THE WEST ANTARCTIC ICE SHEET INITIATIVE

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level

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2013 WAIS Workshop Agenda

Sunday, September 29		
Time	**Topic**	**Location**
4:00–7:00 p.m.	Workshop Check In	Algonkian Conference Center
5:00 p.m.	WAIS Steering Group Meeting	Cabin No. 10
7:00 p.m.	Icebreaker/dinner (pizza and beer)	Cabin No. 7

Monday, September 30		
Time	**Topic**	**Speaker**
7:30 a.m.	Breakfast and workshop check in	Lobby of Conference Center
8:30	Welcome	Anandakrishnan and Detwiler

Session 1	*Land Of Oz* – "The land you know, the story you don't..." Subglacial environments, lakes, grounding lines	
8:40	WISSARDs and GLIDErs: Season Recap and Forecast [Abstract] [Presentation]	Scherer
8:55	Invited speaker Some Lessons on Basal Physics of Ice Motion from Flow Variability of Whillans Ice Plain: the WISSARD GPS Experiment (in a Shadow of a Borehole) [Abstract] [Presentation]	Tulaczyk
9:15	Tidal Pacing, Stick Slip, and the Slow Down of the Whillans Ice Stream [Abstract] [Presentation]	Winberry
9:30	What Basal Crevasses Reveal About Stress State at the Ice-Ocean Interface of Whillans Ice Stream [Abstract] [Presentation]	Jacobel
9:45	Subglacial water and sediment transport across the grounding zone of Whillans Ice Stream, West Antarctica [Abstract] [Presentation]	Christianson
10:00	Bathymetry and geological structures beneath the Ross Ice Shelf at the mouth of Whillans Ice Stream, West Antarctica, modeled from ground-based gravity measurements [Abstract] [Presentation]	Muto
10:15	Panel and open discussion / coffee break	
10:35	Address by NSF and NASA Program Managers, and discussion with Alex Isern, Jessie Crain, Tom Wagner, and Marco Tedesco	
Session 2	*Hurricane* – "There is only one safe place...in each others' arms" Policy, preparedness, outreach	
11:10	Travelling the Last Mile: Communicating Cryospheric Knowledge [Abstract] [Presentation]	Bindschadler

11:25	Abrupt Climate Change and WAIS [Abstract] [Presentation]	R. Alley
11:40	Invited Speaker Melting west Antarctic Ice sheets fuels high biological productivity in the coastal ocean [Abstract] [Presentation]	Arrigo
12:00	Invited speaker Ice Velocity Mapping in Antarctica - Achievements, Challenges and the Way Forward [Abstract]	Scheuchl
12:20	Why Philosophy-of-Science Is Important When Assessing the Outlook for the Ice Sheets [Abstract] [Presentation]	Wikman-Svahn
12:35	Lunch (85 min) Poster set up	Conference Center
Session 3	*Ice Quake* - "Nature unleashed" Ice and solid-earth interactions	
2:00	Deep troughs dissect the Marie Byrd Land subglacial highland: Initial results of the GIMBLE survey [Abstract]	Young
2:15	Invited speaker The Structure and Seismicity of West Antarctica and Implications for the Evolution of the West Antarctic Ice Sheet [Abstract] [Presentation]	Wiens
2:35	Invited speaker Influence of subglacial conditions on ice stream dynamics: Seismic and potential field data from Pine Island Glacier [Abstract] [Presentation]	A. Smith
2:55	Panel and open discussion / coffee break	

3:10	The Sedimentary Record of Meltwater Intensive Glacial Erosion in Pine Island Bay, West Antarctica and Implications for Glacial Dynamics [Abstract] [Presentation]	Anderson
3:25	Dynamic Stick-Slip at the Base of Ice Sheets Generates Massive Internal Deformation [Abstract] [Presentation]	Wolovick
3:40	Rib-like patterns in basal shear of ice streams [Abstract] [Presentation]	Sergienko
3:55	Exposure history of West Antarctic nunataks [Abstract] [Presentation]	Spector
4:10	Panel and open discussion / coffee break	
Poster Session		
4:30	Poster session introductions	One slide per person, 45 sec to introduce
4:50 to 6:30	Poster session	Behrendt (invited poster) Bentley [History] Bittner Chan Child Holschuh Jefferson Koutnik Minzoni Moussavi Pope Seroussi Shuman E. Smith J. Smith Stearns Stevens St-Laurent Tressel Vornberger R. Walker Zoet

