THE WEST ANTARCTIC ICE SHEET INITIATIVE

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level

2004 WAIS Workshop Agenda

Wednesday, September 29, 2004		
2:00 to 6:00	Registration	Floyd
7:00	Pizza, beer and snacks (cottage #1)	Bindschadler
Thursday September 30, 2004		
8:00	CONTINENTAL BREAKFAST	
8:00	Registration	Floyd
8:30	Welcome and Agenda Review	Bindschadler
8:45	NSF Remarks	Palais/Borg
	***Question #1."To the LGM and Beyond"* – What more have we learned about Antarctic paleoclimate and ice sheet configuration prior to the Holocene and how is it relevant to the near-term future of the ice sheet?**	
9:15	Perpetual Motion: The Fatal Flaw in Glaciology [Abstract]	Hughes
9:30	Glacial history of Marie Byrd Land – from thousands to millions of years [Abstract] [PDF]	Stone
9:45	Tradeoff between climate and thickness histories at Siple Dome during the past 25 ka [Abstract] [PPT]	Waddington
10:00	Constraints on the magnitude and timing of post-LGM thinning at Siple Dome from thermomechanical flow modeling [Abstract] [PPT]	Price
10:15	BREAK (30 min.)	

10:45	A Time Marker from the LGM Detected Throughout West Antarctica [Abstract] [PPT]	Jacobel
11:00	Post-LGM changes in ice stream tributary flow near Byrd Camp [Abstract] [PPT]	Welch
11:15	Internal radar layers in central West Antarctica and their implications for Holocene ice sheet changes [Abstract] [PPT]	Blankenship
11:30	**Discussion of Question #1** (30 min.)	PLENARY
12:00	Poster Introductions (1-2 min. each)	
12:30	Poster Viewing (15 min.)	
12:45	LUNCH (1 hr. 15 min.)	
	***Question #2."WAIS Look-Alikes"* - Are there good analogs to West Antarctic behavior elsewhere and what can we learn from these areas?**	
2:00	Possible Role for Surficial Lakes in Meltwater Drainage through Cold Glaciers [Abstract]	Alley
2:15	Modeling of glacial stagnation vs. glacial retreat [Abstract] [PPT]	Vacco
2:30	Numerical modelling of the Eurasian ice sheet and its relevance to West Antarctica [Abstract] [PPT]	Siegert
2:45	WAIS Analogs in Greenland? [Abstract] [PPT]	Joughin
3:00	BREAK (30 min.)	
3:30	A WAIS analog found on Mars polar cap [Abstract] [PPT]	Wang
3:45	What happened to the volcanic debris erupted beneath the West Antarctic ice sheet? [Abstract]	Behrendt
4:00	Self-help: ice streams retain more water by moving faster [Abstract]	Bindschadler
4:15	**Discussion of Question #2** (30 min.)	PLENARY
4:45	International Polar Year (International Planning) [PPT]	Bindschadler
5:00	International Polar Year (US Planning) [PDF]	Albert
5:15	Plans for the 2004-05 Airborne Geophysical Survey of the Amundsen Sea Embayment, Antarctica (AGASEA) [Abstract]	Holt

5:30	Poster Viewing	
6:00	DINNER	
Friday, October 1, 2004		
8:00	CONTINENTAL BREAKFAST	
	***Question #3 "Wild, Wild West"* – What is the latest on variability of the West Antarctic ice sheet and its environment during the Holocene (last 10,000, or so)?**	
8:30	Environmental variability and change impacts on firn memory in West Antarctica [Abstract] [PDF]	Albert
8:45	Antarctic temperatures since 1856 [Abstract] [PPT]	Steig
9:00	Holocene Summer Temperature Increase in West Antarctica [Abstract] [PPT]	Das
9:15	Implications of the deuterium excess record from the Siple Dome ice core [Abstract] [PPT]	Schilla
9:30	A 200-Year Sulfate Record from 16 Antarctic Ice Cores and Associations with Southern Ocean Sea Ice Extent [Abstract] [PPT]	Dixon
9:45	West Antarctic Ice Core Chemistry and Self-Organizing Maps: A First Look [Abstract] [PPT]	Reusch
10:00	BREAK (30 min.)	
10:30	Warm ocean is eroding West Antarctic ice sheet [Abstract] [PPT]	Shepherd
10:45	Latest InSAR/ICESat/CECS-NASA results from Pine Island/Thwaites Glaciers, West Antarctica [Abstract] [PPT]	Rignot
11:00	Basal ice accretion, availability of basal water, ice stream stoppage and potential restart of Kamb Ice Stream [Abstract]	Vogel
11:15	Dynamic significance of the flat-ice terrains in the mouth of Kamb Ice Stream [Abstract] [PPT]	Catania
11:30	Fast-flow signatures on Kamb Ice Stream [Abstract] [PPT]	Conway
11:45	Flow-generated records in the Ross Ice Shelf: evidence for grounding line changes and past shutdown of Whillans Ice Stream [Abstract] [PPT]	Fahnestock
12:00	Poster Viewing (30 min.)	
12:30	LUNCH (1 hr. 15 min.)	

1:45	Reconstructing late-Quaternary surface profiles of Reedy Glacier, Antarctica – 1 [PPT]	Bromley
2:00	Reconstructing late-Quaternary surface profiles of Reedy Glacier, Antarctica – 2 [Abstract] [PPT]	Todd
2:15	Apparent changes in the WAIS surface elevation, 2003-2004 [Abstract] [PPT]	B. Smith
2:30	Better Physics in Embedded Models [Abstract] [PPT]	Fastook
2:45	**Discussion of Question #3** (30 min.)	PLENARY
3:15	BREAK (30 min.)	
	***Question #4. "Minutes to Millennia"* – What time scales are most important in assessing the different influences on ice-stream motion?**	
3:45	Does the Siple Dome Ice Core Provide Evidence of Abrupt Changes in Siple Coast Ice Dynamics? [Abstract] [PPT]	Taylor
4:00	When Buttressing Matters: a sensitivity study [Abstract] [PDF]	Dupont
4:15	Tidal Modulation of Siple Coast Ice Stream Flow [Abstract] [PPT]	Bindschadler
4:30	Seismicity and slip of Whillans Ice Stream driven by neap- to spring-tide cycles [Abstract] [PDF]	Anandakrishnan
4:45	Passive Seismic Observations of Ice Stream Motion Near the Siple Coast Grounding Line [Abstract] [PDF]	Winberry
5:00	Is Anomalous Vertical Motion in WAIS Ice Streams Linked to Subglacial Water Transport? [Abstract] [PPT]	Gray
5:15	**Discussion of Question #4** (30 min.)	PLENARY
5:45	Poster Viewing (30 min.)	
6:15	DINNER	
Saturday, October 2, 2004		
8:00	CONTINENTAL BREAKFAST	
	Ten+ Years of WAIS Accomplishments	

8:30	Atmosphere [PPT]	Bromwich
8:45	A Decade of Frontier Oceanography: Achievments during WAIS [Abstract] [PPT]	Holland
9:00	Geological record of WAIS Ice Stream History and Behavior: Ten Years of Marine Geological Research [PPT]	Anderson
9:15	Terrestrial Geology [PDF]	Stone
9:30	Ice Cores [PPT]	Steig
9:45	Ice Dynamics [PPT]	Alley
10:00	Biology [PPT]	Berkman
10:15	Remote Sensing [PPT]	Joughin
10:30	BREAK (30 min.)	
11:00	Comments by Invited Guests	Gray Thomas
11:45	WAIS Program: Activities, Actions and Needs	Bindschadler
12:00	Adjorn	
	Posters	
	Phase structure of radar stratigraphic horizons within Antarctic firn [Abstract]	Arcone
	Changes in circulation, water mass distribution and ice shelf basal melting in the Ross Sea due to the presence of large icebergs [Abstract]	Assmann
	Are Rifts Brittle Fractures? [Abstract]	Bassis
	The AMPS archive: A resource for the Antarctic research community [Abstract]	Bromwich
	Thickness changes on Whillans and Kamb Ice Streams from airborne laser altimetry and ICESat measurements [Abstract]	Csatho
	Looking into ice shelf rifts with GLAS [Abstract] [JPEG]	Fricker
	LGM Ice Surface Elevations along the Transantarctic Mountains Front [Abstract]	Hall

	Spatial Patterns of mass balance of the Siple Coast and Amundsen Sea Basin, West Antarctica [Abstract]	Hamilton
	Seismic stratigraphy of the Ross Island flexural moat under the McMurdo-Ross Ice Shelf, Antarctica - A prognosis for ANDRILL drilling [Abstract]	Horgan
	Description of the deformation till and reconstructed subglacial environments of the East Antarctic Ice sheet during the LGM at Skarvsnes, Lutzow-Holm Bay [Abstract]	Iwasaki
	The near-surface signature of flow bands in the onset regions of Ice Streams C1b and D1, based on grids of GPR data [Abstract]	King
	Spatial and Temporal Variation of the Characteristic Time Scale of Microwave Emission with Snow Properties over Antarctica [Abstract] [PPT]	Koenig
	West Antarctic Balance Fluxes: Impact of smoothing, algorithm and topography [Abstract]	LeBrocq
	Ice flow property derived from ICESat surface topography in West Antarctica [Abstract]	Li
	Towards radar thermometry: an effective absorption temperature at Siple Dome [Abstract]	MacGregor
	Spatial variability of stable isotope ratios in snow: How representative are ice cores? [Abstract]	Neumann
	Insights into WAIS and GIS dynamics: Summary of modeling results [Abstract]	Parizek
	Modelling the evolution of ice streams [Abstract] [PPT]	Payne
	A Dilatant Till Layer Near the Onset Region of Bindschadler Ice Stream: Implications for the Onset of Streaming Ice Flow [Abstract]	Peters
	Depth-age and annual layer-thickness scales for Siple Dome, West Antarctica: measurements versus predictions from ice-flow modeling [Abstract]	Price
	Accelerating glacier flow on the warming Antarctic Peninsula [Abstract]	Pritchard
	Institute Ice Stream: An analog to the Ross Embayment ice streams in the Ronne drainage [Abstract]	Scambos
	Ice core evidence of 200 years of Antarctic climate change and its connections with the Southern Annular Mode [Abstract]	Schneider
	"Clearing Up" ICESat Data over West Antarctica [Abstract]	Shuman
	Lake Ellsworth: a candidate for Antarctic subglacial lake exploration [Abstract] [PDF]	Siegert
	Ice stream onset regions, shear margins and basal conditions: Observations from Rutford Ice Stream [Abstract] [PDF]	A. Smith
	RABID: Drilling to the bed of Rutford Ice Stream, 2004/05 [Abstract] [PDF]	A. Smith

	Characterizing surface textures on the West Antarctic Ice Sheet [Abstract] [PPT]	B. Smith
	Tracking an Ice-ochrone [Abstract]	Spikes
	Relating Radarsat SAR backscatter variations to ice sheet surface conditions along the US ITASE Traverse [Abstract]	L. Stearns
	High-resolution ice cores from US ITASE (West Antarctica): development and validation of chronologies and determination of precision and accuracy [Abstract]	Steig
	Deglaciation of the southern Ellsworth Mountains, Weddell Sea Sector of the West Antarctic Ice Sheet [Abstract]	Todd
	Magnetic properties of West Antarctic sediment [Abstract]	Vogel
	New radar layers at Siple Dome and Engelhardt Ice Ridge? [Abstract]	Winebrenner

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Previous Meetings

Environmental variability and change impacts on firn memory in West Antarctica

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Ice sheets of the earth are repositories of clues to past climates. It has long been recognized that cold, high accumulation sites provide the optimum conditions for preservation of the climate record in the firn. Sampling in spatial arrays across and ice sheet enables elucidation of local, regional, or global influences, yet local mean annual temperatures and accumulation rates vary across Antarctica; not all sites are high accumulation, cold sites. Snow is one of the earth's most dynamically changing naturally deposited porous media, and can experience dramatic changes in response to changing weather and climate patterns. Snow microstructure and permeability of firn act as indicators of the local climate.

Temporal changes in local climate at any given site may also occur, on many different time scales. Temporal changes in accumulation rate and temperature at a site impact the metamorphic processes in the near-surface snow and firn, and these remain recorded as changes in microstructure and permeability of the firn. Physical characteristics of firn cores gathered from the U.S. International Trans-Antarctic Science Expedition show great spatial variability across West Antarctica, as well as changing local climate at fixed locations. Patterns of change in the microstructure and permeability on interstitial transport in the top meters of firn reflect seasonal patterns and also decadal changes in local accumulation rate and temperature. Local climate and the dynamics of the snow and firn properties are closely linked, and the interaction affects both the extent of near-surface snow-air transfer processes as well as diffusion rates of interstitial gases deep in the firn.

Climate in the years immediately following deposition crates the subsequent profile of permeability in that firn. These patterns in permeability persist as those layers become buried more deeply in the firn. The variation in the microstructure and permeability profile affect gas diffusion as the layers become embedded deeper and deeper in the firn, including near pore close-off. Temporal variability in firn microstructure and permeability and their effects on diffusion in the firn column account most likely account for past anomalous firn air measurements that could not be explained through traditional density-porosity measurements.

Seismicity and slip of Whillans Ice Stream driven by neap- to spring-tide cycles

S. Anandakrishnan, J. P. Winberry, D. E. Voigt, R. B. Alley, M. A. King, R. A. Bindschadler, and I. Joughin

The ice plain of Whillans Ice Stream flows in an episodic “stick-slip” fashion. The slip occurs at high tide and again a few hours later during the falling tide. The magnitude of slip is relatively constant, but there is some fine-structure in the pattern. The flow speed of the ice plain was calculated from GPS position fixes at five minute intervals. Along with the GPS, we deployed a three-component seismometer that recorded seismicity (microearthquakes, referred to as events hereafter). In this talk, we present the results of the seismic measurements. The pattern of seismicity is complex. Bursts of events are always associated with slip events, but not vice versa. In other words, there are some aseismic slips and some seismic slips. The seismic slips dominate during the transition from neap tide to spring tide and the aseismic slips are during the other half of the cycle.

The seismicity is from the base of the ice stream. The accuracy of source location is insufficient to determine whether slip is at the interface between ice and subglacial materials or within the subglacial sedimentary layer. However, the depth accuracy is sufficient to discount surface crevassing. We suggest that the properties of the subglacial material (if that is the source of the seismicity) can be determined by comparing model results from rate- and state-dependent friction laws to this pattern of seismicity. The frictional properties of the bed are balanced close to the failure envelope, with a significant hysteresis associated with the peak high tide (which has a range of close to 2m). At peak high tide, some aspect of the frictional structure of the subglacial sediments is altered to a state that discourages seismic slip, and it takes a few days (4-8 days) before the sediments again exhibit seismic slip. If the slip is at the interface between the ice and sediments, then the hydrology at the bed is the likely cause of this hysteresis.

Phase structure of radar stratigraphic horizons within Antarctic firn

STEVEN A. ARCONE,1 VANDY B. SPIKES,2 AND GORDON S. HAMILTON3

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The majority of strong-amplitude events within stratigraphic radar profiles of firn recorded at several widely spaced Antarctic locations are solitary wavelets with the same form and phase polarity sequence as their successive half-cycles. These wavelets were recorded with 400-MHz short-pulse radar in December over several years. The locations include the South Pole and two ice divides in West Antarctica. They can be tracked for hundreds of kilometers near the more northerly divide, where an accumulation rate of about 45 cm water equivalent per year exceeds the radar resolution. Here, the stronger wavelets are not numerous enough to indicate annual events, while all horizons are too numerous. With the help of modeling, we interpret the horizons to represent a thin, double layer of ice over hoar, which conforms with the standard model of firn stratification and can form anywhere in Antarctica.

Changes in circulation, water mass distribution and ice shelf basal melting in the Ross Sea due to the presence of large icebergs

Karen M. Assmann, David M. Holland

The southwestern Ross Sea is the formation site for the densest shelf waters on the Antarctic continental shelf due to its persistent and well-developed polynyas. High Salinity Shelf Water (HSSW) is formed in the Ross Sea Polynya north of Ross Island (Jacobs & Comiso 1989) and further north along the Victoria Land coast in the Terra Nova Bay polynya (Picco et al. 1999). The Ross Sea continental shelf is generally ice-free during summer (Gloersen 1992). This has made it the primary site for observation of the oceanic shelf processes and lead to one of the longest and most detailed observation records in the Antarctic marginal seas.

In March 2000 the iceberg B-15 broke off the eastern Ross Ice Shelf. Its largest fragment B-15A (approx. 37 x 124 km) grounded north of Ross Island in January 2001 alongside iceberg C-16 (approx. 18 x 48 km) which had grounded there 2 months earlier. Since then these icebergs have remained in their position. In the subsequent years the area of the Ross Sea polynya has been significantly reduced, with B-15A and C-16 blocking the sea ice drift in the steady southerly winds out of the McMurdo Sound region. This anomalously large summer sea ice cover and the increase of fast ice along the Victoria Land coast may have been enhanced by the presence of further fragments of B-15 and of C-19 in the western Ross Sea.

