conditions of Thwaites Glacier revealed by radar-detected internal layer patterns

T.J. Fudge, Ginny Catania, Howard Conway, Donald Blankenship, Duncan Young, Scott Kempf, and Erick Leuro

We use radar-detected internal layer patterns from the Airborne Geophysical Survey of the Amundsen Sea Embayment (AGASEA) project to characterize past flow conditions of Thwaites. We compute the roughness of internal layers and bed and compare them with each other. In general, the bed is rougher than the internal layers in slow-flow regions (divides) while in fast-flow regions (outlet glaciers) the internal layers are rougher than the bed. In slow-flow regions, the internal layers are a muted reflection of the bed topography. In fast flow regions, the greater roughness of internal layers is due to features inherited from upstream. The inherited patterns can be tracked between radar layers roughly perpendicular to the ice flow, particularly in the onset regions where ice velocities are 50-150 m/a. The distinct patterns define individual flow bands and will be used to determine the ratio of paleoflow velocities for the past ~500-1000 years (the transit time of ice through areas where patterns can be tracked).

Modeling Abrupt Change in Global Sea Level due to Ocean–Ice-sheet Interaction

Carl Gladish

The long time scale of ice internal to the Greenlandic and Antarctic ice sheets suggests that any rapid sea level change will be due to faster processes at the margins of the great ice sheets. In particular, mass loss and thinning at outlet glaciers and ice shelves due to contact with the ocean may be significant. This poster describes ongoing work to couple a depth-integrated sub-shelf melt-water plume model to an ice model (GLIMMER/CISM) in order to understand the relation between the internal dynamics of an ice shelf and the melting (or freezing) that occurs at its lower boundary. Specifically, we are looking for a mechanism by which melt-water plumes may form and sustain longitudinal or transverse channels in a shelf.

Surface Elevation Changes at the Front of the Ross Ice Shelf; Implications for Basal Melting

Huw Joseph Horgan (1), Ryan T Walker (1), Sridhar Anandakrishnan (1, 2), Richard B Alley (1, 2)

1. Dept. of Geosciences, Penn State University, University Park, PA, USA.
2. Earth and Environmental Sciences, Penn State University, University Park, PA, USA.

Spatial and temporal elevation changes for the front 60 km of the Ross Ice Shelf are examined using GLAS ICESat laser altimetry data. Elevation profiles show a spatial trend of decreasing elevation towards the calving front, which is explained by temporal changes over a 3—4 year period demonstrating 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. Melt rates are observed to increase exponentially as the front is approached, from near equilibrium at approximately 40 km from the front to an average of 2.7 m/a within the front kilometer. Melt estimates are best fit by the relationship melt rate = 2.1exp(x/11800) m/a. Spatial averaging along the front indicates that regions which have recently calved large tabular bergs (e.g. icebergs C-19 and B-15) may experience a faster decrease in melt rate with distance from the front compared to a gradual decrease in non-calving regions. This points to the dependence of melt rate on basal profile – the basal profile at the front after calving events is not as conducive for melting at greater distances from the front. The estimated basal-melting is thought to be due to a combination of i) the tidally-induced mixing of near-surface ocean water, and ii) plume ascension and entrainment. We simulate this process using a one-dimensional model of plume-entrainment after initiation with a tidal-mixing melt rate.

Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers

Adrian Jenkins

British Antarctic Survey, Natural Environment Research Council, Cambridge.

Ocean circulation beneath or in front of ice shelves and tidewater glaciers is usually considered as being forced by the buoyancy generated by melting at the ice-seawater interface. However, most fast-flowing glaciers have an active (and variable) sub-glacial drainage system, and the discharge of freshwater across the grounding line will provide an additional (variable) source of buoyancy forcing on the ocean. This paper considers the region where this additional (conventionally-neglected) source of buoyancy dominates. When the discharge of freshwater is small, this region is also small, but it can grow to cover 10's of kms, a substantial fraction of many ice shelves. For tidewater glaciers with no floating tongue, the vertical face of the calving front will generally lie entirely within this region. Melt rates are found to be a linear function of water temperature, because the feedback whereby higher temperature produces higher melting that leads to greater buoyancy forcing is, by definition, negligible. However, melting is also a function of the initial freshwater flux to the power of one third. This means that an order of magnitude increase in sub-glacial discharge leads to a doubling of the melt rate.

