THE WEST ANTARCTIC ICE SHEET INITIATIVE

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level

2007 WAIS Workshop Agenda

Wednesday, September 5

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

Thursday, September 6

Time	Topic	Speaker
8:00	BREAKFAST	Main Building
8:00	Registration	Main Building
9:00	Welcomes and Introductions	Main Building
	Topic #1: Ice Shelves and Oceans	
9:30	First (1957-58) Geophysical Investigation of the Filchner-Ronne Ice Shelf [Abstract] [Presentation]	Behrendt
9:45	Basement architecture and sedimentary cover in the Amundsen Sea Embayment: Parameters for reconstructing ice-sheet expansion? [Abstract] [Presentation]	Gohl
10:00	Transient Temperatures and Redoubtable Reticence in the Amundsen [Abstract] [Presentation]	Jacobs
10:15	Location and timing of Circumpolar Deep Water intrusions onto the Amundsen Sea continental shelf simulated with an isopycnic coordinate ocean model [Abstract] [Presentation]	Jenkins
10:30	The Filchner Ice Shelf Water Overflow [Abstract] [Presentation]	Osterhus

10:45	BREAK (30 min.)	
11:15	Modeling the impact of tidal currents on ocean circulation beneath Filchner-Ronne Ice Shelf [Abstract] [Presentation]	Makinson
11:30	Oceanographic and Bathymetric Observations at the Ilulissat Ice Fjord [Abstract]	Holland, D.
11:45	The response of ice-shelf basal melting to variation in ocean temperature [Abstract] [Presentation]	Holland, P.
12:00	Poster Introductions (30 min.)	
12:30	LUNCH (90 min.)	
2:00	Effects of changes in the open ocean on the melting underneath the Ross Ice Shelf in a model of the Ross Sea [Abstract] [Presentation]	Dinniman
2:15	A calving law for ice shelves: spreading-rate control of calving rate [Abstract] [Presentation]	Alley
2:30	When iceberg calving matters: An investigation into the feedbacks between iceberg calving and dynamic changes in the flow of inland ice [Abstract] [Presentation]	Bassis
2:45	Ice-y Breakups: How I Lost My AMIGOS in Antarctica [Abstract] [Presentation]	Scambos
3:00	PANEL DISCUSSION (30 min.)	Plenary
3:30	BREAK (30 min.)	
	Topic #2: Ice Stream Grounding Lines	
4:00	Radar attenuation and temperature near the grounding line of Whillans Ice Stream [Abstract] [Presentation]	MacGregor
4:15	Grounding line migration and ice shelf buttressing in a two-dimensional marine ice stream model [Abstract] [Presentation]	Goldberg
4:30	A Modern Analogy to Explain Relict Grounding Lines of Kamb Ice Stream, Antarctica [Abstract] [Presentation]	Catania
4:45	Treatment of grounding-line dynamics in ice sheet-shelf models [Abstract] [Presentation]	Pollard
5:00	PANEL DISCUSSION (30 min.)	Plenary
5:30	BREAK (30 min.)	
6:00	DINNER	Main Building

Friday, September 7

Time	Topic	Speaker
	Topic #3: Ice Stream Bases	
9:00	GPS measurements from Pine Island Glacier [Abstract] [Presentation]	Scott
9:15	Basal conditions on Pine Island Glacier [Abstract] [Presentation]	Smith, A.

9:30	A recent volcanic eruption in West Antarctica [Abstract]	Corr
9:45	Mapping West Antarctic subglacial processes using detailed basal morphology: Implications for Thwaites Glacier, based on knowledge gained from the Siple Coast [Abstract] [Presentation]	Young
10:00	The evolution of surface flow stripes and stratigraphic folds within Kamb Ice Stream –why don't they match? [Abstract]	Campbell
10:15	BREAK (45 min.)	
11:00	Spatial Variation of Basal Conditions on Kamb Ice Stream [Abstract] [Presentation]	Jacobel
11:15	How sticky are sticky spots? Constraints from passive seismic [Abstract] [Presentation]	Winberry
11:30	Decadal dynamics of basal conditions as viewed from the ice bulge on Kamb Ice Stream [Abstract]	Tulaczyk
11:45	Subglacial lakes: They're (almost) everywhere [Abstract] [Presentation]	Smith, B.
12:00	A linked system of lakes on MacAyeal Ice Stream [Abstract] [Presentation]	Fricker
12:15	LUNCH (90 min.)	
1:45	Effects of the ice-stream basal conditions on its surface elevation. Cry for velocity data [Abstract] [Presentation]	Sergienko
2:00	Using inverse methods to recover basal velocities [Abstract] [Presentation]	Truffer
2:15	PANEL DISCUSSION (30 min.)	Plenary
2:45	BREAK (30 min.)	
	Topic #4: Ice Sheets	
3:15	Advances in describing recent Antarctic climate variability [Abstract] [Presentation]	Bromwich
3:30	Antarctic ice mass fluxes from satellite observations and a regional climate model [Abstract] [Presentation]	Bamber
3:45	WAIS wasting in the Amundsen Sea Embayment since the Last Glacial Maximum [Abstract] [Presentation]	Larter
4:00	Solving for a history of ice thickness in the southern Ross Sea Embayment using inverse methods and surface-exposure ages [Abstract] [Presentation]	Todd
4:15	BREAK (30 min.)	
4:45	A preliminary cyclostratigraphic and paleo-environmental analysis of the new high-resolution McMurdo Ice Shelf (ANDRILL) drill core has implications for WAIS history and dynamics [Abstract] [Presentation]	Powell
5:00	What can ANDRILL tell us of long-term WAIS history? [Abstract] [Presentation]	Scherer
5:15	Antarctic Scientific Drilling: What, Where, and Why [Abstract] [Presentation]	Rack
5:30	BREAK (30 min.)	

6:00	DINNER	Main Building

Saturday, September 8

Time	Topic	Speaker
8:30	Lost, but found: A large WAIS drainage basin existed in the southern Bellingshausen Sea during the last glacial period [Abstract] [Presentation]	Hillenbrand
8:45	Boundary conditions for a full-momentum solver: 1) The dilemma of sliding and 2) how do we do embedded models? [Abstract] [Presentation]	Fastook
9:00	Thermal Convection and the Origin of Ice Streams [Abstract]	Hughes
9:15	Tipping points: nonlinearity and hysteresis in ice sheets [Abstract] [Presentation]	Schoof
9:30	Millennial versus orbital influences on ice marginal fluctuation: the southern signal [Abstract] [Presentation]	Vacco
9:45	Ice sheets in the Community Climate System Model [Abstract] [Presentation]	Lipscomb
10:00	PANEL DISCUSSION (30 min.)	Plenary
10:30	GUEST FEEDBACK	
11:00	WAIS/FRISP business	
12:00	Adjourn	

Poster Session (Wednesday, September 21)

Topic	Lead Author
A Monte Carlo Investigation of Inherited Cosmogenic Nuclides in Moraine Boulders [Abstract]	Applegate
Glacial history of the Ellsworth Mountains, Weddell Sea embayment, West Antarctica [Abstract]	Bentley, M.
Thickness and Structure of the Crust beneath the Thwaites Glacier Catchment, West Antarctica [Abstract]	Diehl
Numerical modeling of subglacial-sediment dynamics [Abstract]	duBois
When the Bough Breaks: Implementing an Empirical Calving Rule in a Dynamic Stream/Shelf Model [Abstract]	Dupont
Investigations of near-vertical subsurface structures near Swiss Camp, Greenland [Abstract]	Greenbaum
Progress towards an Image-Enhanced 250 m DEM for the West Antarctic Ice Sheet [Abstract]	Haran
Developing a long term strategy for using AUVs in polar research [Abstract]	Heywood
A model of tidally-dominated ocean processes near ice-shelf grounding lines [Abstract]	Holland, P.
Patterns of glacier response to disintegration of the Larsen B ice shelf, Antarctic Peninsula [Abstract]	Hulbe

LC-130 Deep Field Capabilities [Abstract] [Presentation]	James
First exposure ages from the Amundsen Sea embayment, West Antarctica: the Late Quaternary context for recent thinning of Pine Island, Smith and Pope Glaciers [Abstract]	Johnson
The influence of sea-ice and the Ross Ice shelf on water properties [Abstract]	Klinck
Connections between meteorology and chemistry in surface snow: Clark Glacier, McMurdo Dry Valleys, Antarctica [Abstract]	Kreutz
Large scale modeling of ice flow for the entire Antarctica continent [Abstract]	Larour
A coupled ice/water flow model for West Antarctica [Abstract]	LeBrocq
Accumulation Rates Over the Thwaites Glacier Catchment, West Antarctica, Using Radar Reflection Layers [Abstract]	Leuro
Potential Vorticity Constraints on Buoyancy-Forced Circulation in Ice Shelf Cavities [Abstract]	Little
Opportunities (?) for Probabilistic Assessment of Ice Sheet Response to Climate Change [Abstract]	Little
Exposure ages from mountain dipsticks indicate little change in East Antarctic Ice Sheet thickness since the Last Glacial Maximum and stability from the mid Holocene [Abstract]	Mackintosh
Detection of in-situ ice fabric anisotropy using polarimetric radar method near WAIS Divide [Abstract]	Matsuoka
A sediment model and retreat history for the Ross Ice Shelf (Sheet) since the LGM [Abstract]	McKay
Sensitivity of ice-shelf/ocean interactions to vertical resolution and thermodynamic parameterizations in the ROMS model [Abstract]	Mueller
Bathymetry of the Amundsen Sea Continental Shelf [Abstract]	Nitsche
Bipolar Atlantic Thermohaline Circulation (BIAC) IPY Cluster # 23 [Abstract]	Osterhus
Focused SAR Processing of Airborne Radar Sounding Data from Kamb Ice Stream [Abstract]	Peters
Basal conditions at two sticky spots along Kamb Ice Stream, West Antarctica [Abstract]	Peters
Cenozoic variations of the Antarctic Ice Sheet: a model-data mismatch? [Abstract]	Pollard
High-salinity waters beneath the margin of the West Antarctic ice sheet - evidence from ANDRILL porwater studies [Abstract]	Quintana-Krupinski
ANDRILL's Education and Public Outreach Efforts [Abstract]	Rack
Significant Glacier Thinning (Or Not) in the Larsen B Embayment [Abstract]	Shuman
Ice shelf melting in the Amundsen Sea from oceanographic observations [Abstract]	Shoosmith
From shelf break to ice shelves: oceanographic observations in the Bellingshausen Sea, Summer 2007 [Abstract]	Shoosmith
Estimating the salinity of subglacial lakes from aerogeophysical data [Abstract]	Studinger
Development of an aerogeophysical imaging system for polar applications: Phase I: Gravimeter test flights to the North Pole [Abstract]	Studinger

Moho topography of the West Antarctic Rift System from inversion of aerogravity data: ramifications for geothermal heat flux and ice streaming [Abstract]	Studinger
Optical probing of glacial ice using short-pulse lasers [Abstract]	Talghader
Surface exposure ages from Reedy Glacier, Antarctica [Abstract]	Todd
The Science and Art of LIMA [Abstract]	Vornberger
Long-term Mass Balance of the Pacific Ocean Sector of Antarctica Based on Multisensor Fusion [Abstract]	Yoon
Comprehensive surface elevations for Thwaites Glacier: Results from AGASEA airborne laser altimetry [Abstract]	Young

2023 WAIS Workshop

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- 2022 Agenda

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2012 Agenda

Previous Meetings

A calving law for ice shelves: spreading-rate control of calving rate

R.B. Alley, I. Joughin, H.J. Horgan, T.K. Dupont, B.R. Parizek, S. Anandakrishnan, and K.M. Cuffey

No generally accepted law or rule relates the rate of production of icebergs from a floating ice shelf to physical controls of the process. The lack of such a ³calving law² for ice shelves restricts accurate modeling of the behavior of ice sheets and their effect on sea-level change (e.g., Meier, M.F., 1990, Role of land ice in present and future sea-level change, Ch. 10 in Sea-level change, National Academy Press, Washington, DC; note that more work has been on calving from non-floating tidewater termini, although a generally accepted calving law is also lacking there.)

For example, the friction from ice-shelf contact with a high spot in the sea-bed contributes to buttressing of flow from the ice sheet, slowing ice motion so that sea level is lower and the ice sheet larger than in the absence of such buttressing. Whether an ice shelf will extend to a potential pinning point cannot now be modeled accurately because of lack of a calving law (except through specification as an initial condition), so the buttressing effect of ice shelves and thus the volume of ice sheets cannot be modeled confidently.

A ³calving law² almost certainly depends in a highly complex way on several things, including: i) forcings contributing to calving (tidal fluctuations, storm surges, collisions from icebergs, meltwater wedging of crevasses); ii) pre-existing populations of flaws along which calving occurs (and which in turn depend on past forcings perhaps in different locations‹for example, the tidal flexing of ice at the grounding line contributes to basal crevasses that may contribute to calving after being advected through an ice shelf to near the ice front); iii) ice properties that affect fracture propagation (temperature, c-axis fabric, impurity loading, thickness, density); and iv) healing of fractures (with temperature likely most important as a control on refreezing of water in basal or surface crevasses). This incomplete list surely shows the daunting task facing anyone proposing a calving law, and explains why an accepted calving law is not available to modelers now.

However, arguably the most important factor in calving from cold ice shelves (those in which meltwater wedging is not dominant) is the spreading tendency of the ice; if crevasses did not tend to open, we can speculate that ice shelves would be very different. This leads to our hypothesis, that the first-order control on the rate at which ice shelves fall apart is their tendency to fall apart.

To test the hypothesis, we note that in most cases the calving rate is very close to the velocity near the ice front. (With notable exceptions such as the Larsen B in early 2002, maps of ice shelves made at different times are recognizably similar after years or decades, allowing a steady-state approximation averaged over the time for a few calving events to occur.) The ice-front-normal spreading stress (which is approximately the along-flow spreading stress except very close to shear margins) is probably the most relevant variable but in general is not measured, whereas the corresponding strain rate is measurable, increases monotonically with the stress, and might be the most important controlling variable in some physical formulations (e.g., if the competition between opening and refreezing of basal crevasses is most important, strain rate rather than stress may be the key variable). We thus hypothesize that, across a range of ice shelves, the observed velocity near the ice front (which approximates the calving rate) will increase with the along-flow spreading rate near the ice front, using data taken away from intense shear zones along ice-shelf margins or pinning points where complex stress states may complicate the situation.

We are in the process of assembling data, primarily from ice shelves in Antarctica but including shelves in Greenland. Our preliminary results are encouraging; shelves with stronger spreading at their ice fronts are faster-moving, implying that the rate at which ice shelves fall apart is controlled primarily by their tendency to fall apart (calving rate increasing as a power of the spreading rate near the calving front). This does not explain all of the variance in the data set, but explains enough of the variance that we are hopeful of obtaining a useful relation.

We have not yet been able as a group of authors to discuss all of the available data, or to agree on exact meanings of terms such as ³near the calving front² (although it appears that almost any reasonable assumptions will yield the same basic answer), nor have we agreed on a preferred form of the probationary ³calving law². We are making a public presentation of the preliminary results at this time in part to encourage holders of other data sets to contribute them, and to stimulate discussion. An ice-shelf calving law is fundamental to ice-flow modeling, has thus far been unavailable, but might prove to be relatively easy in first approximation, although with numerous second-order terms.

A Monte Carlo Investigation of Inherited Cosmogenic Nuclides in Moraine Boulders

Applegate, Patrick J.; Alley, Richard B.

Cosmogenic exposure dating is an important tool for determining the ages of moraines. However, cosmogenic exposure dates are often biased by geologic processes. Moraine degradation, which tends to bias exposure dates toward the young side, has been modeled in detail, but little modeling effort has been devoted to inheritance, which biases exposure dates toward the old side. Here, we present a Monte Carlo investigation of the revalence of inheritance in moraine boulders. We note that the production rates of most cosmogenic nuclides decrease exponentially with depth below rock surfaces. Therefore, in order for a boulder to give a spuriously old age, the boulder must have been exposed for a long time before it was moved by the glacier, and then deposited on the moraine with the side containing the maximum concentration of cosmogenic nuclides facing upward. The boulder also must not have been eroded appreciably during transport. In our model, the apparent age given by each boulder is the sum of the true age of the moraine and an inherited component, which is a well-defined function of the pre-depositional exposure time of the boulder, the size of the boulder, and the face of the boulder that was upright when the boulder was deposited on the moraine. The true age of the moraine is set by the user; the other variables are determined randomly for each boulder. Predepositional exposure times are drawn from either a uniform or exponential distribution, with the form and parameters of the distribution set by the user. Boulder sizes are drawn from a large data set of boulders actually sampled for cosmogenic exposure dating on last-glacial moraines in the western United States. The side of each boulder that faces upward has a 1 in 6 chance of being the side with maximum inheritance, a 1 in 6 chance of being the side with minimum inheritance, and a 4 in 6 chance of being a side with intermediate inheritance. Preliminary results suggest that most moraine boulders contain a relatively small amount of inherited cosmogenic nuclides, regardless of the distribution of preexposure times. We compare the distributions of apparent ages returned by the model to actual distributions from the literature, and we discuss the implications of this work for determining the ages of moraines using cosmogenic exposure dating.

Antarctic ice mass fluxes from satellite observations and a regional climate model

Jonathan Bamber (1), Willem van de Berg (2), Michiel van den Broeke (2), Curt Davis (3), Yonghong Li (3), Erik van Meijgaard (4), Eric Rignot (5)

1 University of Bristol
2 Utrecht University
3 University of Missouri-Columbia
4 KNMI, Netherlands
5 JPL, Caltech

Estimates of the mass imbalance of the WAIS derived from satellite radar altimetry and GRACE differ by more than a factor three, ranging from, for example, -47 ± 4 Gt a-1 for ~1992-2002 to -148 ± 21 Gt a-1 for 2002-2005, respectively. Some of the difference may be due to changes in ice dynamics during the measurement periods. Some is also due, however, to issues related to spatial sampling and assumptions made and methods used during data analysis. Different GRACE estimates of WAIS imbalance are not consistent, for example, within their combined error budget. To improve our understanding of both the spatial and temporal pattern of mass balance changes at the basin scale, we have begun refining mass flux calculations for the whole of the Antarctic ice sheet, incorporating ~90% of the grounding line discharge. We aim to reduce the uncertainty in all components of the mass flux calculation by incorporating i) improved mapping of grounding line locations and thickness using combined GLAS/ERS-1 altimeter data and MODIS imagery, ii) velocity time series from 1996-2005 for glaciers with a significant imbalance, iii) improved and extended drainage basin delineation and iv) estimates of the mean and time-varying accumulation rate from a regional climate model driven by re-analysis data. Here we present the methodology and first results of this analysis for the WAIS along with an overview of the improved data sets being used and developed within the project. Our results indicate a mass loss for the WAIS that falls between the SRA and GRACE estimates quoted above between 1996 and 2006. The results to date do not show an acceleration in mass loss during this time interval. The error in our estimate is currently dominated by uncertainties in accumulation rate, followed by the combined uncertainty in grounding line location and thickness. How we will reduce these errors further is discussed.

When iceberg calving matters: An investigation into the feedback between iceberg calving and dynamic changes in the flow of inland ice

Jeremy N. Bassis

Iceberg calving provides an efficient mechanism to transfer larges amounts of ice to the ocean in a near instantaneous fashion, thereby not only drastically changing the mass balance of a glacier/ice sheet, but the geometry of the glacial system. These changes can have a profound effect on the flow of inland ice through a variety of feedbacks. For example, removal of sections of ice can (i) reduce the back-pressure or "buttressing" of inland ice or (ii) perturb basal hydrology and alter the basal sliding conditions. Furthermore, because iceberg calving tends to be important in regions with high longitudinal stresses, the non-local nature of these stresses allows the possibility that perturbations are transmitted far into the interior of the glacier or ice sheet. As a first step towards understanding the interaction between iceberg calving and flow dynamics, we have developed a depth-integrated flowline model that includes both vertical shear and longitudinal stresses. Unlike traditional, higher-order, models that explicitly solve for all stress components (at great computation cost), we assume that the vertical velocity profile varies weakly in comparison to variations in basal sliding. This approximation reduces the governing equation to a nonlinear ODE that, for different limits in the ratio of the bed-to-ice strength, happily reduces to the traditional shallow ice approximation (strong bed), the ice-stream approximation (weak bed) and ice shelf approximations (very weak bed). The simplicity and computational efficiency of the model provides the potential to explore the time-dependent behavior of a variety of simple parameterizations of iceberg calving in combination with different basal sliding laws and stress regimes. We present preliminary results, using this model to evaluate the interplay between ice dynamics and calving using idealized "rules" to determine when calving events occur in combination with simple basal sliding laws.

First (1957-58) Geophysical Investigation of the Filchner-Ronne Ice Shelf

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SUMMARY The only major field project of the U.S. International Geophysical Year (IGY) Antarctic program was aseries of oversnow traverses (Behrendt, 1998; 2003) mostly in West Antarctica, starting in 1957, making seismic reflection ice soundings (and other geophysical measurements) and glaciological measurements. The 1900-km Filchner Ice Shelf (FIS) oversnow traverse mapped snow surface elevation, ice thickness and bed topography of the Filchner-Ronne Ice Shelf (FRIS) area, as well as snow accumulation, the mean annual temperature of that era, and made a geological reconnaissance of the Dufek Massif. Results included the definition of the Thiel trough beneath the FIS and the maximum ice thickness of the southernmost area of the Ronne Ice Shelf (RIS) of 1300 m which is in contrast to 1100-m thickness remeasured by BAS for this area in 1994-95 of only 1100 m suggesting significant melting during the interval.

FILCHNER ICE SHELF TRAVERSE, 1957-58

On 28 October, 1957, our five man party, co-led by Edward Thiel and Hugo Neuberg, left Ellsworth Station on the Filchner ice front with two Sno-Cats (in contrast to the usual three on the other US traverses) each pulling a 2.5-ton sled filled with fuel, food, explosives, (Fig.1) and all of our scientific and other equipment. For the next 81 days we made a geophysical-glaciological reconnaissance of the Filchner-Ronne Ice Shelf area.

The logistics of the traverse oversnow traverse program were dictated by the fact that state-of-the-art electronics at the time depended on the vacuum tube, rather than the solid-state electronic microcircuits available today. The hundreds of tubes in our seismic system required large amounts of battery power. The power requirements, in turn, required two 250 amp-hour batteries weighing 80 kg each to produce the 24 volts necessary for operation. The only recording system was the heavy oscillograph "camera" with its tanks of photographic solutions. Altogether the seismic Sno-Cat carried a total load of about 500 kg of electronic equipment, gravimeter, magnetometer, and seismic batteries. Each Sno-Cat used about 3 liters of fuel per km or about 200 kg for a 50-km day for two vehicles. This fuel determined how frequently we needed resupply by the single-engine Otter aircraft available. These planes could only carry a few barrels of fuel in one trip depending on our range out of Ellsworth.