The icebergs' impact on the summer sea-ice cover and the resulting reduction of the seasonal phytoplankton bloom are relatively well-documented through the use of satellite remote sensing (Arrigo et al. 2002). The effect of its presence on the ocean is less clear. Jacobs et al. (2002) identified a decrease in HSSW salinities over the last four decades in the available data base. While this appears to originate in the inflowing water masses to the continental shelf, the smaller Ross Sea polynya area and the reduced brine release during sea-ice formation may have enhanced this negative trend. This could possibly lead to a shift of the main formation site for HSSW in the western Ross Sea to the Terra Nova Bay polynya further north and to changes in the shelf circulation.

The main inflows to the Ross Ice Shelf (RIS) cavity are located in McMurdo Sound and east of Ross Island (Locarnini 1994, Assmann et al. 2003). The circulation in both of the areas is probably affected by the presence of the large icebergs north of Ross Island. This may lead to a change in the cavity circulation and basal mass flux from the ice shelf. It may also affect, in future years, the Ice Shelf Water (ISW) outflow in the central Ross Sea.

We use a sub-ice shelf-ocean model coupled to a sea ice model is used to investigate the effect of these large icebergs on the ice-ocean system in the southwestern Ross Sea. The ocean component is a modified version of the Miami Isopycnic Coordinate Ocean Model (MICOM) (Holland & Jenkins 2001). The formulation of the sub-ice shelf-ocean interaction follows Holland & Jenkins (1999). We use a dynamic-thermodynamic sea-ice model with an elastic-viscous plastic rheology (Hunke & Dukowicz 1997). The model domain extends from 85°S to 65°S and from 160°E to 130°W, i.e., it covers the RIS cavity, the continental shelf, and a sizeable portion of the deep ocean basin. A resolution of 0.6° zonally and 0.6°cos (latitude) meridionally corresponds to approximately 13 km at the RIS front and thus sufficient to resolve local processes in the McMurdo Sound region. NCEP reanalyses are used as atmospheric forcing data. The years 1991 to 2000 serve as a 10-year spin-up period. This is followed by one model experiment that includes the icebergs north of Ross Island and a control experiment which does not. We will present preliminary results from these model simulations and draw first conclusions from their comparison.

References
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Are Rifts Brittle Fractures?

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Ice shelf rifts are through-cutting fractures that penetrate the entire ice depth. Most treatments of rift propagation assume that the fracture process can be treated as brittle (i.e. ice is treated as an elastic material and viscous effects are neglected). In this approach the rift is treated as a thin planar crack in the ice. However, over the time scales of rift propagation (years to decades), viscous strains exceed elastic strains by several orders of magnitude, making this an inappropriate assumption. In contrast, ice shelf flow is treated by assuming that ice flows viscously - a process which precludes crack formation. We suggest that a more realistic formulation is to consider the rifting process as the result of strain localization due to a plastic instability in the flow - sometimes called the “necking instability”. In this theory deformation occurs in a zone with a characteristic length scale of several ice thicknesses. Although this approach has not been applied to ice shelf rifts before, it has been used to successfully explain many topographic features of lithospheric rifts on Earth and on Venus. Here we present the linear stability analysis which leads to plastic necking under plane strain conditions and determine the conditions where small perturbations in either the bottom profile or surface profile of the ice shelf become amplified. The predicted surface topography expected from a small initial thickness perturbation is compared with GLAS elevation profiles across a rift, as well as topography of typical lithospheric rifts

What happened to the volcanic debris erupted beneath the WAIS?

John C. Behrendt, David Morse, and Donald D. Blankenship
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Aeromagnetic and radar ice sounding results from the 1991-1997 Central West Antarctica (CWA) aerogeophysical survey over part of the West Antarctic Ice Sheet (WAIS) and subglacial area of the volcanically active West Antarctic rift system have enabled detailed examination of specific anomaly sources. These anomalies, previously interpreted as caused by late Cenozoic subglacial volcanic centers, are compared (Behrendt et al., 2004) to newly available glacial bed-elevation data from the radar ice sounding compilation of the entire area of the aeromagnetic survey to test this hypothesis in detail. We examined about 1000 shallow source magnetic anomalies for bedrock topographic expression. More than 400 steep-gradient, shallow-source, magnetic anomalies observed over the WAIS in the CWA survey area have associated bed topography directly beneath them, of approximately the same width as the anomalies, and which are interpreted as the tops of the sources of these anomalies. The magnetic anomalies examined range in amplitude from 40 to >1000 nT which is very high considering 1 km flight elevation above the WAIS surface and 2-3-km ice thickness. The great bulk of the anomaly sources at the base of the ice have low bed relief (80% <200m), which we interpret as indication of removal of volcanic edifices comprising hyaloclastite, pillow breccia, and other volcanic debris injected into the moving ice during eruption. The sources must be >1-2 km (as shown by models) with very high magnetizations. About 18 of the anomalies, half concentrated in the area of the WAIS divide, have high elevation topography and high bed relief, up to 1600 m. There are no high bed relief (>600 m) magnetic anomaly sources that do not have high elevation topography. All of these high-topography magnetic sources would be above sea level after ice removal and glacial rebound. Because of their form similar to exposed volcano's in the WAIS area with edifices primarily comprising subaerially erupted volcanic flows, which have resisted glacial erosion, we infer that these high topographic volcanic sources are also subaerially erupted volcanoes. A number of anomaly sources are very shallow beneath the very smooth glacial bed in the area of rapidly moving Ice Stream D (Bindshadler Ice Stream), which probably comprises unconsolidated sediment, and yet have no observable bed relief. A few of the very shallow source “volcanic” anomalies overlie the ice shelf just downstream of the grounding line of Ice Stream D, suggesting a causal relationship, if the volcanism is recent. Two core holes (Elston and Bressler, 1986; Barrett, 1989) in the McMurdo area near Ross Island beneath the continental shelf show a range of ages of late Cenozoic volcanic material in the sedimentary section from Pleistocene to mid Oligocene. Because Erebus Volcanic Province (Kyle, 1990) exposures are all much younger than the oldest volcanic detritus in these core holes (e.g. Mt. Terror on Ross Island at <15 Ma and Mt. Morning at <19 Ma are the oldest K/Arages reported in this group), this detritus must have been carried in from more distant areas. The late Cenozoic volcanism has been active in the WAIS area since >30 Ma, the WAIS since >10 Ma, but the oldest ice which presently comprises the WAIS is likely only 100-200 Ka at most. Therefore, if the glacial removal of subglacially erupted volcanic edifices has been active throughout the existence of the WAIS in the area of the inferred volcanic centers we might not expect to see much volcanic detritus in the few core holes into the WAIS. Little or none has been reported. Nonetheless, we might expect recovery of more volcanic material within or at the base of the ice as more coring into the WAIS at inferred volcanic centers or immediately downstream of these is done in the future, if volcanism has been active upstream during the period of present ice deposition.

Apparent changes in the WAIS surface elevation, 2003-2004

Ben Smith

As of October 2004, NASA's ICESat/GLAS mission will have been operating for eighteen months. Using cross-over data from this it is already possible to make estimates of the rate of elevation change in West Antarctica from these data for areas of a few hundreds of square kilometers with decimeter per year accuracy. The short period over which these observations were made implies that densification- and accumulation-rate variabilities may be making a significant contribution to apparent elevation change, and changes in the configuration of the GLAS instrument may have introduced small time-varying biases into the data, so care is required in interpreting apparent elevation changes. However, some parts of the Siple Coast ice stream region have large rates of apparent elevation change that cannot be dismissed as errors. We refrain from reporting apparent elevation changes in this abstract pending a late-breaking data-release in mid September, but we promise the freshest of results.

Self Help: Ice Streams Retain more Water by Moving Faster

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SAIC, Beltsville, Maryland

Recent observations by Gray and others (submitted) have identified inflations and deflations of the surface they hypothesize to be expressions of subglacial water movement out of and into subglacial basins. The locations and sizes of such basins can be predicted by calculating the hydropotential field, that is, the pressure field experienced by water at the bed and at the local ice overburden pressure. We repeat this calculation with the most current fields of surface and bed topography and show that the spatial variability of the hydropotential is far greater for ice streams than for either inland ice or interstream ridges. This result is not surprising given the dominance of the surface topography relative to the basal topography on the hydropotential.

We extend this subject by examining the connection between the spatial variability of the hydropotential and the velocity dependent transmission of basal roughness to the surface. Gudmundsson (2003) completed the most comprehensive analysis of the transmission of basal variability to the surface and we use his equations to illustrate how the spatial variability of the hydropotential is increased with increasing ice sliding speed. For periodic bed undulations with a wavelength set at some factor of the ice thickness, there is a threshold velocity above which closed subglacial basins will be possible. This dependence may play a role in the flow transition from tributary flow, where sliding dominates and increases with increased driving stress, and streaming flow, where sliding increases downstream even though driving stress decreases.

Tidal Modulation of Siple Coast Ice Stream Flow

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2 ESSC, Pennsylvania State University, State College, Pennsylvania
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The discovery of tidal modulation on the motion of Whillans Ice Stream and ice stream D and the seismicity of ice streams C and D was followed up with a more extensive survey of motion and seismicity on all Siple Coast ice streams in 2003-04. 21 GPS stations sampling at 15-second intervals, 7 event-triggered seismometer networks and one tiltmeter collected data for more than two summer months. Seismic data are discussed elsewhere.

All ice streams showed tidal modulation of flow. On streams with multiple stations, the magnitude of tidally modulated flow variations decreased upstream. Whillans Ice Stream was the only case where stick-slip motion was observed. There the magnitude of slip events appears positively correlated with tidal amplitude—four full spring/neap tidal cycles were observed. Slip events were observed as much at the station 190 km from the grounding line, but not at the next station 320 km upstream (Upstream B camp). Slip events were nearly synchronous along Whillans Ice Stream. 3-station solutions of the initial slip location clustered at a point at or near the north margin of the ice plain and produced a propagation speed of 89.9 + 12.6 m/s, very close to the previously published value.

Internal radar layers in central West Antarctica and their implications for Holocene ice sheet changes

Donald D. Blankenship1, Martin J. Siegert2, Brian Welch3, David Morse1, Andreas Vieli2, Ian Joughin4, Edward C. King5, Gwendolyn J.-M. C. Leysinger Vieli2, Antony J. Payne2, Robert Jacobel3

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Upstream of Ice Stream D in West Antarctica, RES data reveal a major and distinctive englacial structure, where internal layers are located at an ice depth up to 1 km deeper than their surrounding elevations. The linear englacial 'fold' that is formed by the layer pattern can be traced well across 10 km, and less well for much longer. The long-axis of the structure is located at a 30° angle to the current ice flow direction. A number of ways in which this layer pattern may have formed are examined. This examination shows that the layer structure is more easily explained if the ice flow direction were along the line of the fold's axis than under the current glaciological setting. Ice flow modelling is used to propose that the englacial feature was developed by significant rates of basal melting in association with ice-sheet downdraw at a time when the ice flow direction was different to today. Current ice dynamics may account for subsequent deformation of the internal layer patterns in the last few thousand years.

The AMPS Archive: An Atmospheric Resource for the Antarctic Research Community

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In response to the need for improved weather prediction capabilities in support of the U.S. Antarctic Program's Antarctic field operations, the Antarctic Mesoscale Prediction System (AMPS) was implemented in October 2000. AMPS employs the Polar MM5, a version of the Pennsylvania State University / National Center for Atmospheric Research Fifth Generation Mesoscale Model (MM5), optimized for use over ice sheets by the Polar Meteorology Group (PMG) of the Ohio State University's Byrd Polar Research Center. AMPS is a collaborative effort between the National Center for Atmospheric Research's Mesoscale and Microscale Meteorology (MMM) group and the PMG. The role of MMM is to run AMPS twice a day, provide a web interface and model products to the U.S. and international forecasting community, and maintain the model code. The role of PMG is to continue development of the model physics and to evaluate the system's performance.

AMPS consists of several domains ranging in horizontal resolution from 90 km covering a large part of the Southern Hemisphere, to 3.3 km over the complex terrain surrounding McMurdo, the hub of U.S. operations. Several published studies have shown the model performs with good skill on hourly to seasonal timescales. On seasonal timescales the intraseasonal and interseasonal variability in pressure, temperature, wind, and moisture are particularly well resolved.

In addition to the real-time applications of AMPS, a continually evolving database of archived forecasts is now beginning to yield high-resolution climatological fields that may be of use to the broader Antarctic research community. For example, temperature, 3-dimensional winds, and several moisture proxies are available for about 30 levels in the atmosphere from twice-daily forecasts at 3-hourly temporal resolution on a 30-km grid covering the entire continent. Precipitation, cloud fraction, and complete energy flux fields are also available at this time and space resolution. These forecasts can be joined together in order to compute time-mean fields on monthly, seasonal, and annual timescales. Applications of these fields over West Antarctica will be highlighted.

Dynamic significance of the flat-ice terrains in the mouth of Kamb Ice Stream

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Ice-penetrating radar reveals several unusual characteristics in the internal layers of the flat-ice terrains that surround the lower end of Kamb Ice Stream, Antarctica. Our data show upper layers that are continuous but lightly disturbed overlying numerous line-diffractors oriented parallel to the edge of the terrains several hundreds of meters below the surface. At the boundaries of these terrains (where they meet the inter-ice stream ridges) layers are strongly downwarped and truncated by the bed. A simple kinematic ice-flow model is used to predict the spatial pattern of isochronal layers in order to match observations. Model results suggest that the downwarping pattern is caused primarily through focused basal melting. We develop a hypothesis that these features represent the limits to ungrounded conditions implying that most of the lower end of Kamb Ice Stream was once floating. Through this hypothesis we explain other characteristics within these terrains including the numerous line-diffractors which are thought to be basal crevasses similar to those seen in floating ice shelves. Using estimates of ice thickness change in this area over the last few hundred years we believe that floatation last occurred $□$400 years prior to ice stream stagnation. It is likely that grounding throughout this area played some part in the stagnation of Kamb Ice Stream as is currently happening in the mouth of Whillans Ice Stream.

Fast-flow signatures on Kamb Ice Stream

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Kamb Ice Stream (formerly called “Ice Stream C”) stagnated about 150 years ago. While its cause of shutdown is still under debate, we recently used surface-radar-detected internal stratigraphy to define ten “flow bands” within the northern tributary (K2). We calculated the downstream paleo-velocity distribution from continuity: results indicate a four-fold velocity increase downstream, implying pre-stagnation velocities in the trunk region exceeding 350 m/yr (Ng and Conway, 2004). Here we report and discuss spatial correlations between our surface-radar data and satellite-detected flow stripes. The flow stripes appear to originate from an inferred bed escarpment/ridge system upstream from the radar profiles and persist for several hundreds of kilometers downstream. We find some correspondence between “flow bands” defined by flow stripes with those delineated by radar-detected internal stratigraphy; flow-stripe patterns may also provide a useful fast-flow signature.

Glacial history of Marie Byrd Land - from thousands to millions of years

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Continued deglaciation of West Antarctica would have profound impacts on future sea level, and an extensive program of glaciological and remote-sensing research has been devoted to identifying trends in the mass balance of the West Antarctic Ice Sheet [1-5]. Geological studies can provide insight into previous deglaciations of West Antarctica. For example, the work of Scherer et al. [6], which suggests that grounded ice withdrew from the inner Ross Sea Embayment at least once during the late Quaternary, illustrates one possible outcome of further recession. Whether deglaciation to this degree has occurred once, or repeatedly; when it last occurred, and for how long, remain open questions.

In previous work, we used conventional cosmic-ray exposure dating of glacial erratics to document the most recent deglaciation of Marie Byrd Land. Our results showed that: (i) the glacial-maximum West Antarctic Ice Sheet (WAIS) overran peaks in the Ford Ranges, (ii) outlet glaciers traversing the ranges retreated gradually between 10,300 - 1800 yr B.P. , and (iii) local icefields surrounding peaks in the ranges have continued to adjust to these changes, exposing fresh deposits as recently as 300 yr B.P. [7]. In order to investigate ice cover prior to the last glaciation, we have measured cosmogenic nuclides in bedrock surfaces throughout the Ford Ranges. These data provide broad constraints on the extent of glaciation in Marie Byrd Land over the past few million years, and show that the present state of West Antarctic (de) glaciation is highly unusual.