6:30	Dinner	Conference Center

Tuesday, October 1		
Time	**Topic**	**Speaker**
7:30 a.m.	Breakfast	Conference Center
Session 4	**Titanic** – "Collide with destiny" Ice/ocean interactions / PIG – ASE	
8:30	Sensitivity of Thwaites Glacier to Ice Shelf Melting [Abstract] [Presentation]	Joughin
8:45	New constraints on the ocean cavity beneath the Pine Island Glacier Ice Shelf, Antarctica [Abstract] [Presentation]	Anandakrishnan
9:00	Invited speaker New constraints on the ocean cavity beneath the Pine Island Glacier Ice Shelf, Antarctica [Abstract] [Presentation]	Bindschadler
9:20	Bathymetry beneath the Abbot Ice Shelf from IceBridge gravity data: Implications for ocean-ice interactions [Abstract] [Presentation]	Cochran
9:35	High basal shear stress vs. high basal melt: accelerations on the Getz Ice Shelf, West Antarctica [Abstract] [Presentation]	K. Alley
9:50	The effect of geometry on ice-shelf ocean cavity ventilation: a laboratory experiment [Abstract] [Presentation]	Stern

10:05	What Can Radar Scattering Tell Us About the Relative Character of Past and Future Retreats in the Amundsen Sea Embayment? [Abstract] [Presentation]	Schroeder
10:20	Panel and open discussion / coffee break	
Session 5	*The Thaw* "Extinction will find you:" Mass balance and processes of the Amundsen Sea Sector	
10:45	Radar characteristics of an ice stream marginal crevasse zone: analysis of a high resolution, three-dimensional GPR dataset from the margin of Rutford Ice Stream, West Antarctica [Abstract] [Presentation]	E. King
11:00	Evidence of rapid subglacial water piracy under Whillans Ice stream [Abstract] [Presentation]	Carter
11:15	Deformation-induced melting in the margins of the West-Antarctic ice streams [Abstract] [Presentation]	Suckale
11:30	Subglacial flood event observed using in situ GPS data, CryoSat-2 altimetry, and MODIS image differencing on the Whillans Ice Plain, West Antarctica [Abstract] [Presentation]	Siegfried
11:45	Crevasses forming in wind-glazed surfaces of East Antarctica [Abstract] [Presentation]	Byers
12:00	Invited speaker The Neglected Middle Child - Snow, Firn, and Water Storage in the Ice Sheet Percolation Zone [Abstract] [Presentation]	Pettit
12:20	Panel and open discussion	
12:35	Lunch (85 min)	
Session 6	Titanic Part 2 Ice / Ocean Interactions	

2:00	Invited speaker Improved elevation change records for Antarctic ice shelves from satellite radar and laser altimetry, 1992–2012 [Abstract]	Fricker
2:20	Invited speaker Differential melting of wAP glaciers by modified upper circumpolar deep water along a latitudinal gradient [Abstract] [Presentation]	Vernet
2:40	Invited speaker Antarctic Peninsula ice surface elevation change – preliminary analysis of CryoSat-2 data [Abstract] [Presentation]	Briggs
3:00	Invited speaker What goes down must come up: viscoelastic deformation in the Antarctic Peninsula [Abstract] [Presentation]	M. King
3:20	Panel and open discussion / coffee break	
3:45	Evolution of basal crevasses links ice shelf stability to ocean forcing [Abstract] [Presentation]	Bassis
4:00	Evolving Toward the Next Antarctic Ice Shelf Disintegration: Recent Ice Velocity, Climate, and Ocean Observations of the Larsen B Ice Shelf Remnant at Scar Inlet [Abstract] [Presentation]	Scambos
4:15	Seabed topography beneath Larsen C Ice Shelf from seismic soundings [Abstract] [Presentation]	Brisbourne
4:30	Controls and consequences of rapid environmental change on the atmosphere-sea ice-ocean system in the Larsen Ice Shelf area [Abstract] [Presentation]	Cape
4:45	ENSO and SAM Relationships Across the Antarctic Peninsula in Contrast to West Antarctica [Abstract] [Presentation]	Clem

5:00	Panel and open discussion	
Poster Session Part Two		
5:15	Poster session (another opportunity)	
6:30	Dinner	Conference Center

Wednesday, October 2		
Time	**Topic**	**Speaker**
7:30 a.m	Breakfast	
8:30	WAIS Planning	
Session 7	*Zoolander* Models of ice, ocean, sediments, water	
9:30	Nested Ice-Sheet Modeling of Long-Term Variations in the Pine Islands-Thwaites Glacier Basins [Abstract] [Presentation]	Pollard
9:45	SIA vs Higher Order: Greenland tests, and thoughts on Antarctica [Abstract] [Presentation]	Parizek
10:00	Response of ice motion to bold tidally influenced subglacial hydraulic systems discussed in large Arial Font [Abstract] [Presentation]	Creyts
10:15	Panel and open discussion / coffee break	
10:35	Rapid grounding line migration induced by internal variability of a marine-terminating ice stream [Abstract] [Presentation]	Robel

10:50	Icepod: Imaging of Ice Sheets from Top to Bottom [Abstract] [Presentation]	Bell
11:05	Determination of local slope using photon-counting laser altimetry [Abstract] [Presentation]	Brunt
11:20	Using zigzags to quantify surface melt (in Greenland) [Abstract] [Presentation]	Tinto
11:35	Panel and open discussion	
12:00	Closing remarks	Anandakrishnan
12:15	Adjourn	