These findings have some important implications. For many tidewater glaciers the seasonal cycle in sub-glacial drainage may have a bigger impact than seasonal change in the ocean temperature on the seasonal cycle of melting at the glacier terminus. Increases in summer melting, driven by a warming atmosphere, will lead to increases in melting at the terminus, independent of any increase in ocean temperature. Drainage of a sub-glacial lake across a grounding line will lead to a temporary increase in the melt rate at and downstream of the grounding line of an ice shelf. Such processes could conceivably have played a role in recent changes that have been observed in outlet glaciers of the Greenland and Antarctic ice sheets. The combination of high seawater temperature and freshwater discharge can explain the exceptionally high melt rates (~10 m/day) reported by Motyka et al (2003) for LeConte Glacier, Alaska.

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A Closer look at evidence for subglacial drainage systems in Pine Island Bay, Antarctica

Alexandra E. Kirshner[1], Frank Nitsche[2], and John B. Anderson[1]

[1]William March Rice University, Houston, Texas
[2]Columbia Lamont Earth Observatory, New York

Pine Island and Thawites Glaciers drain approximately 300,000 km^2 of ice through Pine Island Bay at a rate of glacial thinning up to 3.2m yr^{-1} (Rignot ,1998, 2001; Vaughan et al., 2001), making this one of the most dynamic portions of the West Antarctic Ice Sheet. Pine Island Bay has historically had a paucity of data due to harsh weather conditions. Lowe and Anderson 2003 identified three distinct glacial zones based on sea floor topography. New higher resolution bathymetric data from a larger portion of Pine Island Bay allows a more detailed analysis of the region.

Pine Island Bay is characterized by a rugged sea floor, with many potential pinning points, megaflutings, drumlins, mega-scale lineations and numerous channels and basins; hinting at a subglacial drainage system (Lowe and Anderson, 2003; Evans et al, 2006; Deen et al. 2007). Using the new data set, we are examining connectivity of basins and channels to assess the potential for subglacial meltwater control on ice sheet retreat. The timing of retreat is possibly marked by a distinct silt unit that is interpreted as a meltwater deposit. During an upcoming (2010) cruise to the region, we hope to better constrain both the nature and rate of grounding line retreat by mapping grounding zone wedges and sampling these features to establish their age.

Using the level set method to track ice sheet boundaries

Daniel Seneca Lindsey and Todd K. Dupont

Department of Earth System Science
University of California, Irvine

Simulating ice-sheet volume changes requires tracking the interface of ice and its surrounding media, e.g. water, air, and sediment or rock. This can be challenging when using a _xed, or Eulerian, grid and allowing the interface to move via kinematic boundary conditions. For example, the interface may fall between grid points at a given point in time, making the application of boundary conditions less than straightforward. The level set method of Osher and Sethian (1988) o_ers an alternative approach, wherein a continuous level set function evolves within the domain via the combined kinematics of ice and its encompassing materials. Pralong and Funk (2004) applied this method to the movement of a glacier's ice/air interface, o_ering a glimpse of the potential of this method for glaciology. Here we perform a simple preliminary test of the method for a two-dimensional (owline) model of an ice shelf, comparing the results to analytic approximations of the movement of both the ice/air interface and the ice front. The ultimate goal of this work is provide a practical approach for two and three-dimensional ice-sheet models to naturally track their moving boundaries.

Examining the slope-driven control of basal melting

Christopher M. Little
Princeton University, Department of Geosciences

Anand Gnanadesikan
NOAA/Geophysical Fluid Dynamics Laboratory, Princeton NJ

Previous studies of ice shelf basal melting [e.g. Jenkins 1991] note that slope-dependent entrainment of heat into the oceanic mixed layer is an important control of the rate of basal melting. Because ice shelf thickness gradients may vary by an order of magnitude along an ice shelf, even weak slope-sensitivity drives strong gradients in melting.

Here, we summarize the results of Little et al. [2009], in which a 3-D numerical ocean model is used to analyze the sensitivity of basal melting to temperature and ice shelf basal slope. Entrainment of heat occurs predominately under deeper, steeper sections of the ice shelf; local and area-integrated melting rates are most sensitive to changes in slope in this "initiation region" [see figure]. Stratification, tides, and small-scale topographic features are neglected in these simulations; turbulent heat fluxes are parameterized. In this poster, alternate configurations and parameter choices are included for comparison.