Although we commonly saw open crevasses on the traverse, the ones that gave us the most trouble were bridged with snow and could not usually be seen from the surface as we drove along (Fig. 2). Sometimes we could safely drive across snow bridges, but other times we broke through. The Sno-Cats were nearly as safe as a man on skis because of their relatively low weight and four wide tracked pontoons. It is much easier to see bridged crevasses from the air, but this method is severely limited, even when a plane is flying directly over crevasses. We traveled in crevasse country most of the 81 days of the traverse and had a number of incidents of vehicles and sleds breaking through. One man fell in about 10 m , but was rescued safely.

We spaced seismic-glaciology stations at about each day's travel distance (~50-60 km). The measurements at these consisted of a seismic reflection sounding to measure the depth to bedrock; seismic measurement of the increase in sound velocity (and thus snow density) with increasing depth; and a two- or three-meter snow pit to measure snow accumulation and other glaciological parameters such as density and temperature. We would lay out our 330 m seismic cables in an L shape, which we unrolled from chest reels. We would then hand drill a 2–8m deep shot hole at the apex of the L. We fired a small explosive charge of 0.5-2 kg of ammonium nitrate detonated with an electric blasting cap and a 0.5-kg high explosive primer charge. The sound waves penetrated to the ice-water contact (in the case of the floating ice shelf) and to the water-rock (or ice-rock) contact and reflected back to the surface where they were picked up by the geophones. Each of the 24 geophones was attached to one of the channels in the cables. The seismic signals were amplified and recorded on photographic paper which spewed into my hand at 1 m/s. On a few occasions the wet paper record froze in my hands as I wrote the data on the back. There was some hazard associated with laying out the cables when we were working in crevassed areas. In these cases we skied, which offered some protection. We also used skis when we were not in areas of known crevasses, if the snow was soft.

In addition to a snow pit where stratigraphy leading to snow accumulation was measured, Neuburg and Walker, glaciologists, would hand drill a hole 9 m deep and place an electric-resistance temperature probe on a cable in the bottom.

We made gravity and magnetic and altitude measurements every 8 km (Fig. 1) to study the variations in density and magnetic properties of rock beneath the ice, and therefore to make inferences about the ice-covered geology. We also used the gravity data to determine the depth to bedrock between the seismic reflection stations.

Fig. 1. Traverse at intermediate station. Behrendt reading magnetometer at left. Walker and Aughenbaugh making snow hardness measurement left background. Thiel on track of Sno-Cat after making a gravity measurement. Crevasse detector visible on leading vehicle.

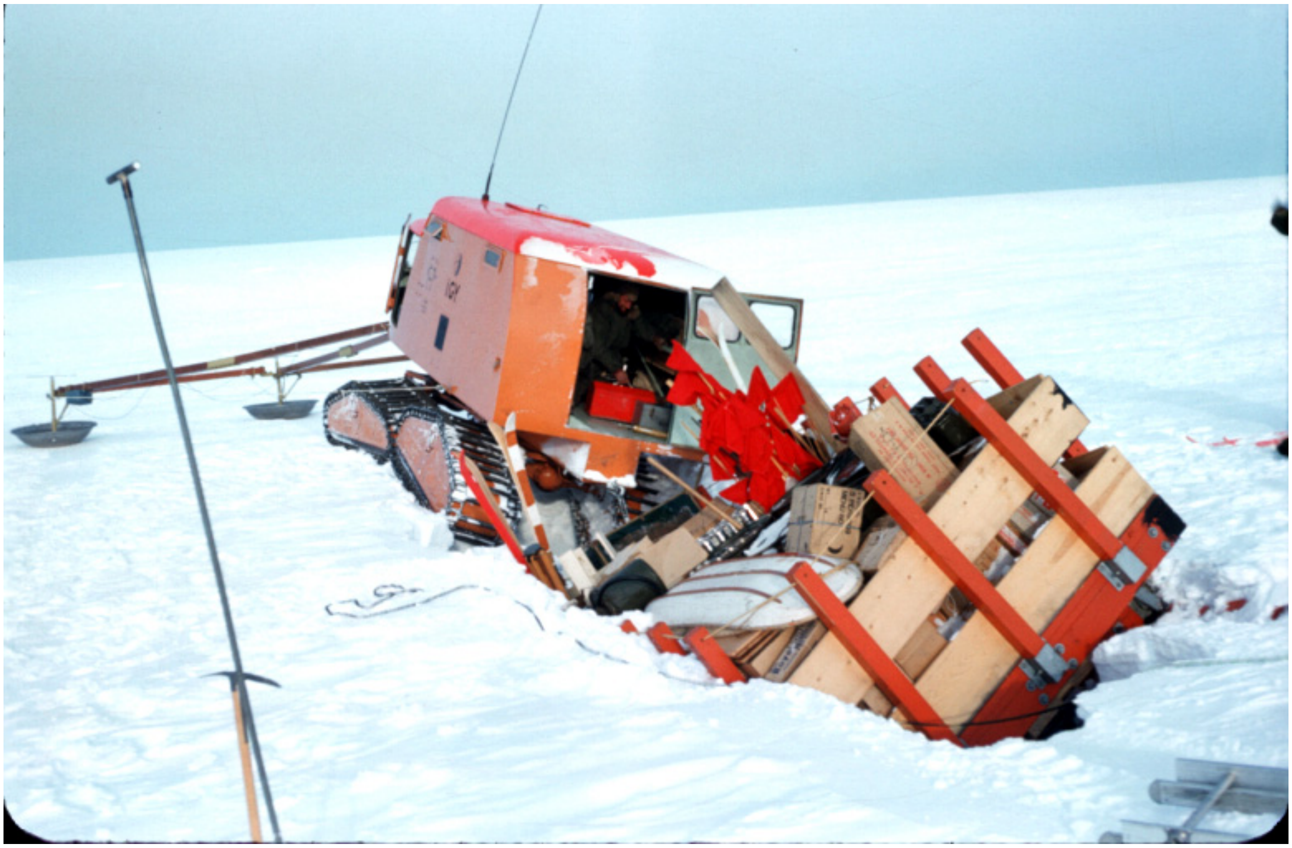

Fig. 2. Sno-Cat and sled broken into hidden, bridged crevasse. Note T-handled probe, ice-axe, and crevasse detector extending forward of Sno-Cat.

CONCLUSIONS

I will discuss results of this first reconnaissance of the FRIS system including the definition of the Thiel trough beneath the FIS and the maximum ice thickness of the southernmost area of the FRIS of 1300 m which is in significant contrast to BAS re-measurement (Johnson and Smith, 1997) of this area in the 1990s of only 1100 m suggesting significant melting during the interval.

REFERENCES

Behrendt, J.C., (1998), *Innocents on the Ice; A Memoir of Antarctic Exploration, 1957,* Univ. Press of Colorado, Boulder, 428 p.

Behrendt, J.C. , (2005), The *Ninth Circle; a Memoir of Life and Death in Antarctica, 1960-1962*, Univ. of New Mexico Press, Albuquerque, 240 p.

Johnson, M.S., and Smith, A.M. (1997), Seabed topography under the southern and western Ronne Ice Shelf derived from seismic surveys, Antarctic Science, 9 (2), p. 201-208.

Glacial history of the Ellsworth Mountains, Weddell Sea embayment, West Antarctica

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We report here the results from a programme of geomorphological mapping and sampling for cosmogenic isotope analysis in the Ellsworth Mountains. The overall aim of the project is to establish the timing and rate of thinning of the West Antarctic Ice Sheet (WAIS) from its maximum extent in an area inland of the Weddell Sea embayment. We have data from along a 350 km-long transect, stretching from Pirrit Hills (81º 06 S, 85º 31 W) in the south to the ridge between Mt Bentley and Mt Hubley in the north (78º 09' S, 86 º 41' W). Most sites are on the western (WAIS) side of the range but we also have data from the Flowers Hills (78 º 24' S, 84 º 31' W) on the east side of the range, adjacent to the Rutford Ice Stream. We studied the geomorphology of 11 field locations in detail, including studies of drift sheets, weathering of sediments and bedrock, plus closely-spaced sampling of erratics and bedrock along altitudinal transects at each site. Our geomorphological mapping has allowed us to determine a series of ice sheet advances and we discuss a preliminary landscape and glacial history of the Ellsworth Mountains extending from the pre-Quaternary to the present-day, including a record of Holocene thinning. Our cosmogenic ^{10}Be and ^{26}Al chronology for the mapped glacial fluctuations suggests that (i) Alpine glaciation of the Ellsworths probably occurred prior to the Quaternary, (ii) a high, previously-mapped trimline records WAIS expansion > 700 ka, and that there may have been multiple expansions to this level; (ii) a lower, less distinct trimline records WAIS expansion at the Last Glacial Maximum, and implies a thinner WAIS in the Weddell Sea embayment than has been previously supposed ; (iv) thinning from the maximum occurred from ~ 15 ka to the Late Holocene. These data are being used to constrain an ice sheet model of the Weddell Sea embayment.

Advances in describing recent Antarctic climate variability

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Several observationally-based Antarctic temperature datasets are compared for the past ~45 years and found to be in good agreement at annual and seasonal timescales. These datasets, which are representative of the entire continent, are useful for assessing global climate model (GCM) simulations of Antarctic near-surface temperature during the 20th century, and thus the reliability of 21st century Antarctic climate scenarios. Five 20th century GCM ensembles run in support of the Intergovernmental Panel on Climate Change Fourth Assessment Report are evaluated. It is found that they overestimate annual Antarctic near-surface temperature trends by a factor of 2-to-3 during the 20th century, and by more than 5 times during the latter half of the century. The overly-vigorous Antarctic temperature increases in the GCMs appear to be due to an increase in total column water vapor that enhances the downward longwave radiation incident at the surface. The relationship between Antarctic temperature changes and the Southern Hemisphere Annular Mode, the primary mode of Antarctic atmospheric variability, is of secondary importance in the GCMs.

Snowfall variability in the GCMs is compared to a recently published 5-decade record of Antarctic snowfall variability. The GCM snowfall compares reasonably to the observations, for which there are generally upward trends. However most of the GCM runs end in the late 1990s, when the snowfall sharply decreases, so it is uncertain whether the models would have captured this fluctuation. Promisingly, the GCMs are able to accurately simulate the observed sensitivity of Antarctic snowfall to near-surface temperature of about 5-6 % K-1, suggesting that if Antarctic near-surface temperature does increase by about 2-3.5 K by the end of the 21st century as the GCMs predict, snowfall will increase by about 10-20%. Properly simulating Antarctic temperature in GCMs is thus critical for understanding how Antarctic snowfall will change, and consequently affect sea level rise.

The evolution of surface flow stripes and stratigraphic folds within Kamb Ice Stream - why don't they match?

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Flow stripes seen in satellite imagery of ice streams and ice shelves are caused by surface undulations with kilometer-scale spacing and meter-scale relief and generally indicate current or recent fast ice flow. They generally form in regimes of fast ice flow, such as in outlet glaciers and ice streams, and are often visible downflow onto floating ice shelves, eg [Hulbe and Fahnestock, 2007; Wu and Jezek, 2004; Fahnestock et al., 2000]. On a similar scale, folding of internal ice stratigraphy depicted in cross-flow ice-penetrating radar profiles is also a common occurrence in ice streams, suggesting a possible relationship between the two sets of features. We have traced surface flow stripes in RADARSAT and MODIS imagery for over 200 km on Kamb Ice Stream (KIS) from the onset of streaming flow into the near-stagnant trunk. We compare the morphology and evolution of these features at the surface to the folds seen in the internal stratigraphy in cross-ice stream radar profiles at five cross-flow transects along the length of KIS. We find essentially no correspondence in the observed locations or spacings between the radar internal layer folds and the flow stripes on the surface. Flow stripes have wavelengths on the order of 1.2 – 2 km and remain roughly sub-parallel for many kilometers, eventually becoming less distinct as the ice stagnates. The wavelengths of internal layer folds are on the order of 0.5 – 3 km, generally with longer wavelengths upstream, shortening as ice flow converges in the main trunk of the ice stream. In places it is apparent that the surface flow-stripes cross over the underlying englacial folds. We explore hypotheses about how flow stripes and internal stratigraphic folds can originate and evolve differently as ice flows downstream. We suggest that following the formation of flow stripes on the ice surface they are subject to processes that can modify their morphology independent of any coeval englacial structure development, leading to changes in the pattern of folds relative to the internal layers below.

A Modern Analogy to Explain Relict Grounding Lines of Kamb Ice Stream, Antarctica

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Ground-based, low-frequency ice-penetrating radar data across the northern grounding-line of Siple Dome reveal internal stratigraphy that becomes sharply downwarped over <4 km with an amplitude that increases with depth. This grounding line is also associated with near-bed diffractors that continue seaward that are interpreted as basal crevasses formed as the ice flowing from Siple Dome goes afloat. Additional crossings of this grounding line further towards the west show internal layers that are not as strongly downwarped across the grounding line. This indicates that the process responsible for the downwarped layers is not uniform. We use a 2-D flow line model to examine several possible mechanisms that can create downwarped layers including temporarily, localized basal melt and temporarily increased basal sliding.

The grounding line stratigraphy at this northern Siple Dome boundary has striking similarity to radar profiles previously acquired up to 100 km inland on Kamb Ice Stream by Catania and others, (2006), JGR, doi:10.1029/2005JF000355, and provides a modern analogy that can aid our understanding of the processes affecting Kamb and its recent ice flow history. On this basis, we argue that Kamb Ice Stream experienced grounding line retreat of up to 120 km prior to its shutdown. In addition, retreat of the Kamb grounding line allowed for the formation of slow-moving embayments on both sides of the ice stream outside of its lateral margins similar to the modern-day situation on the northern side of Siple Dome.

A recent volcanic eruption in West Antarctica

Hugh F. J. Corr and David G. Vaughan

There has long been speculation that volcanism may influence the ice-flow in West Antarctica, but ice obscures most of the crust in this area, and has generally limited mapping of volcanoes to those protrude through the ice sheet. Radar sounding and ice cores do show a wealth of internal horizons originating volcanic eruptions but these arise as chemical signatures usually from far distant sources and say little about local conditions. To date, there is no clear evidence for Holocene volcanic activity beneath the West Antarctic ice sheet. Here we analyze radar data from the Hudson Mountains, West Antarctica, which show an extraordinarily strong reflecting horizon, that is not the result of a chemical signature, but is a tephra layer from a recent eruption within the ice sheet. This tephra layer exists only within a radius of 80 km of an identifiable subglacial topographic high, which we call Hudson Mountains Subglacial Volcano (HMSV). The layer was previously misidentified as the ice-sheet bed; now, its depth in the ice column dates the eruption at 207 ± 240 years BC. This age matches previously un-attributed strong conductivity signals in several Antarctic ice cores. Today, there is no exposed rock around the eruptive centre, suggesting the eruption was from a volcanic centre beneath the ice. We estimate the volume of tephra in the layer to be >0.025 km^3, which implies a Volcanic Eruption Index of 3, the same as the largest identified Holocene Antarctic eruption. HMSV lies on the margin of the glaciological and subglacial-hydrological catchment for Pine Island Glacier. It's very unlikely that water from HMSV could enter the subglacial hydrological system of neighbouring ice streams, and it cannot be responsible for the regional ice-sheet thinning that has occurred across this part of West Antarctica in recent decades. However, similar VEI-3 eruptions in Iceland produced vast quantities of melt water, and so at the time of the HMSV eruption, the flow of Pine Island Glacier could have been substantially altered. We can only speculate on the influence it has on present day ice-flow.

Thickness and Structure of the Crust beneath the Thwaites Glacier Catchment, West Antarctica

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By studying the properties of the earth's crust (such as thickness and changes in density), we can learn more about the ice-crust boundary and how its spatial variability may impact ice flow. Specifically, to understand the evolution of Thwaites Glacier, we need to determine the extents of the West Antarctic Rift System (WARS), the Marie Byrd Land crustal block, and the Thurston Island crustal block- the three tectonic areas that are hypothesized to exist in the Amundsen Sea Embayment of West Antarctica.

Only two techniques for studying the earth's crust are available over an area the size of the Thwaites Glacier Catchment: airborne gravity and magnetics. Here, we consider only the airborne gravity data, which was collected in the austral summer 2004-2005 by the University of Texas at Austin and the British Antarctic Survey. The Thwaites Glacier gravity data covers the entirety of the catchment and reaches slightly beyond into the surrounding areas. The free-air gravity anomalies have an rms crossover error of 7 mGals and a spatial resolution of 9 km. The Bouguer gravity anomalies are fully 3D terrain corrected using a new DEM (Bamber, pers. comm.) for the ice surface and published radar sounding depths for the subglacial bedrock terrain. Errors for the Bouguer anomalies are comparable to the free-air anomalies' errors in areas with good surface DEM coverage. We do not calculate Bouguer anomalies for areas with high surface slopes (such as the Executive Committee Range volcanoes) because the features are not well-defined in the DEM.

The Bouguer anomalies show that the Thurston Island block does not exist in the Thwaites Glacier catchment. Likely, the block is much smaller than previously thought and is confined to the area in and around Pine Island Glacier, though this is yet to be confirmed. On the other hand, both the WARS and the Marie Byrd Land block are immediately discernable as broad Bouguer anomalies, positive and negative respectively. The WARS covers much of the eastern portion of the survey area and indeed underlies the majority of Thwaites Glacier. The Marie Byrd Land block appears to contain most of the known volcanoes, though perhaps not all because the absolute boundary between Marie Byrd Land and the WARS is difficult to identify. Further quantitative analysis of the gravity data for crustal thicknesses is required to pinpoint this boundary.

Our approach to refining the crustal structure (including thicknesses) of each areas is to estimate radial power spectra from gridded free-air anomalies, thus providing spatially-averaged crustal properties over large areas. We calculated power spectra over areas ranging from 438 x 542 km to 200 x 200 km. Areas too much smaller than 200 km square do not provide the long-wavelength information needed to resolve the depth of the Moho. The power spectra, when plotted on a log-log scale, form roughly-linear segments. The segments are fit with linear regression and the slopes of the best-fit lines yield the depths for major density boundaries, such as the Moho. Error estimates for the boundaries' depths are provided by the rms of the residuals from the best-fit line. Initial estimates show that the average Moho depth of the WARS is 24.7 km +/- 2.5 km and that there is an intermediate crustal boundary at 11.1 +/- 0.7 km. For Marie Byrd Land, we find a Moho depth of only 20 km +/- 1.3 km, with an intermediate crustal boundary comparable in depth to the WARS' (at 10.6 +/- 0.9 km). Inversion of gridded Bouguer anomalies will be needed to better resolve the 3D variations in crustal properties at the WARS / Marie Byrd Land boundary.

Effects of changes in the open ocean on the melting underneath the Ross Ice Shelf in a model of the Ross Sea

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In an oceanic numerical circulation model that includes basal melting of a floating ice shelf above the water, the characteristics of the water in the open ocean adjacent to the ice shelf cavity can be critical to the calculation of the basal melting. Therefore, changes in model forcing and bathymetry to just the open ocean portion should still affect the melting underneath the ice shelf.

Satellite imagery shows that there was substantial variability in the sea ice extent in the Ross Sea during 2001-2003. Much of this variability is thought to be due to several large icebergs that moved through the area during that period. In this study, a high resolution (5 km) model of the Ross Sea (including the cavity beneath the Ross Ice Shelf (RIS)) was developed to study the effects of these changes in sea ice on circulation and water mass distributions. It would be difficult to simulate the highly variable sea ice from 2001-2003 with a dynamic sea ice model since much of the variability was due to the floating icebergs. Here, sea ice concentration is specified from satellite observations. To examine the effects of changes in sea ice, simulations were performed using either climatological ice concentrations or the observed ice for that period. The changing sea ice affected not only the open ocean, but the water underneath the RIS. For example, from September 2002 to September 2003, the model average basal melt over the entire RIS was reduced from an average of 14.8 cm/yr to 13.0 cm/yr primarily because the Ross Sea Polynya opened up late that summer (possibly due to the presence of iceberg C-19) and there was less warm surface water adjacent to the RIS available to be advected underneath the shelf. The effects on the basal melting of recent changes in the winds used to force the model and the bathymetry in the open ocean part of the model will also be discussed.

Numerical modeling of subglacial-sediment dynamics

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Basal properties effect the rate and spatial pattern of ice flow. Historically, whole ice-sheet models simulated regions of ice-stream flow based on basal temperatures and an a priori knowledge of subglacial sediment distribution. The new generation of models will include both a temporal and a spatial evolution of basal properties. In this preliminary study, we couple a shallow-ice model to a non-linear bed to simulate the dynamic interaction between ice-sheet flow and subglacial sediment deformation. In future work, we plan to couple the sediment model to a ``full-stress'' ice-sheet model. Through ice-sheet simulations with a dynamic bed, we hope to gain a better understanding of the behavior of past ice sheets based on present landform distributions as well as the stability of the modern ice sheets under various global-warming scenarios. The greatest uncertainty in our present ability to predict sea-level rise results from our inability to simulate the recently observed rapid and ongoing changes in the Greenland and Antarctic ice sheets. Subglacial dynamics likely play a critical roll in grounding-line stability as well as in coupling shelf, outlet-glacier, and inland-ice flow regimes. Gaining insight into the physics underlying the fast response times of ice sheets is important as eustatic sea level and global climate can both be altered by changes in the cryosphere.

When the Bough Breaks: Implementing an Empirical Calving Rule in a Dynamic Stream/Shelf Model

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Given the ability of ice shelves to buttress the outflow of ice sheets, it is imperative to study the dynamic behavior of ice shelves if we wish to predict the contributions of ice sheets to future sea-level variations. Ice-shelf buttressing comes from frictional dissipation, both at the lateral margins of the shelf and any local pinning points or ice rises within the shelf. Disintegration of all or a portion of an ice shelf is one of the most direct ways to reduce ice-shelf buttressing, as evidenced by the accelerations of glaciers feeding the collapsed portion of the Larsen B ice shelf (Rignot and others, 2004; Scambos and others, 2004). This leads directly to the consideration of iceberg calving, as ice-shelf disintegration is simply an extreme calving event.

Here we apply an empirically derived calving rule to ice-shelf/ice-stream dynamics. The shelf/stream model couples dynamic mass balance and stress equilibrium component models for a depth and width-integrated stream/shelf system. The calving rule relates the ice-shelf velocity and a maximum (or yield) strain rate. The character of rule has this yield strain rate increasing with increasing velocity. Implementation of the calving rule within the shelf/stream model involves allowing calving at any point of the ice shelf where the longitudinal strain rate exceeds the yield value for the velocity distribution. We perform numerical experiments to examine the potential for rapid loss of ice-shelf extent due to slight to moderate disturbances in the stress state of the shelf/stream system. The implications for the stability of stream/shelf systems are considered in light of these experiments.