- 2012 WAIS Workshop
  - 2012 Agenda
- Previous Meetings

High basal shear stress vs. high basal melt: accelerations on the Getz Ice Shelf, West Antarctica

Karen E Alley[1], Ted A Scambos[2]

[1]University of Colorado Boulder Geology Department, [2]National Snow and Ice Data Center, CIRES, University of Colorado Boulder

The Getz Ice Shelf of West Antarctica occupies a rapidly changing region of the Amundsen Sea Sector, where the evolving Amundsen Sea Low and intrusions of Antarctic Circumpolar Deep Water (CDW) are re-shaping the shelf from above and below. CDW intrusions are of particular interest, as their influence has caused glaciers just to the east of the Getz, notably the Pine Island and Smith Glaciers, to dramatically increase in velocity in recent decades: velocities measured on Pine Island Glacier have increased by ~50% between 1972 and 2012, and Smith Glacier has accelerated >100% between 1992 and 2008, respectively. For the Getz, intrusions of CDW are melting the base at a rate of 4.3 ± 0.4 meters of water per year (Rignot et al., 2013, Science), causing variable thinning along the shelf of ~3-7 ma^{-1} (Pritchard et al., 2012, Nature), and producing more melt water than any other shelf in Antarctica. Despite the large magnitude of the basal melt, however, the Getz Ice Shelf has experienced only modest accelerations during the past few decades. This study uses MODIS imagery from the past decade, Landsat imagery from 1973-1986 and 1999-2003, and .5- to 3-meter commercial imagery licensed by the National Geospatial-Intelligence Agency from 2008-2013 to examine changes in velocity along the ice shelf, with a focus on the ice edge and grounding line region. The ice shelf, which comprises several relatively narrow regions of rapid outflow separated by slower areas, exhibits its fastest velocities near the western edge at DeVicq Glacier. This region, moving typically 400-800 ma^{-1} at the grounding line and 800-1000 ma^{-1} near the ice edge, has accelerated by ~20% near the grounding line over the past decade. The far eastern edge, where speeds are generally 150-400 ma^{-1} near the grounding line and 250-500 ma^{-1} near the ice edge, and where CDW influence is greatest, has accelerated by ~35% in the last decade. Central sections of the shelf have experienced <10% accelerations. In addition, IceBridge Airborne Topographic Mapper (ATM) data are used to examine elevation profiles across the grounding line of the Getz, revealing very steep slopes just above the grounding line. The IceBridge data are supported by ICESat profiles, and combined can be used to examine dh/dt in the grounding line region. We hypothesize that the steep slopes above the grounding line indicate high basal shear stress, and that this is largely responsible for the lack of significant acceleration. Thinning of the ice shelf increases the slope at the grounding line, raising the driving stress accordingly. However, as the driving stress is already very high, the percentage change is relatively low, making accelerations on the shelf and lower glacier regions modest.

Abrupt Climate Change and WAIS

Richard B. Alley[1] *and James W.C. White*[2]

[1]*Department of Geosciences, & EESI, Pennsylvania State University*
[2]*Department of Geosciences, and INSTAAR, University of Colorado*

The concept of abrupt climate change has expanded greatly from its roots in North Atlantic circulation changes. Humans tend to focus most on how environmental change will affect us, our health and happiness, and how they are supported by economies and ecosystems. We build for the world we have, so at least in the short term most changes tend to be costly, but we are relatively skilled at adapting to sufficiently slow environmental changes that we see coming. Fast and unforeseen changes are thus especially damaging. Such abrupt changes can be caused by abrupt forcing—a meteorite impact or explosive volcanic eruption, for example. Or, slow changes in the physical environment can cross a threshold that triggers abrupt physical change, such as increasing meltwater into the North Atlantic triggering a "shutdown" with great extension of wintertime sea ice, leading to changes around the globe. But, even in the absence of abrupt physical thresholds, slow climate change may push ecosystems or economies or parts of the built environment across thresholds—either a storm surge will overtop a levee in New Orleans or the entrance to the New York subway system, or it won't, and the sea-level rise since the last design changes may be really important.

WAIS continues to play a major role in understanding and projecting abrupt changes. The paleoclimatic results from the WAIS Divide core and other studies are revealing key details of the ice-age events once viewed through a primarily North Atlantic lens. The real potential for large, rapid and difficult-to-predict sea-level rise from WAIS changes, shown through history, ongoing changes, physics and models, presents major challenges on multiple levels, with WAIS the most-likely source of any abrupt sea-level rise. Additional issues motivate continued vigorous research and communications efforts.