As basal slopes steepen and melt rates increase, dynamic and thermodynamic glaciological responses become important [Walker et al. 2008]. Although the oceanographic caveats highlighted here deserve further investigation, local slope remains the dominant driver of mixed layer temperature and melting gradients, indicating that a simple form of slope-dependent melting may be sufficient to investigate the coupled ice-ocean response [Little et al. 2009].

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Glaciology of the Bottleneck, Amery Ice Shelf

Max Lurie max.lurie@umit.maine.edu

Department of Earth Sciences
Climate Change Institute
University of Maine
Orono, ME 04469

The geology of the Amery Ice Shelf is located at the head of Pyrdz Bay in MacRobertson Land in Eastern Antarctica. It is fed from the Lambert Glacier which drains a large portion of the East Antarctic Ice Sheet. The present state of this system is used to model drainage of the EAIS, through the bottleneck created by two wide gaps in the Transantarctic Mountains, in the event of WAIS collapse. Using satellite imagery of surface and bed topography we reconstructed the parabolic curve of the EAIS according to the furthest extent of its grounding line. The calculated floating fraction ($\varphi = h_o/h_i$) for flow lines both before and after collapse model ice-bed coupling in the Lambert Glacier ice shed. This provides insight to the stability of the region and serves to illustrate a potential collapse of the Bottleneck region. Collapse of which could cause a sea level rise o f 2.3 and 4.7 for the Amery and Bottleneck drainage basins.

Limits to WAIS Predictability?

D. R. MacAyeal

Model Simulations of the WAIS suggest that sporadic, perhaps chaotic, collapse (complete mobilization) of the ice sheet can occur 3 or 4 times each million years. This irregular behavior in the model is due to the slow, millennial-scale thermal equilibration time of distributed basal till which lubricates ice-stream motion. The net effect is that the relationship between the ice sheet's volume and environmental conditions (e.g., regional surface temperature, precipitation and, possibly, conditions which influence ice-shelf buttressing) is not linear. Success of the effort to predict the ice-sheet volume changes over the next 100 years, for example, will depend on the ability to know present basal conditions that can either predispose the ice sheet toward rapid collapse, or alternatively, predispose the ice sheet toward basal freeze-up and ice-flow slowdown. Results of the simulations are presented in:

http://geosci.uchicago.edu/people/MacAyeal_irregularWAIS.pdf

Observational support of the notion that basal water and sediment conditions may adversely influence the short-term predictability of ice-stream behavior is found in two arenas: the decadal-scale fluctuations of sub-ice-stream lake volume reported by Fricker and others [2007], and the decadal-scale fluctuations of sub-ice-stream sedimentary systems undergoing erosion, deposition and molding reported by King and others [2009]. The combined effects of the millennial-scale thermal equilibration time of the WAIS sedimentary lubricating bed and the decadal-scales of hydrological and sediment redistribution processes suggests that predictability of the WAIS over a 100 year time span is not immediately obvious.

In spite of this difficult aspect of ice-sheet modeling, ice-sheet predictologists should take heart in the fact that other natural systems also have limited predictability. The problem of forecasting weather is another example of where nature rules out simple deterministic predictability. The unpredictability of weather does not, however, rule out all forecasting success. There are several good examples where forecasts have been made in spite of: (a) not knowing all of the physics that drive weather systems and (b) flaws in observation, numerical technique and specification of initial conditions. A forecast of great historical significance which demonstrates this point was undertaken on 4 June, 1945, for the invasion of Normandy by the Allied Expeditionary Force on the following day. The plans for the invasion were significantly modified using weather forecasts that predicted unfavorable conditions on the 5th of June. These forecasts were made by Norwegian Sverre Petterssen of the Bergen School of Meteorology at a time when potential vorticity dynamics was unknown, the existence of the jet stream was only sketchy and the ability to observe meteorological conditions in the North Atlantic was marred by naval warfare. The effort to forecast the future of WAIS volume in the context of a new IPCC analysis should take heart from this historical example.