Cosmic-ray-produced nuclides such as Be-10, Al-26 and Cl-36 (with half-lives of 1.5, 0.7 and 0.3 Myr, respectively) accumulate in bedrock surfaces at times of deglaciation. During glacial periods when the surfaces are shielded from cosmic radiation, the nuclides decay at different rates, leading to isotopic disequilibrium. Provided bedrock has been protected during glaciation by non-erosive, cold-based ice, the concentrations of these nuclides provide million-year records of exposure and ice cover. Although such measurements cannot be used to date specific glaciations, we can obtain: (i) minimum limits on the total duration of past exposure and glaciation, (ii) a maximum limit on the proportion of time-exposed to time-covered by ice, and (iii) upper limits on total exposure time during the last few half-lives of Cl-36 and Al-26.

Our data show that: (i) All bedrock surfaces, with the exception of ice-scoured pavements at low altitude, retain a memory of intermittent exposure and ice cover ranging from a few hundred thousand years to 3.5 million years. (ii) Mountain transects show that the proportion of "time-exposed" to "time-covered" increases with elevation, as expected. Data from summit surfaces show that, in general, coastal peaks have been ice-free for a greater proportion of the time than inland peaks. (iii) Nevertheless, summits in Marie Byrd Land spend more time buried beneath the ice sheet than exposed. Maximum limits on the fraction of "time-exposed" for the peaks we sampled range from approximately 5% in the eastern Fosdick Mts to 45% for the summit of The Billboard. (iv) Several outcrops, which have been exposed for 2-4 kyr during the present deglaciation, cannot have been exposed for more than 3-30 kyr in the past million years. Thus the least frequently exposed of these surfaces probably did not emerge from beneath the ice sheet more than once or twice in the last 10-15 major interglacials of the late Pleistocene. These data suggest that the present extent of outcrop in the Ford Ranges is unusual, the present-day WAIS in Marie Byrd Land is close to its minimum late-Pleistocene extent, and that the warmth and/or duration of the Holocene rival past interglacials such as Marine Isotope Stage 11 (MIS-11; 400 kyr B.P.) in terms of their effect on the ice sheet. (v) Sites in the Fosdick Mts and Fleming Peaks cannot have been exposed for more than 1-4 kyr and 7 kyr, respectively, during MIS-11, ruling out prolonged, extensive deglaciation of the Ford Ranges at that time. This suggests that the late-Quaternary diatoms found by Scherer et al. (1998) may have been deposited in an earlier interglacial.

We have begun to explore plausible long-term glacial histories that fit these constraints using a calculation that links exposure histories at all our sample sites. In the calculation a single ice-volume parameter is allowed to vary through time; exposure at each site occurs when ice volume drops below a threshold value, constrained by the Holocene deglaciation sequence. We use genetic algorithms to search for an ice-volume time series, spanning the last 4 Myr, that best reproduces our bedrock Be-10, Al-26 and Cl-36 data. The highly non-linear nature of the model precludes finding a unique solution, but repeated runs of the optimization show several common features. Best-fit models concur in indicating that the most extensive deglaciation of the Ford Ranges occurred ca. 2 Myr ago, and all explain the data with a sequence of 3-4 major deglaciations since 2 Myr B.P., rather than a rhythmic glacial-interglacial sequence resembling the marine oxygen isotope record. These preliminary findings suggest that major deglaciations are not simply linked to climatic and sea-level oscillations, but occur when intrinsic "thresholds" in the ice-ocean-climate system are crossed, as proposed in models like that of Macayeal [8].

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Thickness changes on Whillans and Kamb ice streams derived from airborne and spaceborne laser altimetry

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To map mass balance changes of major drainage basins over a relatively short period, ICESat is designed to measure surface elevation changes with an accuracy of 1.5 cm/year for spatial averages of measurements over areas of 100 km2. To achieve this accuracy different post-launch calibration-validation (CV) approaches are used to identify and to remove the non-geophysical artifacts from the data products. As part of the CV effort detailed surface topography was mapped by NASA's Airborne Topographic Mapper (ATM) scanning laser over sites in Greenland, western US and the Dry Valleys in Antarctica. We used the detailed surface topography, derived from ATM data over the Dry Valleys, to verify the accuracy the ICESat products. ATM surveys were conducted over the Dry Valleys in December 2001 in collaboration with NSF and USGS. In addition to survey candidate calibration/validation sites for the ICESat mission, the campaign was going to support NSF projects and to provide data to evaluate the potential of the use of laser altimetry in the Antarctica. The survey resulted "blanket" coverage over several sites. We have developed a procedure using robust estimation techniques to remove the outlier observations and to interpolate the data into regular grids (DEMs). The ICESat elevation and waveform products were verified by comparing them with the DEMs and with simulated waveforms. Surface reflectivity, necessary for the waveform simulation, was derived from satellite imagery. The stable terrain of the site makes it ideal for serving as benchmark surface throughout the ICESat mission.

Ice sheet surface elevations, mapped by airborne laser altimetry surveys, may serve as baselines for the ICESat mission. Precise repeat laser altimetry survey was conducted by the Support Office of Aerogeophysical Research (SOAR, UTIG) in 1997/98 and 1999/2000 over portions of the van der Veen, Whillans and Kamb ice streams in West Antarctica. These ice streams are undergoing substantial changes in length, width, thickness and speed at decadal and shorter time scales. We combined ICESat measurements with the results of the SOAR airborne laser altimetry survey to study surface changes over the last five years. The spatial pattern of recent surface changes is consistent with earlier observations. However, areas on the Van der Veen and Whillans ice streams, where thinning was detected previously, are now very close to being in balance. The Kamb ice stream continues to build up with average thickening rates reaching 0.5 m/year. Our result provides a new evidence for the overall positive mass balance of the region suggested by recent studies. The SOAR survey detected thinning of almost 1 meter/year over the upstream part of Van der Veen and Whillans ice streams. ICESat measurements show significantly reduced thinning rates suggesting that these ice streams are closer to balance and maybe building up again. The Kamb ice stream continues to thicken almost uniformly at the surveyed area. The estimated error of the surface elevation rates measured by the SOAR survey is 0.15 m/year. We believe that ICESat achieves an elevation accuracy of 0.2 m or better in clear atmospheric conditions. Other errors, such as interpolation error and interannual variability are comparable or smaller.

Holocene Summer Temperature Increase in West Antarctica

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Summer climate conditions in West Antarctica changed significantly during the Holocene, as recorded by the frequency of occurrence of rare melt layers in the Siple Dome deep ice core. Surface melting began around 11.7 ka at the end of the glacial/ interglacial transition. This was followed by an extended period of no melt layers from 8.8 - 6.6 ka. There has since been an increase in melt frequency starting at 6.6 ka, with the most rapid increase from 4 ka to the present. The millennially-averaged melt frequency increased from 0% at 7.5 ka to a maximum of 2% observed during the most recent 1000 years. We have calibrated this change in melt frequency using a statistical relationship between mean summer temperature and the melt-layer threshold temperature. We estimate this change represents an increase in mean summer temperature of ?2°C. The broad millennial-scale trend of increasing melt-frequency matches other available Holocene West Antarctic climate records, such as d18O and sea-salt Na from Siple Dome as well as d18O from Byrd Station, which all also show increasing trends from the early Holocene to the present. We interpret these records together as indicating an increase in both mean-annual and mean-summer temperature, as well as indicating an increase in temperature variability and storm (or cyclonic activity) frequency in West Antarctica. This is in contrast to other East Antarctic climate records, which show an early Holocene climatic optimum followed by stable or decreasing temperatures through the mid- to late-Holocene. We interpret the regional mid- to late-Holocene rise as evidence of an increasing marine influence on the Ross Sea sector of West Antarctica, where Siple Dome is located. We believe this is due to the continued lateral retreat through the mid- to late-Holocene of the West Antarctic ice sheet from its furthest LGM configuration resulting in more coastal climate conditions. The delayed draw-down in ice thickness from the Marie Byrd Land area may have also allowed more frequent and stronger cyclonic activity to more easily reach interior West Antarctica beginning in the mid-Holocene. The more rapid increase in melt-frequency seen from 4 ka to the present could also be reflecting a change in Pacific Ocean climatology, such as a southward movement of the Amundsen Sea Low, or an increase in ENSO variability, bringing more climate variability to the Ross Sea sector of West Antarctica.

A 200-Year Sulfate Record from 16 Antarctic Ice Cores and Associations with Southern Ocean Sea Ice Extent

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Data from sixteen, 50m- to 115m-deep, sub-annually dated ice cores are used to examine the recent spatial and temporal concentration variability of sea salt (ss)SO42- and excess (xs)SO42- over West Antarctica for the last 200 years. The preservation of seasonal layers throughout the length of each record results in a dating accuracy of better than one year based on known global scale volcanic events. Our xsSO42- records with volcanic peaks removed do not display any evidence of an anthropogenic impact on West Antarctic SO42- concentrations but do reveal that a major climate transition takes place over West Antarctica at ~1940.

Based on linear correlation analysis ssSO42- concentrations are higher when sea ice extent (SIE) is greater and xsSO42- concentrations are higher when SIE is lesser. The South Pole receives the majority of its xsSO42- from different sources than the rest of West Antarctica and the Weddell region may be a significant source of aerosol chemistry for eastern West Antarctic sites.

When Buttressing Matters: a sensitivity study

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In a warming world the buttressing influence of ice shelves on the ice streams which flow into them may be substantially reduced. The potential impact that this loss of buttressing would have on an ice-stream/ice-shelf system includes thinning and grounding-line retreat, contributing to ongoing sea-level rise. Therefore it is critical to assess the sensitivity of such systems to a change in buttressing. We examine this sensitivity using a model of the couple mass and momentum balance of an ice-stream/ice-shelf system. The diagnostic momentum balance component model is appropriate for thin, channelized flow, and includes longitudinal deviatoric stress, driving stress and lateral and basal drags, with downstream buttressing prescribed as a dynamic boundary condition. The prognostic mass balance component model is derived from depth-integrated continuity, and for simplicity we have neglected accumulation, yielding a simple balance between thinning rate and flux convergence. The equations are nondimensionalized to isolate important parameters. The resulting model equations are cast in numerical form using finite elements in space and implicit finite differences in time, with a form of Petrov-Galerkin upwinding applied to the mass balance to aid in efficiency. Several numerical experiments were conducted to explore the response to a loss in buttressing. The set of experiments include a reference experiment, with parameter values roughly appropriate for Pine Island Glacier (PIG), as well as several experiments to assess the sensitivity of the results to the choice of parameter values. In all of the experiments buttressing was removed from an initially steady-state system and allowed to evolve to a new steady-state. The results show a marked grounding-line retreat, equivalent to an 8-18 km retreat in dimensional terms. The bulk of this adjustment occurs within a few decades. Also of interest is the reduction in the volume of ice that was initially above flotation, which indicates the impact of the loss in buttressing on sea level. Here the results show a 20\ to 43\ loss in this volume, roughly corresponding to a modest net addition of 1 mm to sea level. These results may well underestimate the magnitude of the response for several reasons. For example, our neglect of accumulation means that we do not include the inland migration of sub-ice-shelf melting as the grounding line retreats. The experiments which assessed the sensitivity of the results to the choice in parameter values suggest that systems which are wider, have a stickier bed, or have a larger driving stress will be more sensitive to a loss in buttressing. The Siple Coast ice streams do generally have lower driving stress than PIG, but some are also wider near the grounding line. Thus we cannot rule out significant sensitivity of some of the Siple Coast ice streams to a loss in buttressing. We suggest that further experiments are warranted to explore the sensitivity of the Siple Coast ice streams, as well as to investigate the importance of sub-ice-shelf melting.

Flow-generated records in the Ross Ice Shelf: evidence for grounding line changes and past shutdown of Whillans Ice Stream

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The complicated patterns of flow-related features on the Ross Ice Shelf contain a wealth of information about the history of ice discharge from the ice streams flowing east off of the WAIS. We have been able to read some of this history from satellite image mosaics using a combination of the geometry of the features, the generation of hypothetical past flow scenarios, and the targeted models used to test the plausibility of those scenarios. We identified a pattern of flow variation due to basal freezing, driven by the influence of longitudinal extension on the basal thermal gradient in the ice, that can explain the observed flow features. Recently, we have recognized that there are other profound records of variation on the shelf; these records, when understood in the proper context, will yield a more complete understanding of ice stream slowdowns and grounding line retreat than is currently available.

These new records of flow come in two "flavors". The first "flavor" is groups of fracture-related features that serve as kinematic and dynamic tracers, such as sets of grounding-line parallel depressions in the ice-shelf surface. These tracers present a complicated history that we have made some progress in reading. The second "flavor" of record is a detailed picture of ice thickness variation on the Ross Ice Shelf from the IceSAT laser altimeter. The combination of this ice-thickness-related measurement with whole-ice shelf image composites allows us to begin to constrain the volumes of ice involved with the flow history on the ice shelf; this means that we can now approach the variations in flow from the perspective of relative flux between two outlets, and can constrain shutdown and thinning scenarios based on the presence or absence of thinned ice in the shelf.

These datasets lead us to add several additional events to the flow history recorded in shelf ice: 1) a record of sustained grounding line retreat to the north of Crary Ice Rise, and 2) the possible shutdown of Whillans Ice Stream, likely for several hundred years during the last half millennium.

Better Physics in Embedded Models

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Modeling ice sheets such as Antarctica is an important scientific activity for a number of reasons: 1) ice sheets are an integral part of the world's climate system, both as a mechanism defining climate and as an indicator of change; 2) modeling allows us to test our understanding of the fundamental physical processes that control the behavior of ice sheets and their response to changing climate; 3) modeling provides a virtual laboratory where we can investigate the possible changes that will occur.

Physics-based modeling of ice sheets suffers from the same deficiencies that other fields such as global climate modeling have encountered. This deficiency involves the need for higher resolution than current computers are able to provide with reasonable runtime and memory requirements.

Climate modelers overcome this deficiency by designing mesoscale models which run inside their global climate models. This allows them to use higher resolution in a smaller domain which is driven by the output of the lower-resolution, global-domain model. These mesoscale models, since they run at higher resolution, can also improve on the physics used in the GCM, they can be specifically tuned to work in particular regions, they can examine the interaction between processes operating at different scales, they can look at the effects of processes originating outside their domain, and at processes too small to be picked up in the full GCM.

We propose to follow the climate modelers' lead and develop an embedded ice sheet model, one where a section of the ice sheet (mesoscale) is modeled either at higher resolution with the same physics or at the same resolution with better physics. This embedded model is driven by output from a low-resolution model of the entire ice sheet (global model). By this approach we either obtain higher-resolution results, better able to capture the behavior of small-scale features such as ice streams, or we can include processes such as longitudinal stresses, which are impossible to calculate within the constraints of the shallow-ice approximation.

One serious drawback to most ice sheet models is the basic assumption of the shallow-ice approximation. This approximation basically neglects all stresses except the familiar driving stress, which is assumed to be concentrated at the bed. While a good approximation for much of the ice sheet, it is probably not very good in the interesting regions of the ice streams. As the climate modelers have included different physics in the mesoscale models that is impractical to include in the full global model, so too do we feel it will be possible to provide a more complete solution of the momentum equation.

Another approach is to treat an ice stream as a barely-grounded ice shelf. This solution is considerably more expensive, computationally, requiring three degrees of freedom at each node (Vx, Vy, and h) instead of one (just h). These extra degrees of freedom require considerably more computation resources to calculate, resources that would be prohibitive for the whole ice sheet at even 20 km resolution, but which may be possible for an embedded model. One problem with this approach is that the basal drag that must be specified itself violates the assumptions that go into the derivation of the Morland equations used to model an ice shelf. A second drawback is that the positions and extents of the regions where this barely-grounded ice shelf exists must be externally specified, a requirement we would like to avoid, allowing instead for the model to determine in a self-consistent manner where the fast flow needs to occur.

The shallow-ice approximation and the barely-grounded ice shelf can be considered as end members: only the basal stress is considered in the first, whereas only the longitudinal stress is considered in the second.

Clearly the best physics can be included by abandoning both of these approximations and solving the full-momentum equation with all stress terms included. In this way no stresses are neglected which might be important for regions where longitudinal stresses may play an important role, such as ice streams.

Doing this requires solving simultaneously the full momentum equation for the complete velocity field, the mass conservation equation for the rate of change of thickness, and the energy equation for the internal temperatures. Both the temperature field, which affects the material properties through the ice hardness, and the ice-sheet configuration will affect the velocity solution of the momentum equation. The temperature solution, of course, depends on the ice-sheet configuration, but also depends on the velocity field through the advection term of the heat-flow equation and through the shear-heating term, which contains the product of stresses and velocity gradients. The rate of change of ice thickness, and hence ice-sheet configuration, depends on the velocity-field solution, the current ice-sheet configuration, and the local mass balance.

We present details of the implementation of this full solution, and preliminary results.

We thank the NSF, which has supported the development of this model over many years through several different grants.