New constraints on the ocean cavity beneath the Pine Island Glacier Ice Shelf, Antarctica

Leo Peters, Sridhar Anandakrishnan, Kiya Riverman, Einar Steinarsson, Forest McCarthy, Tim Stanton, Martin Truffer, Robert Bindschadler, Mike Shortt, David Holland, Dale Pomraning, Bill Shaw, Jim Stockel

Pine Island Glacier exhibits some of the largest ice mass loss in all of Antarctica, even though it is currently buttressed by a small ice shelf. Warming ocean waters are potentially threatening the future of this ice shelf, which could lead to even greater ice mass loss from this sector of the West Antarctic Ice Sheet in the future. However, the ability to accurately model how these warm ocean waters will interact with the ice shelf is dependent on constraining ocean circulation patterns beneath the ice shelf, which requires detailed information on the shape of the sub-ice-shelf ocean cavity. We present new constraints on the geometry of the ocean cavity beneath the Pine Island Glacier Ice Shelf, Antarctica, from seismic measurements collected across the ice shelf.

This past field season, the first active seismic observations of the ocean cavity and seafloor geology beneath the Pine Island Glacier Ice Shelf were made in an effort to better constrain the geometry of the ocean cavity beneath the ice shelf and improve ice-ocean modeling studies. 55 point observations were made across the ice shelf and approximately 15-line-kilometers of seismic reflection data were collected across the ice shelf; these data point to an ocean cavity ranging in thickness from ~200 m along a seafloor high beneath the ice shelf to >600 m in some localities. The three-dimensional shape of this cavity, coupled with oceanographic measurements made at three locations across the ice shelf, will provide modelers with the ability to model ocean circulation beneath the ice shelf and predict its fate in a warming climate.

The Sedimentary Record of Meltwater Intensive Glacial Erosion in Pine Island Bay, West Antarctica and Implications for Glacial Dynamics

Alexandra E. Kirshner [1], Carolyn M. Branecky [1], John B. Anderson [1], Witold Szczuciński [2], Dustin Schroeder [3], Don Blankenship [3], and Martin Jakobsson [4]

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[2] *Adam Mickiewicz University, Institute of Geology, Maków Polnych 16, 61-606 Poznań, Poland*
[3] *University of Texas Institute of Geophysics, Austin, TX*
[4] *Stockholm University, Department of Geological Sciences, Stockholm, Sweden*

Here we show that the uppermost sediments in Pine Island Bay were deposited from a meltwater plume, a plumite, which episodically occurred during the late stages of ice sheet retreat since ~7-8.6 k cal yr BP and most recently during modern times. It is a hydraulically sorted, glacially sourced, draping deposit that overlies proximal glacimarine sediments and thickens towards the modern grounding line. The most recent release of sediment coincides with rapid retreat of the grounding line, and has an order of magnitude greater flux relative to the entire unit, indicating episodic sedimentation. These observations are consistent with recent results from Smith et al. (2012) for rapid subglacial erosion beneath Pine Island Glacier.

Our identification of a meltwater-derived deposit has profound implications for understanding glacial instability and numerically modeling ice sheet dynamics for more accurate predictions. This study demonstrates that punctuated meltwater-intensive glacial retreat may have occurred at least three times in the Holocene in this region. We further suggest that the modern Thwaites Glacier is poised for a meltwater-intensive similar retreat.

Reference

Smith, A.M., Bentley, C.R., Bingham, R.G., and Jordan, T.A., 2012, Rapid subglacial erosion beneath Pine Island Glacier, West Antarctica, Geophysical Research Letters, 39, 1-5.

Melting west Antarctic Ice sheets fuels high biological productivity in the coastal ocean

Kevin Arrigo, Anne-Carlijn Alderkamp, Loes J. A. Gerringa, Matthew M. Mills, Charles-Edouard Thuróczy, and Gert L. van Dijken

Stanford University, Stanford, CA

Polynyas of the Amundsen Sea in West Antarctica harbor the highest concentrations of phytoplankton anywhere in the Southern Ocean. At the southern end of Pine Island Bay, circumpolar deep water upwells under the Pine Island Glacier, bringing nutrients (including iron) to the surface and melting the base of the glacier. Concentrations of dissolved iron (DFe) in waters near the Pine Island Glacier and the more westward lying Crosson, Dotson, and Getz Ice Shelves varied between 0.40 and 1.31 nM, depending on the relative magnitude of upwelling, turbulent mixing, and glacial melting. These values represent maximum concentrations since associated ligands (which increase the solubility of Fe in seawater) were saturated with Fe. DFe concentrations were very high compared to what previously has been measured in the Southern Ocean. In the Pine Island Polynya, macronutrients and DFe were consumed by the phytoplankton bloom and concentrations were very low. Atmospheric dust contributed <1% of the Fe necessary to sustain the phytoplankton bloom, while vertical turbulent eddy diffusion from the sediment, sea ice melt, and upwelling contributed 1.0-3.8%, 0.7-2.9%, and 0.4-1.7%, respectively. The largest source was Fe input from the Pine Island Glacier, which satisfied the total Fe demand by the phytoplankton bloom by lateral advection of Fe over a range of 150 km from the glacier. The role of TDFe as a phytoplankton nutrient remains unclear, perhaps representing an important indirect Fe source via dissolution and complexation by dissolved organic ligands.

