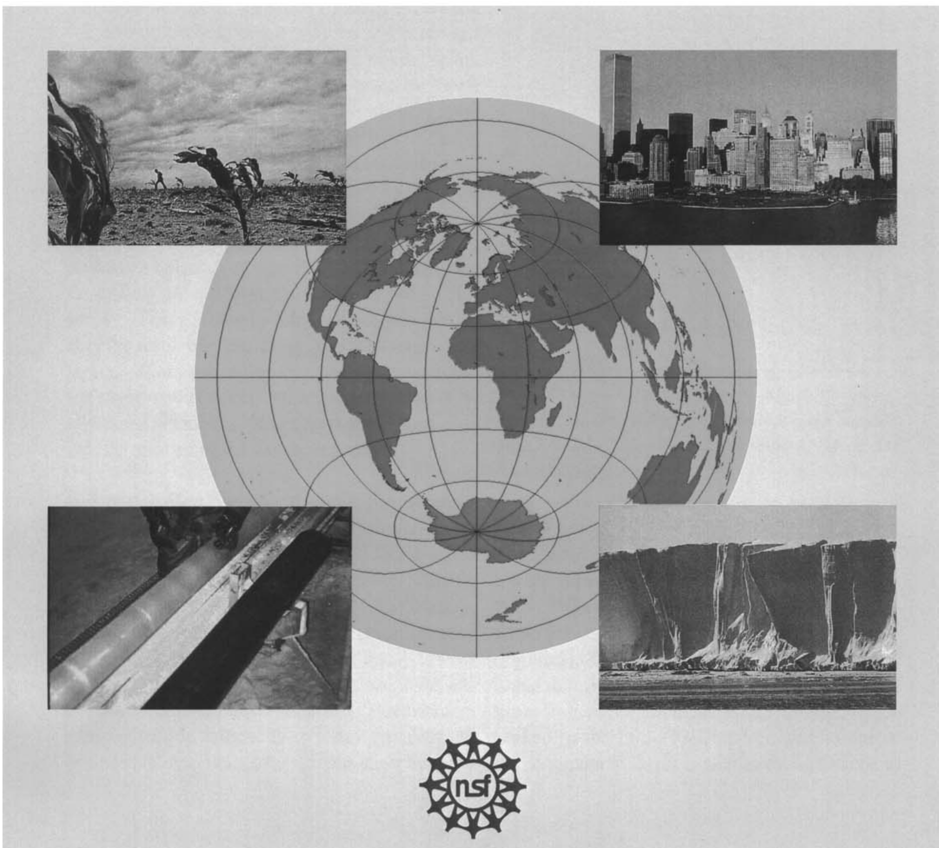
WAIS

THE WEST ANTARCTIC ICE SHEET INITIATIVE

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level



THIRTEENTH ANNUAL WORKSHOP

September 27 - 30, 2006
Pack Forest Conference Center
Eatonville, Washington

Agenda & Abstracts

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

Agenda

Thirteenth Annual WAIS Workshop

AGENDA

Wednesday, September 27, 2006		
2:00 to 6:00	Registration (Pack Hall)	Pack Hall
6:00	DINNER (Dining Hall)	Dining Hall
7:00	Munchie Reception (Pack Hall)	Pack Hall
Thursday September 28, 2006		
8:00	BREAKFAST	Dining Hall
8:00	Registration	Pack Hall
9:00	Welcome and Agenda Review	Scott Hall
	Topic #1. Up, Down and All Around _**How is water moving under the ice sheet and what is its effect?**	
9:15	Bubbling beneath the ice streams: subglacial plumbing mapped from space [Abstract]	Fricker
9:30	Finding subglacial water the "ICESat way" in rough terrain [Abstract]	Bindschadler
9:45	Towards repeat-track elevation rate estimates using ICESat data [Abstract]	B. Smith
10:00	Discovery of till deposition at the grounding line of Whillans Ice Stream and implications [Abstract]	Anandakrishnan
10:15	BREAK (30 min.)	
10:45	Radar Studies on Kamb Ice Stream [Abstract]	Pettersson
11:00	Geothermal controls on a pervasive water sheet at the head of Kamb Ice Stream, West Antarctica [Abstract]	Blankenship
11:15	Radar evidence for past melting and present water distribution beneath Rutford Ice Stream, West Antarctica [Abstract]	King
11:30	Thanks SO Much for ALL the Data: The Amundsen Sea Sector Data Set: Applications with UMISM: Where and How Much WATER? What WILL happen in the future? [Abstract]	Fastook
11:45	Poster Introductions (1-2 min. each)	
12:15	LUNCH (1 hr. 45min.) plus view posters	Dining Hall
	Topic #2. A Wider Shade of Paleo_**How have expanding observations increased our knowledge of past West Antarctic size and behavior?**	
2:00	The RABID Project: Attempts to drill to the bed of Rutford Ice Stream [Abstract]	A. Smith
2:15	Glacial History of the Ellsworth Mountains, Weddell Sea Embayment West Antarctica [Abstract]	Bentley
2:30	Subglacial conditions of inland West Antarctica from US-ITASE deep radar reflection analysis [Abstract]	Welch
2:45	Towards a suite of US ITASE West Antarctic paleoclimate records[Abstract]	Dixon
3:00	On the effects of ice divide motion on Raymond bumps [Abstract]	Martin
3:15	BREAK (30 min.)	
	***Session #3.* Accumulation**	

3:45	Maybe the Siple Dome Ice Core Records Surging Ice Streams? [Abstract]	Taylor
4:00	Statistical properties of Antarctic ice cores [Abstract]	Steig
4:15	Basement control and history of ice-sheet expansion in the Amundsen Sea Embayment - First results of recent RV Polarstern and RRS James Clark Ross cruises [Abstract]	Gohl
4:30	Late Quaternary deglaciation in the Amundsen Sea sector of the West Antarctic ice sheet: Preliminary results from recent cruises of RRS James Clark Ross and RV Polarstern [Abstract]	J. Smith
4:45	Numerical modeling of ocean circulation over the continental shelf and beneath the ice shelves in the Amundsen Sea, Antarctica [Abstract]	Holland
5:00	Poster Viewing	
6:00	DINNER	Dining Hall
Friday, September 29, 2006		
8:00	BREAKFAST	Dining Hall
	***Topic #3. Filling the Gap*_How can observations better meet the needs of improved predictive West Antarctic models?**	
9:00	Above, below and within the ice: Polar technologies NASA and JPL are developing for Earth and Space	Behar
9:15	Radar Measurements and Results from the WAIS Core Site [Abstract]	Gogineni
9:30	Detection of in-situ ice fabric anisotropy using polarimetric radar method near the WAIS divide [Abstract]	Matsuoka
9:45	Modeling radar attenuation at Siple Dome using ice-core chemistry and temperature data [Abstract]	MacGregor
10:00	How is the Ice Stream C doing on a daily basis? [Abstract]	Tung
10:15	BREAK (45 min.)	
11:00	Basal Shear Stress for Pine Island and Thwaites glaciers, Antarctica [Abstract]	Joughin
11:15	Inversion of ice stream surface measurements for basal conditions [Abstract]	Sergienko
11:30	Resolution and informational aspects of surface inversion on ice streams [Abstract]	Gudmundsson
11:45	A high spatial resolution record of near-surface temperature over WAIS during the past 5 decades [Abstract]	Monaghan
12:00	Verifying thermocoupled ice sheet models: whence the warm spokes [Abstract]	Bueler
12:15	LUNCH (1 hr. 45 min.)	Dining Hall
2:00	Roosevelt Island - a good place for an ice core [Abstract]	Conway
2:15	Calculating the Floating Fraction of Basal Ice Along Byrd Glacier, Antarctica, Using Only the Force Balance [Abstract]	Ashley
2:30	Calculating the Floating Fraction of Basal Ice Along Byrd Glacier, Antarctica, Using the Force Balance and the Mass Balance Connected by the Flow and Sliding Laws of Ice [Abstract]	Jones
2:45	Tracing past Antarctic ice flow paths and modern transport processes with TAM till [Abstract]	Licht
3:00	A DEM of West Antarctica from MODIS and ICESat -- Method, Accuracy, and Applications [Abstract]	Scambos
3:15	Recent observations show that WAIS is influenced by sea swell generated in tropics and in Northern hemisphere [Abstract]	MacAyeal
3:30	BREAK (45 min.) and Poster Viewing	
4:15	What have I learned?	Dahl Jensen
4:30	What have I learned?	Andrews

4:45	What have we learned?	
6:00	DINNER	Dining Hall
Saturday, September 30, 2006		
8:00	BREAKFAST	Dining Hall
	***Topic #4. Black on White*_Joint Proposals, IPY, ASEP and Our Future**	
8:30	Ocean-Ice Interaction in the Amundsen Sea: The Keystone of West Antarctic Stability [Abstract]	Bindschadler
8:45	Amundsen Sea Influence on the West Antarctic Ice Sheet [Abstract]	Jacobs
9:00	Flow dynamics of two Amundsen Sea Glaciers: Thwaites and Pine Island [Abstract]	Anandakrishnan
9:15	Deglaciation of the Amundsen Sea Embayment - the Prelude to Recent, Rapid Ice Retreat [Abstract]	Stone
9:30	Amundsen Sea Embayment Project: Glacial Dynamics of Thwaites Tributaries (GlaDTT)	Tulaczyk
9:45	Constraining the Mass-Balance Deficit of the Amundsen Coast's glaciers [Abstract]	Joughin
10:00	The Next Generation: A Community Ice Sheet Model for scientists and educators, with demonstration experiments in the Amundsen Sea Embayment region	Johnson
10:15	Are we headed in the right direction?	Bindschadler
10:45	BREAK (30 min.)	
11:15	WAIS Program: Activities, Actions and Needs	Bindschadler
11:15	IPY Revision of Science Plan-committee needed	Bindschadler
11:30	IPY Education and Outreach-web and beyond	Comberiate
11:45	IPY Future WAIS workshops	Bindschadler
12:00	Adjorn	
12:00	LUNCH	Dining Hall
1:00	Depart for Mt. Rainier	
	Posters	
	Surface exposure ages from the LGM trimline in the Ohio Range, Horlick Mountains [Abstract]	Ackert
	Communicating science to lay audiences	Andrews
	National Snow and Ice Data Center: Antarctic Data Management Support [Abstract]	Bauer
	LIMA: Progress on the Landsat Image Mosaic of Antarctica: an IPY Project [Abstract]	Bindschadler
	Sea-swell interaction with ice shelves: Observations at a site on the Ross Ice Shelf and a model of swell-excited ice-shelf vibration [Abstract]	Cathles
	Why Don't they Match? The Evolution of Flow Stripes and Internal Layers on Kamb Ice Stream [Abstract]	Campbell
	Impact of an Accumulation Hiatus on Physical Properties of Cold Polar Firn [Abstract]	Courville
	What Gravity Can Tell Us About West Antarctica: A Close Look at Thwaites Glacier and a Plan for Future Holistic Studies [Abstract]	Diehl
	Basement control and history of ice-sheet expansion in the Amundsen Sea Embayment - First results of recent RV Polarstern and RRS James Clark Ross cruises [Abstract]	Gohl

	Crossing the "T" in Antarctica [Abstract]	Hamilton
	Aeromagnetic results from the Thwaites Glacier catchment, West Antarctica [Abstract]	Holt
	Analysis of Bed Properties on Kamb Ice Stream with Constant Midpoint Radar Profiles [Abstract]	Jacobel
	Surface exposure dating using cosmogenic isotopes: a field campaign in Marie Byrd Land and the Hudson Mountains [Abstract]	Johnson
	Better physics using full momentum solver in 2D vertical slice domain, where do longitudinal stress really matter? Application to the Thwaites Glacier flowline [Abstract]	Kenneway
	The dynamic drift of mega-icebergs in the Ross Sea [Abstract]	Kim
	An introduction to DELORES: the BAS deep-look radio echo sounder [Abstract]	King
	Histories of Accumulation and Ice Dynamics from Radar Layers and Ice-Flow Inverse Methods [Abstract]	Koutnik
	Mapping the Antarctic's near-surface air temperature trends using satellite and in-situ observations	Mitchell
	Rebuilding glacial retreat histories using inverse methods and surface exposure age data [Abstract]	Todd
	A Two-Dimensional Coupled Model for Ice Shelf-Ocean Interaction [Abstract]	Walker
	Spatial variability in McMurdo Dry Valleys snow and firn - the role of local soil input [Abstract]	Williamson
	Grounding zone geometry of Thwaites, Pope and Smith Glaciers, Amundsen Sea Embayment [Abstract]	Young

Abstracts

(in order of presentation)

Bubbling beneath the ice streams: subglacial plumbing mapped from space

Helen Amanda-Fricker

We have used repeat-track ICESat laser altimeter data to map active hydraulic signatures over the Whillans and Mercer ice streams for the period 2003-2006. The data have revealed the complexity of the subglacial system, and have shown further that it is highly dynamic, changing on time scales of a few months. For the first time, we are getting a glimpse into what the subglacial water system looks like under an ice stream, which is fundamental to how the ice streams flow.

Finding subglacial water the "ICESat way" in rough terrain

Robert Bindschadler, NASA Goddard Space Flight Center
Hyeungu Choi, SAIC
Donghui Yi, SGT
Helen Amanda-Fricker, Scripps Institution of Oceanography

Satellite data analysis has inferred ongoing storage and release of large water volumes beneath fast flowing portions of West Antarctica. To date most of the inferred occurrences have been derived from repeat-pass laser altimetry. Spatial coverage of the GLAS instrument onboard the ICESat satellite is extensive over West Antarctica and is organized into a set of repeat tracks that have been remeasured three times per year since the 2003 launch of ICESat. In reality, however, the tracks are not exact repeats and cross-track offsets can be more than 100 meters horizontally. These offsets lead to elevation differences if there is a sloping surface between near-repeat tracks. In areas of rough terrain, the cross-track slopes can lead to elevation differences of many meters, similar in magnitude to the surface expressions of moving subglacial water, confounding identification of subglacial water movement events. GLAS data have been used to calculate and correct for the cross-track slope, but this is problematic if there are shifts in the elevation caused by water movement and not exclusively due to static topographic variation.

In this work, we describe the use of satellite optical imagery (Landsat in our case) to provide an independent measure of the cross-track slope. This technique enables the elevations of near-repeat profiles to be corrected to a common reference track and should lead to less ambiguous identification of temporal changes in surface elevation. The technique has multiple applications, including the class of temporal events associated with subglacial water movement but also the objective of identifying and quantifying sustained thickening or thinning of the ice sheet.

Towards repeat-track elevation rate estimates using ICESat data

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Analysis of elevation differences between repeat-track ICESat elevation measurements has begun to produce a picture of elevation changes in the Siple Coast ice streams on an extraordinarily small scale. Rapid changes, with rates on the order of decimeters per year, can be detected by differencing raw ICESat elevations from the same reference track. However, because the ice streams have relatively rugged surface topography, with short-scale surface slopes on the order of a half-degree, small displacements between repeat tracks can lead to large errors in the apparent elevation differences. To measure subtle changes, it is important to model local surface slopes to take into account the effects of the repeat-track displacement.

In this talk I will describe a procedure for deriving elevation rates from repeat-track elevation differences. This procedure fits a plane to short segments of data from several cycles of ICESat data, and constrains the slope of the plane based on an analysis of the statistical properties of ice sheet surface textures

The elevation-rate estimates derived with this procedure are self-consistent to within about 7 cm/a; formal errors are of a similar magnitude. Analysis of the covariance between recovered surface slope and elevation rate allows the elevation-rate and slope estimates to be divided into three major categories: (1) Those in which the slope and elevation rate are both well constrained, (2) those in which the elevation rate is well constrained regardless of the slope, and (3) those in which slope errors prevent accurate estimates of the elevation rate. The majority of models based on 500 m segments of data fall into category (2), with category (3) making up a bare majority of the remainder. Although the prevalence of category (3) failures prevents mapping of elevation change everywhere in WAIS, improved processing of ICESat data and further data collection are expected to improve coverage over the next year.

Discovery of till deposition at the grounding line of Whillans Ice Stream and implications

S. Anandakrishnan, G. Catania, R Alley, H Horgan

We report on the discovery of a till deposition delta near the grounding line of Whillans Ice Stream, West Antarctica. Deposition is occurring beneath an active ice stream just upstream of the grounding line, strengthening the hypothesis of subglacial transport of till by ice streams. We suggest that such deposition could lead to the formation of a step at the grounding that will tend to stabilize its position against sea level rise.

If till-deltas exist at the grounding line of ice streams, then an important question is whether the deposition is subaqueous or, as we suggest, subglacial. In the former case, the ice streams will build outwards from their grounding line, and more-importantly, the grounding line will be close to floatation and small changes in sea-level immediately affect the position of the grounding line. If till deposition is subglacial, then the region upstream of the grounding line will thicken and the ice will flow over and down a ``step'' to the ice shelf. In this case, the grounding line will be less sensitive to small changes in sea level and will tend to stabilize at a given position for long periods of time.

Radar Studies on Kamb Ice Stream

Rickard Pettersson, David Osterhouse, Brian Welch, Andrea Mulhausen, Christin Strandli and Robert Jacobel

Department of Physics, St. Olaf College, Northfield, MN 55057

During the past two Antarctic field seasons we acquired approximately 1600 km of ground-based ice-penetrating radar data on the lower trunk of Kamb Ice Stream (KIS) as part of a larger radar, GPS and modeling study with scientists at the University of California Santa Cruz examining the possibility of ice stream reactivation. We present here a summary of radar results from this work and some preliminary interpretations.

We have produced a map of detailed bed topography over the "sticky spot" where ice appears to have become grounded over a large bedrock bump. Archival data from the University of Wisconsin airborne radar profiles (Retzlaf et al., 1993) have enabled us to place this in a regional context. We are able to trace the evolution of folds in the radar internal stratigraphy in this region in both time and space by comparison with ground-based radar data we collected in the late 1980's (Jacobel et al., 1993). These studies depict changes in the horizontal strain rate as ice passes around the sticky spot.

We have also quantified variations in the amplitude of radar reflections from the ice-bed interface which appear to define different provenances of the ice stream. The weakest-reflecting ice-bed interface is found over the sticky spot where bore holes drilled by Cal Tech in 2000 showed a dry bed. A more highly reflective bed is located to either side of the sticky spot in regions of the trunk of KIS including one area where bore holes showed water at the ice-bed interface. The brightest bed, however, is located in the northern branch of the trunk, approximately 80 km upstream of the sticky spot, where ice velocities are still on the order of 120 m/a. Here radar reflected power is up to 1.5 times higher than elsewhere in the trunk despite the ice being 40% deeper. From this pattern of bed reflectivity we hypothesize that conditions allowing for rapid flow still exist under most areas of KIS and that sticky spots, like the one studied here, have played a key role in the ice stream shut down.