Looking into ice shelf rifts with GLAS

Helen Amanda Fricker, Jeremy Bassis, Bernard Minster

Since the launch of ICESat in January 2003, Geoscience Laser Altimeter System (GLAS) has provided glaciologists with unprecedented topographic information for Antarctica, delivering elevation profiles containing exquisite detail. The small footprint of GLAS (65m) has the ability to measure sub-kilometer scale features on the surface of the ice shelves, such as ice shelf rifts, which were previously not resolved by the large-footprint satellite radar altimeters. This makes it an ideal instrument for studying ice shelf rifts. Often when GLAS encounters a rift, there is a double peak in the return waveform, the first corresponding to the ice shelf surface and the second to the rift base. The GLAS processing scheme assigns the peak with the largest amplitude to be the surface. However, over rifts this is often not the case, as the peak from the rift base can have low amplitude, especially if the rift is filled with ice mélange (which has a rough surface and scatters GLAS photons). We have retracked GLAS data over ice shelves to always pick the last return. In this manner we can for the first time measure the thickness of ice mélange within ice shelf rifts, and how this thickness changes over time. This is significant because of the important role that ice mélange can play in rift propagation.

Is anomalous vertical motion in WAIS ice streams linked to subglacial water transport?

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RADARSAT data from the 1997 Antarctic Mapping Mission are used interferometrically to solve for the 3-dimensional surface ice motion in the interior of the West Antarctic Ice Sheet (WAIS). An area of ~ 125 km2 in a tributary of the Kamb Ice Stream slumped vertically downwards by up to ~ 50 cm sometime between September 26 and October 18, 1997. Adjoining areas in the Bindschadler Ice Stream also exhibited comparable upward and downward surface displacements. As the inflation and deflation features correspond to sites at which the basal water experiences a hydraulic potential well, we suggest transient movement of pockets of subglacial water as the most likely cause for the vertical surface displacements. These results, and related lidar observations, will be discussed in the light of the exciting possibility that imaging the change in ice surface elevation may help understand the key role of water in the very-difficult-to-observe subglacial environment, and its important influence on ice dynamics.

LGM Ice Surface Elevations along the Transantarctic Mountains Front

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During the Last Glacial Maximum (LGM), the West Antarctic Ice Sheet (WAIS) expanded into the Ross Sea Embayment. The WAIS was joined along the western margin of the Ross Sea by ice from East Antarctic outlet glaciers. These outlet glaciers thickened substantially at their mouths in response to the damming effect of the WAIS. In contrast, the heads of the East Antarctic outlet glaciers thinned or remained constant, probably due to a precipitation deficit.

Glacial geologic data from the Transantarctic Mountains (TAMS) front, as well as in Marie Byrd Land and on nunataks exposed within the WAIS, provide important constraints on LGM ice-surface elevations. In general, these data suggest ice levels significantly higher than present in the Ross Sea Embayment (although perhaps not in the interior), with ice reaching ~350 m a.s.l. at Terra Nova Bay, 720 m a.s.l. on eastern Ross Island, and well over 1000 m a.s.l. at the mouths of the southern TAMS outlet glaciers. These data are broadly consistent with those showing thicker ice in Marie Byrd Land, but contrast with new evidence from Siple Dome suggesting only minor thickening at the LGM. Here, we review the glacial geologic data in hopes of stimulating discussion on the nature of the ice sheet required to accommodate both sets of data. An accurate reconstruction of LGM ice is necessary not only for properly interpreting data on deglaciation, but also for understanding Antarctica's role (if any) in causing global meltwater pulses during the late-glacial period.

Spatial patterns in mass balance in the Siple Coast and Amundsen Sea Basin, West Antarctica

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Local rates of changes in ice sheet thickness were calculated at numerous sites in West Antarctica using the submergence velocity technique. This method entails measuring the vertical velocity of the ice sheet using repeat GPS surveys of markers and measuring local long-term rates of snow accumulation using firn core stratigraphy. The difference between these two quantities represents a thickness change with time. Measurements were conducted at sites located ~100-200 km apart along US ITASE traverse routes, and at several isolated locations. All but one of the sites are distributed in the Siple Coast and the Amundsen Sea Basin along contours of constant elevation, along flow lines, across ice divides, and close to regions of enhanced flow. Calculated rates of change are variable from site to site. Most of the large rates of change in ice thickness (~10 cm/yr or larger) are occurring in or close to regions of rapid flow. Other changes are observed at these same sites, including shear margin migration and ice stream deceleration. Near-steady-state conditions were calculated at most sites in the slow moving ice sheet interior and near the main West Antarctic ice divide. These results are consistent with regional estimates of ice sheet change at similar locations in West Antarctica, derived from remote sensing measurements.

A Decade of Frontier Oceanography: Achievements during WAIS

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As a marine-based ice sheet, the West Antarctic Ice Sheet (WAIS) is influenced, if not controlled, by the oceanographic regime within which it stands – the Weddell, Ross, Amundsen, and Bellingshausen Seas of the Southern Ocean. Exploration and expeditions over the last century have brought us basic knowledge about the oceanographic environment of the WAIS, most notably in the Weddell and Ross Seas. The last decade, coinciding with the existence of the WAIS Initiative, has seen a particularly large increase in our knowledge about this unique oceanographic regime – the only seas in the world where approximately half of the coastline consists of floating glacier, features referred to as ice shelves. The physical and intellectual challenges presented by this frontier oceanographic regime have required the development of innovative observational and numerical modelling tools. In this talk, we review the key advances made in these areas over the last decade. We also highlight the understanding these advances have brought us and their relevance to other disciplines within the WAIS context.

Plans for the 2004-05 Airborne Geophysical Survey of the Amundsen Sea Embayment, Antarctica (AGASEA)

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The Ross Sea and Weddell Sea embayments have been the primary focus of attention within the West Antarctic Ice Sheet (WAIS) since the potential for ice sheet collapse and its resulting impact on sea level was first recognized. The Amundsen Sea Embayment (ASE), on the other hand, has been comparatively unstudied primarily due to its remoteness from logistical centers. Recent satellite remote sensing studies, combined with limited ice thickness data, indicate that the ASE discharges the largest ice flux in West Antarctica; furthermore, of all the major drainage basins in Antarctica, it is the only one to exhibit significant elevation change over the period of these satellite observations.

Our present knowledge of the ice thickness and subglacial boundary conditions in the ASE are insufficient to understand its evolution or sensitivity to climate change. Stimulated by observations of its non-steady behavior and its dominant role in WAIS mass balance, the glaciers of the ASE have become a focus for future integrated studies by both the U.S. and European scientific communities, as put forth in the Amundsen Sea Embayment Science Plan (ASESP). This plan has the overarching objectives of assessing the present and predicting the future behavior of the ice sheet in the ASE. In order to accomplish some of the primary ASESP objectives and to guide future surface-based research, the University of Texas (UT) and the British Antarctic Survey (BAS) will undertake a comprehensive aerogeophysical survey encompassing the two major drainage basins within the Amundsen Sea Embayment - Pine Island and Thwaites glaciers. We will conduct this survey during the 2004/05 austral summer, operating from two remote field camps and using two survey aircraft (Figure 1).

The multidisciplinary nature of coupled lithosphere and ice sheet studies requires a broad approach for which multi-instrumented airborne surveys are well suited. Laser surface elevations will enable detailed mass balance calculations and satellite altimeter calibration. Radar sounding data will provide measurements of ice thickness necessary to calculate ice sheet driving stress and hydrologic potential for distinguishing glacier dynamical regimes and to support detailed flow model calculations. Shallow radar layer interpolation will provide ice accumulation rates for mass balance and ice dynamics studies. Internal layer preservation depth will be analyzed for evidence of non-steady flow behavior and will contribute to crevasse classification for evidence of recent non-steady behavior and modern stress state. Detailed basal morphology and roughness statistics will enable interface characterization and complement potential fields data for geologic classification.

Coherent radar echo strength and scattering characteristics will be used for basal interface characterization and basal water detection. Gravity and magnetics data will be analyzed for deep crustal block delineation, sedimentary basin identification, volcanic activity assessment, and geothermal flux estimation, all of which are critical to models of ice sheet dynamics.

The survey design that was proposed required modification due to logistical support limitations. Using the latest estimates of fuel and time available for survey operations, we have developed a strategy that balances coarse coverage of the glacier catchments, higher-resolution coverage of the fast-flow regimes, and along-flow profiles. The 2004 WAIS workshop is an opportunity for the WAIS community to provide feedback on survey design and input on priorities prior to the field deployment which will occur shortly thereafter.

Figure 1: Coverage area of planned ASE aerogeophysical survey shown superimposed on (a) balance velocity and surface elevations contours, (b) bed topography, crustal blocks and recent volcanics (red triangles), and (c) existing data coverage. The survey is subdivided into two sections: the Pine Island Glacier basin (PIB) to be surveyed primarily from field camp PNE, and the Thwaites Glacier basin (TGB) block to

be surveyed primarily from camp THW.

Seismic stratigraphy of the Ross Island flexural moat under the McMurdo-Ross Ice Shelf, Antarctica - A prognosis for ANDRILL drilling

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Ross Island volcanic complex began forming with the emplacement of the basaltic shield volcanoes of Mt Bird and Mt Terror between c. 4.6 and 1.3 Ma, though it has developed most significantly over the last 1 Ma during an eruptive phase resulting in the 3794 m high composite vent of Mt Erebus. Throughout this time loading of the lithosphere at the southern end of the Terror Rift by the Ross Island volcanic pile has progressively depressed the crust resulting in a subcircular flexural moat around the periphery of the island.

Multi-channel seismic reflection data collected from the McMurdo-Ross Ice Shelf (MRIS) reveal the stratigraphic architecture of the moat-fill on the south-eastern side of Ross Island. The moat region has accommodated a well-stratified, regionally extensive sedimentary succession of at least 1.2 km below the sea-floor in the deepest part of the depression. Three seismic stratigraphic units are identified that generally thicken and dip towards Ross Island and are bounded by angular (onlap) unconformities. We infer that these 3 units were deposited in accommodation space created during discrete phases of volcanic load-induced subsidence since 4.6 Ma.

The phases of load induced subsidence may have periodically over-deepened the moat, making it likely that the sedimentary fill is relatively continuous and has largely escaped erosion by ice grounding during past glacial expansions of the West Antarctic Ice Sheet (WAIS) and the MRIS. The age relationships provided by radiometric dating of the various volcanic loads imply that the sediments here have the potential to provide a relatively continuous and high-resolution glacimarine record of the past behaviour of the WAIS-MRIS and the climate history of the western Ross Sea region back to ~5 Ma. This stratigraphic record is scheduled to be drilled by the ANDRILL Programme in the austral summer of 2006. From the interpretation of seismic facies we present a stratigraphic prognosis for the proposed drill site.

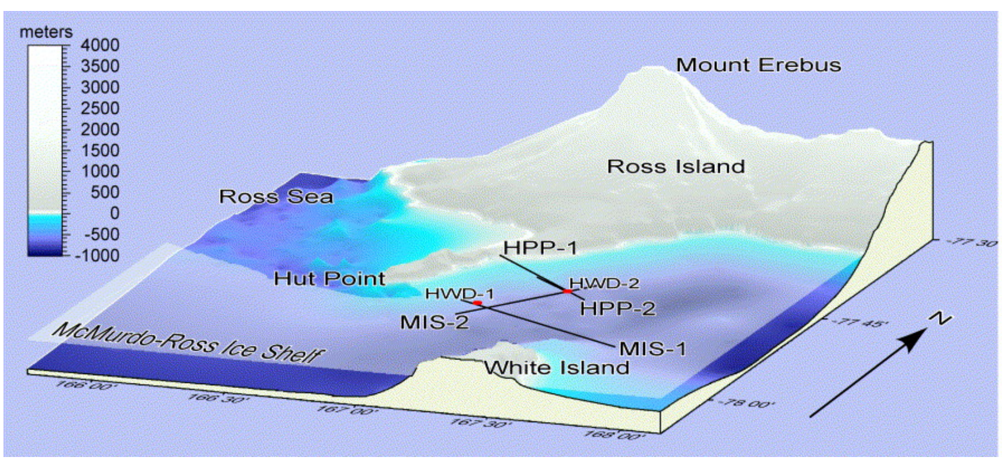

Figure 1: Bathymetry of the Ross Island flexural moat within the study area. The locations of over-ice shelf seismic reflection lines (HPP-1, HPP-2, MIS-1, and MIS-2) and hot water drilling and seafloor sampling sites (HWD-1 and HWD-2) are shown. The hot water drilling sites, HWD-1 and HWD-2, represent 2 possible locations for the ANDRILL McMurdo Ice Shelf drill site. Viewpoint is from 150 degrees at 30 degrees elevation. Topographic data is sourced from the Antarctic Digital Database while bathymetric data is sourced from Geological and Nuclear Sciences archives.

Perpetual Motion: The Fatal Flaw in Glaciology

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Gravitational forcing in glaciers is linked to the product of ice thickness and ice surface slope in the glaciological literature. For glaciers such as continental ice sheets that enter the sea and become afloat, gravitational forcing for the floating part is linked to the height of ice floating above water. This is a consequence of basal buoyancy. Glacial flow in ice sheets begins as slow sheet flow spreading from interior ice domes, with most of that flow converging to become fast stream flow that ends as fast shelf flow when the ice streams become afloat. Therefore, stream flow is transitional between sheet flow and shelf flow, and gravitational forcing in ice streams should be represented by a combination of ice surface slope and height of ice above sea level for a given ice thickness. Failure to do this, and relying only on surface slope to provide gravitational forcing, produces flow that becomes faster as “gravitational forcing” becomes weaker and even vanishes when the surface slope approaches zero. This is the defining characteristic of a perpetual motion machine. It is a fatal flaw in glaciology that makes ice sheets only passive components of Earth’s climate machine, when in fact the geological record of Pleistocene ice sheets shows they are dynamic components. That flaw vanishes when both sources of gravitational forcing are included in computer models that simulate the flow of ice sheets. When full gravitational forcing is included in these models, they will be able to simulate rapid changes in the size and shape of ice sheets that are large enough to trigger abrupt climate change.

Description of the deformation till and reconstructed subglacial environments of the East Antarctic Ice sheet during the LGM at Skarvsnes, Lutzow-Holm Bay

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The late Pleistocene diamicton is exposed in Osen, Skarvsnes of Lutzow-Holm Bay, East Antarctica. This sediment is identified as deformation till (Dreimanis.

1989; Benn and Evans, 1998; Boulton et al., 1996) from the following features:
1) It is consists of more than 10 m thick compacted silt matrix with sub-angular and sub-rounded granules, pebbles and boulders.
2) Two types of crack develop into the sediment: low-angle cracks have a length of 10-30cm and high angle cracks have a length of more than five meters.
3) Both cracks are consistent with the smooth shear planes indicating that the sediment was deformed in a brittle shear zone.
4) Low-angle cracks show a feature of “P shears” which are coupled to each other and often intercalated gravels in a brittle shear zone.
5) High-angle cracks have a feature of “Riedel shears” which continuously developed at regular intervals in the outcrop (Probably high-angle cracks converge on the lowermost part of sediment out of the outcrop).
6) Most of low-angle cracks tend to occur parallel to the ground surface in the upper part of outcrop, suggesting that the shear stress was imposed in the uppermost part of sediment.
7) Shear planes of high-angle cracks incline to the south-west direction, indicating that the share stress was imposed from north-east to south-west.
8) Most of high-angle cracks develop in the whole of outcrop, suggesting that the deformation occurred in the whole of sediments simultaneously.

This description gives us the comparison between the late Pleistocene West and East Antarctic ice dynamics, and the key of resolving the unique history of late

Pleistocene East Antarctic Ice sheet.

A Time Marker from the LGM Detected Throughout West Antarctica

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Deep radar soundings as a part of the US-ITASE traverses in West Antarctica have revealed a bright internal reflector that we have imaged throughout widespread locations across the West Antarctic Ice Sheet and extending to South Pole Station. The layer is seen in traverses emanating from Byrd Station in 4 directions and has been traced continuously for 535 Km toward the Weddell Sea drainage, for 500 km toward South Pole, 150 Km toward the Executive Committee Range and 160 Km toward Kamb Ice Stream. The approximate area encompassed by continuous records of the layer is 250,000 square kilometers. In many locations echo strength from the layer rivals the bed echo in amplitude even though it generally lies at a depth greater than half the ice thickness. At Byrd station where the depth of the layer is 1260 meters, an age of ~17.5 KYBP has been assigned based on the Blunier and Brook (2001) chronology. Hammer et al. (1997) note that at this depth in the Byrd core they found a peak in acidity more than 20 times the amplitude of any other in the core.