Estimating englacial radar attenuation using depth profiles of the returned power, central West Antarctica

Kenichi Matsuoka, PhD
Research Assistant Professor
Department of Earth and Space Sciences
University of Washington
Box 351310, Seattle, WA 98195-1310

We analyzed depth patterns of geometrically corrected returned power P_c from within the ice of central West Antarctica to develop a proxy for englacial radar attenuation. The depth patterns of P_c at individual sites were first approximated with least-square vertical gradients of the local-mean P_c for five depth ranges. Variations of these gradients along radar tracks show identifiable trends but have local anomalous features over distances less than ~5-10 km that are caused by smaller reflection from tilted internal layers above steep beds and other factors. Consequently, extraction of an attenuation proxy from the returned power requires mitigation of reflectivity variations. Next, returned power was synthesized only from bright layers assembled over distances much wider than the local anomalous features. Individual data ensembles have a clear upper envelope in P_c and the envelope decreases with depth monotonically between ~500 m and ~1600 m. With the aid of attenuation and reflectivity modeling, we concluded that the upper-envelope gradient can be an attenuation proxy in the isothermal ice, which is expected in the upper half or more of central West Antarctica. The estimated attenuation rate in the upper ~1600 m varies 5 dB/km (one way), equivalent to lateral temperature variations of about 2^{o}C or chemistry variations of up to a factor of 2. This range indicates that the attenuation variations may alter dependable delineation of bed wetness on the basis of contrasts in power returned from the bed.

Assessing Assessments: a sociocultural history of the West Antarctic Ice Sheet

Jessica O'Reilly

Postdoctoral Research Associate
Princeton University and the University of California, San Diego

The potential for rapid disintegration of the West Antarctic Ice Sheet—and the timeframe over which such ice discharge could occur—are matters of profound debate among the glaciologists who study the West Antarctic Ice Sheet. In the 1980s, several informal workshops and small conferences gathered experts to report on the cutting edge research concerned with the West Antarctic Ice Sheet. As research became more specific and models more complex, WAIS experts moved from attending these smaller workshops to participating in highly organized, large-scale, and international undertakings such as the Intergovernmental Panel on Climate Change (IPCC).

As a case study, I examine the development of WAIS projections in IPCC assessment reports over time. While earlier IPCC assessments contained quantitative estimates of WAIS' contribution to sea level rise during the 21st century and beyond, in the fourth assessment report (AR4), the authors determined that there was insufficient data to provide a credible estimate. Many may not have felt compelled to report an estimate since the ice sheet contribution was regarded as unlikely to be a primary contributor over this century. Many people involved have noted that the authors were brave in deciding to leave the ice sheets out of sea level rise assessments in AR4; others consider it a serious error that weakens 21st century sea level rise estimates as well as longer term projections. I discuss four contributing factors leading to this outcome—1) the composition and group dynamics of IPCC writing teams, 2) the ways in which the IPCC organizes and reorganizes chapters for each assessment report, 3) methods used to make uncertainty calculations, and 4) the role of new data in shaping knowledge—which underscore the complexity of making projections under great uncertainty.

This project uses ethnographic and historical methods to study how scientists produce knowledge about this subject as well as contribute their knowledge to policy-relevant assessments. I analyze the ways in which experts organize themselves and their work as well as the informal discussions that are integral to shaping the assessment reports. Some philosophers of knowledge argue that individuals within such institutions become established in a "network of writing," adopting practices and habits that produce written knowledge. How have WAIS scientists collaborated in assessments through such a network and how was their written understanding of WAIS transformed as it moved through time and between meetings?

Glaciology of the Bottleneck

K.A. Pingree[1], M. Lurie[1], T.J. Hughes[1,2]

[1]Department of Earth Sciences, University of Maine, Orono, ME 04469
[2]Climate Change Institute, University of Maine, Orono, ME 04469

Major advances in ice-sheet modeling and data acquisition make possible addressing a major question in Antarctic glaciology: how high and how fast will global sea level rise if collapse of the West Antarctic Ice Sheet allows massive discharge of East Antarctic ice through the Bottleneck that now joins the East and West Antarctic Ice Sheets? The former is addressed by (1) a recap of how the West Antarctic Ice Sheet collapsed to its present size during the Holocene, (2) showing how ongoing collapse is most likely in the Pine Island Bay polynya in the Amundsen Sea sector of the ice sheet, (3) showing how this collapse may proceed through the Bottleneck into East Antarctica, (4) emphasizing downdraw of interior ice by surging ice streams followed by calving bays that migrate up stagnating ice streams to carve out downdrawn interior ice, and (5) hypothesizing that these events follow from a reduction of ice height cased by reducing ice-bed coupling in a force balance that is independent of the mass balance.