Two profiles crossing from this actively-flowing region of highly reflective bed into the northern margin of KIS (defined by strong velocity gradients) show continuous internal stratigraphy across the margin, indicating that substantial volumes of ice are still flowing across the margin into KIS in this area. The bright layer identified throughout West Antarctic (Jacobel and Welch, 2005) corresponding to 17.5 Ka based on ice core dating at Byrd is easily seen in these profiles.

A 210 km long longitudinal profile has also been acquired following a flow line from the area of bright bed to Siple Dome. We have traced dated internal stratigraphy from the ice core drilled at Siple Dome to the KIS north margin. Similarly, we have traced internal layers for the length of this profile, including the easily-identified bright layer corresponding to 17.5 Ka . However we have not been able to convincingly tie layers in the ice stream to the dated Siple Dome stratigraphy because of the high shear that has taken place across this margin. Bed topography, brightness and internal layer characteristics will all provide constraints to models describing the evolution and possible future of ice flow in KIS.

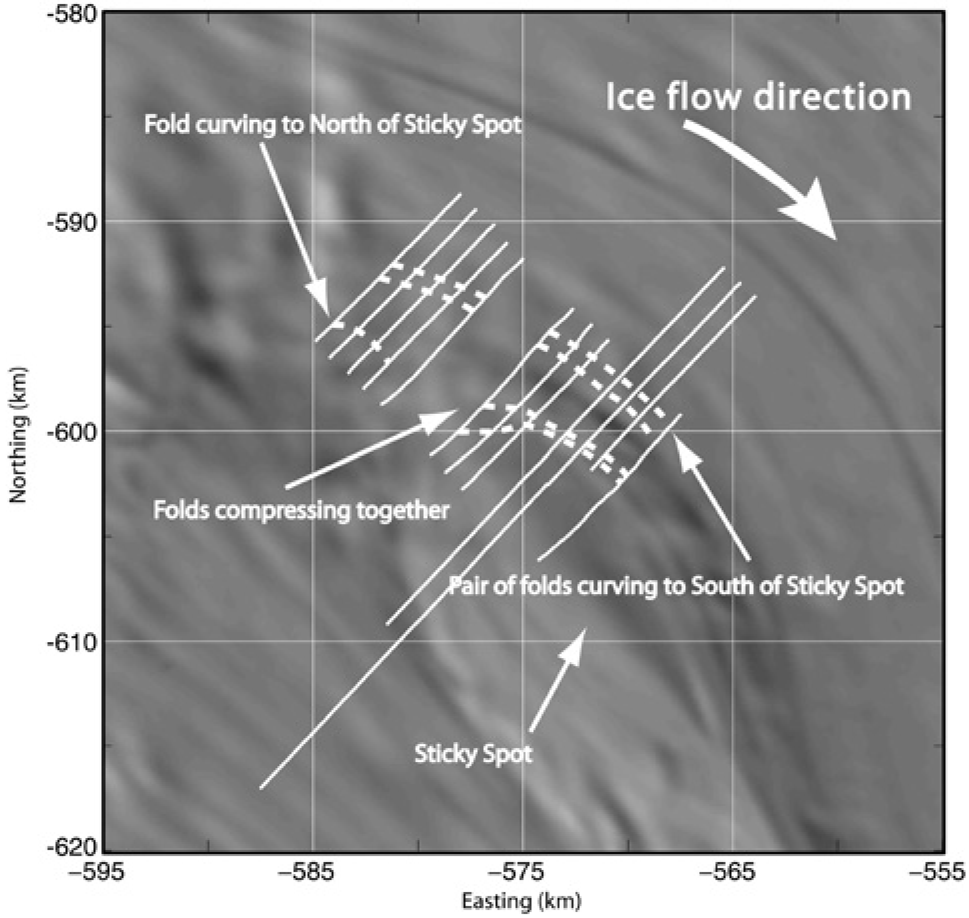


Figure: MODIS image of the KIS sticky spot showing the flow trajectories of several folds in the internal stratigraphy imaged by the radar as ice encounters the bedrock rise beneath the ss.

Geothermal controls on a pervasive water sheet at the head of Kamb Ice Stream, West Antarctica

D. D. Blankenship, I. Y. Filina, M. E. Peters, D. A. Young and D. L. Morse

The University of Texas Institute for Geophysics Jackson School for Geosciences, 4412 Spicewood Springs Rd. Bldg. 600, Austin, TX 78759 United States

The availability of basal melt water has been hypothesized as a key control on the existence and evolution of localized ice streams within the West Antarctic Ice Sheet. Basal melting is controlled by glaciological stresses and the distribution of geothermal flux. While advances in interferometric mapping of surface velocities have improved estimates of ice stresses, the detailed geothermal contribution has proven more difficult to assess.

Until recently, mapping water systems through radar sounding was limited by a lack of fully quanitified reflection coefficients. Using airborne coherent radar sounding profiles, we have sucessfully derived absolute reflection coefficients for the Siple Coast region, and have we used that work to calibrate the radar sounding data for a densely gridded airborne survey over the onset region of Kamb Ice Stream, within the limits of a simple vertical advection temperature model for ice column losses. The validated basal reflection coefficients for the base of the C2 tributary of Kamb Ice Stream reveal an extensive highly reflective region, covering approximately 2000 km2.

We calculate high resolution hydraulic potentials using concurently acquired ice surface and bed elevations constrained by dual carrier phase GPS, and find that the reflective sheet is mostly restricted to three discrete regions of low hydraulic gradient, connected by ramps. We interpret this feature to be an pervasive, energetic water sheet.

Simultaneously acquired potential fields and radioglacialogical observations allow the modeling of the structure of the surrounding crust as well as the ice sheet's response to it. We present evidence for the association of this extensive sub-glacial water sheet with overlying ice column reduction, together with a geological context consistent with local enhancement of geothermal flux.

Radar evidence for past melting and present water distribution beneath Rutford Ice Stream, West Antarctica.

E.C.King

British Antarctic Survey, Madingley Road, Cambridge, CB3 0ET, UK

I collected radar data in the onset region of Rutford Ice Stream where previous seismic surveys indicated free water at the bed in a possible canal system. The objectives were to use the radar to map the bed topography in detail and to determine if there was a correlation between seismic and radar reflectivity which would allow mapping of water distribution.

I used the British Antarctic Survey's Delores system (Deep Look Radio Echo Sounder, a daughter of the Washington and St. Olaf radars), which is a 1 MHz monopulse radar. (See the poster at this meeting for further technical details). The data show internal reflections through the full 2900 m thickness of the ice stream and a bed reflection with very good signal to noise ratio.

My primary observations are:

1) There is a lowermost ice layer that varies in thickness from 200 m to 600 m,
2) The amplitude of the bed reflection is as much as 13 dB greater on the downslope side of basal highs than elsewhere, and
3) There are significant differences between the location of regions of seismic high amplitudes and radar ones

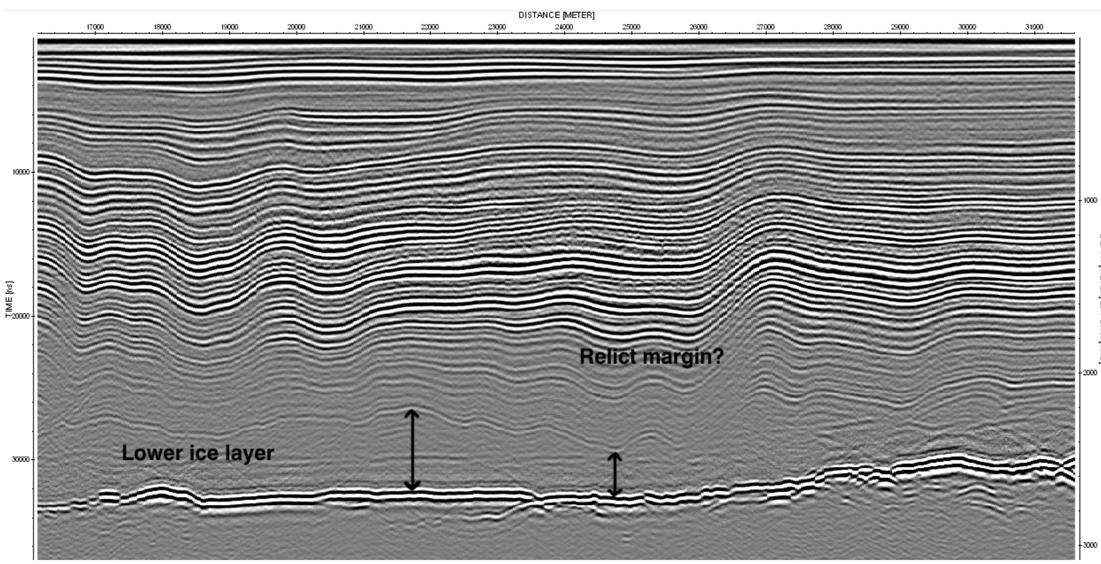


Figure 1. Part of a radar cross-section of Rutford Ice Stream. The lower ice layer thins, suggesting localised basal melting, perhaps in a relict shear margin.

The questions to be answered are:

1) What is the present basal water distribution?
2) What past episodes of basal melting have taken place?
3) Has there ever been re-freezing at the bed?

Thanks SO Much for ALL the Data: The Amundsen Sea Sector Data Set: Applications with UMISM: Where and How Much WATER? What WILL happen in the future?

James L. Fastook

University of Maine

Recent extraordinary programs of the Airborne Geophysical survey of the Amundsen Sea Embayment (AGASEA), by University of Texas [holt06] and British Antarctic Survey [vaughan06] teams in the astral summers of 2004/2005, collected some 75,000 km of flight-line data measuring ice thickness with radar sounders and surface elevation with laser or radar altimeters. Recently these data have been made available as a 5-km gridded data set in a format convenient for modeling. We apply the University of Maine Ice Sheet Model (UMISM) in its embedded mode [fastook04b] to do high-resolution analysis of the velocity distribution within the Amundsen Catchment. We show that the model adequately captures velocity distributions measured by SAR radar [rignot04]. We show the distribution of basal water predicted by the model [fastook97, johnson99, johnson02b, johnson02]. We hope that, within the limitations of our grounding line parameterization, the model has predictive capabilities and will show some examples of possible future retreat.

The nest of embedded models begins with a 40 km grid of the entire ice sheet. Embedded in this is a 10 km grid that includes the entire AGASEA measurement area. Nested inside this medium-resolution grid are two 5 km grids encompassing Thwaites and Pine Island Glaciers. This procedure allows us to obtain the highest-resolution results with very reasonable runtimes. A cycle of growth to an LGM configuration followed by retreat to the present configuration is run for this nest of embedded grids. Advance and retreat is controlled by a "thinning-at-the-grounding-line" parameter (the WEERTMAN) which is coupled to the Vostok Core temperature proxy. Full resolution 5-km results for thickness, velocity, and water distribution are shown for the two focused embedded grids.

We also present a plausible, but perhaps extreme, scenario of future retreat that might arise if conditions ever returned to the state that produced the large retreat from the LGM configuration. One of these scenarios produces complete collapse of the WAIS in a few thousand years, while the other demonstrates how the "weak underbelly" might collapse [hughes81c].

[fastook97] J.L. Fastook. Where does all the water go? In Fourth Annual West Antarctic Ice Sheet Initiative Workshop, 10-12 Sept. 1997, Sterling, Virginia, 1997.

[fastook04b] J.L. Fastook and A. Sargent. Better physics in embedded models. In Eleventh Annual West Antarctic Ice Sheet Initiative Workshop, Sterling, Virginia, 2004.

[holt06] J.W. Holt, D.D. Blankenship, D.L. Morse, D.A. Young, M.E. Peters, S.D. Kempf, T.G. Richter, D.G. Vaughan, and H.F.J. Corr. New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography of the Thwaites and Smith Glacier catchments. Geophys. Res. Lett., L09502(doi:10.1029/2005GL025561), 2006.

[hughes81c] T. Hughes. The weak underbelly of the West Antarctic Ice Sheet. Journal of Glaciology, 27:518--521, 1981.

[johnson02] Jesse Johnson and James L. Fastook. Northern Hemisphere glaciation and its sensitivity to basal melt water. Quaternary International, 95-96:65--74, 2002.

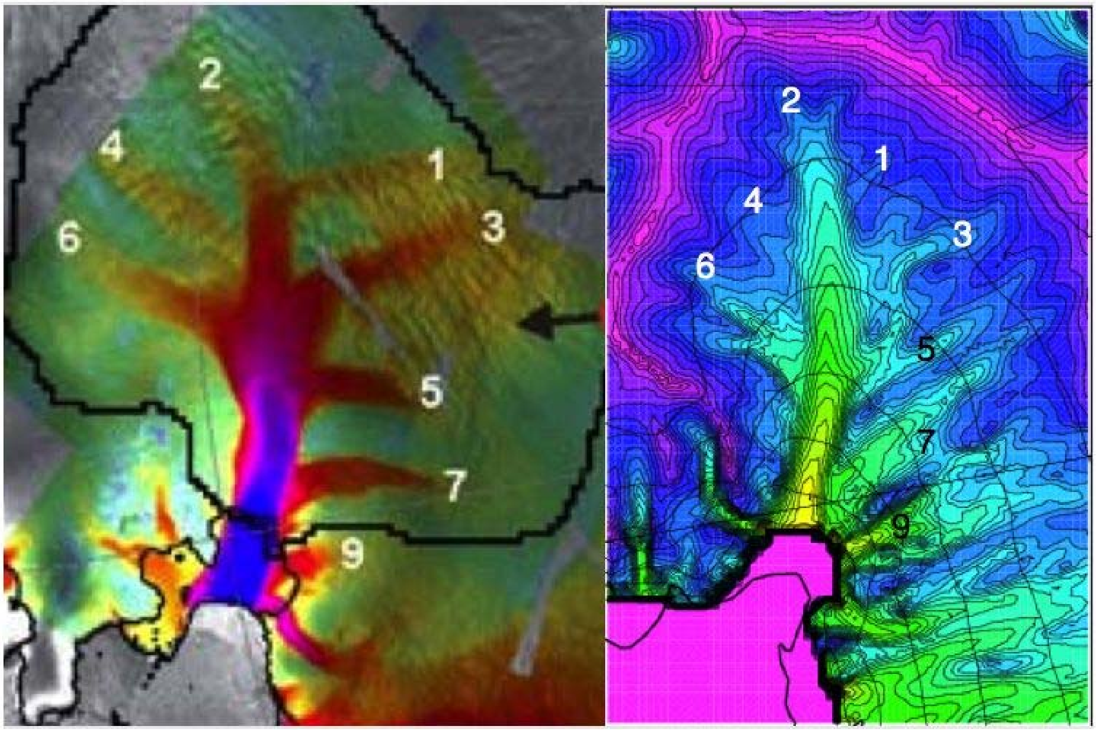
[johnson99] Jesse Johnson, Slawek Tulaczyk, and J.L. Fastook. Further developmenst in the basal water model. In Sixth Annual West Antarctic Ice Sheet Initiative Workshop, 15-18 Sept. 1999, Sterling, Virginia, 1999.

[johnson02b] Jesse V. Johnson. A basal water model for ice sheets. PhD thesis, Department Physcs, University of Maine, Orono, Maine, 2002.

[rignot04] E. Rignot, R.H. Thomas, P. Kanagaratnam, G. Casassa, E. Frederick, P. Gogineni, W. Krabill, A. Rivera, R. Russell, J. Sonntag, R. Swift, , and J. Yungel. Improved estimate of the mass balance of glaciers draining into the Amundsen Sea of West Antarctica from CECS/NASA 2002 campaign. Annals of Glaciology, 39:231--237, 2004.

[vaughan06] D.G. Vaughan, H.F.J. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J.W. Holt, D.D. Blankenship, D.L. Morse, and D.A. Young. New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography beneath Pine Island Glacier. Geophys. Res. Lett., doi:10.1029/2005GL025588, 2006.

Data (Rignot 2004) and Results



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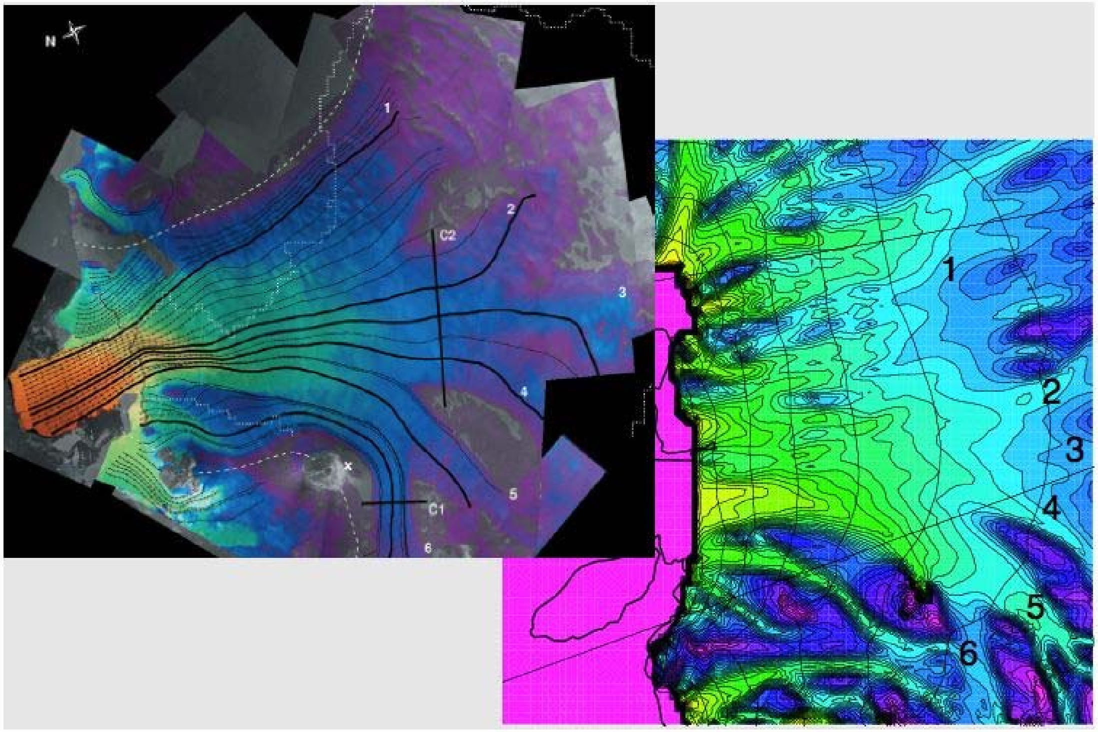

The RABID Project: Attempts to drill to the bed of Rutford Ice Stream

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The main fieldwork for the RABID project was carried out on Rutford Ice Stream in the 2004/05 field season. The biggest scientific task was to access the ice stream bed using a hot-water drill. This would enable a number of investigations within the bed and the ice:

- Sediment sampling for dating and ice sheet history

- Tethered stakes to detect bed deformation

- Pressure sensors and borehole video camera for basal hydrology

- Instrument strings for ice column temperature and deformation as well as recent climate history

- Ice cores (and video) for fabric and sediment content.