The association of this widespread isochrone with a date from the Byrd core provides a useful time marker near the end of the LGM for much of the ice in West Antarctica and possibly beyond. While we find that the internal stratigraphy is disturbed as ice flows through the Bottleneck in the Transantarctic Mts., we have identified the bright layer in the stratigraphic section that continues to South Pole Station. Elsewhere there is evidence for what may be the same layer in the EPICA Dome C core where anomalous concentrations of acid have also been found at 17.5 KY (Wolff, pers. com.). It is also possible that the same layer is present in our radar records from Siple Dome where a bright reflector occurs at approximate the same age, though matching the chemical signature may be difficult. In any case, the area where this layer can be identified may prove to be several times larger than the estimate above.

Using the age from the Byrd Core, we apply a layer-tracing technique and a simple flow model to infer an approximate depth-time scale and estimate the average accumulation rate at two locations in the WAIS, one near the Ross Sea - Amundsen Sea divide and the other at Hercules Dome, both possible sites for future deep ice cores.

WAIS Analogs in Greenland?

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Several regions in Greenland have at least some characteristics in common with areas in West Antarctica. Many WAIS tributaries extend as well defined features deep into the interior of the ice sheet. Similar behavior is observed for the ~700-km long Northeast Greenland Ice Stream, which like the Ross Ice Streams, lies in a low accumulation area favoring warmer bed temperatures. Weak-bedded behavior and ice sheet geometry departing from typical parabolic profiles similar to that of Ross Ice Streams is present at the lower end of the Northeast Greenland Ice Stream and Ryder Glacier. Unlike for the Siple Coast, the weak beds do not persist all the way to the grounding lines. Both Pine Island Glacier and Jakobshavn Isbræ are large fast moving glaciers that have undergone recent acceleration. Roughly doubling its speed, Jakobshavn Isbræ accelerated dramatically over the period during which its floating ice tongue disintegrated. Could a break up of the ice shelf in Pine Island Bay lead to similar rapid acceleration?

The near-surface signature of flow bands in the onset regions of Ice Streams C1b and D1, based on grids of GPR data

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In the onset regions of the ice streams flow converges and accelerates. If this process occurs under conditions of steady-state flow and steady-state accumulation, then a regular pattern of internal layers should result. In order to assess whether or not the flow dynamics were steady-state, we recorded grids of ground-penetrating radar profiles in the areas immediately upstream of the marginal crevasse zones on Ice Stream D1 and the C1b tributary of Ice Stream C. The maximum effective penetration of the radar signal was approximately 120 m (equivalent to approximately 600 years).

The internal layers imaged by the radar reflections undulate in sequences of peaks and troughs on the transverse profiles. Many of the features can be traced between lines (which were 5 km apart on Ice Stream D1) and vertically through the sections, allowing the identification of 'flow bands' similar to those interpreted by Ng and Conway (2004, Geology 32/6) for deeper parts of Ice Stream C (a.k.a. Kamb Ice Stream). However not all the peaks and troughs observed at depth can be traced to the near surface, especially on Ice Stream D1. By tracking changes in the separation of layers though the grid it is possible to evaluate the influence of accumulation distribution and horizontal strain on the development of the internal layer pattern and thus identify changes in flow and/or accumulation.

Spatial and Temporal Variation of the Characteristic Time Scale of Microwave Emission with Snow Properties over Antarctica

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Space-borne infrared and passive microwave sensors are ideal platforms for monitoring spatially distributed snow properties and climate variables on short temporal scales. If properly utilized these sensors have the potential to provide over two decades of valuable temperature and snow property datasets for expansive areas with sparse ground measurements.

Microwave emission is conventionally related to physical temperature via "effective emissivity", a ratio of time-averaged brightness temperature (TB) and physical (usually, surface) temperatures. However, on sub-annual time scales, the effective emissivity is time dependent and fails to account fully for the dependence of TB on the history of surface temperatures. Winebrenner et al. (2004) derived an alternative relationship between surface and brightness temperature time series in terms of a convolution, which depends on a time scale, ?o, which is a ratio of the firn's thermal diffusivity and microwave extinction coefficient. Determination of ?o is accomplished by minimizing the difference between the known TB measured by the SMMR and SSM/I sensors and simulated TB, based on surface temperature measurements.

Simulation of 37 GHz, vertically polarized (37V), brightness temperatures using automated weather station (AWS) temperature data yields excellent agreement with 37V observations (Winebrenner et al, 2003). Time scales range from days to tens of days, depending on location, with uncertainties of about 10%. Here, we use monthly averaged, clear sky AVHRR data (Comiso, 2000) as our surface temperature measurement, compared with 37V TB's to diagnose ?o from 1982-1999 across the entire Antarctic ice sheet. In locations where both AWS and AVHRR data were used there was good agreement in the ?o values obtained.

Through these simulations, insight has been gained on the covariance of ?o with snow properties throughout space and time. ?o maps generated with AVHRR data in the area of Byrd Station, Antarctica mimic radar-generated accumulation maps produced by Morse et al (2002). This area shows a linear relationship between ?o and accumulation (Figure 1), for accumulation rates less than about 50 cm/year (ice equivalent). If this relationship proves valid elsewhere, then retrievals of accumulation rate using this method could yield information on sub-decadal scales since, the physical interactions of the microwave emissions at 37V occur largely in the top few decimeters to meter of firn. Temporally resolved maps of ?o display variability on a 3-yearly time scale. Whether this temporal variability tracks accumulation rate fluctuations remains under investigation.

On a continent-wide scale, ?o values in East Antarctica are generally lower than in West Antarctica. Comparison of our long term (1982-1999) ?o map with the accumulation map of Vaughan et al. (1999) suggests that, on large scales, snow physical properties in addition to accumulation rate must influence ?o.

Figure 1 Comparison of accumulation rates and calculations of t0 for the area of the main West Antarctic ice divide near Byrd Station. (a) shows the 2700-year average data from Morse et al. (2002), (b) shows our calculations of t0, (c) compares the two as a scatter plot.

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West Antarctic Balance Fluxes: Impact of smoothing, algorithm and topography

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Grid-based calculations of balance flux and velocity have been widely used to understand the large-scale dynamics of ice masses and as indicators of their state of balance. This research investigates a number of issues relating to their calculation for the West Antarctic Ice Sheet: 1) different topography smoothing techniques; 2) different grid based flow-apportioning algorithms; 3) the source of the flow direction, whether from smoothed topography, or smoothed gravitational driving stress; 4) different flux routing techniques and 5) the impact of using different topographic datasets.

The different algorithms described below lead to significant differences in both ice stream margins and values of fluxes within them. This encourages caution in the use of grid-based balance flux/velocity distributions and values, especially when considering the state of balance of individual ice streams.

1) Most previous calculations have used the same numerical scheme (Budd and Warner, 1996) applied to a smoothed topography in order to incorporate the stresses that smooth ice flow (over distances of a number of ice thicknesses). There are two options to consider when smoothing the topography, the size of the averaging filter and the shape of the averaging function. However, this is not a physically-based approach to incorporating smoothed ice flow and also introduces significant flow artefacts when using a variable weighting function.

2) Different algorithms to apportion flow are investigated; using 4 or 8 neighbours, and apportioning flow to all down-slope cells or only 2 (based on derived flow direction).

3) A theoretically more acceptable approach of incorporating smoothed ice flow is to use the smoothed gravitational driving stress in x and y components to derive a flow direction. The flux can then be apportioned using the flow direction approach used above.

4) The original scheme (Budd and Warner, 1996) uses an elevation sort technique to calculate the balance flux contribution from all cells to each individual cell. However this cannot be used for smoothed driving stresses, as it is permissible for ice to flow in an uphill direction. Other possible techniques include using a recursive call for each neighbour or using a sparse matrix solution.

5) Two continental scale Antarctic DEMs are used as input data, which have significant differences in coastal and mountainous areas. The largest difference in flux calculations is therefore in these areas. Of particular interest is the difference in the Rutford Ice Stream/Carlson Inlet and Kamb Ice Stream (Ice Stream C) fluxes.

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Ice flow property derived from ICESat surface topography in West Antarctica

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The major difficulty in calculating ice sheet mass balance is a lack of sufficiently precise information on the flow properties. Analysis of the detailed variations in the ice sheet elevation profile against bedrock relives provides valuable means of determining ice flow properties. In this study, the power spectral analysis of the detailed ICESat surface undulation data against available bedrock profiles was performed along selected sections near West Antarctic flow-lines. Results show that the spectra of the surface undulations are characterized by a minimum damping indicated by a peak value of the power with wave-length of several km, while the magnitude of the spectra power for the bedrock intending increase with the wave-length. By using balance velocity and mean damping factor with wave-length 20-40 km the mean ice viscosities were estimated with magnitude of 1016-1018 P, varying clearly along with the temperature changes.

Towards radar thermometry: an effective absorption temperature at Siple Dome

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During the initial development of radioglaciology, several workers studied bulk radar absorption in the hope of estimating the temperature field of the ice (Bogorosky et al., 1985, section 6.4). This work was limited by the available experimental data on the effect of impurities on the dielectric properties of ice. A modern understanding of the linear dependence of high-frequency ice conductivity on acid and sea salt concentration and the strong Arrhenius-form dependence on temperature (Figure 1, recently reviewed in Fujita et al., 2000) allows us to move towards better quantifying the relationship between radar absorption (proportional to ice conductivity) and temperature.

At Siple Dome, 3 MHz radar transects in both common-offset and common-midpoint configurations were used by Winebrenner et al., 2003 to estimate the bulk attenuation length of the ice. Using a revised approach of their method to estimate the bulk attenuation length via common-offset data and assuming a constant acid and sea salt burden in the ice column, an effective absorption temperature of -14 C is calculated. This result is unique with respect to the attenuation length and the impurity concentrations used. The result is biased towards the warmer basal temperature (-2.3 C) because, at constant impurity concentrations, warmer ice is more absorptive (Figure 2, calculated using SDM-A temperature profile). Also, this result is similar to the values reported by Bogorodsky et al., 1985 for Antarctic ice that assumed constant impurity concentrations.

An obvious refinement of this approach is to integrate ECM and CCM data from the SDM-A core as well as the chemistry series so that we will no longer have to assume constant impurity concentrations. Given that the temperature profile at Siple Dome is also known, we can further calibrate our result from radar thermometry. These data could also constrain 1-D temperature profiles by combining with surface parameters (such as the mean annual temperature and accumulation rate) with the effective absorption temperature. Because Siple Dome represents a unusual situation where the bed is fairly homogeneous at 3 MHz over a large area in terms of reflected power (Gades et al., 2000), common midpoint surveys will be the most appropriate for attempting such absorption measurements in other regions.

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Spatial variability of stable isotope ratios in snow: How representative are ice cores?

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Isotopic records from ice cores are used as a proxy for temperature history. However, to what extent annual average (or sub-annual) isotopic values derived from an isotopic record are representative of a larger area is not well known. Prior work has addressed this issue through replicate coring and has shown that the 'deposition noise' (i.e. the uncorrelated variance of two adjacent time series) in isotope records are inversely related to local accumulation rate. These studies have used ice cores separated by a few kilometers (Dome C) or tens to hundreds of kilometers (ITASE). Time series separated by these distances may record different climatic conditions and should not necessarily show a large correlation coefficient.

In this study, we examine the meter-scale spatial variability of stable isotope ratios in snow by collecting several snow samples from a single stratigraphic layer. Samples were collected from snow pits in Antarctica with a range of accumulation rates from 5 to 50 cm a-1. Results confirm that the small-scale lateral variability in high accumulation rate areas is much smaller than the seasonal variability. However, the lateral variability can become as large as (or larger than) the seasonal variability as accumulation rate decreases, and a clear relationship between small-scale variability and accumulation rate is not apparent.

These results suggest that: (1) The large isotopic variation of precipitation and atmospheric vapor on short time scales (e.g. daily variation measured at Summit, Greenland) may be preserved due to the episodic nature of snow accumulation. However, some of the lateral variation in near-surface snow may be due to post-depositional changes, particularly in low-accumulation rate areas. Further measurements should be able to separate these two effects. (2) Caution is required when using annual average isotopic values derived from a single isotope record due to potentially large meter-scale spatial variability. (3) Since the lateral isotopic variability can be as large or larger than the vertical variability, isotopic diffusion may be considered to act in three dimensions (rather than only vertically) when reconstructing seasonal climate parameters from isotopic records.

Insights into WAIS and GIS dynamics: Summary of modeling results

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Thermomechanical flowline simulations based on regional basal thermal controls on ice-stream behavior suggest that post-glacial warming initiated grounding-line retreat in the Ross Embayment with evolution of the ice sheet responding more to climate-forcing feedbacks than to changes in sea level. In addition, results imply that ice in the central Ross Embayment experienced small deglacial thickness changes. Subsequently, simulated modern ice streams are thinning more rapidly than their beds are rebounding at the grounding line. Thus, ice-sheet thermodynamic and isostatic considerations indicate ice streaming along the Siple Coast will continue amidst ongoing retreat.

Meltwater-filled crevasses have been cited as the catalyst to the catastrophic break-up of the Larsen B ice shelf in West Antarctica (Scambos et al., 2000; Scambos et al., in review). In west central Greenland, field observations at the Swiss Camp suggest that surface meltwater reaches and lubricates the bed through moulins, leading to enhanced ice-flow velocities with increased surface melt (Zwally et al., 2002). Alley et al. (in review; this meeting) offer theoretical bases for crack-propagation mechanisms by which surface meltwater can penetrate more than a kilometer of cold ice. Citing these studies, we assume that surface meltwater can access the bed through thick, cold ice and enhance ice flow. With the addition of a sliding parameterization of Zwally et al.'s (2002) correlation between seasonal surface melt and ice velocities, flowline-model results predict an enhanced sensitivity of the Greenland ice sheet to surface warming.

Modelling the evolution of ice streams

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The evolution of the West Antarctic ice sheet has been identified by many authors as a key unknown in future sea-level change. The vast majority (> 90%) of mass lost from the ice sheet flows through a relatively small number of ice streams. An understanding of the long-term behaviour of these ice streams is therefore vital if we are to predict future sea level accurately. Here we use a numerical model of a generic ice stream to investigate the coupled evolution of ice-stream flow, temperature and form, with the particularly aim of identifying internal sources of variability within this system.

The model comprises three main components. These are a first-order model of the stress regime (incorporating all stress components in the horizontal force balances but assuming that the vertical stress balance is hydrostatic) within the ice stream and adjoining slow-flowing ice; the temporal evolution of the internal temperature structure of the ice mass incorporating dissipation, diffusion and advection; and effects of the changing flow field on the geometry of the ice mass (thickness evolution).

We employ the model to investigate the equilibrium thermal regime of a generic Siple Coast ice stream. Using the range of temperature and stress parameters appropriate to the Siple Coast, we find that a generic ice stream cannot sustain a wet bed at equilibrium. The presence of ice streams along the Siple Coast can be reconciled with this result in one of three ways. First, a net influx of basal water from upstream buffers the basal thermal regime. Second, the ice streams are currently in the active phase of surge cycles and will eventually stagnate. Third, the existence of ice streams is a temporary phase through which the ice sheet is passing perhaps as a consequence of decay from the Last Glacial Maximum.

A Dilatant Till Layer Near the Onset Region of Bindschadler Ice Stream: Implications for the Onset of Streaming Ice Flow

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Analysis of the seismic reflector along the ice-bed interface has proven to be a useful tool in identifying a meters-thick dilatant till layer near the onset region of Bindschadler Ice Stream. The amplitude versus offset (AVO) technique measures how the amplitude of a reflection changes with source to receiver offset (or angle of incidence of the seismic wave relative to an interface). We can estimate the properties of the bed beneath the ice from this amplitude variation. The most notable change is a 180 degree phase shift of the basal reflection at intermediate angles. The incidence angle at which this phase shift occurs can be used to better constrain the impedance contrast between the ice and its underlying bed. We suggest that a dilatant and possibly deforming till layer is present in the upper reaches of Bindschadler Ice Stream, which may be closely linked to the onset of streaming ice flow.

Constraints on the magnitude and timing of post-LGM thinning at Siple Dome from thermomechanical flow modeling

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The measured depth-age and layer-thickness patterns in the Siple Dome ice core constrain combinations of ice thickness and accumulation histories, but do not (by themselves) permit a unique determination of these histories individually. Waddington and others (see abstract, this conference) demonstrate the tradeoff between various ice thickness and accumulation histories using a 1-D, transient, kinematic flow model. They find that a "reasonable" accumulation history at Siple Dome for the past ~25 ka requires thinning of <500 m taking place from ~16-2 ka bp, with a transient divide moving through the core site at ~4 ka bp.

Here, we take a different approach; we assume known accumulation-rate and surface-temperature histories (from M. Spencer and R. Alley, J. White and A. Schilla, respectively) and a divide migration history after 2 ka bp that is consistent with previous work (Nereson and others, 1998). These are used to drive a transient, thermomechanical-flow model (see Price and others, poster abstract, this conference) that explicitly accounts for transient thermal effects and the advection of internal layers through transient velocity fields. To fit the measured depth-age scale, we vary (i) the magnitude and timing of thickness changes and (ii) the timing of divide-flow initiation.