Subglacial Landform Analysis and Reconstruction of Miocene Paleotopography of Marie Byrd Land

Perry Spector[1,2], Christine Siddoway[1], and Paul Morin[2]
[1]Department of Geology, Colorado College, Colorado Springs, Colorado 80903
[2]The Antarctic Geospatial Information Center, University of Minnesota, Minneapolis, MN 55455

Analysis of sub-ice bed topography datasets from Marie Byrd Land (ASE05, WMB (SOAR), BEDMAP1_plus), undertaken as part of the international Antarctic paleotopography, or ANTscape, program (www.antscape.org), reveals subglacial landforms that may have implications for ice sheet history, ice dynamics, and determination of isostatic responses of the crust of Marie Byrd Land (MBL) since the onset of continental glaciation. These include subglacial volcanoes, alpine glacier valleys upon elevated topography of volcanos, and a flexural moat around the Executive Committee Range volcanic field (Fig. 1). Observations from the geophysical datasets are augmented by the Landsat Image Mosaic of Antarctica (LIMA) and high resolution commercial imagery held by the Antarctic Geospatial Information Center (AGIC).

Whereas the WAIS initiated at *ca.* 34 Ma *(DeConto et al., 2007, Pollard and DeConto, 2003)*, the volcanoes in the MBL volcanic province are 17 Ma to present (Mt Petras and Reynolds, excepted). Thus, central MBL volcanoes were not present to serve as high elevation sites for ice cap nucleation during the early history of the WAIS. During and after formation, the 2000+m volcanoes would have affected precipitation patterns and been sites of volcano-thermal perturbations that promoted warm-based glaciation, conducive to glacial erosion and development of alpine glacier valleys during times of reduced ice sheet extent. Such considerations, arising from study of bedrock geology and landforms, are the basis for our effort to reconstruct the Early Miocene (*ca.* 21 Ma) paleotopography of Marie Byrd Land through inferring subglacial bedrock response to surficial processes. Our results will be integrated into paleotopographic reconstructions of Antarctica that are being prepared by ANTscape for 6 time intervals (spanning 92 Ma to present) that have paleoclimate and tectonic significance. The geospatial data for the reconstructions of past landscapes are intended for use as inputs for future ice sheet-ice shelf models and for visualizations of Antarctic paleogeography and paleoenvironments.

Cross-sectional profiles of ASE05 and BEDMAP1_plus bed topography data show a pronounced narrow downwarp, bordered by a broad bulge, on the north and south margins of the Executive Committee Range (Fig.2). Sequential topographic profiles at 5 km spacing show that the features are laterally continuous for >40 km and systematic in geometry, suggesting that there is a volcanic moat formed from elastic response of the lithosphere to the lithostatic load of the Executive Committee range. Therefore, our paleotopography reconstruction for pre- Early Miocene time must both remove volcano elevation and allow isostatic rebound from volcano load (subaerial and shallow crustal components) and ice sheet.

Qualitative observations of bed topography of the Executive Committee Range reveals the presence of narrow, steep-walled valleys that we postulate were formed by alpine glacier erosion at a time when WAIS was of reduced extent and the Executive Committee Range hosted alpine glaciers in an environment similar to the present-day Southern Alps of New Zealand. The five major volcanoes of the Executive Committee Range are younger than 14 Ma (LeMasurier and Rocchi, 2005; Smellie et al., 1990), and so provide a maximum age constraint on a time when warm-based ice retreated to the upper elevations of the volcanoes. The finding of warm-based glacial erosion features formed at high elevations at a time after the mid-Miocene climate transition – when there was a change to hyper arid climate and onset of cold-based mode of Antarctic glaciation (Jamieson and Sugden, 2008) – is a possible indication that basal thermal conditions were elevated in the vicinity of the volcanoes.

Following the mid-Miocene climate transition, Antarctica entered an arid period when extensive areas of the ice sheets became cold-based. Warm-based glacial erosion became focused within preexisting drainages at low elevation, leading to development of deeply incised outlet glacier troughs (Jamieson and Sugden, 2008). Therefore, our paleotopography reconstruction restores post-Miocene incision by outlet glaciers and ice streams. Restoration of the changes in elevation due to volcano construction and glacial incision results in an Early Miocene subdued landscape with ~1100 m of topographic relief (Fig. 3), which we will use for calculation of isostatic corrections for removal of volcanic rock and ice. Our ongoing work assesses structural inheritance and the possibility that fault reactivation may be linked to glacial erosion-induced exhumation, tectonic influences, and fluvial or glacio-fluvial processes.