The project also involved a substantial suite of surface geophysical measurements: seismic reflection surveys for basal conditions; GPS and passive seismic networks for ice flow and basal seismicity; and GPR for accumulation and flow pattern.

Together, these formed an integrated programme studying ice dynamics, basal conditions and climate and glacial history. Although the drilling reached within 100 m of the bottom of the ice (ice thickness ~2200 m), irretrievable equipment failure meant that we did not reach the ice stream bed. The surface work was more successful and is giving interesting results, including: rapid subglacial erosion, drumlin formation and changing bed hydrology (presented at WAIS in 2006); spatial and temporal variability in the ice flow during the fieldwork; and evidence for seasonal flow variability from a GPS receiver that recorded into the winter and re-started in the spring.

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

Mike Bentley[1], Chris Fogwill[2], and David Sugden[2]

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We report here the initial 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 from its maximum extent in an area inland of the Weddell Sea embayment. In season 05/06 we worked along a c. 350 km 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 were on the western (West Antarctic Ice Sheet) side of the range but we also worked in 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, and 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. The first exposure dates will also be presented.

Subglacial conditions of inland West Antarctica from US-ITASE deep radar reflection analysis

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Conditions beneath ice sheets, particularly the presence of water, have significant impact on ice flow behavior. Numerous studies have discussed in the dramatic influence of water on the shear strength of the till beneath the WAIS ice streams compared to the nearly stagnant inter-ice stream ridges. Ice-penetrating radar observations provide a method for observing changes in basal conditions over large areas based on the strength of the subglacial reflection.

We present here the results of applying a method similar to that used by Gades et al. (2000) with data from Siple Dome to calculate a depth-attenuation function for the 2002 US-ITASE deep radar profiles in the central WAIS. Challenges arise because of the variability of ice-bed interface as well as within the ice itself. The traverse covers 1,400 km in length including: ice stream tributaries, mountain ranges, nearly stagnant ice, isolated subglacial melt events, and ice thickness up to 3.5 km. We examine the strength of the bedrock reflector as well as a particularly bright internal layer to determine the variation in reflector strength as a function of depth. Using the attenuation curves, we calculate the relative strength of the basal and internal reflections along the traverse. We find a different behavior in the bed reflectivity of the interior regions of WAIS than is seen in regions of the Ross Sea ice streams.

TOWARDS A SUITE OF US ITASE WEST ANTARCTIC PALEOCLIMATE RECORDS

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Instrumental climate records extending back in time more than ~50 years are rare in Antarctica. To further complicate climate interpretations, coastal regions of Antarctica receive relatively heavy snowfall as a result of the frequent incursion of cyclonic systems while the majority of the continent is a polar desert.

The International Trans-Antarctic Scientific Expedition (ITASE) is a 20-nation effort designed to collect and interpret a continent-wide array of environmental parameters relevant to both modern and past climate. Since its inception in early 1990, ITASE has collected more than 20,000km of snow radar data, drilled and recovered more than 240 shallow ice cores totaling more than 7000m in length, remotely penetrated more than 4000m beneath the ice sheet surface, and sampled the atmosphere to heights of more than 20km from traverses spanning much of the Antarctic continent (Mayewski et al., 2005a).

Until now, the United States component of ITASE has concentrated the majority of its collection efforts in West Antarctica, but a few US ITASE East Antarctic sites complement this spatially expansive US environmental data archive. Here we will highlight some of the proxy records developed thus far from recent US and other ITASE coring efforts and provide some insight into the potential for US ITASE derived climate proxies.

On the Effects of Ice Divide Motion on Raymond Bumps

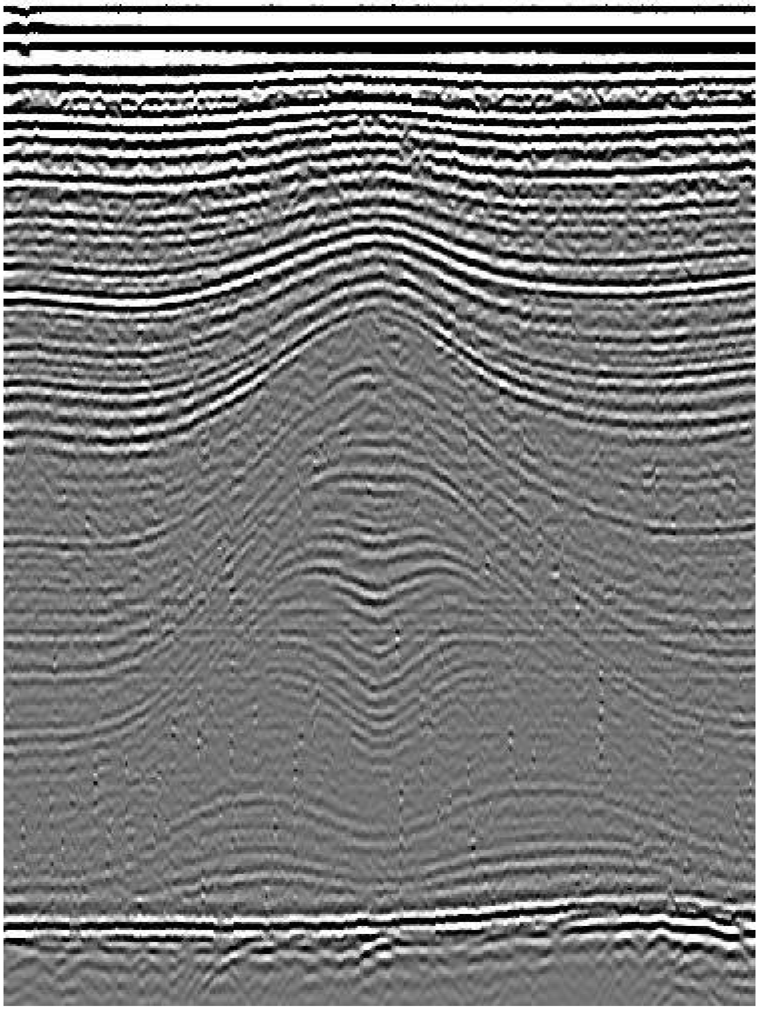
Carlos Martin, Richard Hindmarsh, Hilmar Gudmundsson and Francisco Navarro

Radio-echo sounding of ice commonly reveals reflecting internal layers that are thought to be isochrones. Beneath ice divides the radar layers frequently exhibit anticlines (arches), which are a consequence of the non linear rheology of ice. This phenomena was first predicted by C. F. Raymond (1983) and is known as Raymond effect. Here we investigate the effects of ice divide motion on the geometry of Raymond bumps.

We show that the rate of ice-divide migration fundamentally affects the shape of the Raymond bumps. Slow migration produce a tilt in the axis of the crests of the arches (e.g. Siple Dome, Antarctica) while fast migrations leave Raymond bumps in a flank position which are advected with the flow while new ones develop in the new stationary position (e.g. Roosevelt Island, Antarctica).

We also explore the formation of double-rooted Raymond bumps (see figure).They appear in the radargrams of Kealey Ice Rise and Fletcher Promontory, both flanking Carlson Inlet in Ellsworth Land, Antarctica. We show that those double-rooted bumps can be produced through a fast migration of the ice divide, followed by a fast return to the old position. This explanation suggests that the flow velocities of currently inactive Carlson Inlet have chanced with time, and that Carlson Inlet may have flown considerably faster in the past.

We show how numerical modeling of transient Raymond bumps can be used to give both quantitative and qualitative information about changes in flow velocities and thicknesses of surrounding ice streams. Radar-echo soundings across ice divides are, thus, an effective way of obtaining information about past changes in ice stream configuration. This echoes similar work on the Siple Coast by Nereson, Raymond and co-workers.



Maybe the Siple Dome Ice Core Records Surging Ice Streams?

Ken Taylor, Richard Alley, Ed Brook, Trevor Popp, Jeff Severinghaus,

Eric Steig, Jim White

The Siple Dome ice core records two large climate changes that are not recorded in the Byrd or Taylor Dome ice cores. The changes observed at Siple Dome are difficult to interpret as a rapid regional climate change. A possible alternative interpretation is that during two time periods large and rapid decreases in the surface elevation of the ice streams surrounding Siple Dome altered the air flow around Siple Dome resulting in large but local climate changes at Siple Dome.

The Siple Dome ice core site is surrounded by ice streams. The elongate topographic depressions formed by the ice streams influence air flow around the dome. Satellite observations suggest this may cause a negative lapse rate (Shuman). Changes in the flow of the ice streams influence the surface elevation of the ice streams and alter the local meteorology, making the local climate of the summit of Siple Dome more influenced by ice dynamics then other deep ice core sites.

On the summit of Siple Dome at 15 kyr there was no firn gas diffusive column (gas isotopes [Severinghaus]), there is irregular stratigraphy (gas isotopes [Severinghaus], optical logger [Price], angular unconformities (multitrack [Taylor) and crystal size [Alley]). The lack of an increase in sea salt and crustal species is inconsistent low precipitation rates (chemistry [Mayewski]). Melt layers are present [Alley]. The air temperature changed ~ 6^{o} C (stable isotopes [White]). It is difficult to say how quickly these changes occurred because there may be a hiatus in the record.

On the summit of Siple Dome at 22 kyr there is no evidence of disturbed stratigraphy (gas age-ice age difference [Severinghaus], physical properties [Alley]). The air temperature changed ~ 6^{o} C, maybe as fast < 50 years (ice [White] and gas isotopes [Severinghaus]).

The deuterium excess (an indicator of conditions in the mid latitude Pacific moisture source area) and chemistry (an indicator atmosphere transport to Siple Dome and conditions over ice free southern latitude land areas) do not change significantly at these times, and there are no corresponding changes in the Byrd ice core that is located only 200 km away.

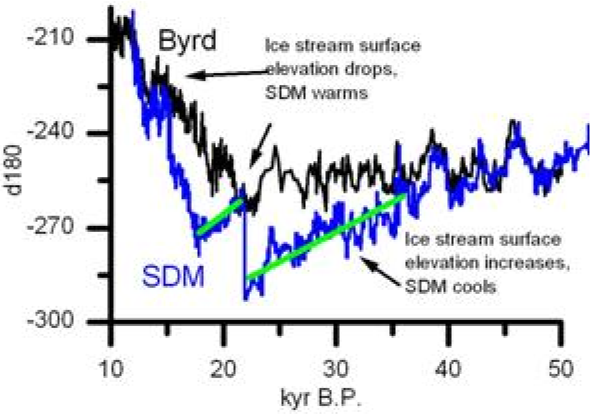
The ^{18}O record from the Mount Moulton ice core, also shows a large short duration excursion around 22.k kyr [White/Popp]. A large dating uncertainty and proximity to a large tephra layer complicates direct comparison to the Siple Dome record. The Taylor Dome record, has a poorly understood low accumulation period around 15 kyr [Steig]. Taken together the ice core record suggests there were at least two significant climate excursions during the deglacial that were expressed most strongly along the Siple coast, with a weaker expression at other coastal sites, and muted response in the interior of Antarctica.

Because the data is difficult to explain as a regional climate change, we consider the following speculative concept to encourage discussion among different disciplines that might lead to a useful interpretation. Between 40 and 22 kya sea level was decreasing and the size of the ice sheets increased. Ice flow in the WAIS adapted to the decreasing sea level by increasing the surface gradient of the ice near the coast. This slowed the Siple Coast ice streams and increased the surface elevation of the ice streams around Siple Dome. If the ice stream was moving at 80% of the steady state rate, the surface elevation would rise at 20% of the ice accumulation rate of ~10 cm/yr. So over a 15,000 year period of consistent sea level change, the ice stream surface could rise by ~ 300m. As the topographic depressions formed by the ice streams were filled in by slow moving ice, the topographic prominence of Siple Dome decreased, altering the local air flow in the Siple Dome region. During this time (40 to 22 kya) the climate at the summit Siple Dome gradually deviated from climate at Byrd in response to the local change in airflow that were forced by the greater thickness of the ice streams.

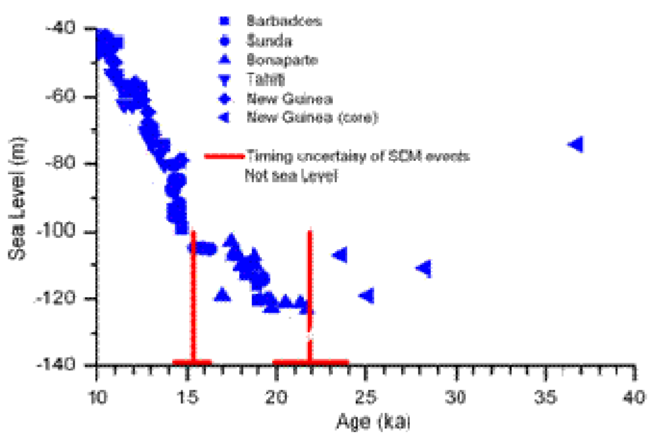
Beginning at 22 kya orbital forcing started to move the climate from a glacial to interglacial condition. The net flux of water from the ocean to the ice sheet was halted, stabilizing sea level. The ice sheet adjusted to the new boundary condition of a stable sea level by decreasing the surface gradient near the coast. During this adjustment phase the ice streams around Siple Dome accelerated and the thinned. Current ice streams have been observed thin at rates of 3 m/yr, so maybe the ~ 300 m of ice that filled in the ice streams during the period of declining sea levels was removed in a period of ~ 100 years. This would have restored the topographic depressions associated with the ice streams around Siple Dome and lead to the rapid local climate changes recorded in the Siple Dome core. The changes were not observed in the Byrd core because these were a local climate change associated with changes in the ice stream elevations.

The discharge of ice through the ice streams around Siple Dome must have only been a small part of similar events. The large seaward flux of ice might have been sufficient to affect ocean circulation, which may be recorded in marine sediment cores. This is a general concept that will require interaction between the ice dynamics, ice core, marine sediment, and climate modeling community to pursue further.

Between 50 ka and 35 ka the SDM and Byrd core respond the same way. Between 35 ka and 22 ka SDM has a cooling trend caused by thickening ice streams that is not recorded at Bryd. At 22 kya there is a rapid decline in ice stream elevation that restores the air flow patterns around SDM to what they were before 40 kya.



The abrupt changes recorded in the SDM core, shown by the vertical lines along with the dating uncertainty, occur near the start of periods of increasing sea level.



Statistical properties of Antarctic ice cores

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Analyses of the relationship between the cross dated Antarctic and Greenland ice core isotope records have shown that there is a significant relationship in climate between the Northern and Southern hemispheres (the so-called "bipolar seesaw"). The Siple Dome record, which is independently dated but highly correlated with Byrd, confirms this general picture. However, the dating precision of both Byrd and Siple Dome remains too low to determine whether there is coherence with the Greenland records for timescales shorter than about two millennia; a clear relationship with Greenland is demonstrable only for the largest longest-lived millennial-scale events. For both Byrd and Siple Dome, as well as Dome C, we find that a simple stochastic climate model with 100-year averaged white noise forcing of amplitude 0.5 K is sufficient to account for the millennial scale variability. Importantly, all three of these Antarctic cores are highly coherent with each other, but not with Greenland, during the Holocene, and the amplitude of the noise forcing need not be larger in glacial compared with Holocene climate. This result casts doubt on the idea that the variability seen in Antarctic records on these timescales is a response to the abrupt climate changes in Greenland, since these are absent in the Holocene. The Greenland Dansgaard-Oeschger events are therefore perhaps better thought as a response to the background noise variability in the climate system, rather than the origin of such variabilty. We also note that the enigmatic low-snow-accumulation event at ~15 ka at Siple Dome, if it also occurred at Taylor Dome, would largely reconcile Taylor Dome with other East Antarctic ice core records.

Basement control and history of ice-sheet expansion in the Amundsen Sea Embayment - First results of recent RV *Polarstern* and RRS *James Clark Ross* cruises

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The Amundsen Sea embayment lies between the Palaeozoic crustal blocks of Marie Byrd Land, Ellsworth Land and Thurston Island. Its continental margin is conjugate to the passive margin of the eastern New Zealand submarine continental plateaux and Bounty Trough, which underwent major extension during Cretaceous rifting between New Zealand and West Antarctica. Later, the embayment seems to have played a role as a plate boundary while the Bellingshausen Plate acted as an independent microplate until the early Tertiary. It is likely that the tectonic architecture, through the formation of deep basins and erosional troughs, laid the foundation for major glacier outflow from the West Antarctic Ice Sheet into Pine Island Bay and the South Pacific since early West Antarctic glaciation.

During successive cruises on RRS *James Clark Ross* (cruise JR141) and RV *Polarstern* (expedition ANT-XXIII/4) in early 2006, we collected seismic, bathymetric, sub-bottom profiler and helicopter-magnetic data from the inner shelf, outer shelf, slope and deep sea of the Amundsen Sea embayment and Pine Island Bay, to address tectonic as well as sedimentary objectives. We will present preliminary results indicating the disposition of structural basement units and the role the tectonic basement and pre-glacial sediments have played as controlling parameters for ice-sheet expansion and retreat in the Amundsen Sea Embayment.