Boundary conditions for a full-momentum solver: 1) The dilemma of sliding and 2) how do we do embedded models?

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The holy grail of ice sheet modeling is the full-momentum solver. In principle, conservation of momentum, coupled with a flow law, can provide a differential equation solvable for velocities at every point within the ice sheet volume. The shallow-ice approximation neglects all but the basal drag and is useful for slow-moving inland ice. The Morland-MacAyeal equations neglect all but the longitudinal stresses and are useful for ice shelves and perhaps, in limited circumstances, ice streams. Both of these approximations take advantage of the different scales of the horizontal versus the vertical dimensions of the ice sheet, and involve an integration and removal of the vertical coordinate. Both of these approximations have severe limitations, especially in the dynamically critical ice streams that drain most of the mass out of Antarctica. The key interaction of shelf and inland ice, though the ice stream, cannot be adequately captured with either of these "end-member" approximations.

While very computationally intensive, a full-momentum solver that neglects no stresses and makes no assumptions or vertical integrations should give us the best and most accurate model for ice streams. Because of the computational requirements, such a model is not reasonable for a whole-ice sheet simulation, and hence we have pursued the embedded-grid approach, whereby a shallow-ice model is run for the whole ice sheet, and the full-momentum solver is applied only to a sub-region where ice stream dynamics are known to be important.

As such there are three different types of boundary conditions that must be specified, the top, the bottom, and the sides. The top is easy, a free-boundary is easily specified.

The sides and bottom are more difficult. On the sides we have a choice, either Dirichlet or Neumann boundary conditions. Dirichlet boundary conditions consist of specified boundary velocities (the unknowns, or degrees of freedom in the full-momentum solver), whereas Neumann boundary conditions are specified pressures or surface tractions (the source of momentum). From the shallow-ice model, we can provide both of these conditions, although the vertical variation in velocity is only of lower order. Pressures are not difficult to specify, however, conservation of angular momentum (net rotational torque should be zero), does require specification of some surface traction (the so-called " dynamical stresses"), and this can be problematic.

The bottom is most difficult, mainly due to the poorly understood nature of sliding (hard rock, deformable sediments, polythermal ice, basal water, etc.). A frozen bed is again easy, a simple Dirichlet boundary condition with velocities specified at zero. A completely uncoupled bottom is also easy, with simply a free boundary condition in the two horizontal dimensions. Of course in both of these cases the vertical velocity is specified to be zero.

Instead with Neumann boundary conditions, we can specify the basal traction. If this is specified to be equal to the driving stress (rho*g*h*alpha), we basically obtain the same solution that we get when we specify no sliding. We have tried specifying a given fraction of the driving stress, but this leads to unrealistic oscillations in the ice sheet profile. A uniform stress works well, but there is no indication that this is a reasonable assumption, nor does that deal well with the transition from inland to streaming to shelf. Both of these also require "yet-another-parameter," and hence are undesirable. A third approach involves a " deformable" basal layer, ie. a thin layer of elements, the order of meters thick, with much softer physical characteristics. With this approach, one can preserve the easy-to-implement Dirichlet boundary conditions of all basal velocities specified at zero, and yet obtain high sliding velocities, and plug-like flow, the dilemma being the requirement of a "parameter" (how soft and how thick is this layer?). Tuning such a model (and remember, this is how the parameters in most sliding laws are obtained, by tuning) would involve comparison of measured and modeled velocity fields in well-documented areas such as the Siple Coast, and soon the Amundsen Sector.

A linked system of lakes on MacAyeal Ice Stream

Helen Amanda Fricker, Ted Scambos, Curt Davis, Robert Bindschadler, Hyeungu Choi

Repeat track ICESat data acquired between October 2003 and April 2007 have revealed three large active subglacial lakes under MacAyeal Ice Stream, one of which is just 30km from the grounding line with the Ross Ice Shelf. This system represents an important pathway for subglacial water to the Southern Ocean. We discuss the hydrologic properties of this system and show linkages between the three lakes. We also analyse a 12-year time series of satellite radar altimetry and show that the results can be ambiguous over 10-20km scale lakes located in deep surface troughs. Instead, image differencing of the region will be used to extend the time series of lake filling and draining backwards to times earlier than 2003.

Basement architecture and sedimentary cover in the Amundsen Sea Embayment: Parameters for controlling and reconstructing ice-sheet expansion?

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An understanding of the glacial history of the Amundsen Sea Embayment and Pine Island Bay (PIB) is essential for proposing models on the future development of the West Antarctic Ice Sheet (WAIS). It requires both an understanding of the tectonic history, because basement morphology and inherited erosional features may control the flow direction of ice-sheets and the influx of Circum-Polar Deep Water (CDW) at later times. We, therefore, attempt to reconstruct the tectonic history with the aim to search for basement features and crustal boundaries which may be correlated to the flow and dynamics of ice-sheet advances.

The Amundsen Sea Embayment of West Antarctica is in a prominent location for a series of tectonic and magmatic events from Paleozoic to Cenozoic times. Seismic, magnetic and gravity data from the embayment and PIB reveal the crustal thickness and significant tectonic features. NE-SW trending magnetic and gravity anomalies and the thin crust indicate a former rift zone which was active during or in the run-up to the breakup process between Chatham Rise and West Antarctica before or at 90 Ma. NW-SE trending gravity and magnetic anomalies, following a prolongation of Peacock Sound, indicate the extensional southern boundary to the Bellingshausen Plate which was active between 79 and 61 Ma. It is likely that the prominent Pine Island Trough follows a structural boundary between the crustal blocks of Ellsworth Land and Marie Byrd Land.

We will show newly collected multichannel seismic reflection data from inner PIB which are interpreted in context with published reconstructions for the retreat history in this area. Differences in the behaviour of the ice-sheet are shown to exist for the western and eastern parts of PIB due to basement structures affecting the inflow of CDW which has been made responsible to the recent fast retreat of the Pine Island and Thwaites Glacier systems.

Grounding line migration and ice shelf buttressing in a two-dimensional marine ice stream model

Dan Goldberg and David Holland
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The role played by warming oceans in the dynamics of marine ice sheets depends on the degree of coupling between ice streams and their floating ice shelves. Ocean thinning of an ice shelf changes the stress balance within the shelf, but these changes must be transmitted across the grounding line in order to effect changes in the flow and extent of grounded ice. This mechanism is thought to be of some importance in several West Antarctic ice streams, including Pine Island Glacier.

We seek to recreate and investigate this driving of ice sheet changes through ocean melting and accretion in an ice stream-ice shelf flow model. The model consists of a depth-integrated stress balance with Glen's Law rheology (MacAyeal, 1989) with a basal stress parameterization applied to the ice stream. We make the model fully two-dimensional and allow the shear (arising, for example, from rigid sidewalls) to be determined by the solution rather than parameterized. Stresses are continuous across the grounding line and are not a priori set to zero anywhere in the interior. The thickness of the stream/shelf evolves through a depth-integrated continuity equation. The grounding line is allowed to migrate (and change topology, such as the formation of an ice rise) by way of a flotation criterion that is evaluated after each timestep.

Grounding line migration is problematic to the modeling of marine ice streams. The sharp transition in basal tangential stress and in thickness makes it difficult for a low-resolution model to capture the steep velocity gradients accurately, and strong qualitative dependence of behavior on numerical discretization and resolution is sometimes observed. We deal with this difficulty without sacrificing computational time and overhead by using an adaptive mesh, which provides higher resolution to the parts of the domain where it is needed. We show that solutions are convergent with respect to resolution, and not very sensitive to discretization details as long as the scheme is consistent.

A preliminary result of the model is that under certain conditions, generated using a domain periodic in one direction, is that grounding lines may be stable to small transverse variations. This implies that receding (or advancing) grounding lines may not exhibit morphological instabilities in the presence of small-scale transverse bed or stream thickness variation. Another is that the presence of rigid sidewalls can lead to much lower along-flow velocities as compared to unconfined shelves, not only within the ice shelf but in a narrow region upstream of the grounding line as well. We plan to investigate more fully this buttressing effect, both with idealized and more realistic geometry and basal stress parameterization.

Investigations of near-vertical subsurface structures near Swiss Camp, Greenland

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Processed Radio Echo Sounding (RES) data reveal vertical subsurface structures near the equilibrium line close to Swiss Camp, Greenland. Moulins, or englacial conduits that extend from the surface to unknown depths within the ice, may allow summer meltwater to drain into the ice sheet and contribute to increased basal lubrication. Moulins that are actively draining meltwater have been observed during ground-based investigations in the ablation zone near Swiss Camp [Behar, Steffen, pers. com.]. While these features have not been directly observed as high upstream as the equilibrium line, they have been inferred as an explanation for observed ice-sheet speed-up events recorded near Swiss Camp [Zwally, 2002; Parizek & Alley, 2004]. Testing this hypothesis is crucial because the location of such moulins may help determine whether they are responsible for changes in elevation that are too large to be caused by surface melt and decreased snowfall alone [Krabill, 1999].

RES profiles collected in spring 2006 reveal a vast number of potential moulin features. To interpret RES data for this investigation, it is necessary to collapse the corresponding diffractors to their approximate original shape using a migration algorithm and to confirm the orientation of the resulting structure. In doing so, it may be possible to determine whether the imaged feature is vertical, similar to a moulin or not vertical, similar to an englacial drainage pathway. A focused investigation was carried out during the following field season in spring 2007 on one feature ~1 km from Swiss Camp and another ~11 km north. Both sites were relatively isolated from other major features, making them ideal for clean data migration. Radar sounding for both sites was collected using a 'race-track' grid pattern analogous to a marine seismic survey to enable the use of 3D seismic migration algorithms in addition to 2D migration that are possible with data from a single profile. Data migration was accomplished using the Paradigm Focus seismic data processing package by appropriately scaling the wave speed and travel times for use with radar data. Post-migration results indicate that both sites have vertical features but different depth penetration. The feature closer to Swiss Camp does not appear to reach the bed while the more distant feature may. Neither of the features appear to be accompanied by dipping layers or those of varied brightness which would be indicative of water content as seen in RES profiles collected over other similar features.

Progress towards an Image-Enhanced 250 m DEM for the West Antarctic Ice Sheet

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An image enhancement technique based on photoclinometry is being applied to ICESat track data and a 1km DEM (with 7.5 km resolution) to generate a new DEM with a 250 meter grid spacing and resolution of approximately 500 m for the West Antarctic Ice Sheet. We present results for the Siple Coast region. The new DEM reveals the full 'undulation field' of the ice sheet catchment areas and glacier trunks, and promises to support improved regional analysis of accumulation and temperature variations around ice sheet topographic features. The DEM also quantifies flow-related features such as streaklines, and the slope break at grounding lines. MODIS data from the MODIS Mosaic of Antarctica, coupled with additional scenes from the same compilation year as the MOA data set, are calibrated by comparison with the initial DEM to generate a slope-to-brightness relationship (the 'photofunction'). This relationship is then used to generate a new, higher-resolution elevation field. Comparison to airborne laser altimetry suggests that the mean elevation precision is better than 2 meters.

Developing a long term strategy for using AUVs in polar research

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Three international workshops have reviewed the use of AUVs (autonomous underwater vehicles) in polar and extreme environments: Acoustic navigation and Communications for High-latitude Research, Seattle, Feb 2006
http://anchor.apl.washington.edu/index.html
Masterclass in AUV Technology for Polar Science, NOCS, March 06
http://www.noc.soton.ac.uk/CASEE/CASEE2/Introduction.html
AUV Science in Extreme Environments, SPRI, Cambridge, April 07
http://www.noc.soton.ac.uk/CASEE/CASEE2/pages/Science.html

These have shown that AUV technology is well developed and can answer a range of scientific questions beyond the capabilities of other methodologies. The final workshop identified that there was a need for strategic planning for the incorporation of AUVs into polar research, especially given the long term legacy objectives of IPY specifically:

- A collective multinational programme drawing upon national assets and resolving the institutional barriers to implementing this. - A move from short expeditions to long term effort, (sufficiently resourced to withstand occasional setbacks) for example: routinely launching and recovering AUV from bases around the Antarctic, Lagrangian drifters and acoustic navigation networks (ANCHOR).

Lost, but found: A large WAIS drainage basin existed in the southern Bellingshausen Sea during the last glacial period

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The southern Bellingshausen Sea is a poorly studied area of the West Antarctic continental margin. Multibeam swath bathymetry data and sub-bottom acoustic profiles collected on research cruise JR104 with RRS *James Clark Ross* revealed the existence of a major glacial trough ("Belgica Trough") on the continental shelf and an associated trough mouth fan on the adjacent slope. Mega-scale glacial lineations, drumlins and grounding-zone wedges indicate that Belgica Trough represents the former pathway of a grounded ice stream, which was fed by ice draining through Eltanin Bay and Ronne Entrance and which advanced to the shelf break during the last glacial period. These studies revealed that, in contrast to the present drainage pattern of the WAIS, ice flow into the southern Bellingshausen Sea played a significant role during past glacial periods.

Over the last years numerous sedimentological analyses have been carried out on marine sediment cores recovered during cruise JR104. The investigations included core logging, measurements of physical properties, grain-size analysis, determination of organic and inorganic carbon content, analysis of clay mineral assemblages, and AMS ^{14}C dating of calcareous (micro-)fossils and the acid-insoluble fraction of the bulk organic matter (AIO). Our results indicate that the shelf sediments reflect a whole suite of (sub-)glacial and glaciomarine environmental settings as they comprise deformation tills (deposited at the base of the ice stream), sub-ice shelf diamictons (deposited subsequently to the retreat of the grounding line), iceberg turbates, transitional sediments (deposited during the transition from subglacial to glaciomarine conditions), and post-glacial sediments (deposited under seasonally open-water conditions).

Provenance analysis of the fine-grained terrigenous sediment fraction (clay minerals) revealed glacial and glaciomarine transport processes and pathways. The clay mineral assemblages in the diamictons are remarkably homogenous at each particular core site. However, the clay mineral contents in the deformation tills vary significantly between core sites with no clear spatial pattern recognizable. This geographical heterogeneity suggests that during past glacial periods the ice stream flowing through Belgica Trough did not always drain the same source area in the West Antarctic hinterland and that the subglacial diamictons have different ages. The catchment area of the ice stream may have changed geographically either within the last glacial period or from one glacial period to another. The clay mineral composition within the transitional sediments changes from an assemblage similar to that in the subglacial sediments to an assemblage resembling that in the post-glacial sediments. We used this clay mineralogical fingerprint to identify samples that we assume to provide reliable ages for ice retreat from the shelf. The AMS ^{14}C ages of the AIO from six cores point to deglaciation of the outer shelf at ~26 ka B.P., the middle shelf at ~19 ka B.P., Eltanin Bay at ~12 ka B.P., and Ronne Entrance at ~7 ka B.P.. This timing of ice retreat indicates a relatively early and prolonged deglaciation of the southern Bellingshausen Sea.

Oceanographic and Bathymetric Observations at the Ilulissat Ice Fjord

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The Ilulissat Ice Fjord (a.k.a. Jakobshavn) may play an important role in connecting the waters of the North Atlantic to the Greenland Ice Sheet. At the eastern end of the fjord, the Jakobshavn Isbrae terminates abruptly at a deep ice front. At the western end, a shallow submarine sill partially separates the waters of Disko Bay from those of the fjord. To date there has been little knowledge gained of the bathymetry or oceanographic conditions in the fjord, and thus little ability to draw inferences about the possible influence of ocean waters on the observed retreating behavior of the Jakobshavn Isbrae. During June of 2007, we measured the depth of the fjord and sampled hydrographic conditions within the fjord and in neighboring Disko Bay. We report on these measurements and describe future plans for using them in a computer modeling study in an effort to understand a possible coupling between oceanography and glaciology in this environment.

A model of tidally-dominated ocean processes near ice-shelf grounding lines

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Glaciological processes at grounding lines may play a crucial role in controlling the dynamics of inland ice. Therefore, understanding the oceanic forcing on ice shelves in this region is of great importance to successful predictions of cryospheric change and sea level rise. As the ocean cavity shallows toward the grounding line, the effects of tidal mixing become proportionately more important until a point is reached, called the tidal front, beyond which the water properties are completely vertically homogenized. The extent of the vertically-mixed zone shoreward of the tidal front is of importance to several scientific questions because the mixed ocean behaves in a fundamentally different manner to the stratified region offshore. In this study a highly simplified one-dimensional model is used to examine the size, properties, and sensitivities of this mixed zone. The model suggests that most tidally-mixed zones are negligibly small, implying that the usual models representing a stratified ocean are generally valid. It therefore seems that in most cases upwelling of warm water, rather than tidal mixing, maintains ice-shelf basal melting. The mixed region can be significant, particularly where tidal flows are more vigorous and gradients in water-column thickness are small, but the model predicts that even these areas are smaller than previously proposed. The model also elucidates the pattern of melting near grounding lines, illustrates the birthplace of Ice Shelf Water plumes, and confirms that, unlike elsewhere in the cavity, melting in the small mixed zone increases linearly in response to ocean warming.

The response of ice-shelf basal melting to variation in ocean temperature

Paul R. Holland, Adrian Jenkins, and David M. Holland

A three-dimensional ocean General Circulation Model is used to study the response of idealized ice shelves to a series of ocean-warming scenarios. The model predicts that the total ice-shelf basal melt increases quadratically as the ocean offshore of the ice front warms. This occurs because the melt rate is proportional to the product of ocean flow speed and temperature in the mixed layer directly beneath the ice shelf, both of which are found to increase linearly with ocean warming. The behavior of this complex primitive-equation model can be described surprisingly well with recourse to an idealized reduced system of equations, and it is shown that this system supports a melt rate response to warming that is generally quadratic in nature. The results of this study confirm and unify several previous examinations of the relation between melt rate and ocean temperature but disagree with others, for which explanations are proposed. The hypothesized warming does not necessarily require a heat input to the ocean, as warmer waters (or larger volumes of 'warm' water) may reach ice shelves purely through a shift in ocean circulation. Since ice shelves link the Antarctic Ice Sheet to the climate of the Southern Ocean, this finding of an above-linear rise in ice-shelf mass loss as the ocean steadily warms is of significant importance to our understanding of ice-sheet evolution and sea level rise.

Thermal Convection and the Origin of Ice Streams

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The density inversion at depth in the Antarctic Ice Sheet is the "elephant" in the living room all modelers pretend isn't there. But it is, and it is an enormous source of gravitational potential energy that, in every other dynamic system where density inversions exist, is ultimately converted into kinetic energy of motion and thermal energy linked to motion. The questions are, how is this conversion manifested, where does it take place, and how can it be detected?

The density inversion exists because Antarctic ice gets hotter near the bottom, and occurs when thermal expansion overcomes compression of ice by the weight of overlying ice. Without taking ice compressibility under pressure into account, the density inversion occurs about halfway down, as Tony Gow demonstrated in 1968 for the Byrd Station corehole, when the compressibility wasn't known. With that knowledge now available, the density inversion takes place in the last few hundred meters of ice above the bed. This greatly increases the volume of ice above the density inversion, but the reduced density difference keeps the reservoir of gravitational potential energy about the same.

When a fluid is heated from below, creating a vertical density inversion like the one in the Antarctic Ice Sheet, thermal convection produces "platform cells" with hot fluid rising in cell centers. If horizontal flow is added, the cells elongate in the flow direction and become convecting rolls with hot fluid rising between two rolls. Horizontal flow in the Antarctic Ice Sheet proceeds from interior ice divides and largely converges on ice streams toward the ice-sheet margin.

Ice is crystalline, so flow begins when internal stresses cause line defects called dislocations to migrate through the crystal structure. In polycrystalline ice, this begins with transient creep, which in turn begins with the infinite strain rate of elastic deformation. During transient creep, dislocations pile up at crystal grain boundaries where internal stresses are concentrated. This causes ice to recrystallize into a fabric of ice crystals having an orientation that maximizes the strain rate for the stress field causing dislocations to move. Therefore, the initially infinite strain rate falls to a minimum strain rate as dislocation pile up, and the strain rate increases during recrystallization to a steady-state strain rate that is stable for the imposed stress field.

The Antarctic Ice Sheet has two stress fields, one due to the height of ice above sea level that drives horizontal flow and one due to the density inversion that should drive vertical flow. Horizontal flow is obvious, vertical flow is not. Nonetheless, vertical flow driven by the density inversion should occur at least during transient creep in the timespan between the infinite strain rate and the minimum strain rate, and perhaps also onward to steady-state creep. In addition, vertical flow should occur in something like convection rolls aligned in the direction of horizontal flow, which is the downslope direction in which ice streams form, first as ice-stream tributaries. These tributaries then converge and merge to produce major ice streams.

Suppose a dynamic threshold is reached at which cold heavy ice above the density inversion begins to sink into the warm lighter ice below, and sinking occurs in directions of converging horizontal flow. Warm ice above the bed will continue to move downstream, but some of it may rise along the sides of the sinking slabs. The ice surface lowers as slabs sink, allowing cold ice from the sides to move into the surface depressions. This lateral motion will allow warm rising ice to overtop cold sinking ice in the depressions and partly replace it. Such a flow pattern would be a version of thermal convection.

Basal meltwater would move laterally into the sinking depressions, following the new pressure gradient. Sinking slabs of cold ice would move faster downslope, carried by the faster downslope motion of warm ice below that slides faster on a wetter bed. Warm ice rising along the sides of the sinking cold slabs would weaken their coupling to cold ice on either side, allowing the slabs to move faster. Since 90 percent of Antarctic ice is discharged by ice streams, 90 percent of the cold ice above the density inversion would be converted into kinetic energy of motion by this process.

Since the process begins with transient creep, which is intermittent and of finite duration, would it cause ice streams to turn on and off intermittently? As cold slabs sink, the vertical temperature gradient increases and may convert a melting bed into a freezing bed, suppressing basal sliding. This would slow downslope motion of sinking slabs, perhaps turning off the tributary ice streams until the original temperature gradient is restored.

Modelers need to investigate this process to determine if it allows their models to more closely reproduce the known behavior of the Antarctic Ice Sheet.

Patterns of glacier response to disintegration of the Larsen B ice shelf, Antarctic Peninsula

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Glaciers that flowed into the former Larsen B ice shelf have responded to its March 2002 disintegration in different ways. Several glaciers (including the large Crane Glacier) experienced prolonged front retreat while others have retreated, advanced, and retreated again, and still others appear not to have responded to ice shelf collapse at all. Here, we document retreat patterns and place them in a glaciological context. The distinct classes of behavior observed around the Larsen B embayment demonstrate the importance of three-dimensional, geographic setting to the response of outlet glaciers to perturbations at their downstream ends.