We find that a range of models fit the measured depth-age scale equally well, with more recent initiation of divide-flow requiring more thinning and vice versa. A further constraint is provided by comparing the measured and modeled layer shapes in the divide region; the more recent the initiation of divide flow, the smaller the "Raymond bump" amplitude and the depth of its maximum (e.g. Conway and others, 1999). The model that best fits both constraints is compatible with that inferred by Waddington and others; 400-500 m of thinning taking place from 7-2 ka bp, initiation of divide-flow between 4 and 3 ka bp, followed by divide migration after 2 ka bp.

The best fitting models require thinning at a rate of ~0.10 m/a for ~5 ka. This large rate of thinning appears to be coincident with significant grounding line retreat that took place after 7 ka bp (Anderson and Shipp, 2002). We discuss the potential implications of these observations with respect to the deglaciation history of the WAIS and, in particular, with
respect to the possibility for enhanced ice flow past Siple Dome during the Holocene (e.g. through the initiation of streaming flow or more vigorous streaming flow). #### References:

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Depth-age and annual layer-thickness scales for Siple Dome, West Antarctica: measurements versus predictions from ice-flow modeling

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The observed depth-age scale and internal layer shapes from Siple Dome are compared to predictions from a new, thermo-mechanical flowline model. The model solves the full, 2-dimensional momentum and heat balance equations in orthogonal, curvilinear coordinates, using the finite volume method. Evolution of the free surface and internal layer shapes are accounted for explicitly, according to the calculated, transient velocity fields.

When driven solely by climate forcing representative of the past ~120 ka, the modeled depth-age scale is, in general, too young. We experiment to find various ice thickness and divide-flow histories that bring the modeled and measured scales into closer agreement. The best fitting models and their interpretation with respect to the deglaciation history of the WAIS are discussed in a related, oral presentation (same authors, this conference).

Accelerating glacier flow on the warming Antarctic Peninsula

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Over the decade from 1993 to 2003, glaciers on the west coast of the Antarctic Peninsula experienced a widespread and significant increase in flow rate. Using Synthetic Aperture Radar feature tracking, we measured flow on two 200 km-long sections of coast, one near the northern tip of the Peninsula (~64?S) and one north of Rothera (~67?S) for 1993, 1996, 1997, 1998 and 2003. >From these measurements, we took 150 glacier long-profiles of flow and these yielded 3600 individual samples common to four of the years spanning 1993 to 2003. These samples show that the median increase in flow rate over this decade was 12 ± 1%. The increase at the southern site was almost linear through time while at the northern site, the increase occurred between 1993 and 1996, after which flow remained 12 % faster.

Rapid warming of the Antarctic Peninsula climate has occurred over the past century and has been associated with a progressive retreat and ultimately collapse of ice shelves north of a southward-retreating -9?C mean annual isotherm. The effect of these shelf collapses on grounded glaciers has been studied intensively, but change in glaciers unaffected by shelf collapse has not. These results show that grounded ice is being lost from the Peninsula on a much larger scale than was previously realised. We tentatively attribute the acceleration in glacier flow to enhanced lubrication resulting from increased summer melt. This implies that the warming climate is raising sea level much more rapidly than would occur through increased melting alone.

West Antarctic Ice Core Chemistry and Self-Organizing Maps: A First Look

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Self-organizing maps (SOMs) are a tool for analysis of variability in large, multivariate and/or multidimensional datasets. The technique provides a complementary nonlinear alternative to more frequently used but linear tools such as empirical orthogonal function (EOF) analysis. SOMs have a number of advantages including readily handling nonlinear behavior and robust interpolation into areas of the input space not present in the available training input. SOMs also have the benefit of being a completely independent uniformitarian analysis pathway and thus provide independent results for comparison with more traditional techniques.

In short, SOM training develops a set of generalized patterns from multidimensional input data by projecting the input to a two-dimensional grid and thereby mapping the probability density function of the input to two dimensions. Unlike EOFs, the patterns are not orthogonal and they do not sum to the original data. The size of the grid is problem dependent and determined somewhat subjectively based on the goals of the analysis. Larger (smaller) grids do less (more) generalization. The grid also has an inherent spatial structure such that similarity between patterns decreases with distance in the grid. This structure leads to opposite patterns being located in the diagonal corners of the SOM grid. While these pattern pairs will not necessarily be mirror images, they often represent a (possibly nonlinear) axis of variability. Once training is complete, each data record maps to a single closest matching SOM pattern. Further analysis of the data often focuses on how these mappings change over time or space, e.g., frequency maps.

A SOM analysis (using a 5x4 grid with 20 patterns, Figure 1) has been started on the Holocene (~20 - 11,200 ybp) portion of the Siple Dome A core major ion chemistry record (Meyerson et al, in review) to explore this dataset from a nonlinear, SOM-based perspective. Two general behaviors are identified by the analysis: high versus low values for nearly all species in the corner patterns on one diagonal and a high NO3/SO4, low NO3/SO4 pair on the other diagonal.

Frequency mapping by time slice broadly identifies the first diagonal as the upward trend in concentrations seen in all species through the Holocene. Early (first 2,000 years, low values) and late (last 2,000 years, high values) portions of the record map to patterns in opposite corners of the SOM grid with the corner pattern itself accounting for 43% and 16% of the early and late part of the record, respectively. The early record is fairly tightly mapped with just three (of the 20 available) SOM patterns in its corner accounting for 82% of the data. In contrast, the last 2,000 years of the record is more variable and the data are more spread out over that corner of the SOM grid: the five leading patterns, located in the opposite corner of the grid, account for only 50% of this subset.

Mapping the data associated with a particular SOM pattern versus is another useful analysis. Plotting records from the two high/low values corner patterns versus time confirms, in part, the trend in species concentration seen in the normal time series. The low values pattern is most frequent in the 9,000 - 11,000 ybp range with a secondary peak around 6,500 ybp while the high values pattern appears most frequently during the last ~800 to 1,000 years. The NO3/SO4 low value pattern has a broad peak over the 6,000 - 9,000 ybp range and a secondary peak around 3,000 ybp. The NO3/SO4 high value pattern first appears around 3,000 ybp and continues to present. Although this behavior is intriguing, interpretation of the two NO3/SO4 patterns should be cautious given the relatively few records involved (~200 records or ~7% of the dataset). Similar mapping of the other SOM patterns, in particular the various forms of all/most species high or low, will give further insights to the temporal behavior of this record.

An additional caution appears when mapping the “instrumental era” portion of the record: 70% of the last 80 years of the record (only 32 samples) maps to just 4 SOM patterns clustered in one corner of the SOM grid. This leaves the majority of the record uncalibrated by modern meteorological data and highlights the extrapolation inherent (and necessary) in this type of work.

Further insights are expected when this tool is applied to other ice core chemistry datasets from West Antarctica and nearby regions.

Figure 1. A self-organizing map analysis of Siple Dome major ion chemistry (normalized) for the Holocene. Percentages within each plot are the frequency mapping for the full record (upper left corner), first 2,000 years (lower left corner) and last 2,000 years (lower right corner). Heavy outline at upper left (lower right) surrounds patterns accounting for 82% (50%) of the oldest (youngest) part of the record.

Latest InSAR/ICESat/CECS-NASA results from Pine Island/Thwaites Glaciers, West Antarctica

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Recent aircraft and satellite laser-altimetry surveys of the Amundsen Sea sector of West Antarctica show that local glaciers (Pine Island, Thwaites, Haynes, Pope, Smith, and Kohler) are discharging about 250 cubic km of ice per year to the ocean, which is 60 percent more than is accumulated within their catchment basins, and sufficient to raise sea level by more than 0.2 mm per year. Glacier thinning rates near the coast for 2002-2003 were approximately double those observed during the 1990s using satellite radar altimetry. Pine Island Glacier continued to accelerate between 2000 and 2004. Most of these glaciers flow into floating ice shelves over bedrock up to hundreds of meters deeper than previous estimates, providing escape routes for continental ice from further inland than anticipated if ice-sheet rapid retreat is underway.

We will discuss these results in details, with a particular emphasis on the comparison of CECS-NASA airborne laser altimetry data with ICESat satellite laser altimetry data.

Institute Ice Stream: An analog to the Ross Embayment ice streams in the Ronne drainage

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Landsat image pairs and and regional ice morphological mapping show a host of characteristics of the Institute Ice Stream (IIS) that are reminiscent of the Ross Embayment ice streams on the opposite side of the WAIS. Surface features in enhanced-resolution images suggest that the Institute has an extensive ice plain on its northeastern side, and an intensely-shearing ice-on-ice margin along the eastern boundary of the stream. Elevation mapping from an image-enhanced portion of the RAMP DEM and velocity mapping from Landsat image pairs provide information on flow speed, strain, and driving stress. These data indicate that the Institute trunk has extremely low average slope (0.0008; lower than several major ice streams) and low driving stress. Maximum flow speed in the lower trunk is just under 400ma-1, and observations spanning 11 years show no significant change in flow speed. As of 1997, the mass flux of IIS was 22.7 +/-2 Gta-1, while input from accumulation is estimated at 25.1 +/-2 Gta-1. Changes in slope and flow speed in the upper trunk define a very clear transition, or 'onset' to streaming ice flow, suggesting a significant change in basal properties there.

In the Ronne Shelf area downstream of IIS, a set of streaklines curves sharply near the Korff Ice Rise, implying a significant in ice flow direction in the recent past. Between the Korff and Henry ice rises lie the Doake Ice Rumples, lightly-grounded regions that partly obstruct outflow from IIS. It is hypothesized that changes in thickness (or basal melt rates) on the Ronne would significantly affect the proportion of IIS ice that flows over the Doake Ice Rumples. Such a change in thickness may explain the curved streaklines. Further evidence of flow changes in the western Ronne Ice Shelf may be preserved in flow-stripes downstream of the Doake rumples.

Implications of the deuterium excess record from the Siple Dome ice core

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Deuterium excess is a proxy for conditions in the regions providing the moisture to ice core sites, and is derived from the combination of deuterium and oxygen isotope records. Correcting for moisture source conditions is fundamental to interpreting temperature from the raw isotopes. Comparing the deuterium excess record from the Siple Dome ice core in West Antarctica with other Antarctic deuterium excess records reveals that Antarctica receives moisture from various regions whose signals are preserved despite strong circum-Antarctic atmospheric circulation. Using the Siple Dome deuterium excess record as a proxy for conditions over the subtropical to polar Pacific Ocean provides us with a long, continuous, highly-resolved and well-dated indicator of sea surface conditions which can be compared with other data, such as sea surface temperature records and reconstructions, to further inform us about the moisture source region. The Siple excess record can also be compared with more distant climate proxies, such as the GISP2 isotope record, ultimately providing insight into extra-Antarctic climate, including ENSO and millennial-scale climate change.

Ice core evidence of 200 years of Antarctic climate change and its connections with the Southern Annular Mode

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A sparse network of meteorological observations in Antarctica extends back only to the late 1950s, making it difficult to characterize Antarctica's climate behavior in the context of natural climate variability and global warming. We show that composites of stable isotope (dD and d18O) time series from several sub-annually dated ice cores closely track 40 years of interannual variations and trends in the instrumental record of Antarctic mean temperatures. Using this calibration, we construct a temperature history since 1800 from ice cores. This time series, representing Antarctic temperatures (especially outside of the Peninsula), has a much smaller positive trend since the 1850s than is seen in the global and Southern Hemispheric means of instrumental records. An independent, station-based reconstruction of the Southern Annular Mode (SAM) since 1905 is also presented. The relationship between the reconstructed SAM and the reconstructed temperature time series is consistent with that observed between the actual modern indices, although both reconstructions have relatively high uncertainties at this stage.

Warm ocean is eroding West Antarctic Ice Sheet

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Satellite radar measurements show that ice shelves in Pine Island Bay have thinned by up to 5.5 m yr-1 over the past decade. The pattern of shelf thinning mirrors that of their grounded tributaries - the Pine Island, Thwaites and Smith glaciers - and ocean currents on average 0.5 °C warmer than freezing appear to be the source. The synchronised imbalance of the inland glaciers is the result of reduced lateral and basal tractions, and the drawdown of grounded ice shows that Antarctica is more sensitive to changing climates than was previously considered.

“Clearing Up” ICESat Data over West Antarctica

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Since it began operations in early 2003, NASA’s Ice, Cloud, and land Elevation Satellite (ICESat) has provided valuable data for glaciological research using its Geoscience Laser Altimeter System (GLAS) sensor. Despite excellent precision under optimum circumstances, several issues have made utilization of the available altimetry data a challenge. First, planned laser lifetime has not been realized leading to discrete data acquisition intervals rather than continuous operation as well as reduced coverage density. Second, data has been acquired using two different lasers and consequently variations in the GLAS optical pathway that must be compensated by iterative post-processing. Third, declining laser energy in both the 1064 nm and especially the 532 nm channel has impacted the precision of the data through the available operational periods. And fourth, clouds have a variable impact on retrieved elevation precision that has been difficult to define on a shot-by-shot basis. This presentation will focus on these issues and will illustrate and quantify their effects using data from West Antarctica.

Lake Ellsworth: a candidate for Antarctic subglacial lake exploration

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Evidence is presented, from a variety of geophysical sources, on the physiography of a small subglacial lake in West Antarctica. Airborne radio-echo sounding defines the position of the lake, its length and tectonic setting. The lake is located at 79°S, 90°W, beneath about 3.5 km of ice, 20 km from an ice divide near the Ellsworth Mountains that separates the ice sheet from the Filchner-Ronne Ice Shelf. Interferometric Synthetic Aperture Radar from the lake's locale, and ice sheet balance velocities, show that ice flow across the lake is likely to be of the order of a few metres per year. The lake appears to be located within a distinct topographic hollow, which is over 1.5 km lower than the surrounding bed. The slope of the lake's ice-water interface is over 10 times greater than that found at Lake Vostok. As the slope of the ice-water interface is thought to control the circulation of water within subglacial lakes, this particular lake may be significantly more dynamic than most others (with less steep surfaces). Judging by the bed slopes flanking the lake, the water depth is highly likely to be several 10s (and possibly 100s) of metres. Numerical modelling of ice flow across the lake reveals the relative rates of ice accumulation and basal melting responsible for the lake formation. Although the lake is unlikely to be as old as Lake Vostok (or other East Antarctic subglacial lakes), its environment will be similar to any subglacial lake, i.e. cold, dark and under pressure of the overlying ice sheet. Consequently, adapted lifeforms may be expected as much in this lake as in any other. A proposal has been made to undertake a comprehensive geophysical survey of the lake. It is hoped that the full extent of the subglacial lake, and its bathymetry, will be evaluated within 5 years. This lake appears ideal for *in situ* observations, judging from the criteria for identifying appropriate candidates for exploration established by the SCAR Group of Specialists on Subglacial Antarctic Lake Exploration (SALE).

Numerical modelling of the Eurasian ice sheet and its relevance to West Antarctica

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The geography of West Antarctica is strikingly similar to the Eurasian Arctic. Both involve a large continental shelf sea no more than a few hundred meters deep, and both have proximity to a pole and to a continental margin (Figure 1). The major difference is that West Antarctica has a 2.5 km thick ice sheet over it, whereas the Eurasian Arctic is now comparatively free of grounded ice. At the last glacial maximum (LGM), however, the Barents and Kara Seas were covered by a large marine ice sheet which subsequently collapsed prior to the Holocene. The geological remnants of the Eurasian ice sheet, and the ice sheet history reflected in this record, may be critical to evaluating the future of the WAIS.

The interpretation of the geology has varied enormously. While some have claimed evidence for a massive 3.5 km thick ice sheet over the whole of northern Europe at the LGM, others have proposed virtually no ice at all on the sea floor to the north of the Norwegian and Russian mainland. To resolve this issue, two research programmes were organised by the European Science Foundation to gather geological evidence from the land, sea and ocean of the former ice sheet. The first (PONAM: POlar North Atlantic Margins) concentrated on the western margins of the Barents Sea where the ice margin during the LGM was located near the edge of the continental shelf. The area of focus then shifted east to the Russian Arctic during the follow-up programme named QUEEN (QUaternary Environments of the Eurasian North). These programmes allowed the limits of the Eurasian Ice Sheet to be determined with some confidence (Figure 2). The glacial history revealed by the geological investigations was developed further through computer simulations of the ice sheet growth and decay.