Late Quaternary Deglaciation IN the Amundsen Sea sector of the West Antarctic Ice Sheet: PRELIMINARY RESULTS FROM RECENT CRUISES OF RRS *JAMES CLARK ROSS* AND RV *POLARSTERN*

J.A. Smith[1], R.D. Larter[1], K. Gohl[2], C.-D. Hillenbrand[1], G. Kuhn[2], T.J. Deen[1], R.A. Livermore[1], F.-O. Nitsche[3], G. Uenzelmann-Neben[2], and Shipboard Scientific Parties JR141 and ANT-XXIII/4

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The Amundsen Sea Embayment drains approximately 25% of the area of the West Antarctic Ice Sheet (WAIS) and its future stability is crucial to predictions about eustatic sea level rise. The majority of ice in this area drains through the fast flowing Pine Island and Thwaites Glaciers, which have thinned significantly in recent decades, probably in response to intrusions of Upper Circumpolar Deep Water onto the continental shelf. In order to put these recent changes in perspective and to determine whether they form part of an ongoing retreat from the Last Glacial Maximum (LGM) or represent recent dynamical changes it is necessary to establish the maximum extent of the ice sheet at the LGM and its subsequent retreat pattern. So far, only the deglacial history in the southeastern Amundsen Sea (Pine Island Bay) has been reconstructed, and its chronology is limited to a few radiocarbon dates. Here we present preliminary results from RRS *James Clark Ross* cruise JR141 and RV *Polarstern* expedition ANT-XXIII/4 undertaken in early 2006 which significantly expanded the existing marine geophysical and geological datasets. Multibeam bathymetry and seismic data collected in the Amundsen Sea Embayment during these cruises illustrate the interaction between seabed morphology and the flow of grounded ice across the continental shelf. Along with determining the maximum extent of the WAIS during the LGM and its retreat history, the new geophysical data and sediment cores will provide information on the controls and locations of rapid ice flow, variability in sedimentary processes on the margin, and whether the size of the LGM ice sheet and its deglaciation are representative of glaciations during earlier Quaternary climatic cycles.

Numerical modeling of ocean circulation over the continental shelf and beneath the ice shelves in the Amundsen Sea, Antarctica

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Using a 3-D numerical model, we investigate the hydrography and circulation of ocean waters overlying the continental shelf in the Amundsen Sea. The goal of this study is to better understand processes which govern the temporal and spatial distribution of 'warm' circumpolar deep water (CDW) on the continental shelf, and its derivatives. That deep water, abundant off-shelf, migrates onto the continental shelf and subsequently beneath the floating ice shelves that drape most of the coastline in this sector. This leads to extensive basal melting, which may be negatively impacting the mass balance of the West Antarctic Ice Sheet. We employ a coupled isopycnic ocean, dynamic-thermodynamic sea ice, and thermodynamic ice-shelf model, along with daily varying atmospheric forcing and available bathymetry, to simulate the pathways and properties of waters on the continental shelf. We compare model simulations to ocean observations taken in the area since
1993.

Radar Measurements and Results from the WAIS Core Site

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We developed an ultra wideband very high-frequency (VHF) radar (120-300 MHz) for simultaneously measuring ice thickness, mapping internal layers at depth and imaging the ice-bed interface, and an ultra high-frequency (UHF) ultra-wideband radar (500-2000 MHz) for fine-resolution mapping of near-surface internal layers. We operated the VHF radar at the center frequency of 150 MHz with a bandwidth of 20 MHz in conjunction with the UHF radar to collect data to a 30-km by 10-km region that overlapped the West Antarctic Ice Sheet (WAIS) Divide drill site and the WAIS ice divide. We reduced the system bandwidth to obtain the high sensitivity required to overcome much large attenuation loss than anticipated. The results show ice thickness varying from about 3100 m to about 3500 m. Also, the strength of the bottom echo is seen to fluctuate by more than 30 dB along the traverse. The strong specular returns are from wet and smooth areas, and weak returns are from rough areas with ice frozen to the bed. We mapped internal layers to a depth of about 3000 m with the VHF radar. To the best of our knowledge this is first ever mapping of layers deeper than about 2500 m.

We will provide a brief overview of the radars and show sample results from the WAIS core site.

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

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The alignment of crystals in ice, called crystal-orientation-fabrics (fabrics), 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 in the WAIS divide region were conducted during the 2005-6 field season. 60-MHz and 179-MHz radar with co-polarized Yagi antennas were installed on a sled. Radar data were collected at 12 azimuths of polarization planes by alternating the azimuth of the sled in 15-degree steps. 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 difference of the horizontal anisotropy in the fabric and that the latter can be caused by birefringence.

The polarimetric measurements were done at 19 sites within an area of 150 km by 60 km including the WAIS ice coring site; nine sites are in the Amundsen side of the current ice-flow divide, 8 sites on the Ross side, and 2 sites on the divide. Radar data from 14 of the 19 sites show significant azimuthal variations of the echo. The variation was found at depths between 600 m and 2000 m depending on site. Radio echo back from depths greater than 2000 m is close to the noise level obscuring azimuthal variation. The biaxial mode was found in both 60-MHz and 179-MHz data. The uniaxial mode was more prominent at 179 MHz. These characteristics are consistent with that found in East Antarctica. Radar data collected at sites close to each other show similar azimuthal patterns. A quantitative analytical algorithm will be applied to find out principal axes of the biaxial and uniaxial modes, which can be used to map principal axes of the ice fabric. Supplemental strain-grid measurements are now underway at all polarimetric radar sites to relate the ice fabric variations detected by radar to the local strain pattern.

This project is supported by NSF-OPP 0440847. Radar system was loaned by National Institute of Polar Research in Tokyo.

Modeling radar attenuation at Siple Dome using ice-core chemistry and temperature data

Joe MacGregor, Dale Winebrenner, Howard Conway, and Kenichi Matsuoka
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The radar reflectivity of an ice-sheet bed is a primary measurement for discriminating between wet and frozen beds. Uncertainty in englacial radar attenuation and its spatial variation introduces corresponding uncertainty in estimates of basal reflectivity. Englacial radar attenuation is proportional to ice conductivity, which depends on the chemistry (acidity and salinity) and temperature profiles of the ice that is being probed. We use experimental ice-conductivity data to model attenuation and test this model using ice-core chemistry and borehole temperature data from Siple Dome. Our model has a mean uncertainty of 8 % using the acidity, salinity and temperature profiles at Siple Dome. The modeled depth-normalized attenuation rate at the Siple Dome ice-core site is several dB/km lower than the radar-derived value. We discuss possible refinements to the conductivity model to explain this discrepancy, including the effect of melting-point depression, the eutectic point of NaCl and the higher conductivity of premelting ice. This work shows how to constrain englacial radar attenuation using detailed ice-core and borehole data and establishes a basis for extrapolating basal conditions from an ice core across an ice sheet.

How is the Ice Stream C doing on a daily basis?

Slawek Tulaczyk[1]*, H. Camas Tung* [1]*, and Ian Howat*[1]

This study is to continuously measure the daily change of surface elevation and ice velocity in Ice Stream C (ISC) area from 2004 to 2005. High resolution GPS receivers were placed along the stream flow in Antarctic Summer 2004 that ran year long and received geographic information every day until the Antarctic Summer 2005.

Our data reveal the deviation of surface elevation along the flow of ice stream in ISC area in a daily scale. There was ~2 meters of surface elevation change over one year. The elevation increase in the upstream was more dramatic and less steady. The error for most of our data point falls within centimeters. The continuous GPS surveys with Ice-Penetrating Radar and numerical simulation provide us a better observation and prediction of the Antarctic Ice Stream behavior.

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Basal Shear Stress for Pine Island and Thwaites glaciers, Antarctica

Ian Joughin
Jonathan Bamber
David Vaughan
Jack Holt
Don Blankenship

We used control-method inversions to determine the basal shear stress beneath Pine Island and Thwaites glaciers. We used an existing inversion algorithm that has been applied successfully to the Ross Ice and Filchner-Ronne Ice Streams. These inversions were constrained by several sources of data. For bed topography, we relied on data from the recent Airborne geophysical survey of the Amundsen Sea Embayment, Antarctica (AGASEA). Surface topography was derived from a combination of ICESAT and ERS altimeter data. Finally, we determined surface velocity using ERS InSAR data.

Inversion of ice stream surface measurements for basal conditions

Olga V. Sergienko, Robert A. Bindschadler, Douglas R. MacAyeal, and Patricia L. Vornberger

Virtually all studies of ice stream dynamics depend on characterizations of subglacial conditions that cannot be directly observed. This difficulty motivates a wide range of methods designed to estimate subglacial conditions from surface measurements. One class of these methods, least-squares inversion of surface velocity data with prescribed surface geometry, depends significantly on the quality (i.e., errors and resolution) of surface geometry and velocity determined by remote sensing. In this presentation, we shall investigate the degree to which estimates of subglacial conditions (a parameterization of basal friction) depend on various aspects of newly derived surface measurements acquired for Bindschadler Ice Stream (a.k.a., ice stream D). Comparisons between 4 distinct digital elevation models (DEM's) ranging from a 1990's "bedmap" product to the latest product available from IceSat radar altimetry, show distinct patterns of inversion performance which warn the user of the methodology about error and resolution issues in the estimates of basal friction. Further analysis will be presented to show the effect of model-resolution on surface velocity matching in lateral shear layers where ice-stream dynamics is only partially addressed by the inversion physics. As a final point, we shall present 3 inversions of surface data to estimate parameters associated with simple basal friction laws to be used in potential forward models of ice-stream change in the future.

Resolution and informational aspects of surface inversion on ice streams

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A Bayesian inversion framework for inverting surface data from active ice streams for both basal perturbations and basal slipperiness is presented. I consider a number of general questions related to this problem, such as how retrieval is affected by the accuracy of measurements, and to what extend bedrock and slipperiness perturbations can be separated (mixing effects). This is done using a linearized forward model including all terms of the momentum equations. The Bayesian inversion procedure uses full covariance matrices. I find that mixing effects do not seem to pose any significant problem if data on both surface geometry and surface velocities are available, but are significant if only data on surface geometry is known. For a flow-line inversion the only fundamental limit to retrieval is the spatial resolution. The spacial resolution of slipperiness retrieval is about an order of magnitude less than for a bed-line retrieval. Furthermore, even when accurate data on surface geometry and surface velocities are available, basal slipperiness retrieval still requires an a priori knowledge off ice thickness to within about 10%.

"A high spatial resolution record of near-surface temperature over WAIS during the past 5 decades"

Andrew J. Monaghan and David H. Bromwich, Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, OH

A network of instrumental temperature records has been available over Antarctica since the International Geophysical Year in the late 1950s. Most of the records are in coastal regions, with only a few in the interior. It has been difficult to assess temperature variability in the large gaps that exist between observing stations.

Over the past 25 years, since about 1980, atmospheric numerical models and infrared satellite measurements have allowed scientists to fill in the voids between observing stations, resulting in a spatially coherent depiction of temperature across the continent. Prior to 1980, atmospheric model temperature data are not reliable, and satellite measurements are sparse. It is clear from these techniques that temperature variability is large over a range of timescales. This noise makes it difficult to elucidate what trends exist, if any, and what may be causing them. It is desirable to extend the Antarctic temperature record back in time over the entire continent, with high-spatial resolution, so that temperature variability and trends can be assessed at regional and larger scales. For instance, a 50-year record of temperature in the Pine Island Bay region (where there are only a few years of instrumental measurements) may help glaciologists understand the large ice sheet wastage occurring there over the past decade, and to place it in a longer-term context.

Our method uses meteorological model reanalysis fields to determine zones of temperature coherence that correlate with the individual records at annual and seasonal timescales. Assuming these zones adequately cover most of the continent given the available observational records, this information can be employed to synthesize the observations into a continent-wide record of near-surface temperature in a self-consistent manner. The model reanalysis temperature dataset we use is the European Centre for Medium-Range Weather Forecasts 40-y Reanalysis (ERA-40). ERA-40 temperature is compared to independent observed records and satellite measurements for overlap periods and shown to reproduce the interannual temperature variability and trends, justifying its use for this study. Figure 1 shows a composite map of the maximum correlation coefficient obtained by correlating the ERA-40 simulated percentage annual temperature anomaly at the grid point closest to each measurement station with every other grid point. Correlations greater than 0.6 ($p<0.01$) occur over most of the grounded ice sheet, indicating that the zones of spatial coherence from the available observational records cover nearly the entire continent. We employ this robust relationship to synthesize the observational data into a series of high-spatial resolution temperature maps over all of Antarctica back to 1960. The result is a nearly 5-decade time series of near-surface temperature over the grounded ice sheet that extends our current high spatial resolution record by 2 decades.

In this study we focus on temperature variability over WAIS during the past 50 years. Basin- and regional-scale trends and time-series will be presented. The temperature reconstruction will also be compared with a recently published 50-year record of snowfall variability to assess the coherence between temperature and precipitation at basin- and larger space scales and interannual-to-interdecadal timescales. Addressing this relationship has consequences for understanding how Antarctic snowfall will change -- and thus contribute to or mitigate sea level rise - in the coming century, assuming Southern Hemisphere and Antarctic climate will warm as projected.

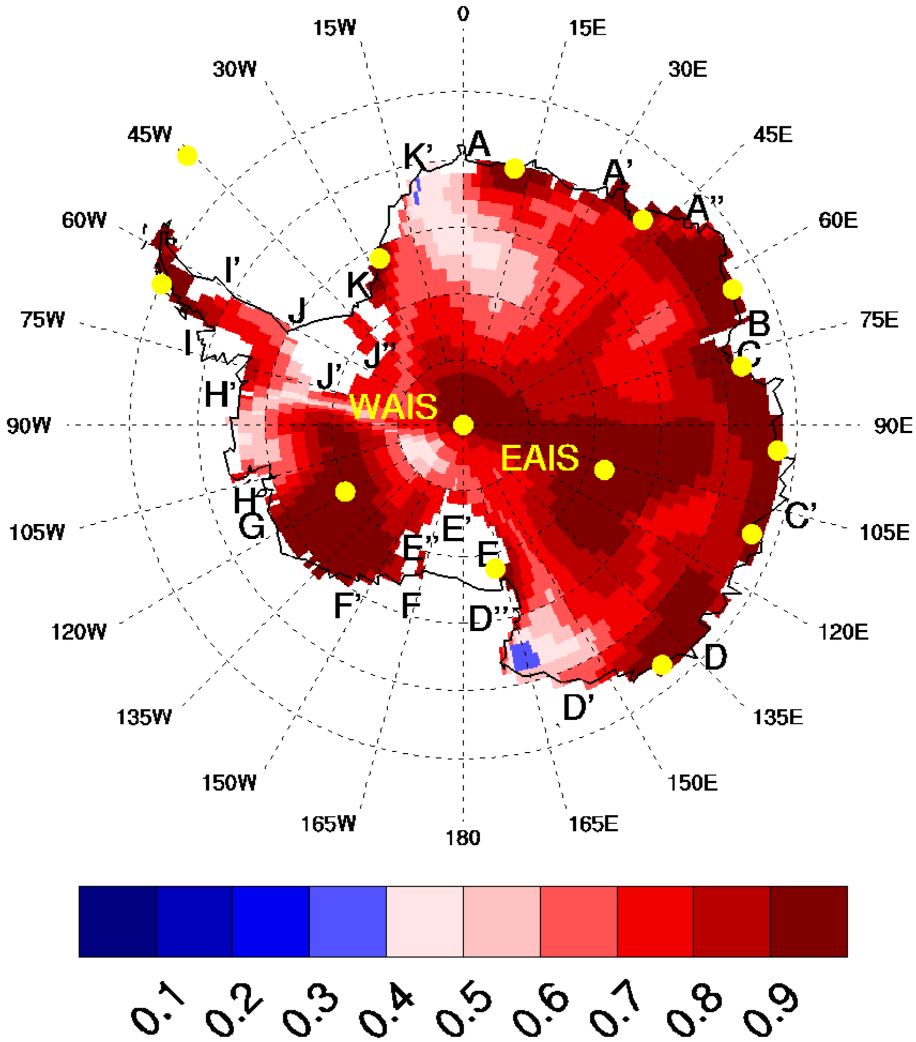

Fig. 1. The composite map of the maximum absolute value of the Pearson's correlation coefficient (|r|) resulting from correlating the ERA-40 1980-2001 percentage annual near-surface temperature change (with respect to the 1980-2001 mean) for the grid box containing each of the 14 observation sites (yellow dots) with every other 1 deg. x 1 deg. grid box over Antarctica (i.e., this map is a composite of 14 maps). Pink/red colors have correlations at p<0.01. The black lines delineate ice drainage basins, which are identified alphabetically by the black letters where they intersect the grounding line.

Verifying thermocoupled ice sheet models: whence the warm spokes

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ABSTRACT: We describe exact solutions to the thermocoupled shallow ice approximation in three spatial dimensions. Though artificially constructed, these solutions are very useful for testing numerical methods. In fact, they allow us to verify (Roache 1998; Bueler and others, 2005) a finite difference scheme, that is, to show that the results of our numerical scheme converge to the correct continuum values as the grid is refined in three dimensions. Comparison of numerical results to exact solutions has helped us to precisely identify and understand a number of numerical instabilities and inaccuracies. Nonetheless our verified numerical scheme shows a version of the basal temperature spokes which arose in the EISMINT II intercomparison (Payne and others, 2000). A careful error analysis identifies the warm spokes as numerical errors which occur when the derivative of the strain-heating term with respect to the temperature is large. This fact motivates smoothing the strain-heating term, a numerical technique which eliminates the spokes. The appearance of spokes for a verified numerical scheme is strong evidence for the effective or actual ill-posedness of the particular EISMINT II experiment F thermcoupled steady state free margin problem.

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Roosevelt Island – a good place for an ice core

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Observations and models indicate that Roosevelt Island in the eastern Ross Sea (Fig.1) is an ideal site for investigating both regional climate variations and Holocene deglaciation of the Ross Embayment. Here we synthesize geophysical observations and models of conditions on the island. Roosevelt Island is grounded 200 m below present-day sea level and rises to 550 m above sea level (Fig.1). Geophysical investigations carried out during the 1960's measured profiles of surface elevation, motion, temperature and accumulation (Clapp, 1965), and ice thickness and bedrock geology (unpublished reports by Clapp, Hochstein and Bentley). Shallow cores (up to 70 m), extracted in the 1970s were used to measure depth-profiles of density and chemistry (Langway, 1975; Langway and Herron, 1977), accumulation rate and stable isotopes (Claussen et al., 1979). We revisited the island during the 1997-98 field season and measured spatial patterns of accumulation (using 16-m firn cores and high frequency radar), and ice sheet geometry and internal stratigraphy using low-frequency radar (Fig.1).

An ice core from Roosevelt Island will help constrain past glacial changes in West Antarctica, necessary for understanding how the ice sheet will respond to future environmental change. Most reconstructions of the Ross Sea Embayment place thick ice over Roosevelt Island during the last glacial maximum (Bentley, 1999; Denton and Hughes, 2002). Depth profiles of age, stable isotopes and temperature from an ice core at Roosevelt Island will contain a record of climate and thickness histories [see Waddington et al. (2004) and Price et al., (submitted) for related investigations at Siple Dome], which can be used to establish the timing of grounding-line retreat (Conway et al., 1999).