Spatial Variation of Basal Conditions on Kamb Ice Stream

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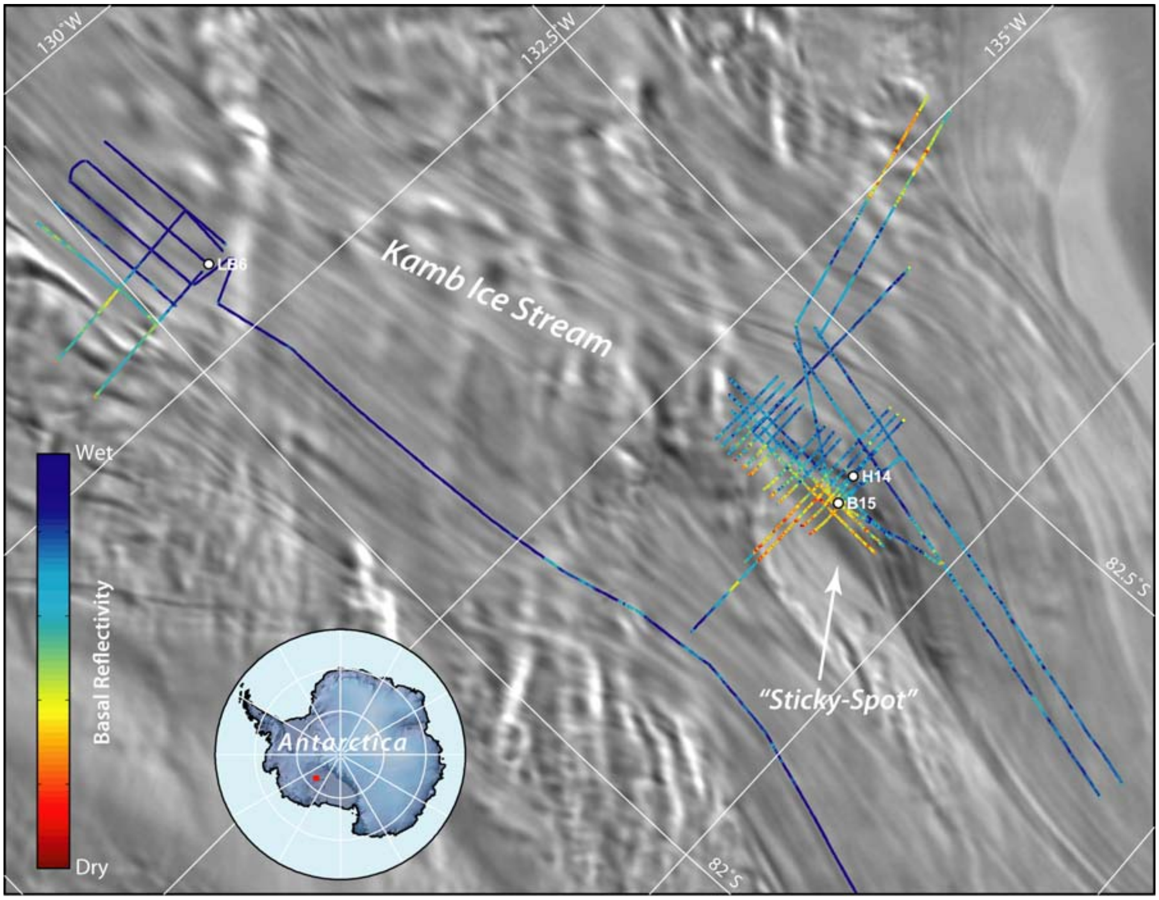
Radar profiles of bed echo intensity provide a way to survey conditions at the ice-bed interface and test for the presence or absence of water. However, extracting information about bed properties from bed echo intensities requires an estimate of the dielectric attenuation loss through the ice. A recent survey [MacGregor et al., 2007] found that the few reported values of depth-averaged attenuation rates in West Antarctica vary by a factor of 3, presumably due to spatial variations in the chemistry and temperature profiles of the ice. Thus, a single value for depth-averaged ice-sheet attenuation cannot be assumed, even over a relatively small region.

We measured attenuation rates at several locations on and near Kamb Ice Stream (KIS) by examining basal echo intensity values as a function of ice thickness from constant-offset radar data acquired in 2004-2006. Our values obtained for Siple Dome of 29 dB/km agree with previous measurements [Gades et al., 2000] and the recent calculations and model results of MacGregor et al. [2007]. On KIS, we measured attenuation values of 20 dB/km over the “sticky spot”, where ice has become stagnant. This value is consistent with an attenuation model over the sticky spot calculated using borehole temperature data [Engelhardt, 2005] and chemistry data from the Siple Dome ice core. Our radar profiles in the main trunk region of KIS yield a slightly lower value of 15 dB/km, presumably because colder ice is still being advected from inland West Antarctica.

Using these values of attenuation, we calculated the basal radar reflectivity at the ice-bed interface in the regions of all our surveys (Figure). We found that most regions of the bed in the trunk of KIS have high basal reflectivities and that these values are similar to those obtained in locations where water was found in the Caltech boreholes [Engelhardt, 2005]. Areas of lower bed reflectivity are limited to the sticky spot, where a borehole found a dry bed, and along the margins of KIS. We use these results to hypothesize about the stagnation of KIS and the possibility of its reactivation.



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Transient Temperatures and Redoubtable Reticence in the Amundsen

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To account for an apparent negative ice sheet imbalance in the Amundsen sector, a current hypothesis is that a warming ocean is thinning its ice shelves, which in turn permit faster ice stream flow, contributing to sea level rise. Documented ocean warmth in this sector exceeds that in most other Antarctic coastal regions, but evidence for a warming trend has been lacking. We will review subsurface temperature measurements in and near the Amundsen Sea over recent years. The relevant data now include repeat late summer vertical profiles and transects at 1-7 year intervals from 1994, and several year-long near-bottom records. Deep ocean temperatures in and west of Pine Island Bay (PIB) are highly variable in space and time, and dominated more by tidal than seasonal cycles. Change over periods from months to several years may relate to postulated and modeled variability in Circumpolar Deep Water inflow. Late summer temperature profiles below 300m in greater PIB were colder in 2000 than in 1994, and warmest in 2007, with a 13-year range of ~1.5°C above 600m and 0.3°C below 800m. While cavity shape, basal slope, and seawater velocity, density and mixing will influence the delivery of oceanic heat to the local fringing ice shelves, this observed thermal variability alone could drive large short-term changes in their basal melt rates.

“Reticence is fine for the IPCC……Do we not know enough to say more?” J Hansen, 2007

LC-130 Deep Field Capabilities

Lt Col Gary James, and Lt Col Mark Doll, 109th Airlift Wing, NY Air National Guard
Lt Col Ian Biggins, USAF Liaison to the National Science Foundation
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The LC-130 possesses a unique capability to fly cargo to remote polar regions, including west Antarctica. The LC-130, by virtue of being the largest ski-equipped aircraft in the world, is a valuable asset to the United States Antarctic Program. The cargo-carrying capacity, speed, range and endurance of the LC-130 make it uniquely suited to support remote, open-field camps in Antarctica. The 109th Airlift Wing, with a long history of operating in the polar regions, is prepared to increase the number of missions dedicated to support deep-field camps. South Pole Station Modernization is nearly complete, and the South Pole surface traverse is scheduled to become fully operational in 2009. This will relieve approximately 100 flights each season. Thus, the LC-130s will have the opportunity to increase their support for deep-field camps.

There are some improvements that promise to enhance the capability and accessibility of the LC-130. A new process for pre-season assessment of new deep-field sites is being developed. It is expected that this will shorten the planning process and allow more timely support. A new 8-bladed NP2000 propeller and new jet-assisted take-off rockets are in early stages of development, both if which will increase take-off capability. The most prominent improvement, still in early development, is the MiniSAR X-band Crevasse Detection Radar. This radar will have the ability to analyze the snow in real-time and significantly increase accessibility and safety of landing in deep-field sites. The potential for scientific uses of the radar have not yet been explored.

Location and timing of Circumpolar Deep Water intrusions onto the Amundsen Sea continental shelf, simulated with an isopycnic coordinate ocean model

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Stan Jacobs, Lamont-Doherty Earth Observatory

Using an isopycnic coordinate ocean model coupled with a sea ice model, we have simulated the circulation in the Amundsen Sea sector of Antarctica over the period 1980 to 2005. The model is forced with daily sea surface temperatures and sea level pressures taken from the NCEP reanalyses. We focus on the flow of Circumpolar Deep Water (CDW) onto the continental shelf. Our results show that CDW intrusions occur at specific locations and at specific times of year. Variability in the strength of the inflows gives rise to interannual changes in the heat content of the waters on shelf and beneath the ice shelves. Preliminary analyses suggest that the seasonal input of CDW is related to changes in the position and depth of a low pressure trough, located close to the shelf break. We show that interannual variability in the behaviour of this pressure trough could be the source of the observed changes in the ice shelves of the Amundsen Sea.

First exposure ages from the Amundsen Sea embayment, West Antarctica: the Late Quaternary context for recent thinning of Pine Island, Smith and Pope Glaciers

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Dramatic changes (acceleration and thinning of major ice streams) in the Pine Island Bay sector of the West Antarctic Ice Sheet (WAIS) have been observed during the last few decades, but the millennial-scale context for these changes is not yet known. We present the first reconnaissance surface exposure ages recording thinning of Pine Island, Smith and Pope Glaciers, which all drain into the Amundsen Sea. From these we infer progressive thinning of Pine Island Glacier at an average rate of 3.8 ± 0.3 cm yr^{-1} over the last 14.5 k.y., and of Smith and Pope Glaciers at 2.3 ± 0.2 cm yr^{-1} for at least the last 4.7 k.y.. These rates are more than an order of magnitude lower than the ~ 1.6 m per year recorded by satellite altimetry for Pine Island Glacier in the period 1992-1996. Similarly low long-term rates (2.5 to 9 cm yr^{-1} since 10 ka) have been reported further west in the Ford Ranges, Marie Byrd Land, but in contrast, there the rates of thinning continue to the present-day. Our data provide the first evidence that puts into context recent rates of thinning of WAIS in the Pine Island Bay sector; it suggests that these are unusually rapid. Our data also provide improved constraints for ice sheet models, which are essential for predicting the future behaviour of WAIS and hence for determining its likely contribution to sea level rise.

In addition to these reconnaissance data we outline the planned field campaign for season 07/08 during which we will undertake geomorphological mapping and extensive sample collection for cosmogenic exposure dating through the Hudson Mountains and Jones Mountains.

The influence of sea-ice and the Ross Ice shelf on water properties

John Klinck, Sinan Husrevoglu, Mike Dinniman

A regional ocean model (ROMS), with a 5 km grid spacing, has been developed for the Ross Sea which includes thermodynamically active ice shelves and dynamic sea ice. Simulations are driven by ECMWF (ERA-40) daily averaged, 2.5 degree atmospheric conditions. The CICE sea-ice model is coupled to the ocean model. High Salinity Shelf water, the dense precursor to Antarctic Bottom Water, is created in the western Ross Sea primarily in the coastal polynyas. Cold Ice Shelf Water is created by circulation under and basal melting of the Ross Ice Shelf (RIS). The warm Circumpolar Deep Water intrudes over the shelf break providing heat to moderate the sea ice cover and to support basal melt under the RIS.

Connections between meteorology and chemistry in surface snow: Clark Glacier, McMurdo Dry Valleys, Antarctica

Karl Kreutz, Bruce Williamson, Paul Mayewski, Benjamin Gross, Mike Handley, Sharon Sneed, and Mike Wasckiewicz

Many studies have examined snow and ice chemistry in polar regions with the purpose of extending our knowledge of climate through the thousands of years captured in seasonal ice stratigraphy. Variation in major ions, stable isotope ratios, trapped gas composition, trace metal contents, and physical properties of the ice, among other studies, have provided information interpreted to yield a picture of the state of the atmosphere in the Holocene period. Sometimes, however, these studies are calibrated in the modern period against instrumental records not from the immediate vicinity of the site of the firn or ice core collected. In 2004-2005, a meteorology station was active on the surface of the Clark Glacier, collecting instrumental information for one full year on surface barometric pressure, temperature, wind speed and direction, and snow depth. In 2005, a snowpit was excavated and sampled directly below this meteorology station. Samples from this pit were analyzed for major ion composition using ion chromatography. The results demonstrate the precise correlations between the chemistry of the snow pack and the weather conditions active at the time of precipitation. Major ions are shown to react in a variable fashion, with some (Na+, Ca2+, Mg2+) demonstrating reaction to multiple individual snow deposition events, while MS- shows a more clearly annual signal, with only one peak shown for the period of meteorology collected. The stable isotopic record, meanwhile, appears to record the most recent year with a reasonable annual signal, but the signal becomes increasingly muted with increasing depth in the snowpack (also representing increasing time after deposition). These results confirm the potential for such records in snow and ice to record not only annual but potentially sub-annual time series in several chemical proxies related to climate study.

Large scale modeling of ice flow for the entire Antarctica continent

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Understanding the evolution of the mass balance of Antarctica and its interaction with the oceans and atmosphere is of tremendous importance when trying to predict future sea level rises on earth. Current models for Antarctic ice flows lack knowledge of its ice rheology over large extents, making the mass balance prediction impossible. Using inverse control methods, we are now able to use data from satellite observations taken in past decades to constrain the rheology of the largest ice shelves in Antarctica; the resulting improvements in ice flow modeling are considerable and seem to suggest it may be possible to build a realistic large scale model for that continent. In this seminar, we will discuss the scientific and technological challenges of such a large scale model. We will also discuss a realistic approach to those challenges using the massively parallel finite element based computer code called Cielo: this code is being developed at JPL under a three year R&TD strategic initiative to model integrated thermal/mechanical/optical behaviors for large deployable aperture systems. We will show how those capabilities can be used as a framework for large scale modeling of Antarctica's mass balance.

WAIS wasting in the Amundsen Sea Embayment since the Last Glacial Maximum

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The Amundsen Sea sector of the West Antarctic Ice Sheet (WAIS) is the most rapidly changing part of the Antarctic ice sheet and could have a significant impact on future sea level rise. However, sea level rise predictions in the recent Intergovernmental Panel on Climate Change Summary for Policymakers excluded the possible effects of future rapid dynamic changes in ice flow because ice sheet model predictions were not considered to be sufficiently reliable.

One approach to testing and refining ice sheet models would be to examine their ability to reproduce ice sheet changes since the Last Glacial Maximum (LGM). Records of ice margin retreat and ice surface elevation change since the LGM also provide a context for recent changes. Until recently, however, knowledge of the chronology of change in the Amundsen Sea sector of WAIS since the LGM has been based on just seven radiocarbon dates from continental shelf sediment cores collected in 1999 on RV *Nathaniel B. Palmer*[1]. These dates indicated that there was already seasonally open water over the middle part of the shelf by 15,800 +/- 3900 radiocarbon years ago, and open water extended to within 100 km of the modern ice margin in Pine Island Bay before 10,150 +/- 370 radiocarbon years ago.

Over the past 18 months we have obtained 34 new AMS radiocarbon dates on samples from 25 Amundsen Sea shelf sediment cores collected during research cruises in early 2006 on RRS *James Clark Ross* and RV *Polarstern*. Some dates are on carbonate (foraminifera) but most are on the acid insoluble organic fraction. Several dates are on modern surface sediment samples to evaluate the marine reservoir correction and the effect of reworked 'fossil' carbon. We have also obtained the first surface exposure ages from the region by analysing cosmogenic isotopes in samples collected from sites accessed using helicopters operating from RV *Polarstern*. These ages provide the first data on long-term changes in surface elevation of ice in the Amundsen Sea sector of the WAIS.

Our new radiocarbon dates, together with swath bathymetry data collected on the same cruises and some previous cruises[2], confirm that the ice grounding line advanced to the continental shelf edge in the Amundsen Sea at the LGM. The retreat of the ice margin to its present position represents a loss of more than 150,000 km^2 of ice sheet, i.e. more than 35% of the area that remains in the Amundsen Sea sector of the WAIS. Our new data are generally consistent with the timing of ice margin retreat suggested previously, and in the western part of the embayment most of the retreat to the present ice margin position was certainly complete by early Holocene time. Average rates of retreat and surface elevation change are more than an order of magnitude slower than those observed over recent decades, but we cannot discount the possibility that there might have been previous short-lived episodes of rapid change since the LGM.

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A coupled ice/water flow model for West Antarctica

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This poster firstly describes the incorporation of a model of subglacial water flow into the GLIMMER ice sheet model (http://forge.nesc.ac.uk/projects/glimmer/), for general application to the WAIS. Secondly, the poster briefly outlines a future application of the model; constraining the deglaciation of the Weddell Sea sector since the LGM.

In the GLIMMER ice flow model, basal sliding is predicted as a function of the basal shear stress (approximated using the gravitational driving stress) and a basal sliding parameter. Previously, a spatially fixed value for the basal sliding parameter was used, producing an ice sheet with a convex morphology, rather than the concave slopes observed in WAIS ice streams. The basal sliding parameter required to reproduce present day WAIS ice stream velocities (with a corresponding concave morphology) is here inferred though inverse modelling techniques, using the measured velocity and modelled basal shear stress for the present day ice sheet. The resulting required basal sliding parameter for the WAIS varies by a few orders of magnitude. The variation in the sliding parameter is proposed to be a result of the water content, and hence yield strength, of the subglacial till known to exist beneath parts of the WAIS. The continental distribution of this subglacial till is not known, so a parameterisation of the water system based on that of Alley (1996), using a Weertman-type film to represent the basal water depth is tested. Using modelled melt rates from Joughin et al. (2004) and the present day ice sheet configuration, a plausible relationship between basal water depth and the basal sliding parameter is established for the Ross Sea Sector. The subglacial water flow model is then incorporated into the ice flow model, using the previously derived relationship between water depth and the sliding parameter for the Ross Sea sector. The model shows a reasonable level of success in representing present day ice velocities whilst retaining the present day ice sheet surface morphology.

The second part of the poster outlines an application of the model; to infer WAIS dynamics (specifically grounding line and ice volume changes) in the Weddell Sea embayment, constrained against the geomorphological record of elevation change through time in the Ellsworth Mountains.

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Accumulation Rates Over the Thwaites Glacier Catchment, West Antarctica, Using Radar Reflection Layers

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The scientific motivation for addressing the spatial and temporal distribution of snow accumulation rates in the catchment of the Thwaites Glacier (TG) is understanding the potential sea level contribution of the West Antarctic Ice Sheet (WAIS) over the next few centuries. TG lies in the Amundsen Sea Embayment (ASE) portion of the WAIS which is thought to be unstable both because its bed lies below sea level and because it's draining glaciers lack protective ice shelves. This instability is reflected in TG sensitivity to external forcing factors such as global climate, sea level rise, ocean temperature and accumulation rates, among others. These forcing factors affect the mass balance of the ice sheet. Given this general perspective, the present and past trends of spatial distribution of accumulation rates in the TG catchment serve as an essential boundary condition needed by the glaciology and climate communities to constrain models of WAIS evolution with the ultimate goal of describing its past and present behavior and forecasting its future evolution.

In this paper, we construct a map of snow accumulation rates over the catchment of TG using shallow internal layers traced from radio echo soundings. Based on these layer profiles, we compute a first order estimation of mass influx and compare it with published values of mass outflux over the grounding line and calculate an estimate of mass balance, a fundamental variable in ice flow and sea level rise models. The radar data was collected during the Airborne Geophysical Survey of the Amundsen Sea Embayment (AGASEA) in West Antarctica, performed by the University of Texas, Institute of Geophysics in the austral summer of 2004-05. In this survey, we collected 43,000 km of data that includes gravity, magnetics, laser altimetry and a 60 MHz coherent ice-penetrating radar.

The accumulation rate is calculated from observations of layer age and depth using Nye's methodology. For this purpose we traced two shallow radar-reflector horizons that are visible through most of the radar profiles and assume them to be isochrones. Since ice core dating for these reflectors is not currently available, we estimate their ages from a simple calculation of radar-layer thickness and accumulation rates from the ITASE ice cores that were close to the ice divide, where there is little lateral deformation of layers. This yields approximate ages of 863 ± 194 and 1092 ± 284 years for the two layers. To compute the accumulation rates we used Nye's methodology which takes into account vertical strain deformation under the assumption of steady state, uniform accumulation through time and no lateral variations of ice thickness. We computed a firn correction as a function of surface temperature and surface elevation and calibrated it with the ITASE ice cores as test points. We compare the resulting accumulation rates with those obtained by Arthern [2006] to assess the accuracy of our estimates and gain insight into accumulation patterns by analyzing the difference between the two methodologies. One potential drawback to our model is the deformation of layers in the ice stream trunk which are not accounted in the Nye's formulation.

The resulting average accumulation rate for the TG catchment was found to be 0.33 m/yr, with higher values close to the coast that gradually decrease inland as a function of surface temperature and surface elevation. This spatial distribution of accumulation rates agrees fairly well with that obtained by Arthern. The main difference between the two methods is that we were unable to track layers close to the coast and, therefore, could not resolve accumulation in that area. This is reflected in our overall estimation of mass volume, for which we obtain a total accumulation of 45.5 ± 10 Km^3/yr, while Rignot [2002] observes an accumulation of 57.6 Km^3/yr and outflow of 80.1 ± 8 Km^3/yr for a deficit in mass balance of -23 Km^3/yr , whereas for the same outflow we observe a deficit of -34.6 Km^3/yr. In order to improve our estimates, we need to include accurate ice core dating and a more comprehensive inversion of accumulation rates. The improved inversion, which is currently under development, will account for factors such as convergence and divergence of ice flow and high velocities over the ice trunk where Nye's model does not apply. In addition, we are working to track layers close to the coast, applying processing such as focused SAR that permit extended visibility of the layers.

Ice sheets in the Community Climate System Model

William Lipscomb
Los Alamos National Laboratory

I am leading the effort to implement an ice sheet model in the Community Climate System Model (CCSM), with the aim of performing credible climate change experiments with dynamic ice sheets for the next IPCC assessment. This work is supported primarily by the DOE Office of Science. We have the following goals in the near to medium term:

(1) Incorporate the GLIMMER ice sheet model as a standalone component of CCSM.
(2) Allow the ice sheet model to exchange fields with other CCSM components, in particular the land surface (CLM, the Common Land Model).
(3) Compute the ice sheet surface mass balance in CLM for multiple elevation classes, and downscale the mass balance from the land grid to the ice sheet grid.
(4) Develop a parallel ice sheet model that can run at fine resolution (~5 km).
(5) Run the ice sheet model with full stresses. (The current version of GLIMMER uses the shallow-ice approximation.)
(6) Implement an ice shelf model with a sub-shelf circulation model that exchanges mass and heat with the global ocean.

Goals (1) and (2) are complete, and (3) is in progress. Once we have finished (3), we will begin climate change experiments with a dynamic Greenland ice sheet. The Antarctic ice sheet will be added when higher-order stresses and a shelf model are available. To the extent possible, these developments will be incorporated in the next model version, CCSM4, which is scheduled for release in summer 2009. In the longer term we plan to focus on subglacial hydrology, deformation of subglacial till, and adaptive grids. The rate of progress will depend on the available resources, and we are working to obtain additional support for model development and analysis.