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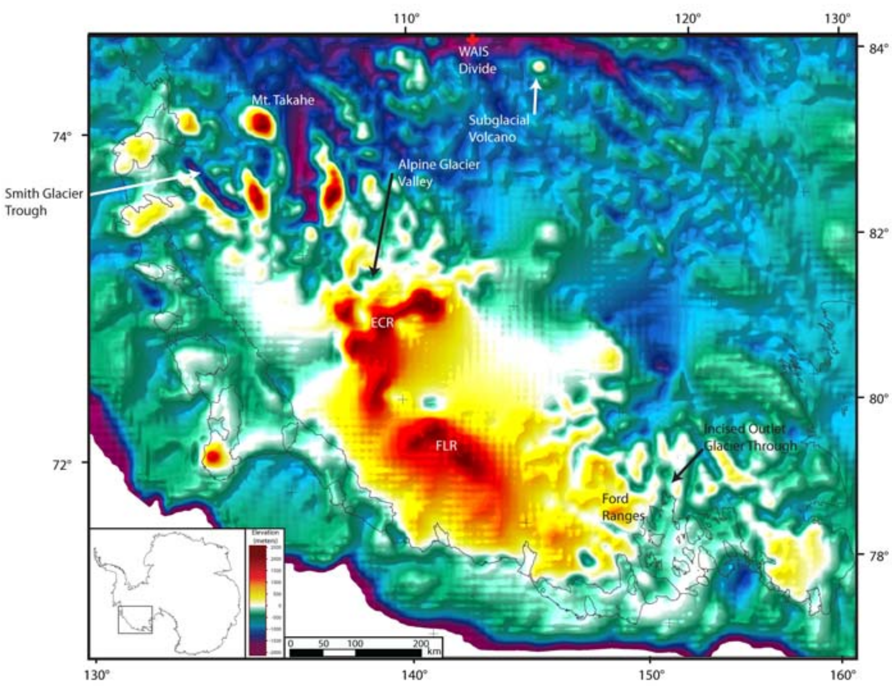

Figure 1. Shaded relief DEM of subglacial topography of Marie Byrd Land and location map for features under study, from BEDMAP1_plus (http://websrv.cs.umt.edu/isis/index.php/Present_Day_Antarctica).

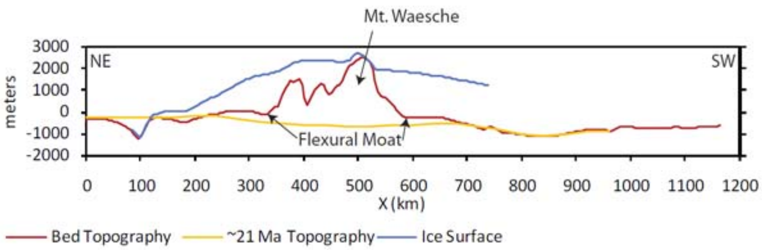

Figure 2. Profile of bed topography (BEDMAP1_plus, 2009), ice surface topography (ASE05), and reconstructed Early Miocene (21 Ma) topography across the Executive Committee Range, MBL. The feature inferred to be a "moat," or circumferential depression around the volcanic field, has topographic relief of ~450 m.

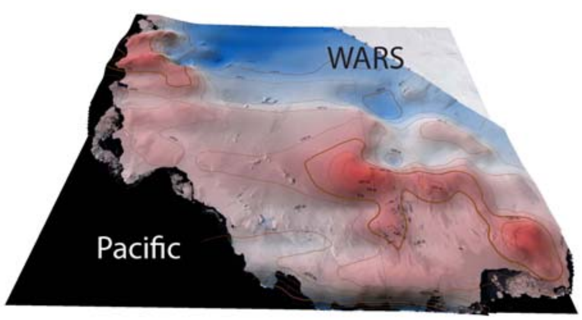

Figure 3. Oblique perspective view to SE of the reconstructed Early Miocene (*ca.* 21 Ma) landscape of Marie Byrd Land, rendered in Fledermaus (ivs3d.com). For purposes of geographic location, the Landsat Image Mosaic of Antarctica (LIMA) is incorporated in the visualization. Broad regions that are at depths <-1000 m correspond to extended (subsided) crust of the West Antarctic rift system.