Evolution of basal crevasses links ice shelf stability to ocean forcing

Jeremy N. Bassis

Department of Atmospheric, Oceanic and Space Sciences, University of Michigan

Basal melting and iceberg calving are the primary mechanisms responsible for transferring mass from the ice shelves to the ocean. Although the connection between basal melting and ocean forcing is clear, the effect of ocean forcing on iceberg calving remains more controversial with conflicting hypothesis about whether a warming ocean will increase or decrease iceberg production. Previous theories of iceberg calving have often relied on various flavors of fracture mechanics, assuming that iceberg calving is a brittle process. Here I use a perturbation analysis to show that the strain weakening nature of ice allows initially narrow basal crevasses with width much smaller than the ice thickness to seed a visco-plastic instability that gives rise to locally enhanced ductile deformation and ice shelf thinning over length scales that are comparable to the ice thickness. This process, called plastic necking, widens basal crevasses and allows crevasses to penetrate an increasing fraction of the ice thickness as they advect downstream. This instability, however, is weak and progresses slowly, allowing enhanced melting or accretion of marine ice within basal crevasses to have a strong influence on crevasse geometry. Despite large uncertainty in ice-ocean interaction on the scale of individual crevasses, this model is able to explain the difference between the quasi-steady short (<15 km long) Erebus Glacier Tongue and much longer (>80 km long) Drygalski Ice Tongue. Moreover, application of the model to the four largest Antarctic ice shelves predicts that deep crevasses form downstream of the grounding line that correspond to locations of fractures visible in satellite imagery. However, accumulation of marine ice within basal crevasses can substantially decrease crevasse penetration heights, increasing ice shelf stability, providing a strong link between iceberg calving and ocean-forcing. Moreover, the plastic necking instability amplifies any perturbation to the ice shelf thickness (with appropriate wavelength) allowing perturbations due to, for example, melt channels, to seed the necking instability.

Evidence for Subglacial Volcanic Activity Beneath the area of the Divide of the West Antarctic Ice Sheet

John C. Behrendt

INSTAAR University of Colorado, Boulder

There is an increasing body of aeromagnetic, radar ice–sounding, heat flow, subglacial volcanic earthquakes, several exposed active and subglacial volcanoes and other lines of evidence for volcanic activity associated with the West Antarctic Rift System (WR) since the origin (~25 Ma) of the West Antarctic Ice Sheet (WAIS), which flows through it. Exposed late Cenozoic, alkaline volcanic rocks, 34 Ma to present concentrated in Marie Byrd Land (LeMasurier and Thomson, 1990), but also exposed along the rift shoulder on the Transantarctic Mountains flank of the WR, and >1 million cubic kilometers, of mostly subglacially erupted "volcanic centers" beneath the WAIS inferred from aeromagnetic data, have been interpreted as evidence of a magmatic plume. About 18 high relief, (~600-2000 m) "volcanic centers" presently beneath the WAIS surface, probably were erupted subaerially when the WAIS was absent, based on the 5-km orthogonally line spaced Central West Antarctica aerogeophysical survey. All would be above sea level after ice removal and isostatic adjustment. Nine of these high relief peaks are in the general area beneath the divide of the WAIS. This high bed relief topography was first interpreted in the 1980s as the volcanic "Sinuous Ridge " based on a widely spaced aeromagnetic –radar ice sounding survey (Jankowski et al,. 1983). A 70-km wide, circular ring of interpreted subglacial volcanic rocks was cited as evidence of a volcanic caldera underlying the ice sheet divide based on the CWA survey (Behrendt et al., 1998). A broad magnetic "low" surrounding the caldera area possibly is evidence of a shallow Curie isotherm. High heat flow reported from temperature logging (Clow et al., 2012) in the WAISCORE and a thick volcanic ash layer in the core (Dunbar et al., 2012) are consistent with this interpretation. A 2 km-high subaerially erupted volcano (subglacial Mt Thiel, ~78.5 degrees S, 111 degrees W) ~ 100 km north from the WAISCORE could be the source of the ash layer if it has been recently active. Models by Tulaczyk and Hossainzadeh (2011) indicate >4mm/yr Basal melting in the general area of the WAIS, again supportive of high heat flow and the presence of subglacial lakes in West Antarctica. These various lines of evidence lead to the general interpretation that the ice divide area of the WAIS overlies present to recent subglacial volcanic activity that may have an influence on the past and future behavior of the WAIS.