The island is subject to strong cyclonic incursions from the Southern ocean. Both atmospheric models (Bromwich et al., 2000) and field observations (Kreutz et al., 2000) suggest that Holocene climate variations, and in particular the El Nino-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) phenomena, should be well preserved at Roosevelt Island. Preliminary ice-flow models suggest that a record of 40 ka could be obtainable; a core from Roosevelt Island would form a component of the International Partnerships in Ice Core Sciences (IPICS) 40-ka array and would contribute to the science goals of several SCAR programs including ACE (Antarctic Climate Evolution) and AGCS (Antarctic and Global Climate System).

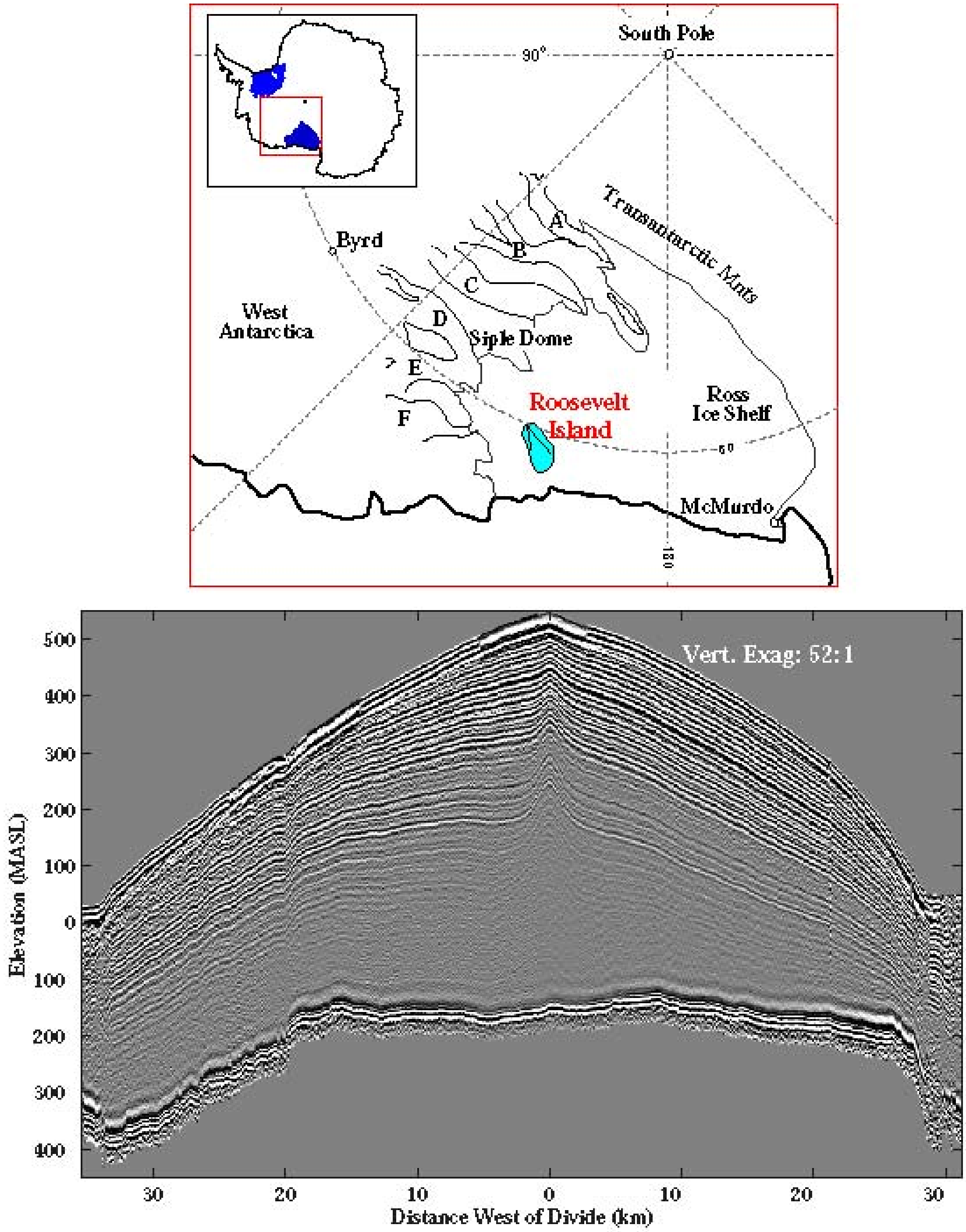

Fig. 1: Location map and 7MHz radar profile across Roosevelt Roosevelt Island. The profile extends onto the surrounding iceshelf on both sides of the island.

Calculating the Floating Fraction of Basal Ice Along Byrd Glacier, Antarctica, Using Only the Force Balance

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A geometrical force balance for stream flow in ice sheets was used to equate floating fraction phi of basal ice with the ratio of ice thickness at an ice-shelf grounding line to ice thickness at any distance upslope along an ice stream supplying the ice shelf. This simple formula for calculating floating fraction phi was then applied to Byrd Glacier, which supplies East Antarctic ice to the Ross Ice Shelf. The method is described for obtaining phi from gravitational forcing that is resisted by basal and side shear and by longitudinal tension and compression along an ice flowband. Then phi is calculated from the ice-thickness profile for Byrd Glacier along a radio-echo flightline up Byrd Glacier that gave nearly continuous top and bottom reflections. This gives a first-order determination of the floating fraction of Byrd Glacier along the flightline from the ice-shelf grounding line to the beginning of stream flow. Experiments are presented comparing the calculated phi variation with continuous phi variations that may have a theoretical explanation. A good fit is obtained with a phi curve that decreases with distance upslope from the grounding line as half-a-period of a cosine squared function that gives smooth transitions from the convex profile for sheet flow to the concave profile for stream flow to the flat profile for shelf flow.

Calculating the Floating Fraction of Basal Ice Along Byrd Glacier, Antarctica, Using the Force Balance and the Mass Balance Connected by the Flow and Sliding Laws of Ice

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A geometrical force balance that links floating fraction phi of basal ice to basal and side shear and to longitudinal tension and compression along an ice stream was combined with the mass balance along the ice stream using the flow law of ice and a sliding law of ice that incorporates the floating fraction of basal ice. This establishes the dependence of floating fraction phi on all the major stresses in an ice stream, the mass balance, the flow law, and the sliding law. The result is a second-order model that calculates how phi changes with the change of ice thickness upslope from the grounding line of an ice shelf supplied by the ice stream, and improves the first-order calculation of phi based on the force balance alone. The model is applied to a radio-echo flightline up Byrd Glacier, Antarctica, from the Ross Ice Shelf to converging flow in the East Antarctic Ice Sheet. The separate contributions of basal shear, side shear, and longitudinal tension/compression to floating fraction phi are presented along the flightline to show how these stresses change as flow changes from converging sheet flow to linear stream flow, to diverging shelf flow.

Tracing past Antarctic ice flow paths and modern transport processes with TAM till

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Ross Embayment till provenance was investigated by comparing the coarse sand composition, as well as the Nd and Sr isotopic composition, of East and West Antarctic source area tills with till samples from across the Ross Sea. Western Ross Sea tills exhibit mineralogic and lithological similarities to East Antarctic tills, whereas eastern Ross Sea tills are compositionally similar to West Antarctic tills, particularly in their dearth of mafic components. Tills from the eastern Ross Sea have Nd and Sr isotopic compositions similar to West Antarctic tills and in the western Ross Sea, the till samples have higher εNd values (-4 to –7). Central Ross Sea tills have εNd values ranging from –7.1 to –12.5, and a mixed source sand composition. Thus, the central Ross Sea trough contains components of both East and West Antarctic derived till, marking the confluence of the East and West Antarctic Ice Sheets during the LGM.

To build a more robust dataset of till composition from East Antarctic outlet glaciers that discharge into the Ross Embayment, samples were collected from sixteen moraines at the head and along the length of the Byrd and Nimrod Glaciers in 2005. Bulk sediment (till) and >300 pebbles were collected at each site in order to assess changes in particle size and composition during transport. Sites at the head of both glaciers contain more abundant silt and clay (fines) than downstream sites. In particular till from the Lonewolf Nunataks at the head of the Byrd Glacier contains >50% fines. Till collected from active lateral moraines along the trunk of both glaciers typically has <10% fines. The presence of abundant fine sediment in upstream and midstream Byrd and Nimrod Glacier till indicates a subglacial component whereas lateral moraines lack fines and are dominated by locally eroded bedrock. This observation is supported by preliminary analysis of the pebble composition. Pebble composition reflects local bedrock outcrops in all lateral moraines from the trunk of both glaciers, whereas upstream sites contain a component of non-locally derived material. These data support the model of debris transport described by Whillans and Cassidy (1983).

The available data indicate that the East Antarctic ice sheet provided a significant flux of ice to the Ross Sea, overcoming the barrier imposed by the Transantarctic Mountains, and despite the apparent lack of an increase in the thickness of the EAIS during the last glacial maximum. This observation supports LGM ice sheet reconstructions in which significant amounts of ice are delivered to the Ross Sea from both the WAIS and EAIS, which implies that the current configuration of the ice streams in the WAIS was formed during deglaciation and thus represent a substantial change in ice flow since the LGM.

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A DEM of West Antarctica from MODIS and ICESat -- Method, Accuracy, and Applications

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An image enhancement approach is being used to develop a new digital elevation map of West Antarctica, combining repeat MODIS imagery and ICESat laser altimetry profile data. The method utilizes the multiple, continent-wide image coverage of MODIS, its high radiometric sensitivity (which equates to a high sensitivity to surface slope in the sunward direction), and the high precision and accuracy of ICESat along-track data.

ICESat has acquired a series of eight near-repeat tracks over the Antarctic during the period September 2003 to June 2006, covering the continent to 86 deg S. ICESat data are aquired as a series of spot elevations, averaging a ~60m diameter surface region every ~172m. Using the multiple-track 'ribbons' of data, two of us (DY and JZ) were able to generate along- and across-track surface slope fields for the Antarctic continent. However, ICESat track paths have spacings wide enough (2 km at 85 deg; 20 - 50 km at 75deg) that some surface ice dynamical features (e.g. flowlines, undluations, ice rises) are missed by the slope and track data.

We are combining the restricted-coverage but high-accuracy ICESat data with cloud-cleared MODIS band 1 data from the 2003-2004 austral summer, used in generating the Mosaic of Antarctica, MOA, surface morphology image map. Past analyses of the slope-brightness relationship for MODIS have shown ice surface slope precisions of +/- 0.00015. Multiple images can improve the single-scene precision (e.g. the effective radiometric resolution) and spatial resolution (nominally 250m for a single scene). ICESat spot elevation have nominal precisions of ~5cm, although thin-cloud effects and mis-location errors can magnify these.

A suite of applications for an enhanced DEM are identified and explored. A full representation of the WAIS undulation field permits a better investigation of the relationship between accumulation and topography, and surface temperature and topography. Further, addressing the shape modifications introduced by the variations in accumulation across undulations is a necessary prerequisite before inverting surface topography for bed elevation. Lastly, surface topography and detailed bed topography are both required for inferring sub-ice-sheet hydrostatic pressure. We will discuss these potential applications.

Recent observations show that WAIS is influenced by sea swell generated in tropics and in Northern hemisphere

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To investigate the source of 'iceberg tremor', we deployed seismometers on the Ross Ice Shelf and on various icebergs adrift in the Ross Sea (including B15A, a large fragment of B15, which calved from the Ross Ice Shelf in March, 2000). The data reveal that the most energetic vibrations in the 0.01 to 0.5 Hz band are associated with sea swell generated in the Pacific Ocean – as far away as the Gulf of Alaska. In one example, a strong storm in the Gulf of Alaska on October 21, 2005, approximately 13,500 km from the Ross Sea, generated swell that arrived at B15A immediately prior to and during its spectacular break-up off Cape Adare on October 27, 2005. Although this temporal coincidence is likely fortuitous, as the iceberg was also grounding on sea-bed shoals at the time, it motivates us to conjecture that long-term exposure to swell can contribute to Antarctic iceberg calving. This would link polar ice sheets to tropical and opposite-hemisphere weather systems, and imply a control on ice-sheet mass balance capable of global teleconnection. If true, then synchronous pulses of iceberg calving on widely separated margins of the North Atlantic ice sheets during Heinrich events, for example, could be explained by increased storm conditions in the Atlantic driven by atmospheric climate change. This presentation will review various case studies of sea-swell influences on the glacial regime of the Ross Sea as well as review historical microseism data from Scott Base to motivate the conjecture that the original calving of B15 was sea-swell induced.

IPY: Collaborative Research: Ocean-Ice Sheet Interaction in the Amundsen Sea: The Keystone of West Antarctic Stability

A joint proposal to NSF and NASA for the International Polar Year

Principal Investigator:	***Robert Bindschadler****/NASA Goddard Space Flight Center*
Co_Investigators:	***Sridhar Anandakrishnan****/Penn State University* ***Alberto Behar****/NASA Jet Propulsion Laboratory* ***David Holland****/New York University* ***Miles McPhee****/McPhee Research Company* ***Timothy Stanton****/Naval Postgraduate School* ***Martin Truffer****/University of Alaska, Fairbanks*
UK collaborators:	***David Vaughan****/British Antarctic Survey* ***Hugh Corr****/ British Antarctic Survey* ***Adrian Jenkins****/ British Antarctic Survey* ***Andy Smith****/ British Antarctic Survey* ***Tony Payne****/University of Bristol*

We propose integrated oceanographic and glaciological field studies linked with regional and local modeling activities to advance our ability to predict future behavior of ice sheets, particularly that portion of West Antarctica that drains into the Amundsen Sea. Our efforts are motivated by the nearly complete absence of direct observations of sub-ice shelf processes, the primary influence the ocean is having on the recent dramatic changes in ice sheet discharge, and the potential increased importance of these changes in the near future through accelerating sea level rise. The societal importance of this work is the need to predict future sea level. Without a process-based understanding of the ocean's interaction on ice-sheet discharge that is supported by measurements and is incorporated into predictive models, policy makers will have no firm basis for action that may protect society.

We will access the never-before seen ocean cavity beneath the Pine Island Glacier directly through hot-water drilling, measure the shape of the cavity by seismic soundings, monitor the properties of the underlying waters with newly developed instrumentation and visually explore the underside of the ice shelf and the seafloor. New instrumentation will monitor both the spatial and temporal variations in water properties inside and outside the sub-shelf boundary layer and associate these variations with the basal melt rate and dynamic response of the glacier. To be most useful to prognostic models, such measurements must include vertical profiling at flexible intervals and at horizontally distributed points. Our measurements link directly to the needs of new models of both ocean and ice behavior by directly measuring both horizontal and vertical fluxes across a model grid cell and we plan to assimilate these measurements into the first-ever coupled model of ice dynamics and ocean dynamics that expressly contains the interactive processes we will measure.

This proposal meets the exceptional challenges of the International Polar Year (IPY). We have assembled an elite international group of leading scientists and engineers with vast Arctic, Antarctic and modeling skills and sterling professional records of success. Our combined talents are focused on overcoming long-standing obstacles to understanding the interactions between ocean waters and ice shelves—urgently needed research in light of increased ice discharge from West Antarctica. Our collaborative approach amplifies the enhancements of linking measurements to models; satellite technology to innovative field instrumentation; modern science to exciting polar exploration; difficult Antarctic field work to our need to know. Working with education and outreach professionals, we believe the public will find our work inspiring and informative. Because it involves aspects directly associated with the International Polar Year solicitations of both NSF and NASA, it is submitted jointly to both agencies. Our success will significantly advance our ability to predict future ice sheet behavior and stand as a major scientific achievement enabled by the IPY.

Amundsen Sea Influence on the West Antarctic Ice Sheet

S Jacobs, A Jenkins & H Hellmer

West Antarctica (WAIS) is a marine ice sheet, grounded below sea level in a warming ocean. Its mass balance in a changing climate hinges on the balance between surface accumulation, iceberg calving and in situ melting under its fringing ice shelves. In the Amundsen Sea, those ice shelves are melting orders of magnitude faster than elsewhere around Antarctica, fueled by massive intrusions of Circumpolar Deep Water (CDW) onto the continental shelf. Remote sensing studies have correlated that melting with thinning ice shelves, accelerating ice streams and drawdown of the adjacent ice sheet. Melting of the WAIS into the Amundsen Sea may also account for a substantial part of observed ocean freshening downstream, and of recent sea level rise. We will undertake a multiyear study of seasonal and interannual variability in CDW access to the Amundsen Sea continental shelf and the regional ice shelves. The project will expand the network of coastal automatic weather stations and evaluate the role of the atmosphere in moisture flux, and in deep water upwelling along the shelf break and coastline. The perennial sea ice thickness will be mapped in relation to the ocean mixed layer, heat transport and meltwater content. Swath mapping of the sea floor will concentrate on the deep troughs that funnel warm, salty seawater to vulnerable ice shelf grounding zones. These varied measurements will be used in the modeling of ocean properties and circulation, the atmospheric forcing and sea ice cover, and their influences on the WAIS. This work will necessitate multiple cruises, robust instrumentation, cooperation with complementary Amundsen Sea Embayment projects (ASEP), and enhanced logistic support to reach key areas typically inaccessible to ice-strengthened research vessels.

IPY: Flow Dynamics of Two Amundsen Sea Glaciers: Thwaites and Pine Island

Anandakrishnan, S, RB Alley, W Carlsen, D Pollard

Relevance to IPY: One of three main areas of emphasis for US scientists during the International Polar Year (IPY) is ``Ice Sheet History and Dynamics." We propose to address that theme on the Thwaites Glacier and Pine Island Glacier in the Amundsen Sea sector of the West Antarctic Ice Sheet. Our work will have greater impact because of the international collaboration that we have established with the British Antarctic Survey: working together, we can conduct a fuller suite of geophysical experiments in one season with more-efficient use of people and logistics than we could individually. This project is one of half-a-dozen proposals to characterize the Amundsen Sea Embayment, which has been identified in numerous planning documents as perhaps the most important target for ice-dynamical research. Taken together, this ``pulse of activity" will result in a better understanding of this important part of the global system.  Finally, we will ``engage the public in polar discovery" with a unique set of audio and video field-podcasts, which will put a public-outreach umbrella over a number of IPY projects (see attached letters of support).