Opportunities (?) for Probabilistic Assessment of Ice Sheet Response to Climate Change

Christopher Little, Michael Oppenheimer, Gabrielle Dreyfus
Princeton University, Department of Geosciences

Climate policy may be implemented within a "risk management" framework, where risk is calculated as the product of a potential impact and its likelihood (the probability of occurrence, derived from scientific assessments) [Schneider, et al., 2007]. A probabilistic approach to assessing anthropogenic climate change impacts is thus a desirable, though often unattainable, objective. In particular, designing a credible quantitative projection of ice sheet response to future climate has proven to be elusive.

Earlier attempts to quantify the probability of future ice-sheet changes include both elicitations [Vaughan and Spouge, 2002], in which expert opinions are solicited and integrated into a probabilistic projection, and more traditional methods of uncertainty propagation (e.g. monte-carlo methods) [Titus and Narayanan, 1995] (TN95). The accuracy of the assessment in these latter methods depends critically upon the selection of the model(s) of the physical system; this choice determines the processes represented as well as the required input parameters. We suggest that a collection of component models (as implemented in TN95) is currently the best quantitative option for constructing a probability density function (PDF) of future ice sheet evolution, yet deciding which models to incorporate in the analysis (and how to bound the uncertainty of assumptions) poses significant challenges. For example, models available to predict basal melting at the ice-ocean interface range from detailed 3-D, fine resolution regional ocean models to crude functional relationships between global ocean temperature and melt rates. Models describing ice dynamics, glacial surface mass balance, and atmospheric variability span a similar spectrum of complexity.

Gains in our understanding of WAIS dynamics (including hydrology, ice stream behavior, and floating-grounded ice interaction), regional oceanography, and global climate likely improve our characterization of WAIS response to climate change. However, probabilistic assessments that incorporate these recent findings must be computationally feasible, the uncertainty of key parameters must be ascertained, and component inputs and outputs must be linked. We are currently exploring the feasibility of several approaches, distinguished by their choice of models of Antarctic ocean, atmosphere, and ice dynamics. In this poster, a survey of available models is presented; alternative combinations are critically examined for their ability to answer policy-relevant questions related to sea level rise, as well as their scientific validity and thoroughness. Our objective is not to define a single "correct" model, but to examine tradeoffs between comprehensiveness, fullness of uncertainty characterization, and policy-relevance, and to investigate the overall feasibility of this approach.

A complementary, ongoing research goal is a critical analysis of paleoclimatic proxies and their use in informing probabilistic assessments. Interpretations of paleoclimate data have been used to constrain processes relevant to ice sheet response (TN95) or as whole-ice-sheet analogues [Hansen, 2005] with no formal assessment of their applicability to anthropogenic warming or characterization of their uncertainty. Otto-Bliesner et al. (2006) use paleoclimate data more objectively (as a constraint on output of numerical models), but uncertainty characterization is difficult, as it is derived partially from paleoclimate data (including the validity of the proxy and experimental error), and partially on model error (both numerical and structural).

Regardless of its eventual success as a policy tool, we believe that an ongoing effort to build a quantitative probabilistic assessment will be helpful for developing a hierarchy of models, assessing the state of scientific knowledge, formulating research goals, and fostering an open discussion of the uncertainty surrounding sea level rise.

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Potential Vorticity Constraints on Buoyancy-Forced Circulation in Ice Shelf Cavities

Christopher Little
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Anand Gnanadesikan and Robert Hallberg
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Idealized model studies indicate that sub-shelf melting rates are highest in the southeast corner of ice shelf cavities [e.g. Holland and Jenkins, 2001]. As oceanic heat transport to the ice interface governs the location and rate of basal melting, this finding implies that "warm", dense water is constrained to flow into these regions. We use theory and numerical models to clarify the dynamic controls underlying favored melt locations under different bathymetric scenarios (Figure 1).

An idealized set of numerical experiments employs spatially and temporally fixed buoyancy fluxes in a two-layer isopycnal model to examine the structure of inflow generated under different topographic scenarios. In addition to an overturning circulation, freshwater fluxes force smaller-scale horizontal circulations resulting from vigorous vertical motion in the presence of potential vorticity (PV) gradients [Hallberg and Rhines, 1996]. Flow in the interior is governed by large-scale topographic gradients, yet the deepest regions of the cavity (near grounding lines) are controlled by recirculation around "melting" regions. These experiments suggest there is a self-reinforcing dynamic explanation for eastern-intensified melting, as the melt-induced circulation near the grounding line controls the heat transport to the ice interface.

Thermodynamically "decoupled" numerical experiments are then compared to those that include heat transfer and freshwater fluxes to and from the ice shelf. Near the southern boundary, "coupled" experiments (figure 2) reinforce the conclusion that channeling of inflow to the southeast is favored under a wide range of topographic conditions, and suggest that the location of melt is stabilized by the coupling of the local circulation to the heat source. However, the influence of bathymetry in the cavity interior is muted by realistic stratification, the slope of the ice shelf, and friction. Near the grounding line any large-scale topographic control of flow is dominated by the ice shelf draft.

Heat transport under ice shelves is also forced by time-varying open ocean dynamics, notably tides, potentially decoupling the heat source and the response of flow at depth. Additionally, small-scale topographic conditions under ice shelves may modify the scale and strength at which these phenomena are manifested. The insensitivity to bathymetry demonstrated in these initial experiments suggests extension of this work along two distinct lines - an investigation into the scale (both horizontal and vertical) of bathymetric influence, and further studies into the control exerted by the ice shelf draft. These latter studies may be especially important in strongly forced ice shelf cavities, where ocean dynamics near the ice interface strongly influence heat transport associated ice shelf melting rates [Holland and Jenkins, 1999; Holland and Feltham, 2006].

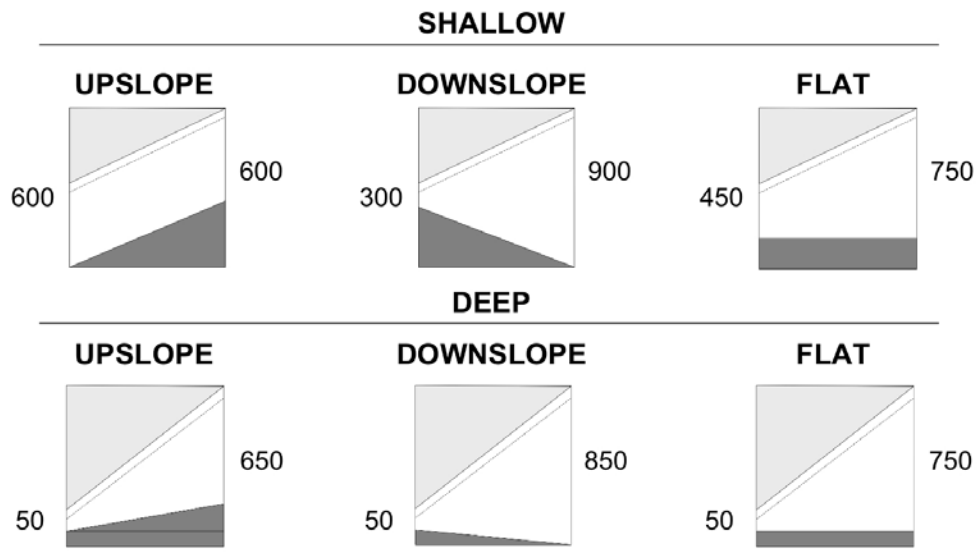

Figure 1. Meridional cross-sections of the (zonally uniform) topographic configurations employed in the experiments. All scenarios have dimensions of 500 km meridionally by 400 km zonally; water column heights at the meridional boundaries are shown (north is to the right). In "decoupled" experiments, a diapycnal mass flux of 0.05 Sv (corresponding to a melt rate of approximately 10-3 Sv) is distributed uniformly over the northernmost and southernmost 7.5% of the domain.

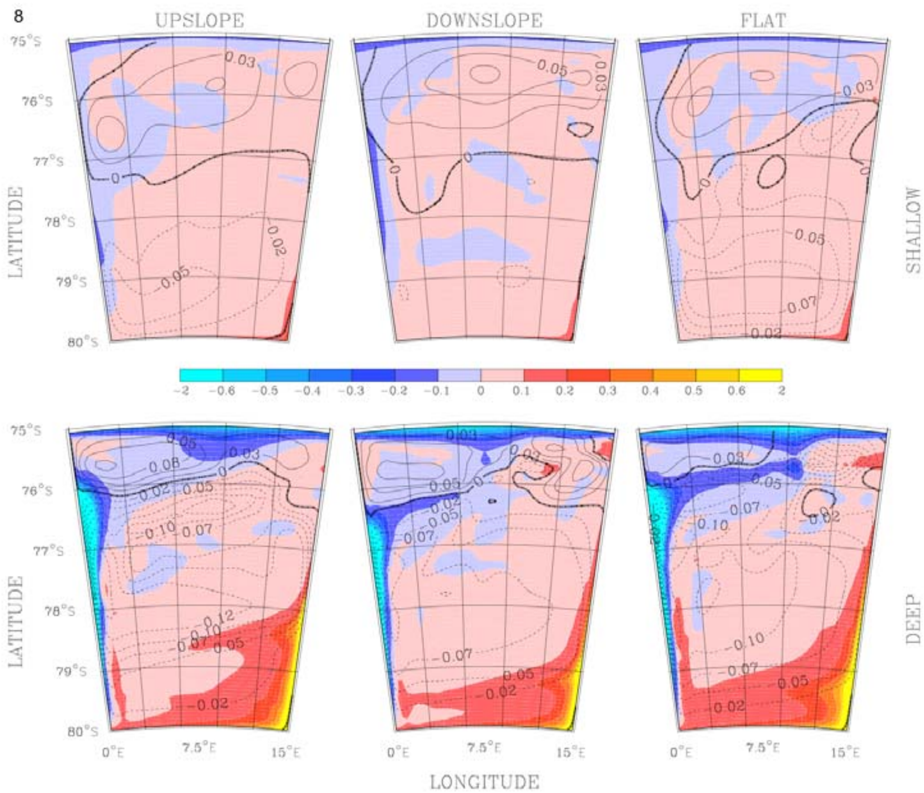

Figure 2. Barotropic volume transport streamfunction (contours, in Sv) and melt rate (shading, in myr-1) in year 30 of the "coupled" experiments. SHALLOW (DEEP) experiments are shown in the top (bottom) row. Although the strength of the horizontal circulation varies, melt locations (and overall rates) are fairly consistent across the topographic scenarios.

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Radar attenuation and temperature near the grounding line of Whillans Ice Stream

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Both ice deformation and the attenuation of radar waves in ice are strongly temperature-dependent. Measurements of radar attenuation could thus constrain the temperature fields used in ice-flow models. Here we present a novel measurement of radar attenuation using a multiple echo from the ice-shelf-ocean interface detected by a 20-km long, ground-based, 2-MHz radar transect near the grounding line of Whillans Ice Stream, West Antarctica. The measured attenuation rate is calculated using the ratio of the intensities of the primary and multiply reflected echoes over the ice shelf and estimates of the air-firn and ice-ocean reflectivities. We then compare this measured value to that from a temperature-dependent attenuation model to estimate the temperature profile at this site. This model also depends on ice chemistry and density although these dependencies are weaker than the temperature dependence and have less spatial variation; here we use mean values of chemistry data from Siple Dome and nearby ITASE ice cores, and density and surface temperature data from the J-9 ice core and nearby RIGGS sites. The measured attenuation rate is close to the modeled attenuation rate when the temperature profile is linear between the surface and the ice-shelf bottom, which is consistent with the nearby and nearly linear J-9 temperature profile further out on the Ross Ice Shelf. Modeled attenuation-rate values using temperature models that include significant vertical heat advection, i.e., lower temperatures at shallower depths, are too low to match the measured attenuation rate. Attenuation measurements could therefore discriminate between possible temperature profiles when combined with an attenuation model. While here we only use the measured attenuation rate to the basal reflector, attenuation-rate measurements to several internal reflectors and the bed could further constrain the temperature profile. We have measured an in situ, depth-averaged attenuation rate that is significantly higher than those of previous studies from the grounding line of the Ross Ice Shelf; this variability emphasizes the need for reliable estimates of attenuation rates in studies of basal radar reflectivity.

Exposure ages from mountain dipsticks indicate little change in East Antarctic Ice Sheet thickness since the Last Glacial Maximum and stability from the mid Holocence

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Past changes in East Antarctic Ice Sheet (EAIS) volume are poorly known and difficult to measure, yet are critical for predicting the response of the ice sheet to modern climate change. In particular, it is important to identify the sources of sea level rise since the Last Glacial Maximum (LGM), and ascertain the present-day stability of the world's largest ice sheet. We present altitudinal transects of 10Be and 26Al exposure ages across the Framnes Mountains in Mac.Robertson Land which allow the magnitude and timing of EAIS retreat to be quantified. Our data show that the coastal EAIS thinned by at most 350 m in this region during the last 13 ka. This reduction in ice sheet volume occurred over a ~5,000 yr period and the present ice sheet profile was attained at ~7 ka, in contrast to the West Antarctic Ice Sheet which continues to retreat today. Combined with regional offshore and terrestrial geologic evidence, our data suggest that the reduction in EAIS volume since the LGM was smaller than that indicated by some ice sheet models and added little meltwater to the global oceans. Stability of the ice margin since the mid Holocene provides support for the hypothesis that EAIS volume changes are controlled by growth and decay of Northern Hemisphere ice sheets and associated global sea level changes.

Modelling the impact of tidal currents on ocean circulation beneath Filchner-Ronne Ice Shelf

Keith Makinson

British Antarctic Survey, Cambridge, UK

A modified version of the Miami isopycnic coordinate ocean circulation model (MICOM) is applied to the southern Weddell Sea and the ocean cavity beneath Filchner-Ronne Ice Shelf (FRIS). The model is used to investigate the response of ocean circulation to significant tidal activity which, until now, has been neglected in 3-D models of the region. Beneath FRIS, tides are the primary source of motion with mean tidal current speeds varying from a few cm/s to 50 cm/s, with peak speeds about twice this during spring tides. Strong tidal currents occur in the relatively shallow regions near Ronne Ice Front, the broad channel south of Henry Ice Rise and close to grounding lines. The model shows that as the water column shallows, intense vertical mixing creates a well-mixed water column that is separated from the deeper stratified water column by a tidal front. Tidal fronts form a barrier to lateral exchange, forcing the mean currents to go around these well-mixed regions, thus modifying the circulation pattern. Elsewhere, tidal mixing continues to enhance water mass modification and the flow of heat up through the stratified water column, increasing basal melting. These initial results show that if ocean circulation, together with the evolution of water mass properties and basal melting patterns are to be effectively modelled, the inclusion of tidal forcing in ocean circulation models is essential.

Detection of in-situ ice fabric anisotropy using polarimetric radar method near WAIS Divide

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Crystal-orientation fabric (fabric) has an important effect on ice deformation. As ice deforms, anisotropic fabrics are produced, which, in turn, influence further deformation. To detect spatial distribution of ice fabric pattern, polarimetric radar measurements were conducted in the WAIS Divide region during the 2005/6 and 6/7 field seasons using 60 MHz, 179 MHz, and 1.3 GHz radars. These radars allow us to examine frequency dependent effects of fabric over a wider depth range. If ice fabric is not perfectly symmetric around the radio-wave propagation axis (vertical in our case), the azimuthal variation of the echo intensity is expected to be uniaxial (180-degree periodic) or biaxial (90-degree periodic). Theory and radar evidence from Greenland and East Antarctica suggest that the former can be caused by a vertical variation of the horizontal anisotropy in the fabric (fabric-origin anisotropic reflection) and that the latter can be caused by horizontal anisotropy in the fabric integrated along the radio-wave propagation path to that depth (birefringence).

The polarimetric measurements were done at 19 sites within an area of 150 km by 60 km including the WAIS Divide coring site. Strain-grid measurements using GPS were performed over the two years at these sites. Since our measurements collected the radar signatures from the top half of the ice sheet, strain configuration responsible for the radar detected fabric is more controlled by the ice-sheet surface topography than the bed topography. Thus, we hypothesize that the radar detected fabric signatures can be a proxy for past ice-sheet surface topography.

At sites close to the current ice-flow divide, fabric-origin reflection is apparent at depths ranging between 700 m and 1500 m. It suggests that large contrasts in fabric occur over a short distance at these depths. Farther from the divide, birefringence is more apparent. It implies that contrasts in fabric are too weak to make reflections. Rather, ice fabric develops more gradually through the ice column. The principal axes of the current strain are consistent with radar derived principal axes of the fabric at most of these sites. In contrast, radar data collected at two sites about 100 km NW of the ice coring site show that principal axes of the fabric shift in terms of depth. We argue that the azimuth of the surface slope near these two sites shifted so that ice flowed from Executive Committee Range in the past but nowadays it flows from the divide. Examination of timing and spatial extent of this azimuthal shift of the slope can be related to the history of the divide area in the context of deglaciation at Executive Committee Range revealed by geological evidence. It ultimately provides regional constraints to the ice-core interpretations.

Retreat history of the West Antarctic Ice Sheet since the Last Glacial Maximum from deep-basin and sub-ice shelf sediment cores in the Western Ross Sea

Rob McKay, Gavin Dunbar, Tim Naish, Peter Barrett, Lionel Carter, and Margaret Harper
Antarctic Research Centre, Victoria University of Wellington, New Zealand

Three sediment gravity cores from beneath the McMurdo Ice Shelf (Fig. 2) and three piston cores from beneath seasonally-open water in the Erebus (in McMurdo Sound) and Lewis Basins (north of Ross Island) display a characteristic succession of sedimentary facies that document the retreat of the Ross Ice Sheet since the Last Glacial Maximum (LGM) to its present configuration. The succession of facies records a transition from sub-glacial to open-marine environments that comprises in ascending stratigraphic order: (1) slightly consolidated, clast-rich muddy diamict dominated by basement clasts from the Transantarctic Mountains, and interpreted as melt-out from the basal debris layer debris proximal to a retreating grounding zone; (2) sparsely-fossiliferous (reworked diatom frustules) and non-bioturbated mud lacking lonestones, interpreted as a sub-ice shelf facies; and (3) diatom mud and diatom ooze indicative of open water conditions with evidence of iceberg rafting. We present a chronology based on radiocarbon dates from post-LGM muds and diatom oozes, which indicates that lift off of the grounded Ross Ice Sheet in deep basins of the McMurdo Sound region began at ~10,000 ^{14}C yr BP. Retreat of the grounding from the outer Dryglaski Trough to Ross Island was rapid and occurred within ~1000 yr. By ~8,900 ^{14}C yr BP, there was open water immediately to the north of Ross Island, and since this time the calving line of the Ross Ice Shelf has remained to pinned to Ross Island, despite ice core evidence for a mid-Holocene climatic optima 1-2ºC warmer than present (Steig et al. 1998). We suggest the post-LGM retreat of the Ross Ice Sheet shifted to its contemporary ice shelf mode when the calving line became pinned by Ross Island. This revised chronology implies an earlier and more rapid retreat history than previously reported, and allows for the possibility that the retreat of the Ross Ice Sheet was associated with global eustatic sea-level pulses during the early Holocene.

Sensitivity of ice-shelf/ocean interactions to vertical resolution and thermodynamic parameterizations in the ROMS model

Rachael Mueller, Laurie Padman, and Mike Dinniman

Recent studies demonstrate that ice shelves play an integral role in moderating the offshore flow of Antarctic glaciers and ice streams. The extreme case of a collapsed ice shelf (e.g., Larsen B) has been shown to cause an acceleration of contributing ice streams. While conditions for collapse depend on various processes (e.g. downward percolation of surface meltwater in response to atmospheric warming, iceberg calving, and basal melt/refreezing processes), we focus on the influence of ocean circulation on changing ice shelf thickness through melting and refreezing at the ice-ocean interface.

Models of ocean/ice-shelf interactions have already been run for several ice shelves; however, model solutions are sensitive to setup choices, such as grid resolution and different parameterizations. Thus, in this study we step back from real-world applications to explore the sensitivity of basal melt rate (M_b) to model setup. We use the Regional Ocean Modeling System (ROMS) community ocean model (version 2.2), augmented with basal thermodynamic processes following Dinniman et al. (2007). George VI Ice Shelf is used as a test environment, as it is a small shelf with relatively well-known grounding line, ice thickness, and seabed bathymetry. At this time, thermodynamic forcing is provided by idealized initial ocean temperature and salinity. We compare the steady-state melt rate for various model configurations, focusing for now on the sensitivity of M_b to the model's vertical resolution under the ice base. Future studies will include an assessment of M_b sensitivity to the sophistication of the thermodynamic exchange processes at the ice/ocean boundary, and dependence of M_b on the representation of tidal forcing.

Bathymetry of the Amundsen Sea Continental Shelf

F. Nitsche, S. Jacobs, R. Larter, K. Gohl
Lamont Earth Observatory, British Antarctic Survey, Alfred-Wegener Institute

The Amundsen Sea is one of the remotest areas of coastal Antarctica, and was relatively unexplored until the mid-1980s. Over the last two decades, oceanographic, glaciological and geological interest has led to several cruises, one result of which is sufficient bathymetric data to compile a fairly detailed regional map of the area. We have combined all known single and multibeam bathymetry to create a new chart for the Amundsen continental shelf and slope. After editing individual data sets we used a natural neighbor algorithm to interpolate between existing tracklines and produce a grid at 2 km resolution. The most prominent regional features are deep inner shelf troughs, aligned with present glaciers and separated by shallower ridges, that coalesce and shoal seaward. Cut by larger ice streams during past glacial periods, these troughs now channel oceanic heat to a vulnerable WAIS.

The Filchner Ice Shelt Water Overflow

Svein Østerhus

In this speech I will give a status report for our research on processes, fluxes and circulation in the southern Weddell Sea where about 50% of the bottom water in the Antarctic is believed to be formed (Orsi et al. 2001, Foldvik et al. 2004). Cooling and freezing on the shallow shelves are producing HSSW at the freezing point. Some of the HSSW will cascade down the continental slope and contribute directly to bottom water production. In addition, some of the HSSW penetrates underneath the floating Ronne - Filchner Ice Shelf in the Southern Weddell Sea (Foldvik et al., 2001), see Fig.1. Here it becomes super-cooled, Ice Shelf Water (ISW) and is observed to overflow the sill of the Filchner Depression at a rate of about 1.6 Sv (Foldvik et al., 2004). As it flows down the continental slope it forms a bottom plume which is deflected westwards because of the Coriolis force, see Fig.2. Here we believe that the bottom topography may give rise to different pathways; the upper part will descend at a moderate angle with the isobaths due to friction (Killworth, 2001). Deep canyons and ridges (Fig.3) provoke other branches to descend more rapidly towards the deep Weddell Sea.