Icepod: Imaging of Ice Sheets from Top to Bottom

Robin Bell, Nick Frearson, Chris Zappa, Kirsty Tinto

Lamont-Doherty Earth Observatory of Columbia University

Icepod is a modular airborne imaging system capable of high resolution imaging of the surface morphology, the surface thermal structure, the internal structure and bed topography of ice sheets. Icepod is designed to be flown on the rear-paratrooper door of the New York Air National Guard's ski-equipped LC-130s. In January 2013 the Icepod system was flight certified in a series of test flights in the New York. The system was deployed to Greenland in the April and July 2013 to test the instrumentation suite over ice. The instrumentation suite includes scanning laser, high-resolution visual camera, an infrared thermal swath imaging system, a shallow ice radar and a deep ice radar positioned with GPS and IMU systems in the pod and within the aircraft. The plan is to operate the Icepod both in a piggy back mode and in a dedicated science mode. The Greenland operations demonstrated the viability of the piggyback mode. The Icepod system acquired collect data during flights that include landings on the ice sheet and combat offloads. The Greenland data demonstrated that the Icepod system is uniquely positioned to capture the seasonal melt cycle in Greenland along. Icepod will be commission during a final test deployment to Antarctica in January 2014. The new phase will be to operate the Icepod in piggyback mode in both Greenland and Antarctica measuring change and enhancing our understanding of the ice sheets and polar oceans while fostering the development of new science programs using the Icepod system as the dedicated mode.

CosmoDrillWAIS: Novel application of cosmogenic isotopes from subglacially-drilled bedrock to determine direct evidence of West Antarctic Ice Sheet collapse during interglacials

M.J. Bentley [1], R. Mulvaney [2], D. Fabel [3], K. Makinson [2], S. Jamieson [1], N. Ross[4]

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The West Antarctic Ice Sheet (WAIS) is an important control on global sea level but is thought to be inherently unstable. Understanding the risk of WAIS collapse has been identified as one of science's Grand Challenges but requires robust models of the WAIS, fully tested against geological data. A wide variety of such data exists and suggests that the WAIS has probably collapsed in the past, but with substantial uncertainty and disagreement between the proxy records of precisely when. Some records even suggest no collapse has occurred in the last 2 million years. The only well-dated evidence is largely indirect and from outside Antarctica (e.g. past sea-levels in low latitudes) and is difficult to directly ascribe to WAIS, whilst the only direct evidence from beneath WAIS itself is not well dated. We argue that what is needed is a fresh approach, one that provides evidence of WAIS retreat that is both *direct* and *can be dated*. *CosmoDrillWAIS* aims to provide this evidence via a new approach that exploits the potential of rapid drilling to the ice sheet bed to retrieve direct records of past collapse and critically assess the published hypotheses of collapse timing. We present new modelling of cosmogenic isotope concentrations for a range of scenarios. This shows that the different hypotheses for WAIS collapse can be discriminated by measurement of isotopes on subglacial bedrock from sites carefully selected on the basis of key criteria. The objectives of *CosmoDrillWAIS* are to develop a new subglacial rock drill - for which a design concept is presented - and once built and tested to gain access to the bed of WAIS using hot water drilling technology and sample bedrock cores. We propose a transect drilling approach, whereby bedrock will be sampled at progressively deeper locations, and used to determine past downdraw of the ice surface associated with WAIS collapse. At each drillhole, cosmogenic isotope analysis on the rock core will test collapse scenarios. Numerical modelling will be used to link the measured changes in past ice levels to grounding line change, and furthermore to quantify the sea level contribution of each collapse, and explore the forcing factors responsible. The proposal is timely because it exploits a combination of developments in engineering technology and in laboratory analytical and modelling techniques.

Post-glacial thinning history of the Foundation Ice Stream, Weddell Sea embayment, Antarctica

Bentley, M.J.1, Hein, A.2, Sugden, D.E.2, Whitehouse, P.1, Vieli, A.3, Hindmarsh, R.C.4

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The Antarctic ice sheet is the largest on earth and any instability is likely to dominate global sea level change. We therefore require models of the ice sheet to make more reliable and robust predictions of future change. One problem in meeting this challenge is the lack of past data on deglaciation with which to initialize and calibrate the models. This problem has been particularly acute in the Weddell Sea embayment and in particular its eastern part where the Foundation - Thiel Trough has been a principal drainage route for the West Antarctic Ice Sheet (WAIS), and its southern extension may be a potential location for future instability. Two significantly different models of glacial history have been proposed for the trough. The first, based largely on marine geology suggests that grounded ice extended to the continental shelf at the Last Glacial Maximum (LGM), filling the Foundation-Thiel trough. The second, based largely on terrestrial glacial geology suggests a much more restricted advance of ice in the trough with relatively minor or even zero thickening of the ice sheet onshore. Here we present new glacial geologic data from the margins of the Foundation Ice Stream, which currently occupies the southern extension of the trough. We sampled erratic clasts from several nunataks along > 100km transect of the ice stream, and will present the 10Be ages on these clasts. The data show several hundred metres of thinning occurred along the lower Foundation Ice Stream and its tributary the Academy Glacier in the Holocene. We also present preliminary results from flowline modelling of the Foundation Ice Stream through the LGM. We discuss the implications of the data-modelling comparison for the competing models of LGM and post-LGM glacial history.