Provenance Implications of Cenozoic Basalt in East Antarctica

J. Townsend, A. Schilling, and K. Licht

Department of Earth Sciences Indiana University Purdue University-Indianapolis

Mt. Howe is a nunatak at the head of the Scott Glacier in East Antarctica and features multiple moraines that include rocks from unmapped regions in the interior of Antarctica. To understand the evolution of the West Antarctic Ice Sheet (WAIS) it is important to be able to determine the contributions of material from East Antarctica and West Antarctica. Determining the geology of the Scott Glacier area is an important step in differentiating these materials. The local geology of Mt. Howe was described in detail by Doumani and Minshew (1965), as intercalated sandstone, siltstone, and shale units with large diabase sill intrusions, collectively part of the Mesozoic Beacon Supergroup. However, rock samples obtained from a Mt. Howe moraine by an IUPUI field party in 2007 include igneous rocks such as granite and vesicular basalt. The purpose of this study was to determine the age and chemical composition of several basalts obtained from glacial till from Mt. Howe and downstream at Karo Hills. The basalts collected from these two sites could be Jurassic in age or they could be from Cenozoic volcanic activity similar to that of nearby Sheridan Bluff, where olivine basalts described by Stump et al. (1980) have K-Ar ages of 19.43±0.65 Ma. The hypothesis based on hand specimen appearance is that MH-35 will match the Cenozoic volcanics found at Sheridan Bluff and that other basalt samples (MH-18, KH-1) will be similar to Jurassic dolerites and basalts. If any of these basalts are Cenozoic, they would represent the most interior Cenozoic volcanic rocks ever recorded in Antarctica.

Geochemical analyses were obtained at XRF Laboratory at Michigan State University using a Bruker S4 Pioneer WDXRF. KH1 was classified as basalt and MH18 was classified as basaltic andesite. Geochemical data for MH35 was omitted due to low totals. To determine the age of these basalts, Ar/Ar dating will be carried out at New Mexico Tech. Interestingly U/Pb analyses of detrital zircons of Mt. Howe till revealed 3 Cenozoic age grains (19.4±0.9, 23.1±0.05, 25±0.09 Ma) similar to the age of basalts observed downstream at Sheridan Bluff (Stump et al., 1980), however, no such ages were obtained from West Antarctic subglacial tills.

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Recent thinning and migration of the Western Divide, Central West Antarctica

H. Conway, L.A. Rasmussen, and E.D. Waddington

Here, we report observations recently published in *GRL* (Conway and Rasmussen, 2009) that show the Western Divide, between the Ross and Amundsen Sea sectors in West Antarctica, is currently thinning ~0.08 m a^{-1} and migrating toward the Ross Sea at 10 m a^{-1}. The asymmetric pattern of thickness change across the divide is not caused by changes in the accumulation gradient, but rather by dynamical thinning that is stronger in the Amundsen Sea sector than in the Ross Sea sector. Available geological and glaciological data indicate that this pattern of thinning has persisted for at least two millennia, with increased asymmetry likely over the past few centuries. Our data however, are not sufficient to determine whether the present-day migration of the Western Divide is a response to long-term (millennial) forcing, shorter-term (centennial) forcing, or both.