On its path down the slope the ISW plume mixes with overlaying water masses. These mixing processes are not well understood, but supercritical plume speeds and associated hydraulic jumps are believed to be important (Holland et al., 2002). On its way down, the cold bottom plume increases its volume transport to more than 4 Sv. This is an upper estimate of the total production of WSBW believed to be formed in the whole region. WSBW is a precursor to the AABW, so our study area is a key location for processes with global impact.

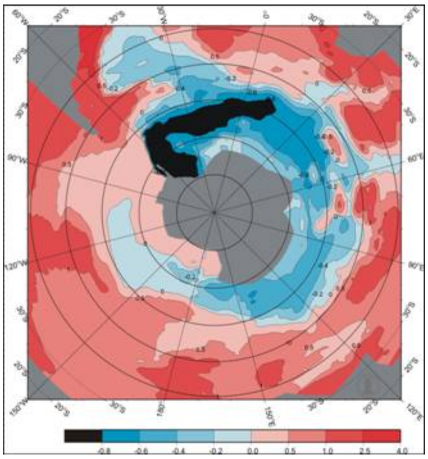

Figure 1. Potential temperature for the bottom water in the Southern Ocean.

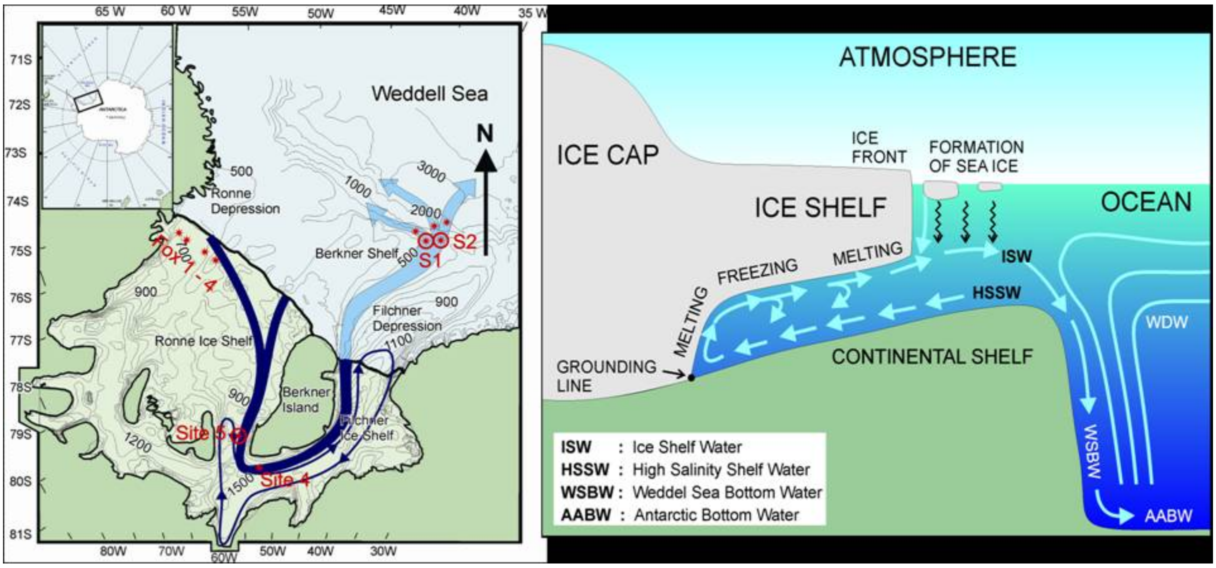

Figure 2. Left: Bathymetric map of the southern Weddell Sea, Antarctica showing the vast shallow shelves in the Southern part. The arrows indicate simplified circulation in the cavity beneath ice shelf and the pathways for the ISW. The monitoring sites Site 4 and 5, Fox 1 to 4, and the S2 CLIVAR/OceanSITE mooring on the Filchner sill. Right: Schematics of the dense water production and circulation.

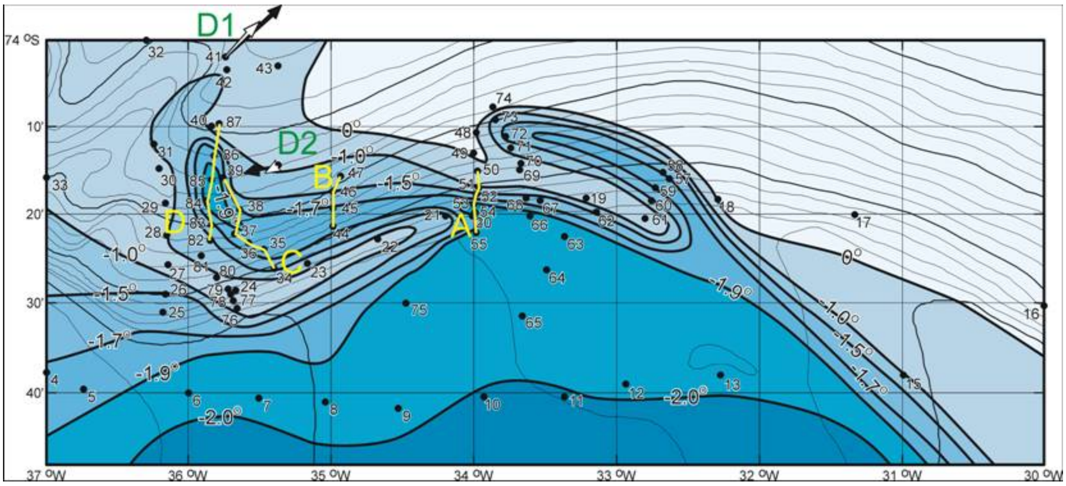

Figure.3 Bottom temperatures obtained in 1985 with K/V Andenes indicating the ISW overflow over the Filchner sill and how it is deflected towards the left as it penetrates down slope.

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On its path down the slope the ISW plume mixes with overlaying water masses. These mixing processes are not well understood, but supercritical plume speeds and associated hydraulic jumps are believed to be important (Holland et al., 2002). On its way down, the cold bottom plume increases its volume transport to more than 4 Sv. This is an upper estimate of the total production of WSBW believed to be formed in the whole region. WSBW is a precursor to the AABW, so our study area is a key location for processes with global impact.

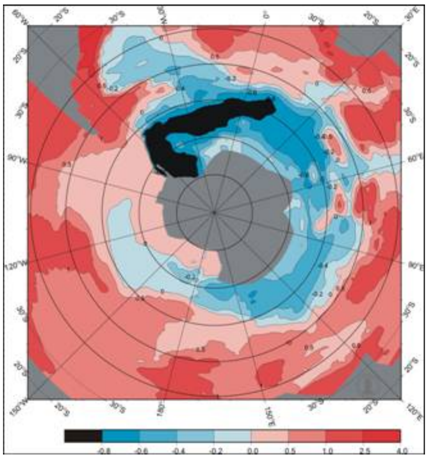

Figure 1. Potential temperature for the bottom water in the Southern Ocean.

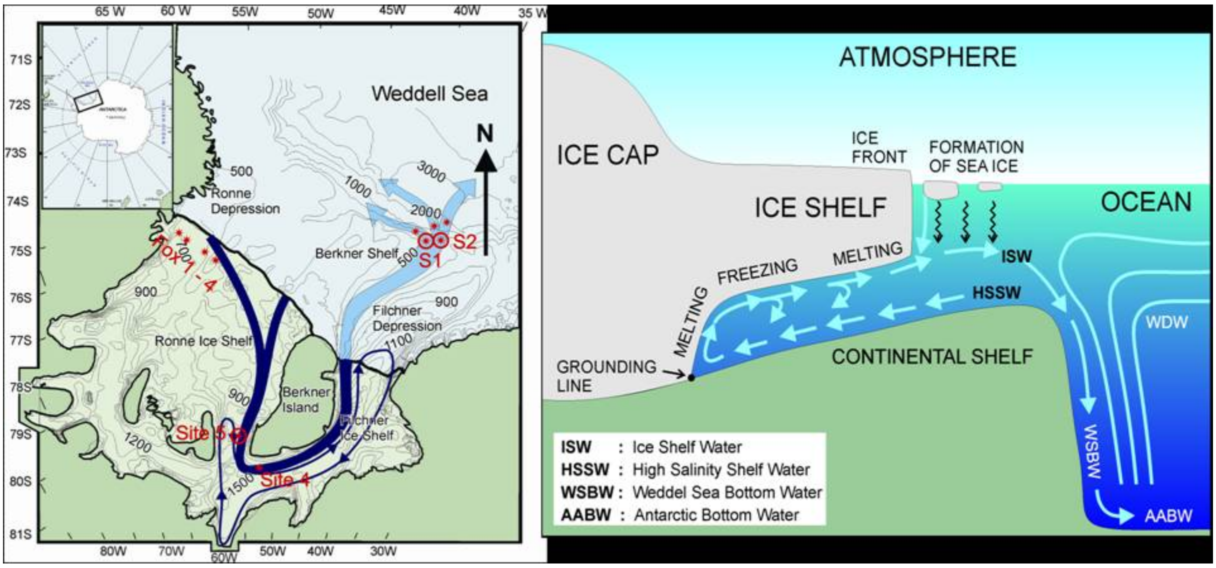

Figure 2. Left: Bathymetric map of the southern Weddell Sea, Antarctica showing the vast shallow shelves in the Southern part. The arrows indicate simplified circulation in the cavity beneath ice shelf and the pathways for the ISW. The monitoring sites Site 4 and 5, Fox 1 to 4, and the S2 CLIVAR/OceanSITE mooring on the Filchner sill. Right: Schematics of the dense water production and circulation.

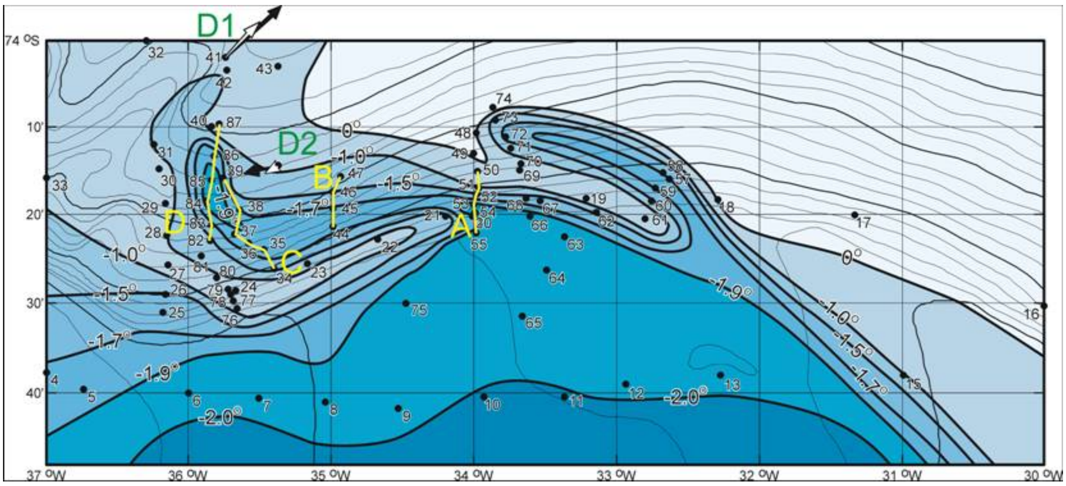

Figure.3 Bottom temperatures obtained in 1985 with K/V Andenes indicating the ISW overflow over the Filchner sill and how it is deflected towards the left as it penetrates down slope.

Focused SAR Processing of Airborne Radar Sounding Data from Kamb Ice Stream

Matthew E. Peters, Donald D. Blankenship, Sasha P. Carter, Scott D. Kempf, Duncan A. Young, John W. Holt

Radar sounding is perhaps the most important technique for investigating the internal structure of ice sheets and the underlying interface. This remote sensing technique can be well-suited for estimating the likelihood of melted and/or frozen conditions at the basal interface. Basal water is known to be an important factor affecting the existence and dynamics of the West Antarctic ice streams. Ice streams are generally difficult environments for quantitative radar sounding investigations because crevassing can significantly increase the surface clutter and propagation losses. Furthermore, any internal layer structure can be seriously disrupted due to the complex ice flow and dynamics.

We present focused synthetic aperture radar (SAR) processing of airborne radar sounding data acquired with the High-Capability Radar Sounder (HICARS) system operating at 60 MHz. The SAR processor correlates the radar data with a suite of geometry-dependent reference functions for subsurface point targets. These references can be either 1-D pulse-limited along-track variations (allowing intermediate apertures 375-550 meters) or 2-D variations that also include the echo tails (allowing very long apertures 1200-1700 meters). The advantages of focused SAR include: 1) improved gain and signal-to-noise ratio (SNR), 2) accurately preserved amplitudes of echoes from sloped interfaces, leading to improved basal reflection analysis and water detection, 3) improved internal layer detection and tracking, and 4) improved along-track spatial resolution.

The focused SAR processing and basal reflection analysis are applied to HICARS data from the Kamb Ice Stream. In general, the results show that focused SAR processing provides measurable improvements over unfocused SAR and incoherent integration. However, the "best" processing method may not be the same for all situations, and different processing may be required of the same raw data in order to best answer the variety of scientific questions that radar sounding can address.

Accurate echo amplitudes are necessary for quantitatively predicting the likelihood of water at the basal interface. For airborne radar sounding of Kamb Ice Stream using HICARS, basal echo amplitudes should be accurately preserved from slopes up to about 0.5 degrees for unfocused SAR, up to about 3 degrees for 1-D correlation focused SAR, and up to about 10 degrees for 2-D correlation focused SAR. The amount of detected basal water increases roughly threefold from unfocused SAR to 1-D correlation focused SAR, indicating that significant basal water exists on moderately sloped interfaces. Very little additional basal water is detected using 2-D correlation focused SAR. However, 2-D focused SAR can significantly improve the detection and tracking of internal layers with along-track slopes greater than about 3 degrees, as well as improve the spatial resolution in rough regions.

Basal conditions at two sticky spots along Kamb Ice Stream, West Antarctica

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We present the results of seismic observations made upstream of the trunk of Kamb Ice Stream, West Antarctica, that point to sticky spots, basal freeze-on, and a discontinuous basal water system as reasons for the ongoing shutdown of Kamb Ice Stream. Seismic data from two 10.8 km profiles were collected during the 2002 - 2003 Antarctic field season: one crossed the south flank of the pronounced sticky spot visible in satellite imagery and near the CalTech boreholes, and the other was oriented transverse to ice flow about 30 km upstream. Both seismic profiles reveal considerable variations in basal topography, highlighting the fact that basal highs are present in the region that act as sticking points and resist fast ice flow. Each location also exhibits variable basal conditions, ranging from frozen sediments to soft, dilatant till to water. These variations in the basal regime of the ice stream arise from spatial discontinuities in the subglacial water system, as well as basal freeze-on. This discontinuity of soft, dilatant till and water at the bed, along with the presence of sticky spots, leads to unfavorable conditions for fast ice flow and the observed ongoing shutdown of Kamb Ice Stream.

Cenozoic variations of the Antarctic Ice Sheet: a model-data mismatch?

D. Pollard and R.M. DeConto

Cenozoic variations of global ice volume deduced from deep-sea-core benthic d18O records are compared with results from 3-D ice sheet-climate models. After the initial growth of major Antarctic ice at the Eocene-Oligocene boundary ~34 Ma, d18O records indicate numerous excursions throughout the Oligocene and early Miocene with timescales of ~10^4 to 10^6 years and amplitudes of ~20 to 80 meters of sea level. During most of this period, atmospheric CO2 levels in proxy records were low, around 1x pre-industrial (PAL). These observations conflict with coupled model results that once a large East Antarctic ice sheet formed at 34 Ma, CO2 levels must have varied in the ~3x to 4x PAL range to induce significant retreat and re-growth. Several mechanisms are discussed that could possibly have caused large ice-volume fluctuations, all of which are speculative.

Treatment of grounding-line dynamics in ice sheet-shelf models

D. Pollard and R.M. DeConto

Previous model intercomparison tests with dynamical ice sheet-stream-shelf models have found that the treatment of grounding-line migration is critical, and can spuriously affect results even in simple idealized situations. Recent theoretical advances (Schoof, 2007, JGR-Earth Surface) show that it is necessary either to resolve the transitional boundary layer upstream of the grounding line, or to apply analytic constraints on the ice flux flowing across the grounding line.

Here a marine ice sheet-shelf model is used to simulate grounding-line migration in simple 1-D flowline scenarios. Results are compared using fine (0.1 km) and coarse (10 km) grids, and also using the Schoof grounding-line constraint embedded within a coarse grid. It is found that all coarse-grid results using the Schoof constraint agree very well with those using fine grids. We conclude that in order to correctly simulate grounding-line migration, large-scale ice models need to use either very fine grids (~0.1 km) that resolve the grounding-line boundary layer, or coarse grids with embedded constraints at the grounding line following Schoof (2007).

A preliminary cyclostratigraphic and paleo-environmental analysis of the new high-resolution McMurdo Ice Shelf (ANDRILL) drill core has implications for WAIS history and dynamics

ANDRILL-MIS Science Team - Ross D. Powell[1] and Tim R. Naish[2] Co-chiefs

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In the austral summer of 2006-2007 the ANDRILL Program undertook its first drilling project on the McMurdo Ice Shelf in the northwest part of Ross Ice Shelf where it has been pinned by Ross Island for the last ~8ka. The drillsite was situated above a 915m-deep flexural moat basin adjacent to Ross Island that had formed in response to Quaternary volcanic loading of the crust, superimposed on more regional subsidence associated with Neogene extension of the Terror Rift. The drill rig employed a wire-line diamond-bit coring system through a tide-compensated sea-riser, which was kept free from the 85m-thick ice shelf, by a hot-water over-reamer. Multichannel seismic reflection surveys linked the site regionally and indicated a >1km-thick accumulation of sediment that probably spanned the last 5-10Ma. Drilling recovered a 1285m-long core of Late Miocene to Recent age that included cyclic glacial and glacimarine sediment with interbedded volcanic sediments, lava and tuffs contributed from the surrounding alkalic volcanoes of the McMurdo Volcanic Group. Core recovery rate was better than 98%.

A preliminary age model for the upper 600m of core implies the recovered succession is a detailed record spanning the Pliocene through Pleistocene. Facies are attributed to a set of depositional processes and possible range of depositional environments using criteria that include texture, internal structures, contacts, geophysical properties, composition, and paleontological components. The strongly cyclic stratigraphy has three dominant cycle "motifs" reflecting oscillations in glacial proximity. One motif represents environmental changes associated with cold polar ice, another with warmer (polythermal) ice with interglacials being dominated by pelagic diatomites, another warmer (polythermal) ice with interglacials being dominated by glacimarine hemipelagites. Some transitions within and between motifs are very abrupt with rapid facies changes or dislocations; others are more gradual with many physical amalgamations or progressive, logical facies successions.

Repetitive vertical successions of facies bounded by ice contact surfaces show regular fluctuations attributed mainly to changes in WAIS volume. Pleistocene cycles are characterized by a thick interval of subglacial massive diamictites passing up into thin intervals of grounding-line proximal interstratified mudstones, sandstones and volcanic sandstones. Early-Middle Pliocene cycles display subglacial to ice proximal massive and stratified diamictites in their lower parts passing up into proglacial interstratified sandstone and mudstone followed by open water, ice distal mudstone. The Middle to late Pliocene is dominated by strongly cyclic alternations between diamictite and diatomite of probable Milankovitch duration. An ~100m-thick Early-Middle Pliocene interval of diatomite shows no apparent glacial cyclicity and represents an extended period of ice-free conditions.

High-salinity waters beneath the margin of the West Antarctic ice sheet - evidence from ANDRILL porewater studies

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Porewater chemistry in Antarctic sediments may provide important archives of past ice sheet interactions with their substrata. Here we report preliminary results from analyses of porewater chlorinity and stable isotopes on samples taken from the 1.2-km-deep core collected from McMurdo Ice Shelf (MIS) in the austral 2006/07 season as part of the ANDRILL project. Chlorinity and stable isotopes have been selected for this study because they represent relatively conservative chemical indicators of physical processes, such as melting, freezing, or mixing.

Sediments collected close to the modern seabed have porewater composition similar to that of seawater. However, at depths ranging between dozens of meters to ~600 meters, porewater stable isotopic composition becomes significantly more negative than that of seawater, indicating influence of ice-porewater interactions. The same depth interval is characterized by elevated chlorinity, reaching nearly twice the chlorinity of seawater. Below ~600 m, both stable isotopic composition of water and its chlorinity return to values close to seawater values.

The depth of the core interval showing signs of ice-porewater interactions is consistent with onset of these interactions within the last few million years. This timing is in agreement with the pronounced onset of colder climatic conditions inferred from sedimentary properties of the MIS ANDRILL core (Naish et al., 2007). The elevated chlorinity of the 'cryo-altered' porewater indicates that ice-porewater interactions were characterized by predominance of basal freezing over basal melting during the last few million years.

Our findings aid reconstructions of glacial conditions and history at the MIS ANDRILL core site. In addition, we will discuss the potential implications of these results for modeling of ice sheet thermodynamics and understanding of chemical boundary conditions for deep microbial subglacial life in Antarctica.

Acknowledgments: Authors gratefully acknowledge financial and logistical support from the NSF-funded ANDRILL project as well as science input from the ANDRILL Science Team, including MIS project lead investigators, Drs. T. Naish and R. Powell.

ANDRILL's Education and Outreach Efforts

Frank R. Rack, Megan Berg, David Harwood, Richard Levy, Laura Lacy and Louise Huffman

ANDRILL Science Management Office, 126 Bessey Hall, University of Nebraska-Lincoln, Lincoln, NE 68588 United States

The ANDRILL Program is combining a mix of talents from across the world to bring world-class science into focus and providing in-depth immersive experiences to educators from each of the participating member nations in ANDRILL through the ARISE Program and Project Iceberg.

ARISE
The ARISE (ANDRILL Research Immersion for Science Educators) Program provides an immersion experience for the educators participating in ANDRILL (ANtarctic geological DRILLing), a multinational collaboration involving 150 scientists from Germany, Italy, New Zealand and the United States. The program is administered and coordinated through the ANDRILL Science Management Office, located at the University of Nebraska-Lincoln (For more information see: http://andrill.org).