Intellectual Merit: This proposal addresses a number of questions listed in the NSF solicitation, including the first-listed one: What are the critical boundary conditions for development of comprehensive predictive models of ice sheet behavior? We propose a field season during which we will measure the subglacial environment of Thwaites and Pine Island Glaciers using three powerful, but relatively simple tools: reflection seismic imaging, GPS motion monitoring of the tidal forcing, and passive seismic monitoring of the seismicity associated with motion. The results of the field work will feed into ice-sheet modeling efforts that are tuned to the case of an ocean-terminating glacier. Taken together, we will assess the influence of these glaciers on current sea level and project into the future. We will also assess the role of Thwaites Glacier as a ``lynchpin" of the Amundsen Sea sector of the West Antarctic Ice Sheet and whether it is uniquely vulnerable to abrupt downdraw and discharge of water in the future.

Broader Impacts: In addition to the science program, we are proposing an informal-education and public-outreach effort that is an umbrella over many, if not all, of the IPY Ice Sheet Dynamics-themed science projects. Penn State Public Broadcasting (PSPB) has partnered with us in offering a series of weekly podcasts from the field that will trace an arc through ice sheet dynamics. We refer to each week's product as an ``episode" (e.g, ice-core science, surface glaciology, geology, etc.), which will be broken up into three or four segments of, e.g., primary science, background science, meet-the-scientist, and science-for-kids.

Every week a different field team will host the podcast crew (our field team some weeks, and other IPY-participant field teams other weeks---see attached letters of support) allowing the podcast episodes to cover a range of subjects, field environments, personalities, and viewpoints. The hosts of all the episodes will be a Penn State professor of science education and a science reporter at PSPB. The tight coupling of the media and science teams will result in accurate, timely, and focused reporting.

Deglaciation of the Amundsen Sea Embayment - the Prelude to Recent, Rapid Ice Retreat

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Daniel Mann; Institute of Arctic Biology, University of Alaska
Sujoy Mukhopadhyay, Robert Ackert
Brenda Hall; Climate Change Institute and Department of Earth Sciences, University of Maine

Research into the history, present-day dynamics and future stability of the West Antarctic Ice Sheet (WAIS) has concentrated strongly on the Ross and Weddell Sea sectors of the ice sheet. This research has revealed complex ice-stream dynamics and evidence of unsteady flow, but no sign of a strong negative mass balance or imminent collapse in either region. The Amundsen Sea Embayment Project (ASEP) is motivated by recent satellite and airborne studies of the much less accessible Amundsen Sea area; these have revealed rapid thinning and grounding-line retreat on Pine Island, Thwaites, Smith and Kohler Glaciers resulting in an annual loss of 85 +/- 20 GT of ice [1]. The changes underway in this region are much greater than observed in other sectors of the ice sheet, and are likely to dominate the mass balance of the WAIS in the near future. The purpose of the proposed ASEP Glacial Geology program is to provide long-term context for these changes – on timescales from hundreds to thousands of years.

The existing photographic, instrumental and remote-sensing record for the Amundsen Sea region extends back to 1947 [2]. This makes it difficult to determine whether the present pace of deglaciation represents unsteady ice-stream flow, a response to a recent change in boundary conditions, such as loss of buttressing ice shelves, or is the continuation of conditions that have prevailed steadily for hundreds, or thousands of years. Geologic records of the ice-sheet's thickness and behavior over the past few thousand years will greatly extend the time-base of glaciological studies, complement marine geophysical and geochronological records from the Amundsen Sea, and provide an important addition to the observational and instrumental record to be obtained by other ASEP research groups.

We have proposed an intensive, ground-based glacial-geologic study of Pine Island, Pope, Smith and Kohler Glaciers (Unfortunately there are no bedrock outcrops along Thwaites Glacier, so there is no geologic record of its past thickness). Our plan is to:

(1) Reconstruct ice levels at sites bordering Pope, Smith and Kohler Glaciers, ranging from Mt Murphy and Toney Mountain, large volcanoes at the upstream ends of the glaciers to outcrops close to and beyond their grounding lines. Exposure dates on moraines and glacial erratics, and C-14 dates on ice-marginal sediments stranded above glacier level should provide thinning histories at these sites. We expect to be able to derive past ice elevations, determine if thinning has been steady or episodic, and obtain thinning and retreat rates that can be compared to those derived from remote sensing.

(2) Search for evidence of former glaciation and/or isostatic emergence on islands in Pine Island Bay. Dates on exposed bedrock, glacial debris and uplifted marine sediment will provide constraints on the former extent and retreat rate of Pine Island Glacier, which can be compared to existing marine records (e.g. [3]).

(3) Integrate our results with those of the British Antarctic Survey GRADES Program (Glacial Retreat in Antarctica and Deglaciation of the Earth System; [4]). Researchers participating in the QWAD (Quaternary West Antarctic Deglaciation) program, a sub-component of GRADES, visited Pine Island Bay and the Hudson Mts during the 2005-06 field season, working from R.V. Polarstern. Their geological and chronologic work on samples collected form these areas will complement our proposed work.

(4) Integrate our results with those of the broader Amundsen Sea Embayment Project. We expect both to provide background to ASEP glaciological studies, and to incorporate ASEP findings into our own interpretations, with the overarching goal of determining whether the ongoing, rapid retreat of Amundsen Sea glaciers part of a long-term trend or a recent anomaly.

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IPY, COLLABORATIVE RESEARCH: Constraining the Mass-Balance Deficit of the Amundsen Coast's glaciers

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Relevance to IPY: The West Antarctic Ice Sheet is losing mass, in large part because of rapid thinning of the Amundsen Coast glaciers. Estimates of Amundsen Coast thinning range from 46 to 86 Gtons/yr, with the 40-Gton/yr difference being nearly equivalent to the combined outflow of Mercer, Whillans, Kamb, and Bindschadler ice streams (46 Gtons/yr). While warmer ocean temperatures may drive this thinning, the large uncertainties in the current mass balance estimates largely arise from poor knowledge of the snowfall accumulation over Pine Island, Thwaites, Smith, Pope and Kohler glaciers. This international project will determine accumulation rates in this vastly under-sampled region to remove the large uncertainties in current mass balance estimates and, in doing so, it will directly address the NSF IPY emphasis on "*ice sheet history and dynamics*."
Intellectual Merit: The field effort consists of a series of airborne accumulation radar profiles to map internal layers and ice thickness. Near-surface radar layers will be dated using age-depth profiles derived from shallow ice cores. The combination of these data will yield multiple transects of decadal-scale average accumulation extending back through the last century. Spatially complete, annually-resolved maps of accumulation will be obtained from these data using EOF-based interpolation schemes guided by weather hindcast results (i.e. NCEP, ECMWF, Polar MM5 output). Comparison of the basin-averaged accumulation with ice discharge determined using Interferometric Synthetic Aperture Radar (InSAR) velocity data will provide improved mass-balance estimates. Study of changes in flow speed will produce a record of mass balance over the last three decades. Analysis of the satellite altimeter record in conjunction with annual accumulation estimates also will provide estimates of changes and variability in mass balance. Finally, these data will constrain a modeling effort to determine how coastal changes propagate inland, to allow better prediction of future change.
Broader Impacts: During the period while the next IPCC assessment was being prepared, new credible estimates of Antarctic mass balance were published that range from thickening by 45 Gtons/yr to thinning by 152 Gtons/yr. The difference in these estimates represents nearly one third of the ~1.5 mm/yr 20th Century sea level rise. By removing uncertainty in the region where imbalances are the largest, this project will make a significant contribution to subsequent IPCC estimates of sea level, which are important for projection of the impacts of increased sea level on coastal communities. The research will contribute to the graduate education of students at the Universities of Washington and Kansas and will enrich K-12 education through the direct participation of the PIs in classroom activities. Informal science education includes 4-day glacier flow demonstrations at the Polar Science Weekend held annually at the Pacific Science Center in Seattle. The project also will communicate results through Center for the Remote Sensing of Ice Sheets (CRESIS) outreach effort. All field and remotely-sensed data sets will be archived and distributed by the National Snow and Ice Data Center.

Posters

(alphabetical by first author)

Surface exposure ages from the LGM trimline in the Ohio Range, Horlick Mountains

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Reconstructions of the West Antarctic Ice Sheet (WAIS) during the last glacial maximum (LGM) and ice sheet models of deglaciation require knowledge of past ice elevations. However, data from the interior is sparse (Steig et al., 2001). Mountains that project through the ice sheet serve as dipsticks that gauge past ice elevations that are recorded by glacial deposits and erosional features preserved on their slopes (Ackert et al, 1999; Stone et al. 2003). The Ohio Range, located at the southern end of the Transantarctic Mountains (85°S, 114°W), and near the WAIS ice divide is ideally situated to record past ice elevations in this interior sector of the WAIS (Figure 1).

The Ohio Range forms an east-west trending escarpment rising 500 m above the adjacent surface (~1550m) of the WAIS. During the 2004-2005 field season we mapped trim lines and sampled glacial erratics at Discovery Ridge, Darling Ridge and several nunataks along the escarpment (Figure 2). At Discovery Ridge, granite erratics first reported by (Mercer, 1963), occur on a bedrock bench at an elevation of 1725 m. The lack of erratics on the sedimentary rocks comprising the slopes above the terrace suggests that the ice level was not significantly higher. A trim line, determined from the lowest elevation of delicate weathering features occurs at 1765 m on Discovery Ridge and at 1750 m on the adjacent Treves Butte provides a maximum ice elevation at this location. Along ridge Darling Ridge, fresh-looking erratics occur at elevations up to 1705 m. Cavernous weathering with delicate features are preserved on the cliff about 20m above. A transition from smoothed to deeply weathered rock is evident at a similar elevation on the adjacent ridgeline near the northern end of Darling ridge. This trim line indicates a maximum WAIS elevation of ~1725 m at Darling Ridge. Assuming that the trim lines at both locations are the same age, these observations are used to reconstruct a WAIS surface 150 - 200 m higher than the present ice surface. However, the age of the trim line is not certain; it may correspond to the last ice expansion (LGM) or an earlier event.

The age of the most recent high stand of the WAIS at the Ohio Range is constrained by cosmogenic ^{3}He and ^{10}Be exposure ages of glacial erratics near the trim line. The combination of weathered bedrock surfaces and minimal erosion by cold-based ice means prior exposure of erratics is likely. Cosmogenic ^{3}He was measured in 44 erratics in order to screen the samples for prior exposure prior to selecting samples for ^{10}Be. Although helium is known to diffuse out of quartz, at Antarctic temperatures, diffusion is slow enough that significant ^{3}He is retained (Brook et al., 1993). Sample preparation for ^{3}He is significantly faster, requiring no wet chemistry and the isotopic measurements are made using conventional mass spectrometry rather than AMS. Consequently, sample through-put is higher and more samples can be run at less cost. Although we collected only angular granite erratics with little evidence of weathering for exposure dating, we found prior exposure to be pervasive with only seven ^{3}He ages less than 20 ka. We take the youngest ^{10}Be exposure ages as the best estimate of the age of ice surface lowering from the elevation of the samples. The ^{3}He and ^{10}Be exposure ages of the youngest sample from Discovery Ridge (1725 m) are indistinguishable with a mean of 10.3 ± 0.6 ka. At Darling Ridge (1705m) the ^{10}Be age (12.5± 0.9ka), is slightly older than the ^{3}He age (9.3 ±0.3 ka). These samples indicate that ice elevations remained within 20 m of the trimline until ~12.5 ka at Darling Ridge and that Discovery Ridge bench remained ice covered until ~ 10 ka.

These ages are similar to the beginning of ice lowering at Mt Waesche, near a Dome of the WAIS in Marie Byrd Land that also began ~10 ka (Ackert et al., 1999). These results indicate that maximum WAIS elevations were ~1750 m at the Ohio Range and that ice elevations remained within 20 m of the trimline until 10 ka. These results place the first constraints on interior ice elevations near the WAIS divide during the last glaciation. As such they provide benchmarks for ice sheet models that attempt to capture the dynamics of the WAIS.

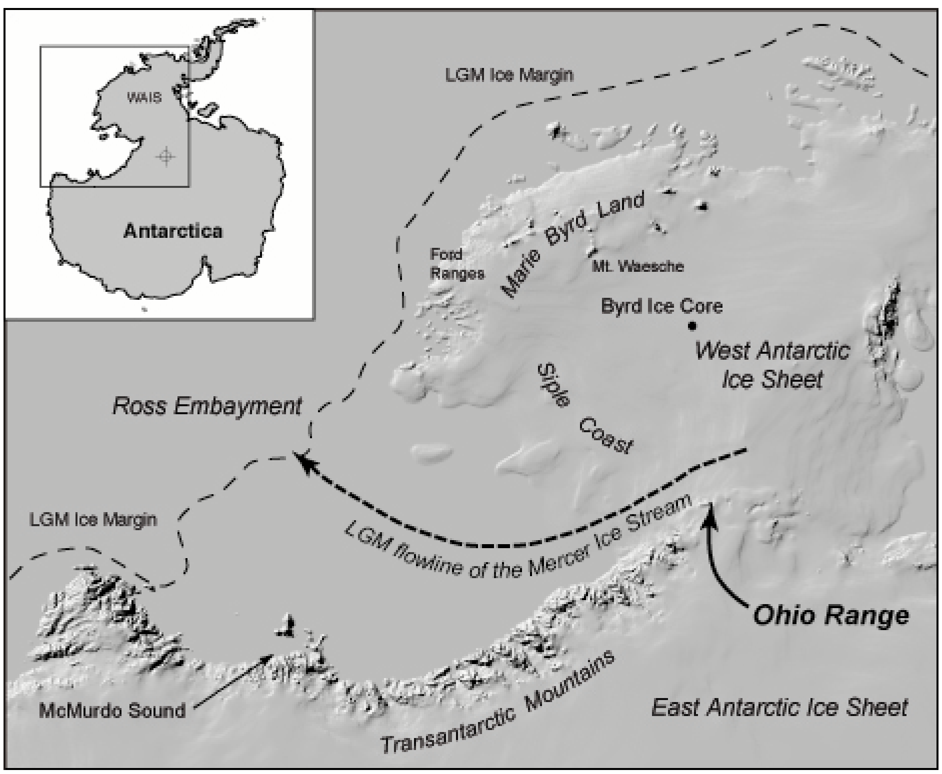

Figure 1. Radarsat image of the WAIS. Near the onset area of the Mercer Ice Stream and the WAIS divide, the Ohio Range is ideally situated to record past ice sheet elevations in this key region of the WAIS.

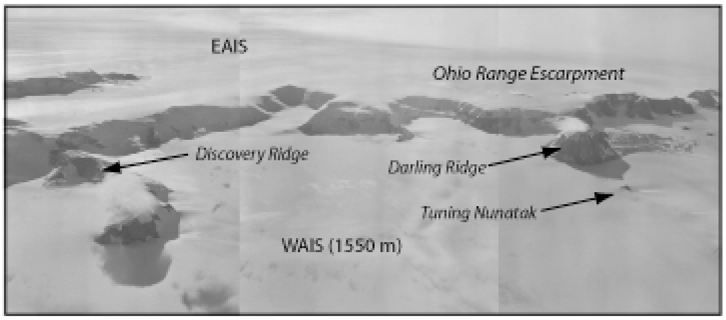

Figure 2. Oblique view of the Ohio Range Escarpment looking toward the south showing localities discussed in the text. The trimline is at the elevation of the arrows on Discovery Ridge and Darling Ridge. Because relatively little ice flows over the escarpment from the EAIS, ice elevations at the base of the escarpment are determined by the WAIS.

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Sea-swell interaction with ice shelves: Observations at a site on the Ross Ice Shelf and a model of swell-excited ice-shelf vibration

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It has been shown that storm events in the far field, e.g., in the tropics, and as far away as the high latitudes of the opposite hemisphere, are observable in seismic signals recorded on icebergs and ice shelves as well as at long-term land-based seismic stations (MacAyeal et al., in press; and Wadhams et al., 1983). Previous studies have observed the motion and induced stresses on small tabular icebergs and have suggested that sea swell is a mechanism capable of breaking up icebergs (Wadhams et al., 1983; Holdsworth and Glynn, 1978). This study presents data collected using broad-band seismometers installed at various locations on the Ross Ice Sheet. One seismometer location, called Nascent Iceberg, is expect calve and become another large tabular iceberg as a result of a large rift that currently is propagating parallel to the icefront, about 30 km back. Another seismometer is located near Scott Base, on the McMurdo Ice Shelf. This second site offers the opportunity to calibrate the "microseism" observations of the land-based seismometer so that it can be used to extend the observation of sea swell influences on the Ross Ice Shelf to times prior to seismometer deployment, e.g., to the time when B15 and other icebergs originally calved. We will describe the motion of the ice shelf during the 2004 and 2005 austral summer, and correlate the observed motion to size, duration and distance of far-field storm events. If sufficient progress permits, we will also present the results of finite-element modeling of sea-swell/ice-shelf interaction that addresses the possible influence of swell in the calving process.

Impacts of an accumulation hiatus on the physical properties of firn at a low-accumulation polar site

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Recent field investigations of a megadunes region of East Antarctica provide evidence that differences in grain size, thermal conductivity, and permeability across a megadune are due to relative accumulation patterns in the absence of significant variations in microclimate. The differences in accumulation patterns include distinct areas of perceptible but low accumulation (less than 40 mm w.e. a^{-1}) and areas of accumulation hiatus within several kilometers proximity, as determined by remote sensing, surface feature classification, and GPR (ground penetrating radar) profiling. We show that near-surface firn properties are very sensitive to the amount of accumulation in low accumulation rate regions, with relatively small differences in accumulation rate (less than 40 mm w.e. a^{-1}) creating large differences in grain size, thermal conductivity, and permeability, accompanied by distinct variations in satellite-based microwave data from both passive and active sensors. The differences in physical snow structure due to varying levels of recrystallization between low accumulation areas and accumulation-hiatus areas in the near-surface are sufficiently distinct that evidence of a past accumulation hiatus should be observable in the physical and chemical properties of an ice core.