New surface-based observations of the environment beneath Pine Island Glacier ice shelf

Robert Bindschadler1, Martin Truffer, Tim Stanton, Leo Peters, Mike Shortt, Dale Pomraning, Jim Stockel, Bill Shaw, Sridhar Anandakrishnan, Kiya Wilson, David Holland, Einar Steinarson, Mitch Bushuk, Alberto Behar, Cedric Cocaud, Christina Stam

1 NASA Emeritus

Extensive surface, sub-shelf cavity and seabed observations of the Pine Island Glacier (PIG) ice shelf environment were collected by a surface field team during the 2012-13 austral summer. Three sites aligned along a central, flow-aligned surface valley were occupied for about one week each during which two hot-water holes were drilled at each site. In one hole a mast-mounted set of oceanographic sensors recorded water temperature, current and salinity in the few meters immediately below the ice-shelf bottom. In the other hole, a similarly instrumented profiler was deployed to make quasi daily vertical transects of the sub-shelf cavity by rising and sinking along a cable suspended in the cavity. These instruments are already returning data that provide direct rates of heat and momentum transfer in the boundary layer, basal melt rates and the temporal variation of water movements on daily and longer time scales. Shallow cores of the sea bed and a photographic record of the drill holes, ocean cavity and sea bed were also collected at two of the drill sites.

The geophysics program was spatially much broader and consisted of phase-sensitive radars to measure basal melt rates and active seismic instrumentation to explore the character of the sea bed. Continuous profiling between the drill sites established the previously discovered ("Autosub") sea bed ridge is asymmetric with a steeper downstream face. Spot measurements upstream of the drill sites were reached by helicopter and refined the shape of the ocean cavity where extensive melt rates were measured.

Travelling the Last Mile: Communicating Cryospheric Knowledge

Robert Bindschadler

NASA Emeritus Scientist

There is no doubt within the cryospheric community that "our" world, dominated by ice and low temperatures, is reacting strongly to increased warming of our planet. I address the challenges these physical changes pose for our scientific community. In a sense, we were caught with our pants down, equally astonished as was the global audience, by the surprises of disintegrating ice shelves, accelerating outlet glaciers and shrinking land ice. We have responded by focusing on new areas of research and been treated to impressively precise data sets that inform us about ongoing change. The excitement and, I'd like to think, the importance of what is happening to land ice across the globe has attracted new colleagues to share in our investigations forming new collaborations and interdisciplinary teams. But are these changes enough? Are we simply recasting the science we do rather than transforming the landscape of what it means to be a "cryosopher"? Being thrust to the front and center of the climate change stage not only provides new attention and frequent headlines, but new responsibilities, as well. What are these new responsibilities and how do we meet them?

Estimating long-term ice thinning rates from cosmogenic exposure dates

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Terrestrial evidence of the Antarctic Ice Sheet's adjustment from the last glaciation to the warm conditions of the Holocene is provided by glacial deposits on nunataks that lie above the present-day ice surface. The ages of these elevated deposits are commonly estimated using cosmogenic exposure dating, a technique that relies on the accumulation of rare chemical species (cosmogenic nuclides) in surface rocks over time. However, cosmogenic exposure dates from Antarctic rocks are commonly "too old," creating apparent stratigraphic reversals when samples from different levels on the same nunatak are compared, and complicating the estimation of ice surface lowering rates from the dates. Here, we present progress toward an internally-consistent method for estimating ice surface lowering rates from cosmogenic exposure dates in Antarctica, and we apply this preliminary method to a selected group of studies that are geographically well-distributed around the edges of the Antarctic Ice Sheet. We further comment on how our estimated thinning rates can be used as a tuning data set for ice sheet models.

Antarctic Peninsula ice surface elevation change – preliminary analysis of CryoSat-2 data

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The Antarctic Peninsula (AP) has recently experienced rapid climate warming, ice shelf thinning and collapse, accelerated glacier thinning and flow, and widespread retreat of tidewater glaciers. These changes have major implications for the regional ice sheet mass balance and for global sea level rise. Geodetic estimates of the AP Ice Sheet (APIS) mass balance indicate that it lost mass at an average rate of 20 ± 14 Gt/yr over the period 1992-2011 (Shepherd *et al.,* 2012); this equates to approximately 25% of all Antarctic ice sheet mass losses, despite occupying only 4% of the continental area. Continued and comprehensive observations of changes to the APIS are therefore essential.

Data from the CryoSat-2 mission has the potential to offer the first comprehensive satellite altimeter estimate of APIS mass balance. The complex topography and the relatively large number of small glaciological systems that comprise the APIS have, in the past, proven an obstacle to altimetry estimates of its mass balance. However, the fine resolution and densely sampled observations possible from CryoSat-2 will enable reliable measurements of surface elevation change in such regions. As part of the European Space Agency (ESA) funded Antarctic Peninsula Mass Balance (APMB) project, we aim to produce time series of dh/dt and dm/dt measurements from CyroSat-2 that will extend the radar altimetry records from the ERS and EnviSat missions. Here we present an initial analysis of the performance of CryoSat-2 data over the Antarctic Peninsula.