Both the PONAM and QUEEN programmes employed ice sheet modelling to provide quantitative details about the size and dynamics of the former ice sheet. The model's environmental inputs were adjusted until the ice sheet size fitted with the geologically-inferred LGM ice margin (Figure 2). Ice sheet modelling was also used to predict the decay of the ice sheet in a manner consistent with the geological evidence for deglaciation. Deglaciation was actually quite difficult to model at the time when geological evidence reveals ice decay (deglaciation took place early, at around 15,000 years ago, and rapidly as full decay of the Barents Sea was completed within a few thousand years). In order to reconstruct the proper deglaciation, enhanced rates of iceberg calving had to be artificially included in the model (Figure 3), so allowing rapid break up of the ice sheet at the marine margin. The rationale for increasing iceberg calving (or ice loss at the marine margin) is two fold. First, sea level may lead to enhanced rates of calving if the ice is grounded and to enhanced flow as the ice sheet becomes buoyant. Second, if the ocean temperature increases, ice loss at the grounded margin via melting may occur.

At the LGM, grounded ice was probably in place across the whole of the West Antarctic continental shelf, just as it was in the Barents Sea. Ice decay in West Antarctica (from its maximum state to its present condition) was different to the decay of ice in the Barents Sea in two ways. First, deglaciation began much later than in the Barents Sea. Secondly, ice decay in West Antarctica resulted in the formation of large floating ice shelves between the open ocean and the grounded ice sheet. These differences suggest that two conclusions can be drawn about the stability of the West Antarctic ice sheet. First, the ice shelves may be influential in maintaining the stability of the ice sheet because they act as a buttress to support the grounded margin of the ice sheet, whereas in the Barents Sea they may have been absent and the grounded margin was actively involved in iceberg calving. Secondly, given the ice shelf buttressing effect on the ice sheet, the present sea level is not high enough to encourage ice decay in West Antarctica to the extent witnessed in the Barents Sea.

The West Antarctic Ice Sheet is clearly capable of resisting substantial rises in sea-level. The reason for this resistance could be that floating ice shelves in West Antarctica are the key to maintaining grounded ice upstream. It has been well documented that we should be concerned with the stability of the ice shelves in West Antarctica. If they decay, the West Antarctic Ice Sheet will look much more like the former Eurasian Ice Sheet just before it broke up. In this situation, the processes which caused the break up of the marine portions of the Eurasian Ice Sheet (as observed in the geological record) may act over West Antarctica.

Figure 1. Comparison between the geography of West Antarctica and the Eurasian Arctic.

Figure 2. Ice sheet margin of the Eurasian ice sheet at the LGM as determined by the QUEEN programme.

Figure 3. History of the Eurasian ice sheet as predicted by numerical ice sheet modelling.

Ice stream onset regions, shear margins and basal conditions: Observations from Rutford Ice Stream

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On-going analysis of new ground-based observations from the onset region and shear margin of Rutford Ice Stream are presented. They include some of the first direct observations of basal conditions within these glaciological regimes. The data were obtained from three survey lines, perpendicular to ice flow, which all straddle the boundary between ice sheet and ice stream. Two lines were located towards the downstream end of the onset region; the third line was further downstream where a distinct shear margin is well established. These three lines are supplemented by data from nearby Carlson Inlet (slow flowing) and Fletcher Promontory (ice sheet with frozen bed). Surface elevation and velocity were measured using GPS techniques; ice thickness and basal conditions were determined from seismic surveys; and shallow ice structure was obtained from ground-penetrating radar.

Observations so far include:
1. With downstream distance, both the bed trough and the width of the lateral flow increase, become increasingly well-defined.
2. The bed beneath all three survey lines is wet sediments (deforming in some places and not in others). There is no evidence for hard bedrock or frozen bed/permafrost.
3. The lateral change in ice flow is associated with a friction difference at the bed, though in the onset region the change in bed conditions does not correlate as well with the ice velocity or the bed as it does further downstream.
4. The difference in basal friction between the ice stream and the ice sheet increases downstream.
5. Within the ice stream, basal friction increases with downstream distance, though earlier work suggests a switch to a progressive decrease, from here onwards.

Comparisons are made with recent reviews and studies of onset regions and shear margins. Future work is aimed at incorporating more bed topography and ice velocity (from airborne radar and InSAR); and at investigating how well the data support theoretical models of ice stream shear margins.

RABID: Drilling to the bed of Rutford Ice Stream, 2004/05

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We report on preparations to access the bed of Rutford Ice Stream, West Antarctica, during the 2004/05 austral summer. Holes will be drilled to the bed using the BAS hot-water drill, used successfully many times over the last 15 years and now upgraded to the required 2.5 km capability. We plan to drill in two locations: first where the bed is believed to comprise dilatant, deforming sediments; and second where the bed is non-deforming and ice motion is by basal sliding. Sediment samples will be retrieved from the bed using a gravity corer. Short sections of ice will also be collected at specific target depths, using a hot-water corer. Tethered stakes (copies of the CalTech design) will be inserted into the bed, to detect differential motion between the basal ice and the bed. Instruments measuring water pressure, temperature, tilt and orientation will be deployed in the boreholes. Sensor packages will span the whole ice column but will be concentrated towards the bed. On the surface there will be a combined network of GPS receivers and passive seismic recording stations. These will be supplemented by seismic reflection and shallow radar (GPR) surveys. Finally, we are in the process of arranging a collaboration with NASA-JPL to enable their upgraded high-resolution video camera to be deployed in the boreholes.

The project will contribute to a number of research areas, including:
1. West Antarctic Ice Sheet history in the Weddell Sea sector
2. Ice Stream basal processes and conditions
3. Ice Stream dynamics

Preparation for this project has already been underway for more than 4 years. The field location is 1300 km from the main support base at Rothera and everything must be input by Twin Otter. A depot containing 200 fuel drums and approximately 15,000 kg of equipment (mostly for drilling) was completed at the end of the 2003/04 season. A further 9,000 kg of equipment will be deployed, along with up to 8 personnel, for the field project itself.

Tracking an Ice-ochrone

Vandy Blue Spikes, Gordon S. Hamilton, and Steven A. Arcone

Regional and continent-scale estimates of mass balance changes occurring on the ice sheets in Antarctica and Greenland have improved in recent years, but even the most advanced studies have not addressed the issue of accumulation variability. Both repeat laser altimeter measurements of surface elevation and mass flux calculations covering large regions can provide reliable results of short-term changes in mass balance if they incorporate accumulation data that are highly accurate, highly resolved, and spatially continuous. By tracking continuous radar reflections dated with ice cores, we show that undulations on the surface of ice sheets cause accumulation rates to be highly variable over short distances. As a result, current accumulation estimates for Antarctica and Greenland are inadequate for estimating ice sheet mass balance, because they are based on measurements that are too widely spaced to capture the full range of variability present on ice sheets. In order for either of these methods to produce reliable results, they must be coupled with accumulation data that are at least as accurate and continuous as those produced by shallow radar profiling.

Relating Radarsat SAR backscatter variations to ice sheet surface conditions along the US ITASE Traverse

Leigh A. Stearns and Gordon S. Hamilton

The RADARSAT-1 Antarctic Mapping Project (RAMP) mosaic shows significant variations in radar brightness, or backscatter, across the ice sheet. Radar backscatter over Antarctica varies according to the physical properties of the near surface, such as surface roughness, grain size, density, stratigraphy and moisture content. These physical properties are intrinsically linked to larger scale properties including ice divide location, topography, accumulation rate, ice flow and surface melt patterns. Comparing brightness variations in radar imagery with field observations of surface properties enables a fuller understanding of backscatter patterns and makes the Radarsat mosaic a powerful tool for exploring ice sheet processes and behavior.

Detailed surface topography maps and shallow radar profiles along the >5,000 km of US ITASE traverse routes in West Antarctica are used to study causes of radar backscatter variations. A series of isolated ice cores, connected to one another by isochronous horizons tracked with ground penetrating radar, yield accumulation rates along the traverse routes. Here, we correlate satellite radar brightness variation with surface topography, accumulation rate and density along the ground traverses, then proceed to infer the surface characteristics of other regions of the ice sheet.

Antarctic temperatures since 1856

Eric J. Steig, David P. Schneider, Michael E. Mann, Scott D. Rutherford, Tas van Ommen, Christopher A Shuman, D. Dixon, P A. Mayewski, James W. C. White

Antarctic is undergoing notable changes. The rate of warming of the Peninsula is as great as anywhere else on Earth, while cooling observed over much of East Antarctica seems enigmatic compared with the majority of the globe. These changes are significant over recent times, but it is difficult to assess the significance of these trends without long-term climate information. Antarctic is notoriously data poor in this respect. With few exceptions, the ground-based instrumental record is limited to the last ~45 years (since IGY), and satellite observations cover less than half that period. Ice core records have been used to infer longer term climate variability, but until recently have been too limited spatially and too poorly resolved temporally to provide an adequate sampling of the Antarctic atmosphere over the relatively short timescales (~decades) of interest.

Ice cores drilled under the ITASE (International Trans-Antarctic Scientific Expedition) program offer a means to correct this by providing multiple well dated cores covering the instrumental period and extending back more than 200 years. Details on the precision and accuracy of dating obtained for the US ITASE cores is given in an accompanying poster (Steig and others). We have combined oxygen and deuterium isotope records from cores from US ITASE with additional cores from the Australian and Italian programs, and earlier published work, to obtain a reconstruction of Antarctic temperature over the past ~200 years. The reconstruction is based on the calibration of these cores against the instrumental temperature data, described in detail in a second accompanying poster (Schneider and others).

Here, we present additional results from an independent assessment of Antarctic temperature variability, using extrapolar instrumental weather data as our predictor variables. This method takes advantage of the observed covariance between Antarctic temperatures and climate variability at lower latitudes. For example, temperatures in West Antarctica are significantly influenced by El Nino/Southern Oscillation variability, which is associated with large temperature variations in the tropical and subtropical Pacific. North of the Antarctic convergence, there is instrumental temperature data available for most latitudes and longitudes back to 1856 A.D., though not for all years. We filled in missing annual data using a covariance method (from T. Schneider, 2003) that is similar to conventional EOF calibration/reconstruction techniques, but takes advantage of the full covariance information by (effectively) using all EOFs but downweighter higher orders to avoid overfitting. We used the same technique to infill Antarctic instrumental weather station temperatures since 1856. We also used a more conventional reconstruction, using a simple screening of the gridded extrapolar temperature data to isolate those grid points that correlate with Antarctic mean temperature at the >95% significance level during the calibration (1961-2001) interval. These methods resolve the same fraction of interannual variance (20-50%) as the ice-core based reconstruction, and yield the same results for long term temperature change in Antarctica.

On the basis of these two independent results, we find that the last 150 years have on average seen a slight warming. Thus, recent Antarctic cooling does not represent the long-term trend. However, Antarctica appears to have warmed less significantly than the Southern Hemisphere and globe as a whole. This is possibly attributable to the large heat sink provided by the Southern Ocean. The reconstructed temperature histories also show pronounced decadal variability, a characteristic of the record which makes it difficult to demonstrate that recent cooling in the summer has been caused by anthropogenic ozone destruction, as has been proposed by others.

High-resolution ice cores from US ITASE (West Antarctica): development and validation of chronologies and determination of precision and accuracy

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Shallow ice cores were obtained from widely distributed sites across the West Antarctic ice sheet, as part of the US ITASE program. The US ITASE cores have been dated by annual layer counting, primarily though the identification of summer peaks in non-sea-salt sulfate (nss-SO4) concentrations. Absolute dating accuracy of <2 years and relative dating accuracy to within +/-1 one year is demonstrated by the identification of multiple volcanic marker horizons in each of the cores, Tambora (1815) being the most prominent. Independent validation of the +/-1 year accuracy is provided by the tracing of isochronal layers from site to site using high-frequency ice penetrating radar observations, and by the timing of mid-winter warming events in stable isotope ratios, which demonstrate significantly better than 1 year accuracy in the last 20 years. Dating precision to +/-1 month is demonstrated by the occurrence of summer nitrate peaks and stable isotope ratios in phase with then nss-SO4, and winter-time sea salt peaks out of phase, with high coherence and a phase variation of <1 month. Dating precision and accuracy are uniform with depth, for at least the last 100 years.

Does the Siple Dome Ice Core Provide Evidence of Abrupt Changes in Siple Coast Ice Dynamics?

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The Siple Dome Ice core shows the temperature and accumulation rate on the summit of Siple Dome change abruptly (~6o C in ~ 40 years) at 15 and 22 KYR B.P. The local climate changes were not accompanied by a regional climate change, which would be expected for a change of this magnitude. This makes it difficult to attribute the local climate changes to changes in regional ocean, atmosphere, or sea ice conditions. An alternation mechanism is suggested were abrupt changes in the surface elevation of the ice streams (~ 100 m in ~40 years) altered atmospheric flow patterns around and on the summit of Siple Dome creating a large but local climate change. This hypothesis is consistent with the ice core data, but needs to be evaluated with ice flow and atmospheric modeling. If this interpretation of large and abrupt changes in the ice dynamics is correct, it indicates the Siple Coast region was a likely a contributor to abrupt increases in sea level.

Deglaciation of the southern Ellsworth Mountains, Weddell Sea Sector of the West Antarctic Ice Sheet

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The stability of the marine West Antarctic Ice Sheet (WAIS) is the greatest source of uncertainty in predicting future sea level. Study of the deglaciation history of West Antarctica provides 'ground truth' for ice-sheet models, enabling more accurate predictions of the future behavior of the ice sheet.

While recent work has established a deglaciation chronology for the Ross Sea sector of the ice sheet since the last glacial maximum (e.g. Ackert et al., 1999; Hall and Denton, 1999; Conway et al., 1999; Stone et al., 2003), the Weddell Sea sector remains largely unconstrained. Marine geophysical data indicate that grounded ice extended to the shelf edge in the late Pleistocene (Bentley & Anderson, 1998), but the timing of this advance is poorly dated. Moraines and trimlines in the Ellsworth Mountains, at the head of the Weddell Sea, record ice levels up to 1900 m higher than the modern ice-sheet surface (Denton et al., 1992), but again, there is no age control. Nonetheless, most reconstructions use these data to infer the configuration, volume and flow patterns of the last glacial maximum (LGM) ice sheet (e.g. Bentley and Anderson, 1998; Denton and Hughes, 2002). We are measuring cosmogenic Be-10 in erratics from the Marble Hills, a nunatak in the southern Ellsworth Mountains, to date deglaciation and explore the possibility of obtaining constraints on LGM ice thickness in the Weddell Sea sector of West Antarctica.

The Marble Hills rise ~600 m above present-day glacier level in the southern Heritage Range, at the southern end of the Ellsworth Mts. Bedrock surfaces are ice-moulded to summit level, consistent with earlier mapping that placed this peak below the regional trimline (Denton et al., 1992), and striations on nearby peaks indicate northeasterly flow of overriding ice, roughly normal to the direction of present-day glaciers. Bedrock surfaces are littered with cobble- to boulder-sized erratics, which range from highly angular to rounded, and are mostly derived from metasedimentary rock types found elsewhere in the range. The majority of our samples are resistant, fine-grained quartzite of the Crashsite Group (Webers et al., 1992).

Out of 22 samples analyzed, we obtained only eight exposure ages younger than the LGM. These come from the four lowest sites (870-1250 m), and decrease systematically with decreasing altitude. Our youngest samples on bedrock have ages of 3500-3700 yr B.P.; samples from a blue ice area beneath the peak have ages less than 350 years. These data are consistent with deposition as LGM ice retreated from the peak. If so, LGM ice cover was at least 430 m thicker in the Marble Hills, and retreated gradually from some time prior to 10,600 yr B.P. through the late Holocene. The implied deglaciation history closely matches results from Marie Byrd Land (Stone et al., 2003). Five samples from these lower sites give scattered ages that: (i) exceed the age of the LGM, (ii) greatly exceed the Holocene ages obtained from nearby erratics, and (iii) do not form a single consistent trend with altitude, indicative of progressive deglaciation. For these reasons, we attribute the high Be-10 concentrations in these samples to recycling from older deposits exposed during earlier interglacial periods.

Samples from the two highest sites on the mountain have apparent ages which significantly exceed the age of the LGM, but cluster into two loose groups: Four samples from a bench at 1340 m give ages ranging from 41 +/- 3 to 67 +/- 5 kyr B.P. Four samples from the summit, at 1390 m, give much older ages ranging from 571 +/- 40 - 770 +/- 56 kyr B.P. Given the scatter in apparent ages among pre-exposed samples deposited at sites lower on the mountain, we consider it unlikely that these groupings arose through chance deposition of pre-exposed erratics during LGM glaciation. Two other interpretations are possible: (i) The old erratics were deposited at these sites during glacial episodes > 41 kyr and > 0.57 Myr ago, and have been exposed intermittently since. In this case, ice that overrode the peak during the LGM and earlier glaciations neither removed these erratics, nor deposited younger erratics at the summit. (ii) The old erratics were deposited by glaciations prior to the LGM; their survival, and the absence of younger erratics, indicate that ice did not reach these sites during the LGM. In this interpretation, the Marble Hills have not been overrun by ice since ca. 0.5 Myr B.P., and the glaciation responsible for sculpting ice-smoothed topography below the regional trimline occurred before this time. Unfortunately, although these interpretations have very different implications for LGM and earlier glaciation of the Ellsworth Mts, we cannot verify or distinguish between them without additional fieldwork, sample collection and cosmogenic nuclide analyses.