What Gravity Can Tell Us About West Antarctica:

A Close Look at Thwaites Glacier and a Plan for Future Holistic Studies

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As the climate warms, the potential for rapid discharge of the West Antarctic Ice Sheet (WAIS) grows. Despite our recent activity towards understanding the WAIS' behavior, our community is currently unable to predict the magnitude or spatial extent of the WAIS' response to global warming. One of the reasons that we are unable to do so is that our current WAIS models- while improving rapidly- still fall short of accurately representing ice dynamics. The West Antarctic subglacial environment, for one, is fundamentally different than that of East Antarctica and yet ice sheet models use constants for lithospheric thickness, mantle rheology, and subglacial heat flux that are entirely appropriate for East Antarctica, but inappropriate for West Antarctica. The complicated tectonic history of West Antarctica causes these particular boundary conditions to be spatially heterogeneous. In order to better constrain these boundary conditions, we must stitch together our "up-close" subcontinental-sized surveys (that capture much of West Antarctica's small complexities, such as sediment and volcanics distributions) into a more holistic view that will be useful to WAIS modelers. Towards this end, we present here our most recent "up-close" airborne geophysical survey in West Antarctica and then we fold this survey into our holistic plan for examining West Antarctica's subglacial geology and lithosphere.

The threat of rapid WAIS collapse is stronger in the Amundsen Sea Embayment (ASE), which contains two of the fastest moving and highest discharge outlet glaciers in West Antarctica: Thwaites and Pine Island Glaciers. However, boundary conditions that affect the flow of these glaciers- such as sediment distribution and bedrock characteristics- have been previously unknown and, therefore, are inaccurate in current ice flow models of the catchments. In order to provide better constraints, the University of Texas (supported by NSF) conducted an airborne survey of the Thwaites Glacier catchment during the 2004-2005 austral summer. The British Antarctic Survey worked concurrently to complete an assay of the neighboring Pine Island Glacier catchment. Our surveys are the first and only large-scale geophysical surveys of this area. Over 43,500 line-km of data were collected by UT with an aerogeophysical platform that included ice-penetrating radar, gravity, magnetics, laser and pressure altimetry, and GPS.

With respect to gravity, this was a very atypical airborne survey. Planned altitude changes were necessary to keep the ice-penetrating radar within its optimal distance of ~500m from the steeply sloped ice surface. Airborne gravity meters, however, are notorious for being unable to recover quickly from the large accelerations induced by flight elevation changes, often resulting in greater than 30 min of irrecoverable data post-maneuvering. However, this survey was the first use of a LaCoste & Romberg Air/Sea II gravimeter in an airborne survey. The new Air/Sea II performed beyond expectation and data loss was limited to only the immediate area of the elevation change. Careful flight planning minimized the impact of this data loss on the final gravity products.

Here we present our primary results of free-air and 3-D Bouger gravity anomalies for the Thwaites Glacier survey. We assess the theoretical anomaly detection threshold, actual anomaly resolution, and data error. Upon comparison of the gravity anomalies with our airborne magnetics and subglacial topography results, we delineate West Antarctic crustal block boundaries and postulate their controls on the flow of the ice sheet through this area. Since the area of the Thwaites catchment (~800 x 600 km) is very large, we are able to compare the best extant satellite gravity anomalies to the long-wavelength airborne ones. This provides ground-truth for the Gravity Recovery and Climate Experiment (GRACE) satellite data and yields a feel for the inability of our community to use this satellite data at the limits of its resolution. In the end, this ground-truth comparison highlights the benefits using satellite and airborne gravity measurements in tandem to significantly improve satellite gravity measurements.

In a holistic sense, two different methods have already been used to provide modelers with constraints for lithospheric thickness and subglacial heat flux: surface wave tomography (Shapiro and Ritzwoller, 2004) and satellite magnetics (Fox Maule et al., 2005). However, these two models differ greatly and a third is needed to resolve their differences and improve on their coarse (~200km) spatial resolutions. The results presented here show that gravity can be used for such a task in West Antarctica where the spatial coverage is now available, especially since gravity can be constrained there by a suite of other geophysical measurements. It may be time to look past typical small-scale airborne gravity analysis and also consider gravity data holistically- on a continent scale; perhaps then we will be able to provide WAIS modelers with the spatially-dependent solid earth constraints that they need.

Basement control and history of ice-sheet expansion in the Amundsen Sea Embayment - First results of recent RV *Polarstern* and RRS *James Clark Ross* cruises

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The Amundsen Sea embayment lies between the Palaeozoic crustal blocks of Marie Byrd Land, Ellsworth Land and Thurston Island. Its continental margin is conjugate to the passive margin of the eastern New Zealand submarine continental plateaux and Bounty Trough, which underwent major extension during Cretaceous rifting between New Zealand and West Antarctica. Later, the embayment seems to have played a role as a plate boundary while the Bellingshausen Plate acted as an independent microplate until the early Tertiary. It is likely that the tectonic architecture, through the formation of deep basins and erosional troughs, laid the foundation for major glacier outflow from the West Antarctic Ice Sheet into Pine Island Bay and the South Pacific since early West Antarctic glaciation.

During successive cruises on RRS *James Clark Ross* (cruise JR141) and RV *Polarstern* (expedition ANT-XXIII/4) in early 2006, we collected seismic, bathymetric, sub-bottom profiler and helicopter-magnetic data from the inner shelf, outer shelf, slope and deep sea of the Amundsen Sea embayment and Pine Island Bay, to address tectonic as well as sedimentary objectives. We will present preliminary results indicating the disposition of structural basement units and the role the tectonic basement and pre-glacial sediments have played as controlling parameters for ice-sheet expansion and retreat in the Amundsen Sea Embayment.

Aeromagnetic results from the Thwaites Glacier catchment, West Antarctica

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The glaciers of the Amundsen Sea Embayment (ASE) have become a focus for integrated studies by both the U.S. and European scientific communities due to satellite observations of non-steady behavior and the ASE's dominant role in WAIS mass balance. In order to accomplish some of the primary objectives of the Amundsen Sea Embayment Science Plan and to guide future surface-based research, the University of Texas (UT) and the British Antarctic Survey (BAS) undertook a comprehensive aerogeophysical survey encompassing the two major drainage basins within the Amundsen Sea Embayment - Pine Island and Thwaites glaciers. This survey was conducted during the 2004/05 austral summer, operating from two remote field camps and using two survey aircraft.

The multidisciplinary nature of coupled lithosphere and ice sheet studies requires a broad approach for which multi-instrumented airborne surveys are well suited. Radar sounding data were acquired to determine bed morphology and ice thickness [Holt et al., 2006; Vaughan et al., 2006], necessary to calculate ice sheet driving stress and hydrologic potential. Gravity and magnetics data were collected to help identify crustal blocks, sedimentary basins, volcanic activity, and to characterize geothermal flux, all of which are critical to models of ice sheet dynamics. Laser surface elevations were acquired to enable detailed mass balance calculations and satellite altimeter calibrations.

This presentation describes aeromagnetics results for the Thwaites catchment acquired by UT. Over 43,500 line-km of total-field aeromagnetic data were acquired with a towed Geometrics cesium magnetometer. Geometrics cesium base station magnetometers acquired data for diurnal variations of the geomagnetic field. Due to the gridded nature of the survey, crossovers were plentiful providing the means to remove diurnal variations far from the base stations. Data reduction included base station and IGRF corrections followed by leveling.

Although the Thwaites catchment is dominated by an erosional landscape [Holt et al., 2006], the underlying crustal structure may have a strong influence on the distribution of geothermal flux and hence, ice dynamics. Previous studies indicate a general scenario of geologic complexity, with the deep Byrd Subglacial Basin tenuously connected to the West Antarctic Rift System and bounded by the Marie Byrd Land volcanic province to the northwest and the Thurston Island Ellsworth/Whitmore blocks to the northeast and east, respectively [Dalziel and Elliot, 1982; Behrendt et al., 1992; Dalziel and Lawver, 2001]. The aeromagnetic data will enable better delineation of subglacial geology in the Thwaites catchment than previously possible, especially when combined with radar sounding and aerogravity results. These new data will contribute to improved constraints on important basal boundary conditions needed for modeling ice dynamics in the Amundsen Sea Embayment.

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Crossing the "T" in Antarctica

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In the Battle of Trafalgar, the British fleet demolished the Franco-Spanish fleet by abandoning the traditional deployment of aligning the two fleets side-by-side and blasting away with broadsides. Instead, as the Franco-Spanish fleet sailed slowly northward, the British fleet approached from the west and crossed the path ahead of the Franco-Spanish fleet, aiming broadsides at the lead ship, sinking it, then aiming broadsides at the next ship as it approached, and so on, until nearly the entire Franco-Spanish fleet was sunk or disabled with no losses to the British fleet. This tactic took advantage of the fact that ships-of-the-line in the days of sail had few cannons in the bow. It became known as crossing the "T" in the annals of naval engagements.

Our poster presents a similar tactic for mastering the dynamics of ice discharged from the Antarctic Ice Sheet by way of ice streams. Studies of West Antarctic Ice Streams show that tributaries develop in slow sheet flow and converge to produce fast stream flow. How these tributaries develop is a major unsolved glaciological problem. Crossing the "T" consists of designing an ITASE tractor-train traverse that crosses the tributaries of major ice streams along the main traverse, and then crosses the main traverse with a side traverse that follow a central flowline into the main trunk of the ice stream. This has the advantage of collecting data from several tributaries, to get a sense of how they develop in separate paths, and then follow the main path to track development along flow. This captures development of stream flow transversely and longitudinally. It overcomes a main drawback of "flowband" modeling while avoiding the logistical cost of establishing a traverse grid needed for gridpoint modeling in the map plane.

Two applications of crossing the "T" are presented. The first application will take place during the 2006-2007 ITASE traverse from Taylor Dome to the South Pole. It will consist of crossing the upper end of tributaries feeding into Byrd Glacier, crossing the "T" with a traverse along part of the flowline from Vostok Station to Byrd Glacier. This will connect glaciological records at Vostok and climate records down the Vostok corehole with the ITASE data set and surface velocity data on Byrd Glacier spanning a half-century. It will complement a proposal submitted to NSF to map Byrd Glacier and the zone of tributary glaciers by radar sounding to the bed. A similar strategy is contemplated for another outlet glacier, perhaps Beardmore Glacier, during the 2007-2008 leg of the ITASE traverse.

The other application is presented here as a proposal. After completing the 2007-2008 leg of the ITASE traverse, the tractors will continue to the site of the WAIS deep-drilling site on the West Antarctic ice divide. We propose that the route be around the east side of

Crary Mountains near the heads of Foundation Ice Stream and Support Force Glacier, which deliver the great bulk of East Antarctic ice through the Bottleneck into West Antarctica. This, combined with the already-completed ITASE traverse through the Bottleneck on the west side of Crary Mountains, will provide comprehensive data for modeling discharge of East Antarctic ice into both the Ross and Weddell sectors of West Antarctica. It will allow prognostic modeling of how much East Antarctic ice can be discharged through the Bottleneck as (and if) the West Antarctic Ice Sheet continues its Holocene gravitational collapse. This traverse would also be crossing the "T" and it would look to the future on a scale much larger and more important than what took place by way of Byrd Glacier (and Beardmore Glacier) as the West Antarctic Ice Sheet collapsed in the Ross Sea Embayment to leave the Ross Ice Shelf.

These applications of crossing the "T" in Antarctica provide a pilot study (or studies) of Byrd Glacier (and Beardmore Glacier) that will prepare us for a study of the main event aimed at predicting future ice discharge through the Bottleneck.

Analysis of Bed Properties on Kamb Ice Stream with Constant Midpoint Radar Profiles

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Constant midpoint radar profiles (CMP's) illuminate a fixed area on the bed or an internal reflector from a variety of angles, thereby allowing the target to be imaged through a range of ice path lengths (the so-called moveout). These experiments can be used to study ice properties (eg. velocities and attenuation) and also the reflectivity of the internal layers or areas on the bed.

Four CMP experiments were carried out on Kamb Ice Stream (KIS) in locations where the bed is suspected to be water-saturated and dry. Two of these were done as an orthogonal pair in the same (wet) location to test for anisotropy within the ice. RMS velocities to all imaged internal reflectors and the bed have been calculated for each of the profiles using a semblance analysis. RMS velocities decrease with depth to values near 173 m/μs as higher velocities within the firn make a smaller contributing fraction. From these RMS velocities we extract a velocity versus depth function at each location.

We have also modeled the variation in reflected power as a function of illumination angle (and thus path length) based on the Radar Equation and Fresnel's Equations. From these calculations we have extracted the coefficient to the exponential term in the Radar Equation accounting for the dielectric losses due to scattering and attenuation. These losses can be characterized by the mean path length in the ice, L, for radar reflectivity to decrease by 1/e. By comparing L for internal layers and the bed at different depths, we find a rough measure of the mean absorption path length as a function of ice thickness, L(z). In these studies, reflections from deeper ice show more absorption per unit length than reflections from shallower ice, presumably showing the effects of temperature on absorption with colder ice in the upper layers being less absorptive.

Knowing the absorption losses based on the path increase from the individual cmp moveouts, we use this information to compute the depth-corrected reflectivity of internal layers and of different locations on the bed. From this we characterize the dielectric reflective properties of these respective regions and internal layers. Our results show that the deep wet bed in the northern branch trunk of KIS still flowing in excess of 100 m/a is several orders of magnitude more reflective than the bed in the lower trunk.

Why Don't they Match? The Evolution of Flow Stripes and Internal Layers on Kamb Ice Stream

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Flowstripes are ubiquitous features indicating fast ice flow on glaciers, ice streams and floating ice shelves. According to model studies by Gudmundsson and Raymond (1998) they are an expected consequence whenever velocity at the bed is large compared to shearing through the ice thickness. Under these conditions, basal undulations are effectively transmitted to the surface where they are advected for long distances downstream. Folding of internal layers depicted in radar profiles is also a common occurrence in ice streams. In the case of Kamb Ice Stream (KIS), "stacks" of internal layers folds on the scale of 1-3 kilometers in wavelength in the cross-flow direction have been traced for over 100 kilometers (Ng and Conway, 2004). The question is what relationship, if any, do these folds have with respect to surface flowstripes?

We have traced surface flowstripes in Radarsat and MODIS imagery for several hundred kilometers on KIS from the onset of streaming flow into the stagnant trunk. We compare the morphology and evolution of these features at the surface to the internal layer folds in cross-ice stream profiles at five transects along the length of KIS, including those analyzed by Ng and Conway (2004). We find little correspondence between the radar internal layer folds in the cross-flow direction and the flowstripes on the surface directly above. The wavelengths of internal layer folds generally begin with a range of 1-3 km and tend to converge downstream, ending with wavelengths typically less than a kilometer. Flowstripes, though having similar wavelengths (on the order of 1.5 to 3 km at onset), remain roughly subparallel for many kilometers, eventually becoming less distinct as the ice stagnates but retaining their separation. We are thus able to identify examples where flowstripes cross above internal layers.

The amplitude of internal layer folds we have measured decreases towards the surface in a way that suggests they are formed by stresses at the bed in the same way as flowstripes analyzed by Gudmundsson and Raymond (1998). This decay in amplitude is consistent with the scale of topography of the folds at the surface, so the issue is, if the flowstripes are the surface expression of the internal folds, why don't they match? We suggest that topographic features on the ice surface are subject to processes that can modify their morphology leading to changes in the pattern of folds relative to the internal layers below. We explore hypotheses about how flowstripes can evolve differently from the folds in internal layers.

Surface exposure dating using cosmogenic isotopes: a field campaign in Marie Byrd Land and the Hudson Mountains

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We present preliminary findings from fieldwork undertaken in Marie Byrd Land and western Ellsworth Land in March 2006, during which we obtained the first (to our knowledge) samples for surface exposure dating from eastern Marie Byrd Land and the Hudson Mountains. This work was supported by helicopters from *RV Polarstern*, on expedition ANT XXIII/4 to Pine Island Bay.

Samples were taken from glacially-derived erratic boulders found on bedrock surfaces at Turtle Peak (near Mount Murphy), Hunt Bluff (Bear Peninsula), Mount Manthe (Hudson Mountains), and an unnamed island in Pine Island Bay. Granite and granitoid erratics were found at all locations except Hunt Bluff, where metasedimentary erratics were found lying on granite bedrock. Striated surfaces were found only at Hunt Bluff.

We plan to undertake exposure dating of the quartz-bearing boulders using the cosmogenic isotopes, ^{10}Be and ^{26}Al. Surface exposure dates from these boulders will provide a record of elevation change for the ice sheet surface in this region, and thus will help to constrain thinning of the ice sheet since the Last Glacial Maximum. They will also be used in conjunction with radiocarbon dates from marine sediments (obtained on this expedition as well as on the *RRS James Clark Ross* cruise to the Amundsen Sea in early 2006) to provide a more complete deglaciation history, i.e. to assess both the vertical and lateral retreat of the WAIS. A well-dated record of changes in the extent and thickness of the ice sheet earlier in the Quaternary will provide strong constraints for ice sheet models and thus aid efforts to predict future behaviour of the WAIS. To this end, we aim to collect a greater density of geomorphological data and samples during a BAS-supported field season to the Hudson Mountains in 2007/08.

Better physics using full momentum solver in 2D vertical slice domain, where does longitudinal stress really matter? Application to the Thwaites Glacier flowline

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The commonly used shallow-ice approximation neglects all stresses except the basal drag, an assumption that is very good for inland ice but may be very poor for fast-flowing, low-surface slope ice streams, where longitudinal stresses may not only be important, but may in fact be the dominant stress [fastook04b]. A higher-order approach is to couple the mass- and momentum-conservation equations (the prognostic and diagnostic equations [macayeal97]) and solve with no neglected stresses. In the process of developing such a full-momentum solver in 3D, for embedded application within the map-plane University of Maine Ice Sheet Model (UMISM) [fastook93c], we are testing a 2D simplification which models a vertical slice through the ice sheet along a flowline. This allows us to do two things: 1) implement and test the complex boundary conditions that must be specified for a full-momentum solver, and 2) evaluate when and where longitudinal stresses are important or even dominant.

Specification of the differential equation describing conservation of momentum (also referred to as the "balance of forces") allows for two types of boundary conditions [thjhughes87]: 1) Dirichlet, where the state variable, in this case the velocity, is specified, and 2) Neumann, where the conserved flux, in this case the force applied on the boundary, is specified. Where the bed is frozen, Dirichlet boundary conditions are the obvious choice, as the velocity is zero and can be specified as such. Where the bed is not frozen, where sliding is occurring (for example, in ice streams, where our shallow-ice approximation breaks down), we cannot specify the velocity, but instead must specify the force exerted on the ice by the bed in resisting its forward motion. We know that this resistive force cannot exceed the driving stress (if it equals the driving stress, we have the shallow-ice solution). A temptation is to use some fraction of the driving stress, and indeed, this approach does produce the concave profile characteristic of an ice stream, but the fraction is hard to define (a model parameter). A better approach, and the one we have taken, is to use a boundary-layer. We can preserve our Dirichlet-type specification of zero velocity on the boundary, but allow greater deformation within the boundary layer to simulate sliding at the bed. This soft layer can be interpreted either as a deformable till or as a layer of water-saturated ice at the melting point (slush). In either case its thickness will be negligible compared with the ice thickness, and while the geometry and mechanical properties (how thick and how soft) are still difficult to define, at least they have a physical meaning, which is a good thing for a model parameter to have.