The educators participating in the McMurdo Ice Shelf (MIS) Project, who were chosen by independent selection committees in their respective countries, include: LuAnn Dahlman, Mesa, Ariz.; Vanessa Miller, New York, N.Y.; Betty Trummel, Crystal Lake, Ill. (United States); Matteo Cattadori, Trento (Italy); Alexander Siegmund, Heidelberg (Germany); and, Julian Thomson, Belmont, Lower Hutt (New Zealand). Six educators will participate in the Southern McMurdo Sound (SMS) Project and two additional educators will participate in the Mackay Sea Valley (MSV) seismic survey in 2007-2008

PROJECT ICEBERG
During the McMurdo Ice Shelf (MIS) Project (October 2006 - January 2007), 14 video journals were produced, documenting activities that were undertaken as the scientists worked their way through over 1,284 meters of rock core that was recoverd from beneath the McMurdo Ice Shelf. An accompanying guide provided correlating background information, discussion starters, and engaging activities for students, with a targeted age range of 10-15 years old. Subtitles are available on each of the video journals in German and Italian, as well as in English. These products were titled, "ANDRILL: A REAL WORLD GEOSCIENCE ADVENTURE". The objective was to introduce teachers, students, and the general public to Antarctica and the ANDRILL Program, and to provide preliminary insights into the following questions: What secrets does this rock have in store? How do scientists from around the world come together in the coldest, windiest, driest place on Earth to uncover these secrets that have been shrouded beneath the ice for millions of years? In addition, educator blogs, collections of Antarctic images, and supporting classroom activities were provided online.

Antarctic Scientific Drilling: What, Where and Why

Frank R. Rack, David Harwood, Richard Levy and the ANDRILL Science Committee

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Antarctic scientific drilling, meaning drilling down to recover the sediment and rock record of geologic and environmental change, has been going on for almost 40 years. This scientific drilling has included marine, ice, and land-based platforms. In the ocean, these have included the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), Integrated Ocean Drilling Program (IODP), and SHALDRIL; for land- and ice-based programs these have included the Dry Valley Drilling Program (DVDP), McMurdo Sound Sediment and Tectonic Studies (MSSTS), Cenozoic Investigations in the Western Ross Sea (CIROS), the Cape Robert Project, and now ANDRILL. Future efforts will depend on new drilling proposals being submitted to international funding agencies and a community-based effort to develop an integrated science plan to galvanize international support for additional scientific drilling projects to improve our understanding of the temporal and spatial evolution of landscapes and environments on and around Antarctica.

Limited exposures of Cenozoic strata in Antarctica (due to the ice cover), the low number of stratigraphic drillholes on the continental margin, and the short time that Antarctica has been explored, led geologists to rely on information derived from lower latitude proxy records. The oxygen isotope record from deep-sea cores, and eustatic changes inferred from sequence stratigraphic records on passive continental margins have been leading paradigms for the interpretations regarding Antarctic ice sheet history. However, interpretations based on these proxy records of glacio-eustasy have little direct confirmation from geologic records in Antarctica, and in numerous cases have led to conflicting interpretations. ANDRILL, SHALDRIL and other drilling projects in and around Antarctica seek to remedy this situation with the recovery of new sections of Cenozoic strata from locations proximal to the ice sheet that are ideally suited for recording and dating ice sheet oscillations, and associated oceanic and climatic variations. These will contribute to a better understanding of the global climate system and clearer linkage between the high and low latitude records.

ANDRILL (ANtarctic geological DRILLing) is a multinational initiative with the objectives to recover stratigraphic core records for use in interpreting Antarctica's climatic, glacial and tectonic history over the past 50 million years and at varying scales of age resolution (0.1 to 100 k.y.). A key motivation of ANDRILL is to understand the role of the Antarctic cryosphere (ice sheets, ice shelves & sea-ice) in the global climate system. Understanding the past history of ice volume variation in Antarctica and associated physical changes in this region is critical to proper assessment of the global climate system and interaction of ice sheets with the ocean, atmosphere and biosphere.

During the 2006-2007 field season, the ANDRILL Program was initiated by the McMurdo Ice Shelf (MIS) Project, which is the first of a portfolio of sites grouped under the McMurdo Sound Portfolio (MSP). The Southern McMurdo Sound (SMS) Project, which will conduct drilling during the 2007-2008 Antarctic field season, will continue the execution of this portfolio. Additional field activities will be undertaken to advance the level of maturity of the remaining projects in the MSP through the execution of geophysical and environmental surveys. In addition, new proposals are being prepared for national and international review in the coming year.

The portfolio approach is designed to help guide the recovery of sediment and rock sequences representing critical intervals of Earth's past climate history, where the dynamic behavior of ice sheets, ice shelves and sea-ice on Antarctica is thought to have influenced global ocean & atmospheric circulation and global sea-level elevation. In adopting this approach, we acknowledge that efforts to understand the role of Antarctic drivers on global climate variability requires a fundamental knowledge of Antarctic cryospheric evolution not only in recent times, which is plainly vital, but also for past times when global temperature and atmospheric carbon dioxide were last similar to that which might well be reached by the end of this century.

Determination of the scale and rapidity of changes affecting large ice masses is of vital importance because (i) ice volume variations lead to changing sea levels, (ii) ice sheets influence sea-ice distribution and latitudinal climatic gradients, and (iii) ice sheets, and particularly the bordering ice shelves, generate cold bottom-water that flows through the world's oceans. In order to validate climatic models, we need to look to archives of climatic change preserved in the ice core record (100,000 year time scale) and in the sedimentary record (10 million year time scale), to determine the relationship between ice sheet fluctuations and climatic change.

The ANDRILL consortium currently consists of four member countries - Germany, Italy, New Zealand and United States - with additional guidance provided by the United Kingdom. Other interested nations are welcome to join this initiative. Additional opportunities exist to broaden the participation in SHALDRIL and other projects, and to partner with IODP and the ICDP (International Continental Drilling Program) to achieve better integration of overall community efforts to advance the scientific goals of the community. In the future, the development of a better understanding of Antarctic climate and glacial history and this region's influence on global climate will benefit from the combined efforts of the Integrated Ocean Drilling Program (IODP), the ANDRILL Program, and various SHALDRIL projects, among others. These are all complimentary efforts with similar goals, but they are each able to reach different stratigraphic targets around the Antarctic margin using a range of drilling technologies and platforms.

Ice-y Breakups: How I Lost My AMIGOS in Antarctica

T. Scambos, R. Bauer, R. Ross, P. Skvarca, Y. Yermolin, J. Thom, J. Bohlander, and T. Haran

A field and remote sensing study of two icebergs drifting northward from the Antarctic Peninsula towards South Georgia Island reveals details and rates of processes that lead to both iceberg and ice shelf disintegration. The study made extensive use of new robotic observing systems, termed AMIGOS, for Automated Met-Ice-Geophysics Observing Stations. Data gathered from the two AMIGOS units includes multiple daily in situ digital images, air temperatures, radio echo soundings of ice thickness, and iceberg position, uploaded daily by Iridium data-phone transmission. Supporting this study was a host of remote sensing data, gathered from the MODIS and ICESat sensors. Results show that calving rates and shelf break-ups are highly dependent on two parameters: water temperature and firn water saturation. While icebergs were located within the sea ice back, rates of ice loss were near-zero. These rates increased, scaling with surface ocean temperature, as soon as the icebergs emerged from pack ice; but icebergs retained their shape to a high degree even though repeated calvings occurred (edge-parallel calvings). Rates then increased 10-fold upon the observation of firn water saturation, and shape was not well-preserved. Previous analysis of ICESat data suggests a mechanism for the calving based on waterline erosion of the iceberg plates. The very rapid increase in calving after firn saturation supports the contention that surface water drives rapid fracturing of an ice plate. Other mechanisms, such as wave action and thinning of the ice plate, may play a role. We will review the relationship of iceberg evolution to the current ideas for ice tongue retreat and ice shelf collapse.

What can ANDRILL tell us of long-term WAIS history?

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#http://www.andrill.org/support/references/appendixc.html

WAIS long-term history is written in the pages of Antarctica's marine sedimentary record. But reading these important books presents several challenges. First of all, more often than not, most of the pages are missing. Secondly, most of the books are buried in technologically and logistically inaccessible places. Third, we have an incomplete grasp of the various languages simultaneously printed on those exciting pages. Once recovered, the independent and collaborative toils of a diverse group of scientists, including sedimentologists, paleontologists, geochemists, and geophysicists unlock the secrets of the precious recovered pages.

A thick, detailed, and fantastic new volume has been discovered! We now enjoy a huge step forward following the inaugural drilling season of the ANDRILL (Antarctic Geological Drilling) McMurdo Ice Shelf project in the 2006 field season. ANDRILL-MIS (Core AND1B) recovered – by far – the best and most detailed record available from the Antarctic marginal sea, spanning most of the last 12 million years, with a particularly remarkable record of the last 5 Ma – a key interval in WAIS history.

AND-1B, recovered from beneath the northwest corner of the Ross Ice Shelf, south of Scott Base, contains a superb record of Antarctic continental shelf sediments. 1,285 m of core, with ~99% recovery, was retrieved from 900m of water beneath 80m of ice shelf. The upper c. 600m of core includes a detailed Pliocene and early Pleistocene sedimentary record, composed of alternating glacial diamictites and relatively pure diatomites, with episodic volcanic facies. The diatomites document extended periods of open marine conditions with reduced ice, in an area currently covered by an ice shelf. The diatomites reflect high biosiliceous productivity, and most reflect warmer than present conditions with variable sea ice and ice rafting. Many or most represent an absence of a large ice shelf, whereas diamictites reflect glacial advances. The late Pleistocene record consists overwhelmingly of massive glacial diamictites reflecting last glacial maximum and possibly earlier late Pleistocene grounding events.

Several key warmer than present events are well represented, including a brief but unusually warm early Pleistocene interglacial, strongly cyclic late Pliocene glacial-interglacial cycles, and a massive (>100m thick) early Pliocene diatomite that likely reflects significantly reduced ice, including West and likely parts of the East Antarctic ice sheet. Studies of transitions between diatomites (interglacials) and diamictites (glacials) are underway in an effort to constrain the rapidity and style of the changes between major climatic regimes.

Establishing the long-term development and evolution of the Antarctic ice shelves and ice sheets will provide critical constraints for models that seek to predict future ice sheet behavior.

Tipping points: nonlinearity and hysteresis in ice sheets

Christian Schoof

One of the central concerns in ice sheet dynamics, and in the wider field of climate dynamics, is the possibility of abrupt changes. In ice sheet dynamics, such abrupt changes could be surges in ice streams with major impacts on decadal to centennial time scales. A more subtle type of abrupt change occurs when a bifurcation or `tipping point' is reached. For instance, given enough atmospheric warming, the Greenland ice sheet may a reach a point of no return past which the ice sheet is doomed to melt completely if the warming trend is not quickly reversed. This is a type of abrupt change that does not manifest itself instantly, as it could still take many centuries for the ice sheet to decay completely and observations may not initially reveal whether a the tipping point has been reached; nonetheless, reaching the climatic tipping point is an abrupt change in the sense that the ice sheet goes from being long-term viable to being destined to disappear.

Tipping points of this type thus represent a change in long-term behaviour, rather than a dramatic short-term effect. From the modeller's perspective, they represent changes in the steady-state configuration of the ice sheet. Importantly, the change in steady-state configuration is also non-reversible: if the climatic tipping point for Greenland were reached and enough time had passed for the ice to melt, then reversing atmospheric warming to just below the tipping point would not make the ice sheet reappear. Instead, much more significant cooling would be required to make the ice sheet re-form, and the ice sheet can undergo hysteresis under climatic forcing.

In this presentation, I focus on the fundamental processes that underly the main tipping points that occur in ice sheet dynamics. For a largely continental ice sheet with significant ablation zones, like Greenland, hysteresis can occur under temperature changes as described above. This is the case because the ice sheet generates its own topography, and the elevated surface in its centre will lead to net snowfall there even at relatively high temperatures. Take the ice sheet away, the exposed land surface has a much lower elevation and may not receive net snowfall, and hence melting the ice sheet is an irreversible process. For a marine ice sheet like West Antarctica, hysteresis need not be driven by temperature changes but may occur due to sea level forcings. To explain this, I will explain how the mass balance of a marine ice sheet is controlled by ice sheet-ice shelf mechanisms, and how in two-dimensional geometries, steady states are controlled by a combination of climatic factors, ice rheology, sliding behaviour, and bed geometry.

Short-term variability, for instance due to cyclic behaviour in ice streams or changing environmental forcings, and observational uncertainty can make it different to determine observationally whether a given ice sheet is close to a steady state or not, and therefore whether it has passed a tipping point or not, or if it is approaching one. Can modelling help here? Up to a point, but it is unlikely that models will provide a completely conclusive answer soon, and policy makers will have to leave with significant uncertainty for the time being. The basic hysteresis mechanisms I describe are based on simple models, and I will describe some of the future advances that will improve them, but in keeping with the theme of this session, I will also delve into some that I suspect ice sheet models will not be able to do for the foreseeable, both in terms of spatial and temporal resolution and due to lack of sufficiently long observational time series.

GPS measurements from Pine Island Glacier

Julian Scott & Andy Smith
British Antarctic Survey

Satellite measurements have demonstrated the recent acceleration and thinning of Pine Island Glacier (PIG). Annual percentage velocity increases of up to 4% have previously been published. Recent GPS work on other Antarctic ice streams, notably the Rutford and Bindshadler ice streams, has identified strong tidally driven variations in the ice stream velocities. It has been suggested that these tidal variations could reduce the accuracy of satellite derived velocity measurements.

Until recently no ground based GPS measurement data existed on PIG. The glacier is a long way from the main Antarctic bases and is therefore logistically difficult to conduct fieldwork on. The first, and possibly the only previous visit, to PIG was on the U.S. Ellsworth Highland Traverse in 1961, where seismic reflection ice thickness measurements and shallow snowpit studies were conducted. In the 2006/2007 season a team of four from the British Antarctic Survey conducted 2 months of fieldwork on the main trunk of PIG. The area was notable for its frequent katabatic winds. The wind speed was greater than 15 knots for 40% of the season and greater than 10 knots for 60% of the season. The main work consisted of seismic reflection profiling. Some passive seismic measurements and shallow cores studies were also made. Three GPS stations were placed along a flowline, approximately in the centre of the ice stream. These three GPS stations recorded data at 10 s intervals for periods!
of between 20 and 54 days. The stations were located at distances of approximately 50, 105 and 165 kilometers from the grounding line.

The data was analysed for tidal components and acceleration. It was found that the acceleration during the season was greater than has been shown in previous publications. Further GPS measurements are due to be made in the coming 2007/2008 season. There are also plans to site a GPS on the glacier over the following winter, 2008. This will help determine any seasonal changes in the motion of PIG.

Effects of the ice-stream basal conditions on its surface elevation. Cry for velocity data

Olga Sergienko, Robert A. Bindschadler, and Douglas R. MacAyeal

Using simplified numerical model of the ice-stream flow we demonstrate that observed ice-stream surface elevation changes most recently interpreted as temporal changes in basal water volume could be explained by variations in ice-stream basal conditions. Our results suggest that subglacial water volumes may not by directly proportional to limited sampling of surface elevation changes. Simultaneous measurements of surface velocity would be tremendously valuable in improved interpretation of surface elevation changes.

Ice shelf melting in the Amundsen Sea from oceanographic observations

Deborah R. Shoosmith and Adrian Jenkins
British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET

The Amundsen Sea, located in the eastern Pacific sector of the Southern Ocean, is a region where ice shelves are rapidly thinning. The widespread, coherent nature of the thinning, in a region where air temperatures are rarely above freezing, suggests a response to oceanic forcing. Around most of Antarctica, warm Circumpolar Deep Water (CDW) is only found in the Antarctic Circumpolar Current. However, in the Amundsen and Bellingshausen Seas the continental shelves are flooded by CDW, which is ~3°C warmer than the surface freezing point. When CDW has access to the base of an ice shelf, melting is one to two orders of magnitude higher than it would otherwise be.

Our knowledge of heat and fresh water transports under the Amundsen Sea ice shelves is limited by a sparsity of observations. To address this, in February 2006 we conducted a high resolution hydrographic survey along the front of Dotson Ice Shelf. Studies using satellite data have indicated that Dotson Ice Shelf is thinning by about 3 m per year. Since the ice shelf is bounded by land, the CTD section fully encloses the cavern of water beneath the ice, thus sampling both inflows and outflows. The purpose of this study was to quantify the rate of melting at the base of the ice shelf by determining the changes between inflows and outflows.

From shelf break to ice shelves: oceanographic observations in theBellingshausen Sea, Summer 2007

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The Bellingshausen Sea, West Antarctica, experiences a variable and warming climate, and as a result, the sea ice and land ice cover in the region are declining. One of the aims of the BAS core program, ACES-FOCAS, is to understand the processes causing these changes. This poster provides an overview of cruise JR165 on RRS James Clark Ross in February - April 2007. The cruise set out to investigate the oceanographic regime of the Bellingshausen continental shelf, in particular the processes that introduce warm Circumpolar Deep Water (CDW) to the shelf, drive its circulation on the shelf and regulate the amount of heat it gives up to the overlying ice cover and atmosphere. To this end, we occupied a number of CTD sections that cross two major troughs on the Bellingshausen continental shelf, as well as further sections across the shelf break at the mouths of the troughs. These will allow us to track the progress of CDW along the shelf edge, onto the shelf and up to the floating ice shelves. A CTD section spanning the Bellingshausen Sea from Fletcher Peninsula to Charcot Island shows the predominance of CDW across the shelf and enables us to determine circulation and transports for the entire region. In addition, sections across the fronts of the Wilkins and George VI Ice Shelves will allow us to quantify heat and meltwater transports, giving an estimate of the rate of basal melting, and thus determine the oceanographic impact on these ice shelves.

Significant Glacier Thinning (or not), 2002-2007, Larsen B Embayment, Antarctica

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Abstract
Laser altimetry data from two long-range NASA/CECS aircraft missions using the ATM instrument and eleven ICESat operational periods between November 2002 and April 2007 quantify dramatic elevation changes that now extend over the >50 km length of the Crane Glacier. This glacier flows into the area of the Larsen B Ice Shelf that collapsed in early 2002. At a location on the Crane ~5 km in from its new ice edge and ~13 km from its pre-collapse grounding line, the combined ATM-ICESat time series shows a >152 m total elevation change over a ~4.5 year period. An average >40 cm/day elevation loss was observed over ~3 months in late 2004 into early 2005 at this location as the glacier responded to the collapse of the Larsen B. Very recently, the nearby but smaller Melville Glacier that also flows into the open Larsen B embayment has shown a ~9 m elevation loss near its terminus as does the larger and more southerly Leppard Glacier (-6, -9 m) whereas the Flask Glacier shows a ~6 m elevation rise and changes to its roughness near its seaward end. Smaller elevation changes (few m level) are observed elsewhere in the region. The Flask and Leppard glaciers are similar in size to the Crane but are buttressed by the remainder of the Larsen B Ice Shelf. Although the recent mass loss from the Crane is now reduced and a small portion of sea level rise, these results suggest additional losses may be coming from the area.

Basal conditions on Pine Island Glacier

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British Antarctic Survey

During the 2006/07 season we completed two seismic reflection profiles approximately half-way up Pine Island Glacier to investigate the basal conditions. One line was perpendicular to ice flow (~12 km long) the other was in line with the flow (~4 km long). The data allow an interpretation of the nature of the bed material, its interaction with the ice motion and some speculation over the bed's potential to change over time.

In the area of the seismic surveys, the main trunk of Pine Island Glacier is joined by a number of large tributaries. The cross-flow seismic line straddled the main glacier trough and the rising bed slope into an adjacent tributary. Along virtually all of this line, the bed is composed of wet sediments. There are areas where the bed is dilated, deforming sediment and others where ice flow appears to be mainly by basal sliding. Areas of each bed type, varying in width from a few hundred metres to a few kilometres, alternate along the line. In the deep trough beneath the main part of the glacier, there is an area of free water, at least 400 m wide.

In the deeper part of the bed, the along-flow seismic line also shows a water-saturated sediment bed. Most of this is deforming sediment, with the exception of a ~15 m high step, over which the ice rises. The upstream face of the step is harder sediment and the ice is sliding over it, whereas both further upstream and downstream, the bed is deforming.

Pine Island Glacier, therefore has a mixed type of bed - both deforming bed and basal sliding, with some areas of free water. This is much more similar to Rutford Ice Stream than to the Ice Stream B fully-deforming bed model. The large areas of basal sliding and the large amounts of water present, combined with the fast ice flow, may reflect a potential for incorporation of water into the harder sediment areas and a reduction in overall basal friction. The basal conditions and topography on the along-flow line may indicate the presence of a drumlin or other subglacial bedform type.

Subglacial lakes: They're (almost) everywhere

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A survey of the Antarctic ice sheet using satellite laser altimetry has detected 45 small regions of surface uplift or drawdown in thirteen different glacier drainages around Antarctica. Surface displacements are measured relative to the best-fitting plane passing through multiple (4-11) elevation measurements on the same repeat-track, allowing correction for across-track slopes. Volume displacements are derived by interpolating displacements from multiple tracks to a common grid.

These ECAs (Elevation Change Anomalies) range from less than four km to more than 60 km across, with vertical displacements ranging from a few decimeters to over ten meters. Typical volume displacements are on the order of 0.05 cubic kilometers over the three-year survey, and the largest displacement is more than 1.7 cubic kilometers. Although the majority of the ECAs are within the Filchner-Ronne catchment, others (including those discussed by Fricker and others, 2007), are found in the Ross Embayment, in the drainages of Byrd Glacier and Lambert Glacier, and in the interior of Wilkes Land. Notably, none are within the Amundsen Sea drainage.

As have other researchers who have observed ECAs, we take these features to result from water motion at the bed. In all cases where the ice sheet velocity structure is known, the ECAs are in regions of ice stream or tributary flow, which implies that they are associated with melting bed conditions. Some of the ECAs appear to be downstream of linear features in the ice sheet surface, suggesting that they are associated with localized reductions in glaciostatic pressure caused by cavitation when ice flows over obstructions at the bed. Others have no clear association with surface topography.

The relatively small number of ECAs precludes drawing strong conclusions about spatial and temporal correlations between filling and drainage events. However, a few conclusions are clear: Because adjacent ECAs are more likely to have correlated filling or drainage rates than to have anti-correlated filling or drainage rates, it does not appear that water is conserved among the ECAs. This suggests that the ECAs exchange water with other water systems at the bed. Of critical importance for our understanding of ice stream dynamics is whether inflation of the ECAs represents a withdrawal of water from the system that lubricates fast basal motion. If the correlation of drainage and filling over distances of hundreds of kilometers is not coincidental, it suggests either that large-scale channel systems connect the ECAs, or that filling or drainage is triggered by large-scale velocity variations.

Moho topography of the West Antarctic Rift System from inversion of aerogravity data: ramifications for geothermal heat flux and ice streaming

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The West Antarctic rift system, a region of thinned continental crust, dominates the lithospheric structure of the Ross Embayment in West Antarctica. It has long been hypothesized that the lithospheric structure beneath the West Antarctic Ice Sheet is a major influence on the formation, nature and dynamics of the ice sheet. The structure of the crust-mantle boundary is a fundamental geophysical parameter for understanding lithospheric processes and for geodynamic interpretation. In this paper, we use aerogravity data to derive a map of the crust/mantle boundary beneath the West Antarctic Ice Sheet and to reveal the impact of relative changes in thickness of the crust and lithosphere on surface heat flow and ice streaming.