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Reconstructing late-Quaternary surface profiles of Reedy Glacier, Antarctica - 2

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Glacier surfaces in the Transantarctic Mountains are graded to the thickness of ice in the Ross Sea - advance and retreat of the Ross Sea grounding line forces thickening and thinning of outlet glaciers along the mountain front. Previous studies have tracked the retreat of grounded ice in the western Ross Sea since the last glacial maximum (LGM) using carbon-14 dates of marine deposits and sediment from ice-marginal lakes (Stuiver et al., 1981; Bockheim et al., 1989; Denton et al., 1989; Anderson et al., 1992; Shipp et al., 1999; Licht et al., 1996; 1999; Conway et al., 1999; Hall and Denton, 2000; Anderson et al., 2004). These studies have shown that the grounding line adjacent to the western Ross Sea coast retreated from a position near Coulman Island (74 degrees S) to a position south of Hatherton Glacier (80 degrees S) between approximately 17 cal. kyr B.P. and 7.1 cal. kyr B.P. The subsequent retreat history of the grounding line to its present position (at 85 degrees S) in the inner Ross Sea is less well established. Reedy Glacier is the southernmost outlet for ice flowing from the polar plateau into the Ross Sea. Because the outlet of Reedy Glacier is south of the grounding line, and thus still blocked by grounded ice, its thinning history records grounding line behavior up to the present day (Mercer, 1968). Here we present preliminary exposure ages for lateral moraine deposits of Reedy Glacier which allow us to reconstruct this thinning history, and will eventually help to constrain grounding-line migration through the late Holocene.

In the Quartz Hills, approximately 90 km upstream from the grounding line at the mouth of Mercer Ice Stream, ice-cored deposits at approximately 1400 m indicate LGM thickening of approximately 260 m (Bromley and Hall, this volume). Cosmogenic Be-10 measurements on two erratics from these deposits yield preliminary exposure ages of 15,900 +/- 1000 and 17,100 +/- 1100 yr B.P. A third sample gives an age of 55,200 +/- 3500 years, which may be attributable to recycling from an older deposit. We collected, but have not yet analyzed, samples lying between the LGM ice limit and the modern glacier, whose ages will constrain the timing of glacial retreat.

At Cohen Nunatak (740 m), close to the confluence of Reedy Glacier and Mercer Ice Stream, we collected from scattered fresh erratics extending from summit level to the ice margin. Two samples, from the summit and 20 m below the summit of the nunatak, give preliminary exposure ages of 5800 +/- 430 and 5600 +/- 370 yr B.P., respectively. A sample from the foot of the mountain, 110 m lower, gives an age of 1700 +/- 130 yr B.P. Although we cannot determine the LGM ice thickness at this site, or the timing of onset of deglaciation, these results suggest either: (i) a more gradual retreat of grounded ice through the second half of the Holocene, following the relatively rapid retreat along the Scott Coast to Hatherton Glacier, or (ii) steady thinning throughout the Holocene from a maximum ice elevation of only a few hundred meters above the modern ice surface. The cessation of thinning on Reedy Glacier 1700 years ago may be linked to re-organization of flow in the nearby WAIS, where radar profiles on Conway Ice Ridge show a transition from disturbed layering to undisturbed reflectors at a depth of 300 m.

More detailed interpretation of our results depends on knowing how the thickness and gradient of Reedy Glacier respond to changes in temperature, accumulation and boundary conditions such as the location of the Ross Sea grounding line. In the coming year we plan to explore these relationships using a flowband model coupled with radar data from the glacier and present-day velocity measurements (cf. Anderson et al., 2004).

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Modeling of glacial stagnation vs. glacial retreat

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Terminus response of glaciers and ice sheets to climate forcing can lead to stagnation or retreat, with implications for contribution to sea-level change and for effects on landforms. When the mass balance of a glacier becomes negative, it returns to equilibrium by losing mass either by retreating or stagnating. Glacial retreat is the process whereby the glacier loses mass as the terminus recedes up-valley, and the glacier remains whole. Stagnation occurs when a mass of ice in the ablation zone becomes detached from the main glacier during a negative mass-balance state. This modeling effort seeks to understand the parameters that control whether a glacier stagnates or retreats during a state of negative mass balance.

Results of a 1-d flowline model will be presented. This model is based on conservation of mass, where the glacier is driven only by vertical shear stress. We attempt to determine the extent that bed geometry controls glacial stagnation. For a suite of bed geometries (sinusoids), a steady state profile was established. The glacier terminus location was shown to have a weak dependence on the specific bed geometry. Glacier terminii prefer to span a sinusoidal overdeepening as opposed to residing in the crest or trough. The steady-state profiles were subjected to a warming to start negative mass balance. The results show that bed geometry controls whether or not ice in the ablation zone can be pinched off from the main glacier, resulting in stagnation.

Future modeling efforts will explore the many parameters than control glacier flow. Specifically, experiments will be run to include flowline geometry, heterogeneous basal geology, subglacial water, longitudinal stresses, and dynamic bed-geometries. We anticipate that the results will yield insight into the physical mechanism of paleo- and modern glacial stagnation such that we better understand observations of modern glaciers, and the forcings that left stagnation deposits in the geologic record.

Basal ice accretion, availability of basal water, ice stream stoppage and potential restart of Kamb Ice Stream

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The West-Antarctic Ice Sheet (WAIS) contains enough ice to raise global sea level by 5 to 6m. A few up to several hundred meters per year fast flowing ice streams dominate its dynamic. These ice streams have been in the focus of Antarctic research since Mercer (1968) raised concerns about a possible collapse of the WAIS. Recent changes in the behavior of these ice streams, stoppage of Kamb Ice Stream (KIS), switched the WAIS to a positive mass balance, currently counteracting global sea-level rise. For an accurate assessment of the WAIS future it is essential to determine whether these changes are transitional or are indicative of the end of the Holocene WAIS decay.

Several mechanisms have been proposed to explain the stoppage of KIS. They all involve a decrease in basal lubrication, either due to changes in subglacial water drainage or due to basal freeze-on. However the exact timing and spatial extend of such reduction in the availability of basal water is sofar unknown.

Borehole videos from the base of Kamb Ice Stream (West-Antarctica) revealed a 12 to 14 m thick layer of clear sediment laden basal ice and a 1.5 m tall water filled cavity. This basal ice layer has formed by freeze-on of basal water to the ice sheet/stream base in contact with the ice streambed and represents a several thousand yearlong record of basal conditions, covering the time prior, during and since the KIS-stoppage. We have used the sediment content in the accreted ice as a proxy for the availability of basal water in the sub-ice stream drainage system and beneath the former shear-margin to obtain further constrains on events leading to the KIS-stoppage. The timing of these events fits well with dynamical changes in the UpC area over the past half a millennium.

While limited since ~300 yrs it appears that basal water was present at all time in the sub-ice stream drainage system. However it also appears that the resupply of basal water to the ice stream shear margin was interrupted around the time of stoppage (~130 yrs. ago), leading to the subsequent accretion of a thick frozen-on till layer. The cause for such interruption may be found in a continuing reorganization/evolution of the subglacial hydrological system. Since about 60 years basal water has found its way back to the former ice stream shear margin, leading to the accretion of sediment poor basal ice and the formation of an at least 1.5 m tall water filled cavity. Gradual leaking of basal water from this cavity into the sub-ice stream drainage system may have increased the availability of basal water in the ice stream. Here the availability of basal water is equal or exceeds the amount of basal water used in the freeze-on process since ~ 20 years.

While the downstream extent of this relubrication of the ice streambed is unknown it is clear that a down-stream propagation of the lubrication front towards the grounding line could lead to a restart of the ice stream sooner than ice stream models would predict.

Overall the basal ice record confirms that the shutdown of Kamb Ice Stream was due to basal freeze-on and a limited availability of basal melt water. It appears that the cause for the limitation has disappeared and basal water is currently building up. We further conclude that relubrication of the Kamb Ice Stream is underway and that a restart of Kamb Ice Stream may occur sooner than expected.

Magnetic properties of subglacial sediment from West-Antarctic Ice Streams

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We present magnetic susceptibility and intensity data for granitic pebbles collected from subglacial sediment from West-Antarctic ice streams, Crary Ice Rise and Byrd Station in comparison to magnetic data of rocks outcropping around the West-Antarctic Ice Sheet

Tradeoff between climate and thickness histories at Siple Dome during the past 25 ka

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The WAISCORES project comprises 2 cores, one at Siple Dome, and one inland, on the Ross-Amundsen divide. The Siple Dome core has sometimes been called the “ice dynamics” core, because greater dynamic changes in the ice sheet are expected there, and such changes would have a measurable impact on the ice-core stratigraphy and geochemical records. In particular, dramatic post-glacial thinning of Siple Dome would impact the observed layer-thickness pattern in the core.

The thickness of a layer spanning a known time interval in an ice core is influenced by both the accumulation rate at the time of deposition (i.e. its initial thickness), and the total vertical strain experienced since deposition as a particle moves along its trajectory. The vertical strain rate scales with the magnitude of the vertical velocity (which tends to scale with accumulation rate). Strain rate is also influenced by divide proximity, and by ice-cap thinning rate. Therefore, the total vertical strain is a function of the ice-divide migration history, the accumulation-rate history, and the thinning history of the ice cap. As a result, thickness and accumulation-rate histories are coupled; if we accept a particular thickness history, then the ice-core depth-age scale forces us to also accept the paired accumulation-rate history, and vice versa.

First, we specified 2 different ice-divide migration histories. In the first, the divide moved across the ice-core site during the past 4 ka, and was more than 1 ice thickness away at earlier times. In the second, the ice divide was always nearby. Then, we specified a range of ice-thickness histories, ranging from no thickness changes, through thinning of 1200 m between 16 ka and 2 ka. We used velocities from a steady-state finite-element momentum-balance profile model of Siple Dome to parameterize ice dynamics in a transient 1-D ice-flow model. We then used the 1-D transient model to find the accumulation history required by each thickness history, in order to reproduce the observed depth-age relation and layer-thickness pattern in the Siple Dome ice core.

We selected the most reasonable solution pairs by comparisons with stable isotopes, accumulation trends, and inferred thickness changes at Byrd Station and Taylor Dome. We conclude that Siple Dome was thicker by at most 500 meters, and possibly significantly less, during the last glacial maximum (LGM). Although the ice divide migrated across the ice-core site over the past 4 ka, the layers in the core were probably not in a near-divide region at prior times.

A low-profile ice sheet in the central Ross Sea sector does not preclude substantially thicker ice in the western and eastern sectors, but it does imply that the Ross ice streams remained active during the last glacial cycle, and has consequences for the contribution of West Antarctica to sea-level lowering during the LGM.

While our simple kinematic 1-D model captures the general features of ice-cap flow, it does not explicitly account for horizontal advection of ice layers, or for transient thermal impacts on ice deformation. In addition, our parameterized treatment of the special divide strain-rate pattern is relatively crude. We have deliberately not incorporated any accumulation-rate data from Siple Dome. The presentation by S. Price et al. confirms that the general features of our thickness history are reproduced in a thermomechanical ice-flow model, and provides an independent test of our preferred divide-migration history.

A WAIS analog found on Mars polar cap

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Measurements by the Mars Orbiter Laser Altimeter (MOLA) provide a detailed surface topography of the north polar cap of Mars. The surface profile through the head of Chasma Boreale shows a concave-up shape which is similar to West Antarctic ice stream.

“Onset”, defined as the location of the transition between inland ice flow (corresponding to a convex-up shape profile) and ice-stream flow (corresponding to a concave-up shape profile), is clearly detected. Chasma Boreale is the largest reentrant in the north polar cap of Mars and has been considered to form likely due to localized basal melting, water production and outflow. A flowline model is applied to simulate the ice flow along the transect of Chasma Boreale. The polar cap is assumed to deform as water ice according to Glen’s flow law. The basal melting and sliding over the bed of Chasma Boreale are examined. The calculations suggest that basal melting and sliding may have been experienced in the region of Chasma Boreale.

Oral
Focused question: *“WAIS look-alikes” – Are there good analogs to West Antarctic behavior elsewhere and what can we learn from these areas?*

Post-LGM changes in ice stream tributary flow near Byrd Camp

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Englacial stratigraphy is disturbed as ice passes over and around subglacial mountains. Greater stratigraphic disruption is expected when the mountain height is a significant fraction of the ice thickness. The stratigraphic disruptions of these mountains are advected downstream and act as ice flow tracers, at least until the stress regime changes substantially. The presence of numerous subglacial mountains near Byrd Camp and the tributary to Bindschadler Ice Stream (BIS) allows us to examine the interaction between the ice and mountains and to track changes in ice flow near the tributary.

The deep radar data from the 2002 US-ITASE traverse shows a cross-cutting reflector roughly 40 km south of Byrd Camp. Stratigraphic correlation of the buried upper surface of this reflector with the age-depth record from the Byrd Core indicates a formation age of 1900 years BP. We interpret this feature as a remnant of ice flow over Mt. Resnik, a large subglacial mountain approx. 60 km SE of Byrd. However, modern flow lines from InSar-derived velocities (Joughin et al., 1999) point to a source location within the BIS tributary about 15 km south of Mt. Resnik. This projected source area is today a region of shear strain rates well below what is required to cause crevassing and stratigraphic disruption.

This presents two possibilities for the source region of the cross-cutting reflector: 1) the modern flowlines have remained constant throughout the advection history of the feature, but strain rates were higher in the past at the source site, possibly due to faster flow in the BIS tributary; or 2) the feature originated at Mt. Resnik and flow direction subsequently changed. Either scenario represents a change in ice flow in the inland region of BIS tributary development within the last 2000 years.

Passive Seismic Observations of Ice Stream Motion Near the Siple Coast Grounding Line

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During the 2003-2004 field season a geophysical survey was carried out to better characterize tidal influences on ice stream motion. As part of this project a series of passive seismic arrays were deployed near the grounding lines of ice streams B (Whillans) through E (MacAyeal) to monitor basal processes associated with GPS derived velocity variations. Preliminary results reveal distinct patterns and styles of basal seismicity on each ice stream, reflecting varying basal processes. Initial results are consistent with previous observations and models of tidal forcing.

These data show that ice streams with similar surface velocities accommodate motion by different basal processes, as observed near the grounding line of Ice Streams D and E. While these arrays were located only 25 km apart they exhibit dissimilar styles of seismicity. The differing spectral content of the waveform and the temporal pattern of icequake occurrence suggest that basal conditions beneath the ice sheet may change rapidly over very short distances.

New radar layers at Siple Dome and Engelhardt Ice Ridge?

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Mapping deep and continuous radar layers enables the extension of age-depth scales from ice cores and, in the Siple Coast region, a better interpretation of Holocene deglaciation. In order to improve detection of isolated radar layers across wider areas, we have applied several processing schemes to 3-5 MHz radar transects from Siple Dome and Engelhardt Ice Ridge. These methods include differential semblance, sloped lateral averaging, matched filtering and adjacent echo cross-correlation. Observed deeper layers (assumed to be isochrons) can be used to extend age-depth scales from Siple Dome if they can be correlated with features observed in the core.

Using sequences of these methods, several deeper layers previously appeared discontinuous or incoherent after only bandpassing can now be justifiably extended for several tens of km across the study areas. Matched filtering requires a reflector model, for which we use a laterally-averaged bed reflector. Differential semblance and sloped lateral averaging require limits on the maximum layer slopes to be tested, which we estimated from the flanks of the Raymond bumps at Siple Dome. By windowing about layers of interest and then cross-correlating each trace with adjacent traces, a metric that quantifiably separates layers from noise has been developed. This approach is based on a confidence test that the layer is not white noise and it extends layer identification beyond simple visual continuity.

The layer that intersects the Siple Dome core near 675 m is considerably sharpened on the south flank and possibly extended into the thicker ice of the north flank (Figure 1). At Engelhardt Ice Ridge, a pair of deep layers that were not previously traceable due to their weak magnitude and a time-synchronous system glitch become easily observable (Figure 2), and their trends diverge near the summit from that predicted by shallower layers.

These methods allow more robust layer identification and detection than simply applying time-varying gain and bandpass filters. Also, they are best-suited to detected weak, deep and isolated layers. This is because closely-spaced shallow layers can be obscured by the multi-peak result of the cross-correlation performed by matched filtering that is common with radar pulses. Shallower layers from low-frequency radar are less consequential for the age-depth scale, but they can also potentially be recovered via a careful deconvolution using the mean bed reflector as a source model.