We apply this to a flowline along the Thwaites Glacier in the Amundsen Sea sector using excellent new data from the Airborne Geophysical survey of the Amundsen Sea Embayment (AGASEA), by University of Texas [holt06] and British Antarctic Survey [vaughan06] teams.

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The dynamic drift of mega-icebergs in the Ross Sea

Young-Jin Kim, Doug MacAyeal

Current estimates suggest that a few giant-tabular icebergs account for roughly half of the fresh water flux due to icebergs into the Southern Ocean. Since mega-icebergs drift over a period of several decades and inject their meltwater elsewhere they represent a kind of teleconnection between parent iceshelf and the rest of the Southern Ocean. Locally they modify sea ice conditions, coastal ecosystems and create logistical challenges for Antarctic field operations. Despite their many documented impacts, their drift pattern is still not well understood. We present in situ observations from our autonomous AWS/GPS stations over the last 6 years and our prognostic numerical model of iceberg drift. Our observations clearly show that mega-icebergs once set in motion frequently interact with the parent iceshelf through highly energetic collisions, which in turn might lead to a weakening of the parent iceshelf and initiate a subsequent calving response. Implications for paleo-studies of ice-rafted debris and meltwater flux into the Southern Ocean will be discussed.

The delights of Delores:
The new B.A.S. DEep LOok Radio Echo Sounder

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The British Antarctic Survey's Delores system (Deep Look Radio Echo Sounder) is a daughter of the Washington and St. Olaf radars. It is a 1-4 MHz monopulse radar configured for towing by skidoo. It was deployed during the 05-06 season on the Rutford Ice Stream, Fletcher Promontory and Berkner Island.

The poster provides details of:

1. Construction and deployment
2. Data processing
3. Problems
4. Solutions

The data examples show:

1. Raymond bumps
2. Drumlinised bed topography
3. Shear margins * both stable and outward-stepping
4. Comparison of radar and seismic bed reflectivity

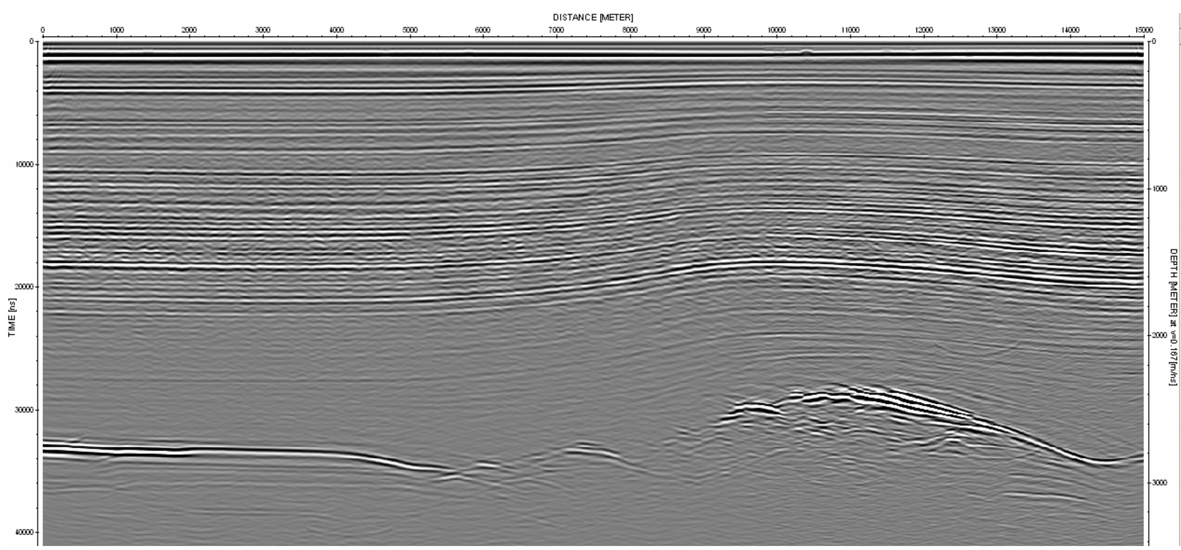

Figure 1. Part of an in-flow profile from Rutford Ice Stream acquired with Delores

Histories of Accumulation and Ice Dynamics from Radar Layers and Ice-Flow Inverse Methods

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Depth-age relationships from ice cores contain a record of past accumulation and ice-sheet dynamics. Profiles of radar-detected internal layers (assumed to be isochrones) add the spatial dimension to temporally resolved records from ice cores. The deeper, older layers record conditions from further in the past, but they have also been subjected to larger horizontal gradients in strain and accumulation, making them more difficult to interpret than near-surface layers. As the depth to the layer increases to a larger fraction of the total ice thickness, accumulation rates based on depth variations alone or corrected using a 1-D flow model are no longer appropriate. We use a flow-band model to calculate ice-surface and layer evolution and to predict internal layer positions and shapes. Solving this forward calculation requires information about spatial and temporal variations of accumulation rate and ice sheet dynamics, which are not known. Inverse methods are used to find physically reasonable values for the unknown parameters that generate internal layers that fit the data within a defined tolerance. This procedure assimilates radar data to extract a spatially and temporally variable accumulation history as well as information about ice divide migration and ice thickness evolution.

We report on development and application of this tool. Future work will focus on obtaining histories of accumulation and ice dynamics for portions of the West Antarctic Ice Sheet (WAIS). Extensive airborne and ground-based radar data obtained over the inland WAIS will be used to help interpret the upcoming ice core near the Ross-Amundsen ice divide. Our modeling will provide information about divide migration, ice thickness changes, and accumulation variations during the most recent deglaciation. This information is needed to calculate ice-volume history of the WAIS, and to provide calibration for testing paleoclimate global climate models.

National Snow and Ice Data Center: Antarctic Data Management Support

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The National Snow and Ice Data Center (NSIDC) operates two Antarctic data management projects for the National Science Foundation's Office of Polar Programs (OPP).

The U.S. Antarctic Glaciological Data Center (AGDC) provides data management for the U.S. Antarctic Glaciological Program and related cryospheric science investigations. AGDC archives and distributes physical and geochemical data from ice cores, ice surface elevations, ice thickness, and bedrock topography, snow accumulation data and 10-meter temperatures, ice velocity measurements from remote sensing imagery and field survey data.

The U.S. Antarctic Data Coordination Center (USADCC) provides a U.S. focus for the development of data set descriptions (metadata in the form of Directory Interchange Format entries) for the Antarctic Master Directory (AMD). The AMD contains more than 3000 data set descriptions submitted by 22 countries with Antarctic science programs. The USADCC provides access to easy to use web based tools to create metadata, and can advise investigators on compliance with the OPP Guidelines and Award Conditions for Scientific Data.

Recent data acquisitions for the AGDC include AWS, GPR, and GPS data for the megadunes region of East Antarctica (Scambos, Fahnestock), ice core data from medium-depth coring at the South Pole (Severinghaus), Siple Dome ice core data (Saltzman and Aydin), Siple Coast radar data (Conway and Raymond), and ITASE glaciochemical data (Dixon and Mayewski). Further, we are providing documentation and links to the PI-generated distribution site for Amundsen Sea Embayment aero-geophysical data.

NSIDC is also pursuing new approaches to data representation, data discovery, and data ordering through the use of interactive geo-spatial search tools. The Mosaic of Antarcitica serves as a basemap, implementing a Minnesota Map Server functionality that contains several additional data and metadata layers. The site is useful for quick evaluation of potential field site, and for locating more detailed data available upon request.

Rebuilding glacial retreat histories using inverse methods and surface exposure age data

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Ice thinning and retreat at Reedy Glacier, in the southern Transantarctic Mountains, is controlled by the thickness of grounded ice in the southern Ross Sea. Thus, the surface profile of the glacier is an indicator of the extent and volume of grounded ice in the Ross Sea Embayment, the largest embayment in West Antarctica. We want to reconstruct the evolution of the surface profile of Reedy Glacier from the Last Glacial Maximum (LGM) configuration to the modern ice surface in order to constrain LGM ice thickness in the southern Ross Sea and to improve constraints on the region's contribution to sea level since the LGM.

Surface exposure ages from lateral deposits at Reedy Glacier track the retreating ice margin and provide a chronology of retreat at different locations along the length of the glacier, but sampling is often limited by the availability of glacially-derived material at accessible and appropriate sampling sites. As a consequence, even exhaustive sampling of suitable sites can result in an incomplete or piecemeal deglaciation chronology. To address this problem, we use a one-dimensional, steady-state glacier flowband model to infer past glacier surfaces between locations of contemporary deposits. This forward model requires estimates of the flux of ice into the head of the glacier, accumulation rate at discrete locations along the length of the glacier, bed elevation, glacier width, and an ice elevation at the mouth of the glacier. We are developing an inverse procedure to apply to our forward model that will solve for the glacier surface history that best fits the surface exposure age data. Our procedure will find a tradeoff between fitting the data and requiring model parameters to be smooth in time. Through this study, we hope to constrain the range of possible LGM ice thicknesses in the southern Ross Sea, improve our understanding of the response of Reedy Glacier to deglaciation, and develop an inverse procedure applicable to other surface exposure age data sets from glacial environments.

LIMA: Progress on the Landsat Image Mosaic of Antarctica: An IPY Project

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Jerry Mullins, Charles Larson, Rachel Kurtz, and Douglas Binnie,
EROS Data Center, U.S.Geological Survey
Andrew Fleming, British Antarctic Survey
Patricia Vornberger, Science Applications International Corp.

Since the launch of Landsat-7 in April 1999, over 20,000 images of Antarctica have been acquired, offering unprecedented coverage of the continent by high resolution optical imagery. This quality imagery is commonly in demand for an array of scientific and aesthetic purposes that include map-making, change detection, feature tracking, surface grain size studies, and elevation mapping using "shape from shading" models. It is highly desired in field work situations for assessing the safety of surface travel and to identify safe aircraft landing sites. The International Polar Year will include extensive field programs and large amounts of scientific research on Antarctica, and there will be associated public outreach activities. Landsat data are perfectly suited to many purposes involving the IPY, and beyond. While the other image data available for Antarctica as continental-scale mosaics (AVHRR, Synthetic Aperture Radar (RAMP), and MODIS (MOA)) are in common use, their coarser spatial resolution or microwave wavelength does not match the level of utility that would be provided by a Landsat mosaic, particularly for field planning.

The creation of a digital Landsat mosaic of Antarctica to 82 degrees South latitude has been funded by the National Science Foundation and the British Antarctic Survey (BAS). Scene selection performed at NASA Goddard Space Flight Center identified 1058 individual images for the mosaic, 60 of these scenes cover the Antarctic Peninsula, and the Peninsula portion of the mosaic will be generated by BAS. The digital mosaicking of the remainder of the continent will be performed at the U.S. Geological Survey's EROS Data Center. Distribution of the final products will be handled by the National Snow and Ice Data Center.

Technical details of mosaicking include processing individual images to Level 1G and then orthorectifying them. A comparative study of 3 candidate DEMs of Antarctica resulted in the RAMPv2 DEM being chosen as the base for orthorectification. Individual bands will next be transformed from radiance to reflectance values, and then mosaicked. The final step will be contrast enhancement to optimize the detail seen in all types of terrain. This will be accomplished by use of an adaptive filtering method that is under development.

Available products planned are a panchromatic band mosaic at 15 meter resolution, a 3-band false color composite at 30 meter resolution, a 3-band true color composite at 30 meter resolution, and the individual Level 1G orthorectified scenes. We aim for completion in March 2007.

A Two-Dimensional Coupled Model for Ice Shelf-Ocean Interaction

Ryan Walker

A simplified coupled model of ice shelf-ocean interaction including an evolving ice shelf is presented. This model is well suited to climate simulation, as it is computationally inexpensive and capable of handling significant changes to the shape of the sub-ice shelf cavity as the shelf profile evolves. The ocean component uses a two-dimensional vertical overturning streamfunction to describe the thermohaline circulation. In order to smoothly accommodate evolution of the shelf, the equations have been converted to a time-dependent terrain-following (sigma) vertical coordinate. The shelf component is a model for the flow of a confined ice shelf of non-uniform thickness, which consists of equations for longitudinal spreading rate and velocity. The advection of ice thickness has been modified to include separate marine and meteoric layers. The ice shelf and ocean interact thermodynamically through a three-equation formulation for basal melting and freezing.

The model is applied to an idealization of Filchner Ice Shelf, Antarctica. Following a 600 year simulation, the shelf is found to have reached an equilibrium which represents a loss of approximately 10% of mass relative to its steady state when ocean interaction is not considered. Significant changes in the shelf morphology are also observed, notably an increase in basal slope near the grounding line. These changes are accompanied by shifts in the pattern of basal melting and freezing. Warming of the ocean produces a greater than linear increase in basal melting on decadal timescales, gradually slowing to linear over centuries.

Spatial variability in McMurdo Dry Valleys snow and firn - the role of local soil input

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August, 2006

Samples of snow and firn from accumulation zones on the Victoria Upper Glacier, the Clark Glacier, the Commonwealth Glacier, and the Blue Glacier in the McMurdo Dry Valleys (~77 to 78º S and 161 to 164º E), Antarctica (Figure 1), are evaluated chemically and isotopically to determine the relative importance of local (site-specific) factors versus regional-scale climatic influences in defining glaciochemistry. Multivariate statistical analyses provide constraints for interpretation of connections between Dry Valleys climate and the broader Ross Sea and East Antarctic Ice Sheet climate systems. Spatial variation in snow and firn chemistry confirms documented trends within individual valleys regarding ion deposition relative to elevation and to distance from the coast. The results here, however, demonstrate that intra-valley trends break down when chemistry is compared among valleys.

Instead, site-specific exposure to marine and local (soil) chemical sources plays a dominant role in defining glacier chemistry along the coastal axis of the Dry Valleys. A survey of mean chemistry among the sites discussed here, for example, shows the Clark and Commonwealth Glaciers with the highest concentrations in marine species (350 μg/L and 167 μg/L for Na^+, 25 μg/L and 21 μg/L for MS^-), while the Blue Glacier shows unexpectedly low concentrations (72 μg/L Na^+, 10 μg/L MS^-), likely related to shelter provided by a coastal range to the east. Trace metals are in highest abundance at the Clark Glacier (Al concentration = 234 μg/L), with the lowest concentrations found at the Commonwealth Glacier (Al concentration = 45 μg/L). This result demonstrates that where chemical signals are influenced by locally derived particulates, differences in local context between two locations may overwhelm broader climate signals. In areas of complex terrain, the influence of these local factors must be understood before climate inferences can be drawn.

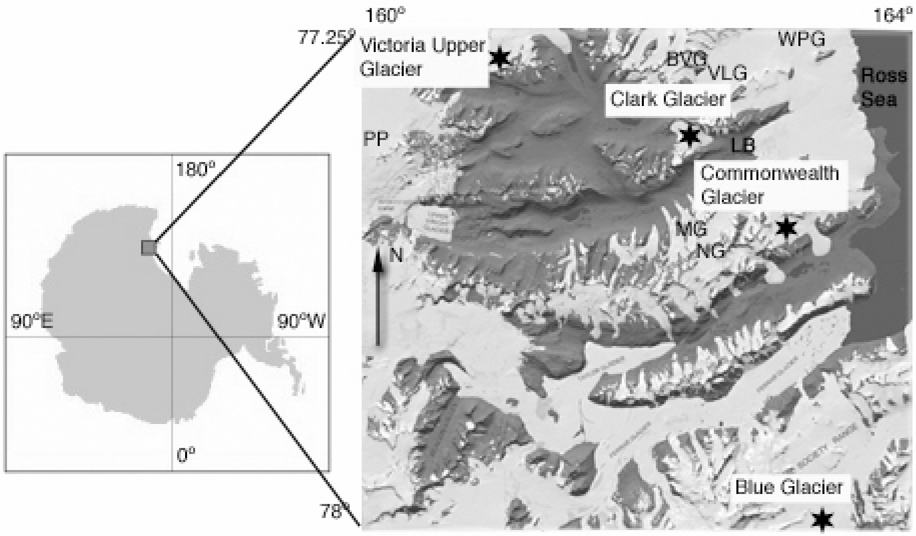

Figure 1. Index map showing locations of Victoria Upper, Clark, Commonwealth and Blue Glaciers. Base map by GeographX, 2006.

Grounding zone geometry of Thwaites, Pope and Smith Glacier, Amundsen Sea Embayment

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Exposed grounding lines abutting Antarctica's relatively warm Amundsen Sea may represent an important locus of ice sheet erosion. Recent satellite remote sensing has indicated both expansion and retreat of active grounding lines in the region, with implications for global sea level change. As part of the 2004/05 AGASEA project, the University of Texas Institute for Geophysics (UTIG) surveyed Thwaites Glacier and Smith Glacier, two major marine outlet glaciers on the Amundsen Sea coast, using an aerogeophysical platform configured for simultaneous glaciological and geological investigations. The primary glaciological tools were a high-power coherent radar sounder and a laser altimeter, positioned by dual carrier phase GPS. Coverage of the Thwaites Glacier grounding line includes nine longitudinal radar and laser altimetry profiles collected by UTIG, two longitudinal radar profiles collected by the British Antarctic Survey, and three transverse radar and laser altimetry profiles collected by UTIG. Grid spacings for Thwaites Glacier were ~15km. The Smith Glacier grounding line location is constrained by two converging longitudinal profiles and three transverse lines at 15 km spacing, all five of which are UTIG radar and laser altimetry profiles. Surface elevations and ice thicknesses were derived from these data. These laser/radar profiles allow us to analyze buoyancy across the Smith Glacier and Thwaites Glacier grounding line zones. We use laser altimetry and the GGM02 geoid model to establish local sealevel to within a meter, and using this reference and modeled firn structures, predict from glacier surface elevations apparent hydrostatic compensation depths. We compare this result to published tidal hinge lines delineated by satellite-based interferomic imaging radar between 1992 and 2000. The two methods match at the center of main trunk, but diverge considerably at the shear margins, which other work has suggested may be actively migrating. The main trunk of Thwaites Glacier floats at a relatively shallow depth, and a broad lateral sill appears to localize the grounding line. Smith Glacier has a deep grounding line, but is pinned downstream.