Development of an aerogeophysical imaging system for polar applications:
Phase I: Gravimeter test flights to the North Pole

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We are currently developing an aerogeophysical imaging system for polar applications during the IPY and beyond in collaboration with the Center for Remote Sensing of Ice Sheets (CReSIS) at the University of Kansas. The complete system will include an ice-penetrating radar, a laser altimeter, a magnetometer and a gravimeter. The purpose of a major flight testing program in Spring 2007 was to install and fly two different airborne gravimeters on a single Twin Otter aircraft for side-by-side testing first over a known test range in Calgary and secondly at higher latitude, out of Eureka, Ellesmere Island (80Â°N) to the North Pole. More than 12,00 line-km of data have been collected during these test flights. Either of these systems provides the academic community with a tremendous increase in accuracy and horizontal resolution that will enable major advances in understanding of the subglacial environment. The new systems are capable of draped flying of airborne gravity – broadening potential applications. The performance of the new gravimeter systems under various test conditions will be presented at the meeting.

Estimating the salinity of subglacial lakes from aerogeophysical data

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The widespread occurrence of more than 145 lakes underneath the Antarctic ice sheet demonstrates that these aquatic ecosystems are an important part of the subglacial hydrosphere. The recent discovery of water flux between subglacial lakes beneath the East and West Antarctic ice sheet on timescales of several years indicates interconnectedness within the subglacial hydrological network and the potential for catastrophic drainage into the ocean. Subglacial lakes are now being recognized as an integral part of the global cryosphere and the global climate system. Knowledge of the physical, chemical and biological processes operating within these features is crucial for addressing questions about the presence and functioning of life in subglacial lakes. However, little is known about the prevailing *in situ* environmental conditions. Existing airborne ice-penetrating radar and laser altimeter data over large subglacial lakes can be used to estimate the salinity without penetrating the lakes.

Optical Probing of Deep Glacial Ice using Short Laser Pulses

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Glacial ice has been called the most transparent naturally occurring solid on earth[1]. In the Greenland and Antarctic ice sheets, below where air bubbles convert to air hydrate clathrates, light at blue and violet wavelengths can propagate for tens of meters before being scattered and hundreds of meters before being absorbed. Currently, one can obtain simple in situ optical measurements of annual layers and dust using borehole logging[2,3], and ex situ measurements of fabric and chemical composition[4]. However, three dimensional maps of glacial properties and in situ fabric and chemical measurements are well-beyond the present state-of-the-art. The extreme propagation length of light in ice is comparable to that of early optical fibers, and this suggests that much of the technology developed for characterizing optical communication systems can be modified to characterize deep glacial ice. One of the most powerful optical fiber techniques is optical time-domain reflectometry (OTDR), where the time of flight of a light pulse is used to determine the position of features in the fiber. In this presentation, we propose that three dimensional maps of many properties of deep glacial ice may be obtained using fiber optic time-domain techniques. Perhaps the simplest OTDR measurement is that of ranging. Here a short laser pulse would be sent into a borehole wall, perhaps as part of a borehole logging system, where it would propagate for a certain distance, reflect or scatter off of an object, and return to the source. In glacial ice, this type of measurement might, for example, determine the distance to bedrock or the location of a meteorite. Ranging can also obtain data about dust content because the laser pulse continuously backscatters small amounts of light from dust in the ice. Therefore, regions of ice with different dust content will produce different scattering intensities, and a single borehole could provide a map of dust concentrations for hundreds of meters in all spatial directions, allowing researchers to evaluate whether layer-to-layer fluctuations in an ice core represent actual deposition conditions or just a local fluctuation. Such information may even allow one to avoid drilling multiple holes at the same site.

OTDR will also advance the state-of-the-art for determining ice fabric. Currently, the average orientation of crystals in large volumes of ice is determined using acoustic wave measurements, which have poor resolution. Since the speed of light changes with polarization, time-of-flight differences from laser pulses with different polarizations will be able to map the average fabric of ice with a resolution of millimeters in height and width and centimeters in depth. Such resolution brings up the interesting possibility that OTDR could identify the minimum stress planes for glacial ice even when they are oriented obliquely to a borehole wall, which would simplify flow modeling based on borehole data. Finally, since an OTDR system for ice would use wavelengths of light (e.g. ƒÜ=405nm) where ice is maximally transparent, Raman spectroscopy measurements could be taken using the same optics to obtain information on the chemical content of ice and the gas content of bubbles within it. These measurements could be performed in situ in a borehole without any concerns about contamination, outgassing, cracking, or other depressurization issues. Bubbles in the upper section of an ice sheet and bubble-free ice in the lower sections can be tested. Among the features of interest would be the concentration of N2/O2 and CO2 in bubbles, the concentration gradients of gases near bubbles, the relative concentrations of H2O, HDO, H218O in ice, and the composition of dust grains and salt inclusions. Early data on (laboratory based) fabric measurements in ice and Raman measurements in bubbles will be discussed.

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Surface-exposure ages from Reedy Glacier, Antarctica

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Glacial deposits from the most recent advances of Reedy Glacier, Antarctica, are 50 – 250 m above the modern glacier surface. We measured cosmogenic Be-10 in glacial erratics collected from these deposits in order to determine the timing of surface elevation changes along Reedy Glacier during the last glacial period. Surface exposure ages calculated from Be-10 concentrations provide evidence of differential and asynchronous thickening along Reedy Glacier.

At the mouth of Reedy Glacier, where the glacier flows into the southern Ross Sea Embayment, surface-exposure ages of erratics collected from the summits of nunataks indicate that the ice surface was ~ 110 m higher than the present ice surface ~ 7 kyr before present (B.P.). Surface-exposure ages of erratics collected from the flanks of these nunataks show that ice at the mouth of Reedy Glacier thinned from ~ 7 kyr B.P. through the late Holocene. Surface-exposure age results from a large deposit located at the middle of the glacier length show that the glacier surface was ~ 250 m higher than the present glacier surface from ~17 kyr to ~ 14 kyr B.P. Surface-exposure ages from the head of Reedy Glacier show that maximum ice surface elevations occurred there during the early Holocene.

Our results show that the most recent maximum ice surface elevations at Reedy Glacier post-date the age of the last glacial maximum in the Northern Hemisphere, and occur at different times at different locations along the glacier length. Surface-exposure ages suggest that maximum ice thickness occurred at the lower half of Reedy Glacier before ice-sheet retreat occurred in the western Ross Sea Embayment. In contrast, maximum ice thickness at the head of Reedy Glacier occurred during the early Holocene, when ice-sheet retreat was underway in the western Ross Sea Embayment and when ice was thinning at the mouth of Reedy Glacier. These results suggest (1) that Reedy Glacier was still responding to post-glacial mass balance changes through the mid-Holocene, (2) that the relative influence of the East Antarctic Ice Sheet and the West Antarctic Ice Sheet on ice surface elevations at Reedy Glacier has varied during the late Quaternary, and (3) that post-glacial changes in East Antarctic accumulation have affected ice surface elevations at Reedy Glacier.

Solving for a history of ice thickness in the southern Ross Sea Embayment using inverse methods and surface-exposure ages

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Surface-exposure ages calculated from 10Be concentrations in erratics track the history of ice thickness along Reedy Glacier from approximately 17 kyr before present (B.P.) through the late Holocene. However, due to limited availability of glacially-derived material at accessible and appropriate sampling sites, surface-exposure ages from lateral deposits at Reedy Glacier provide only partial ice-thickness histories for a limited number of locations along the length of the glacier. Specifically, surface-exposure ages from nunataks near the mouth of Reedy Glacier provide a history of ice thicknesses that begins approximately 7 kyr B.P., several thousand years after the last glacial maximum (LGM) is thought to have occurred in West Antarctica. Thus, in order to constrain the LGM configuration of the West Antarctic Ice Sheet (WAIS), we set up an inverse problem to solve for the history of ice thickness at the mouth of Reedy Glacier.

An inverse problem occurs when there are data that are produced by a known physical process, but the initial conditions or the parameters governing that physical process are unknown. Inverse procedures require (1) a forward algorithm that simulates a known physical process, given a set of parameters, (2) a set of observations or data that are the result of the known physical process, (3) an inverse algorithm that calculates estimates of the data by iteratively running the forward algorithm using estimates of the model parameters. The solution to an inverse problem is the set of model parameters that are physically reasonable and that yield results from the forward algorithm that best fit the data at a defined tolerance.

In this inverse procedure, our data are known ice thicknesses at discrete points on the glacier at different times in the past. The forward algorithm is a numerical model that calculates ice thicknesses along the glacier, given a history of ice thickness at the mouth of the glacier. This history of ice thickness at the mouth of Reedy Glacier is our parameter set. Our inverse procedure finds the parameter set that (1) yields glacier surfaces that best match our surface-exposure-age data at a defined tolerance, and (2) is within a range of ice thicknesses that are physically reasonable. Preliminary results suggest that LGM ice thickness at the mouth of Reedy Glacier, in the southern Ross Sea Embayment, was between approximately 1000 and 1200 m above sea level.

Using inverse methods to recover basal velocities

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One of the biggest challenges for ice sheet models is a treatment of the basal boundary condition. Measurements at the base of the ice are useful to accurately describe and understand basal processes, but in the absence of a large coverage of such measurements, it is also necessary to derive basal conditions from data gathered at the surface or through remote sensing. This is, by necessity, an exercise in inverse modeling. We have developed an iterative method to find basal velocities and shear stresses, given data about ice thickness, rheological properties of the ice and surface velocities for a simplified model. The model we are considering is derived from a first order treatment of flow along a longitudinal cross section (Colinge and Rappaz, 1999). Incidentally, the same nonlinear Poisson equation also describes flow through a transverse cross section under the assumption of no out-of-plane gradients.

Our iterative scheme is derived from an idea developed by Kozlov and Maz'ya (1990). They suggested that the problem be solved by starting with an initial guess of basal boundary Neumann data (here essentially shear stress) and solve the forward problem with that and the measured surface Dirichlet data (surface velocity). This solution is then used to extract basal Dirichlet data (velocities) and a new model is solved with Dirichlet data at the bottom boundary and the measured Neumann data (zero shear stress) at the surface. This cycle can now be repeated. Kozlov and Maz'ya (1990) showed that this iteration converges in the linear case.

This method cannot be applied in a straight-forward manner to nonlinear ice flow. The reason is that convergence, even in the linear case, is extremely slow. We have developed an accelerated scheme and have shown that it works well in the case of flow through transverse cross sections of temperate valley glaciers (Maxwell et al., subm.). The method was applied to a glacier with measured basal velocities, and has been found to reproduce that well. It is also possible to qualitatively assess resolution, that is, to assess at what spatial scale one can expect to resolve variations in the basal velocity field.

Here we will apply the method by considering ice flowing along a flow line from slow inland ice to a fast moving ice stream. This is a challenging area for continental scale models, such as UAF's parallel ice sheet model (PISM, Bueler et al., ??, website), because it represents a switch between where ice is treated with the Shallow Ice Approximation to one where it is treated with the Shallow Shelf Approximation. We will discuss how well our inverse method can detect a hard switch from no-sliding to sliding conditions and we will then apply the method to data from the onset area of Bindschadler Ice Stream.

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Decadal dynamics of basal conditions as viewed from the ice bulge on Kamb Ice Stream

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The ice bulge on Kamb Ice Stream (KIS) represents the strongest positive mass balance anomaly in the interior of the Antarctic Ice Sheet (Zwally et al., 2005). This anomaly is caused by internal ice sheet dynamics, i.e. the stoppage of KIS about 150 years ago. High ice sheet thickening rates, up to ~1 m/yr, indicate that this regional imbalance anomaly will not persist for extended time period (e.g. thousands of years) but will force rearrangements in ice drainage to increase mass output from the region.

Here we report results of a GPS-based study aimed at constraining recent dynamics of the KIS ice bulge. In the course of this study (2004/05 and 2005/06 seasons) we conducted GPS measurements of ice surface velocity in ~300 locations, measured deformation of 5 large strain grids, and performed continuous GPS measurements over a small subglacial lake underlying the ice bulge. Repeat velocity measurements indicate that the ice bulge has been moving at relatively steady rates over the last decade, with some localities showing small accelerations and decelerations. Four of the five strain grids were located at the leading edges of the ice bulge, where ice velocity changes from moderately fast (>20 m/yr) to slow (~5 m/yr). Force budget calculations indicate that the faster-flowing areas have lubricated bed (local basal stress < local driving stress). Much of the locally unbalanced driving stress is transferred downstream to the unlubricated bed of slow-moving ice. This stress transfer may be important in enhancing basal shear heating and either slowing down continued bed strengthening or enabling re-lubrication of basal conditions at the leading edge of the ice bulge. One strain grid was located over the small subglacial lake whose existence beneath KIS was inferred from repeat airborne lidar surveys by Gray et al. (2005). This strain grid showed also local force imbalance over the location of the subglacial lake. However, continuous GPS measurements between December 2004 and December 2005 performed over the lake show little clear evidence for 'unusual' vertical displacement patterns, which could be associated with filling or draining of the lake. GLAS altimetry data suggests that the period of our continuous GPS observations may have coincided with a relatively quiescent stage of subglacial lake hydrology, when lake volume changes were relatively small.

Millennial versus orbital influences on ice marginal fluctuation: the southern signal

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Exposure ages on moraines in the southern hemisphere indicate that significant millennial-scale fluctuations of glaciers took place during the last deglaciation, not simply a steady retreat between the Last Glacial Maximum (LGM) and modern (Evans et al., 2005, Bentley et al., 2006, Lowe and Anderson, 2002). The millennial North Atlantic Deep Water (NADW) signal potentially had a large control on southern hemisphere deglaciation decoupled from the orbital deglaciation signal. We hypothesize that millennial-scale climate changes strongly influenced the ice sheets and glaciers of the southern hemisphere during the last deglaciation. Such advances would have created observable moraines around the southern high latitudes, yielding an interesting glacial chronology of the last termination.

In this study, we model southern hemisphere moraine deposition using a coupled ice-sediment model. The temperature forcing for the model was the Byrd ice core record (Sowers and Bender 1995), and Dome C ice core record (Jouzel et al., 2001) spanning the time period between LGM and modern. We decoupled the orbital deglacial signal and the millennial-scale signal using a high band-pass filter with cut-off at 10,000 years. We then applied the ice core records as the forcing to the glacier-sediment model while systematically varying the strength of the millennial scale signal.

Our results are examples of moraines deposited with varying degree of strength of Southern Hemisphere millennial-scale signals. These results can help us interpret deglacial history of the southern hemisphere based on exposure ages and the stratigraphic configuration of observed moraines on the Antarctic Peninsula and high latitudes of the Southern Hemisphere. There is evidence in Peninsula glacial deposits, and glacial moraines from the Southern Hemisphere that the last deglaciation was not necessarily the steady warming observed in EAIS ice cores.

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The Science and Art of LIMA

Patricia Vornberger and Robert Bindschadler

The Landsat Image Mosaic of Antarctica is almost complete with a 4-agency formal release scheduled in early October 2007. NASA, USGS, British Antarctic Survey and NSF have contributed to this IPY project. Nearly 1100 Landsat scenes from 1999-2001 have been used to create a nearly cloud-free composite of Antarctica north of 82.5oS. A variety of versions of the mosaic will be available including a 24-bit true color composite, a 24-bit false color composite; and digital stretches that enhance both saturated snow slopes and ice flow features. Every scene is available to the public (http://lima.usgs.gov), however all mosaic products will be "sharpened" using the panchromatic band to produce products with a 15 m spatial resolution. Great care has been taken to preserve the scientific meaning of the digital values of every pixel. Scenes were orthorectified using the RAMP digital elevation model and adjusted for solar illumination gradients caused by earth curvature. At-sensor radiances were converted to surface reflectances and corrected for non-Lambertian scattering effects to produce a nearly seamless mosaic.

The final products will facilitate a variety of scientific studies. In addition, the mosaic is being used as a means to familiarize the public with Antarctica through a NASA funded project called "Faces of Antarctica". This project takes advantage of the beauty of Antarctica, captured in the true-color LIMA mosaic to engage the public in a variety of educational activities and exercises (http://lima.nasa.gov).

How sticky are sticky spots? Constraints from passive seismic observations

Paul Winberry, Sridhar Anandakrishnan, and Richard Alley

The fast movement of ice streams is permitted by efficient basal lubrication over most of the ice stream bed. For this reason isolated regions of enhanced resistance, or sticky spots, play a significant role in restraining ice stream motion. To help quantify the importance of sticky spots in the force budget of an ice stream we deployed a seismic array approximately 5 km from a small sticky spot near the grounding zone of Bindschadler ice stream. The sticky spot, delineated by heavy surface crevassing, is about 1 km in diameter and is associated with a small bedrock bump. Our array operated for a three week period during the 2005-2006 field season. During our observational period we recorded over 10 large icequakes (larger than magnitude 1) originating from the ice stream bed near the sticky spot. These icequakes are several orders of magnitude larger than icequakes previously observed on the Siple Coast and represent large releases of energy in less than one second. The largest events require as much as 1 meter of displacement on a 1 square kilometer patch of ice stream bed during a single icequake. Given our short observational period, our data suggest that over long time scales this sticky spot may balance a significant portion of the ice streams driving stress. This presentation will report on locations and energy release from these events to provide insight into the dynamics of ice stream sticky spots.

Long-term Mass Balance of the Pacific Ocean Sector of Antarctica Based on Multisensor Fusion

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It is well documented that many Antarctic ice streams and outlet glaciers have changed dramatically during the last two decades. In order to understand the significance of these short-term changes it is desirable to extend the time line as far back as possible, by including historical aerial photographs in the analysis. This has rarely been done, however, mainly because of the lack of ground control points that are required to orient old photography. Our poster presents results on computing long-term changes of outlet glaciers draining to Amundsen Sea from a series of historical aerial photographs, ASTER images and satellite laser altimetry profiles acquired by NASA's Ice, Cloud and land Elevation Satellite (ICESat) mission.

To determine changes all data must be registered in the same reference frame. We achieve this by using elevation profiles, derived from ICESat data, as control features. An example of control features are break lines and they can be extracted from neighboring ICESat profiles as well as from aerial photos. This enables us to precisely register the aerial photographs with respect to the ICESat reference system—an absolute prerequisite for tracking features and determining surface elevation changes.

Another important aspect is to compare elevation profiles acquired by ICESat during different mission phases. Since repeat ICESat satellite ground tracks are not exactly overlapping, elevations must be interpolated at identical points. Our approach is based on the assumption that the surface of the ice sheet can be approximated by analytical functions. This allows us to derive changes by computing the coefficients of the surface models from point data sets representing different time epochs.

Comprehensive surface elevations for Thwaites Glacier: Results from AGASEA airborne laser altimetry

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Accurate surface elevation data is vital for modeling ice sheet dynamics and estimating ice sheet change. Currently, satellite observations using incoherent radar and laser ranging dominate evaluations of Antarctic ice sheet topography; however, both of these methods have limitations. Space borne radar altimetry is sensitive to slopes, while existing orbital laser altimetry is strongly impacted by clouds and has limited coverage at the coasts. It is precisely these coastal areas of the West Antarctic ice sheet that appear to be changing most rapidly and are most poorly understood dynamically. A more effective approach to gathering surface elevations both in the coastal environment and regions of high surface slope is airborne laser altimetry

Between mid December 2004 and February 2005, the University of Texas Institute for Geophysics (in collaboration with the British Antarctic Survey and supported by the National Science Foundation), conducted the first comprehensive areogeophysical survey of the Thwaites Glacier catchment. Survey lines extending up to 500 km from the base camps in a 15 X 15 kilometer grid over the entire catchment; ultimately 35,000 line-kilometers of laser range data was acquired, in addition to ice penetrating radar, gravity and magnetic measurements. We collected laser altimetry data using a Riegl nadir-pointing distance meter, which output modal range data at 3.5 Hz (~20 meters along track) representing spots of 1 meter X 20 meters on the surface. Range data were filtered for clouds and merged with aircraft pitch and roll data at 8 Hz to find the height above the surface. Distance meter orientations were measured in the field and validated through inversion of line crossings.

For positioning kinematic GPS data collected at 2 Hz to find the surface elevations was merged with our 3.5 Hz distance ranges. We used both a K&RS kinematic differential GPS system with a basecamp positioned using static GYPSY, and kinematic GPYSY software. Kinematic GPYSY positions were more reliable far from the camp; however, we discovered a 17 cm bias between kinematic K&RS using a static GYPSY for the base and kinematic GYPSY. To remove this offset use a cross-over deviation minimization scheme to determine the best of eighteen computed solutions for each line. An initial set of best K&RS solutions (comprising two thirds of the transects) gave a crossover RMS error of ±5.5 cm after leveling. The remaining transects which including biased GYPSY solutions were linearly fitted to the best lines, providing surface elevations with an RMS error of ±19 cm.

We present these surface elevations, that are being prepared for release, as well as comparisons with GLAS data crossovers and reflights.

Mapping West Antarctic subglacial processes using detailed basal morphology: Implications for Thwaites Glacier, based on knowledge gained from the Siple Coast

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We use hectameter to kilometer basal roughness, a property accessible to airborne ice penetrating radar, to examine the dynamics of the West Antarctic Ice Sheet. We quantify roughness through analysis of the along track variability of basal elevation profiles collected over the Siple Coast and the Thwaites Glacier catchment, at length scales of 400 meters, two kilometers, and four kilometers. There are significant differences in the patterns of roughness between catchments and between dynamic zones of the ice sheet. We demonstrate using synthetic data the validity of this technique with both coherent radar data collected in the eighties, incoherent radar data collected in the nineties and coherent radar data collected as part of the more recent ATRS and AGASEA surveys, processed using unfocused synthetic aperture radar (SAR). In particular, we carefully accounted for signal to noise issues in our interpretations of this variability.

A one-to-one correlation between roughness and proposed sedimentary basins identified in potential fields data in the Siple Coast is not apparent. The smoothest regions of grounded ice are the bedrock platforms underlying the interstream ice ridges of the Siple Coast. However, roughness does systematically increase upstream, likely reflecting erosion and downstream redeposition of mobile tills. In the deep interior, near Byrd Station where flow reorganization of tributaries has previously been recognized, basal roughness is greatly reduced at hectameter scales.

Under Thwaites Glacier, smooth areas are more localized, correspond to bedrock depressions and are restricted to the interior. A downstream gradient in roughness is not observed, suggesting that sub-glacial tills play a more restricted role in the Thwaites Glacier catchment.

We plan to extend this analysis to tens of meter length scales by integrating will integrating higher resolution observations obtained using focused SAR techniques over Thwaites Glacier and the Siple Coast.