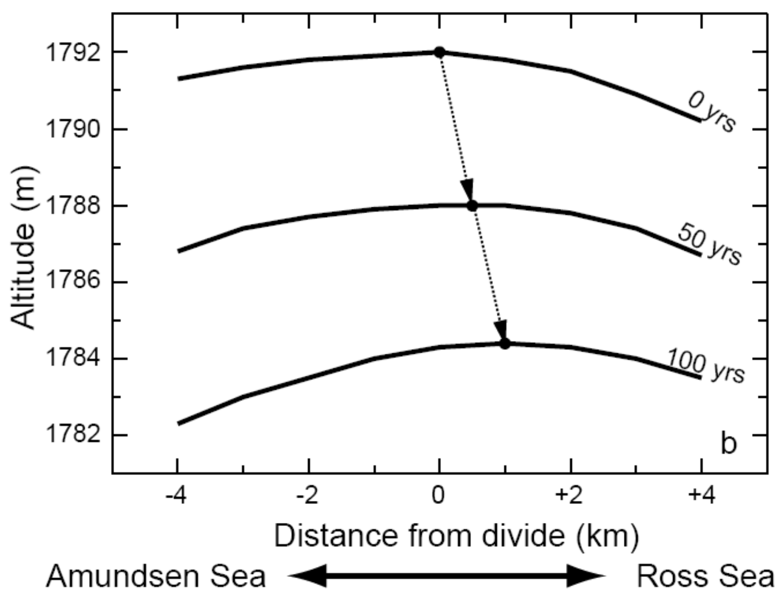

Figure 1: Thinning and migration of the divide that would occur if the present-day pattern of thickness change persists for 50 and for 100 years.

Conway, H, and L.A. Rasmussen. 2009. Recent thinning and migration of the Western Divide, central West Antarctica. *Geophys. Res. Lett.*, 36, L12502, doi:10.1029/2009GL038072.

Initial effects of oceanic warming on a coupled ocean-ice shelf-ice stream system

Ryan T. Walker, Todd K. Dupont, David M. Holland, Byron R. Parizek, Richard B. Alley

The initial retreat of ice-shelf grounding lines stabilized on seaward-sloping beds is influenced by the rheology of these beds, according to new model results. We apply a fully-coupled process model to investigate how the response of an ice stream to increased ocean temperature beneath its ice shelf depends on the assumed form of its basal flow law. For the same applied oceanic warming, the increase in grounding-line flux can be twice as great for an effectively-plastic bed as for a linear-viscous bed, suggesting that improved knowledge of the basal flow law of ice streams is necessary for predicting ice-sheet response to climatic forcing.

Autonomous unmanned platforms and sensors for polar research applications

Lois Wardell, PhD

Development of small unmanned aerial systems (UAS) has progressed dramatically in recent years along with miniaturization of sensor technology. The small UAS is deployable from ships or field camps to carry a range of sensor payloads for a broad range of scientific applications. Recent applications include small UAS for studies involving hurricanes, volcanic activity, sea ice changes, glacier melt, biological monitoring of land and sea species, wildfire monitoring, and others. Small UAS sensor capabilities that are currently available include optical imagers (including multi- and hyperspectral); gas spectrometers; chemical sensors and samplers; microbal sensors; and numerous others, including magnetometers and LIDARS. Other technologies such as nanotechnology and imaging software offer another new range of sensing capabilities and many other technologies.

A recent example of UAS assisting in Greenland climate research includes utilizing a miniaturized hyperspectral sensor in a preliminary study at the Greenland Ice Sheet in August 2007. The scientific goal was to collect preliminary data to use the hyperspectral sensor to remotely measure the depth of the supra-glacial meltpools to assist in quantifying the rate of glacial melting. Recent advances in sensor technology has also been applied to microbial prospecting in the arctic, the developed method and prototype devices have resulted in a sensitivity of ~10 cells/cm^2 under environmental conditions with handheld or airborne systems available. This technology can distinguish viable and non-viable cells as well as spores. It has been most recently use in the determination of the microbial load of soils in glaciated soils and rocks in Svalbard. Additional examples will be discussed.

Analyzing TAMSEIS for Seismic Events of High Temporal Regularity Beneath David Glacier in the Transantarctic Mountains

Lucas Zoet

Highly regular seismicity associated with the flow of David Glacier in the Transantarctic Mountains of Antarctica has been detected and analyzed. We used data from the Transantarctic Mountains Seismic Experiment (TAMSEIS) network, which consisted of 42 broadband seismometers deployed from November 2000 through December 2003. The seismic events recur at a regular time interval of approximately 20 min. Travel times suggest that the events originated from the base of the David Glacier (approximately 1.8 km deep in this area). P-wave first motions are consistent with low-angle reverse faulting. A fault strike of 185 degrees was calculated, which is normal to the flow of David Glacier. The events are likely caused by an asperity beneath David glacier that regularly released stress that accumulated as David Glacier flowed over the asperity. The regularity of the events is due to the constant and homogenous driving stress of the overlying ice as well as the weakness of the bed. Models of earthquake source regions that include a few asperities within a weak active fault are though to display similar behavior.