Seabed topography beneath Larsen C Ice Shelf from seismic soundings

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Seismic reflection soundings of ice thickness and seabed depth were acquired on the Larsen C Ice Shelf in the austral summer of 2012-13. Over 100 sites at 3, 5 or 10 km spacing along 10 lines were recorded, from the Churchill Peninsula in the north to the Joerg Peninsula in the south, and also towards the ice front. Sites were selected using a bathymetry model derived from the inversion of IceBridge gravity data, which indicated key regions where sub-shelf oceanic circulation may be restricted. The seismic velocity profile in the upper 100 m of firn and ice was derived from shallow refraction surveys at a number of locations. Temperatures measured previously within the ice and water column were used to define the seismic velocity profile through the remainder of the ice column and also the sub-shelf cavity. Uncertainties in ice and water cavity thickness are in general <10 m. Compared with the seismic measurements, the root-mean-square error in the gravimetrically derived bathymetry at the seismic sites is 162 m. The derived seismic bathymetry profiles indicate that a number of significant topographic features of the seabed, which could potentially inhibit oceanic circulation beneath the ice shelf and are present in the gravity inversion model, are not observed. The discrepancies between the gravity inversion results and the seismic bathymetry are attributed to the assumption of uniform geology in the inversion process and the sparsity of IceBridge flight lines. These results will be used to improve existing sub-shelf ocean circulation models. Results indicate that care must be taken when using bathymetry models derived by the inversion of free-air gravity anomalies. The bathymetry results presented here will be used to improve existing sub-shelf ocean circulation models.

Determination of local slope using photon-counting laser altimetry

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The greatest changes in elevation in Antarctica are happening along the margins of the ice sheet, where the surface frequently has significant slopes. For this reason the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), which is a photon-counting laser altimeter scheduled to launch in 2016, will utilize pairs of beams that are perpendicular to the flight direction in order to determine across-track slope. An airborne instrument, the Multiple Altimeter Beam Experimental Lidar (MABEL), was developed to provide data needed to, among other things, simulate this sampling strategy. We present local slopes as determined by MABEL and compare them to those determined by the Airborne Topographic Mapper (ATM) over the same flight lines on the Greenland Ice Sheet, through a range of slopes comparable to those of the margin of the West Antarctic Ice Sheet. Results from MABEL suggest that the ICESat-2 beam geometry is appropriate for the determination of slope on ~90 m spatial scales, a measurement that will be fundamental to deconvolving the effects of surface slope from the ice-sheet surface change derived from ICESat-2.

Crevasses forming in wind-glazed surfaces of East Antarctica

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We present a crevasse map of East Antarctica based on observations of optical and radar satellite imagery. Crevasses are found not only near the coast, where strain rates and the causal stresses are high, but also far within the plateau where both accumulation and surface slopes are very low. A comparison of crevasse initiation sites to the distribution of surface facies reveals that crevasses are preferentially forming in wind-glazed surfaces across the ice sheet, yet are almost entirely absent within megadune areas.
The likely cause of crevasses in low stress areas is tension imposed on randomly oriented, macroscale, cracks present in wind-glazed surfaces. Such cracks have previously been invoked as conduits aiding deep firn convection and firn recrystallization. Crevasses initiating in wind-glazed surfaces from shallow cracks are potentially larger conduits for atmospheric circulation than have been previously described.

Controls and consequences of rapid environmental change on the atmosphere–sea ice–ocean system in the Larsen Ice Shelf area

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The catastrophic breakup of the Larsen A and B ice shelves in 1995 and 2002 stand as vivid examples of the effect of climate change on the cryosphere along the east coast of the Antarctic Peninsula (AP). While several studies have considered the physical causes of ice shelf breakup and the implications of their demise for ice sheet mass balance, little is known regarding the significance of these changes for the polar marine ecosystem. With the removal of ice shelves, primary production becomes possible in the previously dark, oligotrophic waters. High seasonal phytoplankton biomass and rates of primary production are now observed in the Larsen embayments, with the spatial extent of phytoplankton growth modulated by sea ice cover. Because open water is a necessary precursor for water column production, gaining an understanding of sea ice dynamics and the factors controlling sea ice cover can give insight into the present state and future evolution of the pelagic marine ecosystem. As part of the LARISSA (LARsen Ice Shelf System, Antarctica) project, we investigate the link between climate variability, regional atmospheric patterns and sea ice dynamics in the Larsen Ice Shelf region using high-resolution, in situ weather records spanning January 2010 – May 2013. These include data collected from AMIGOS (Automated Met-Ice-Geophysics Observation System) and cGPS met systems adjacent to the Larsen B. We find that opening of the embayments is tied to the frequency and intensity of foehn wind events, with the embayments acting much like coastal polynyas. Persistence of open water conditions is tied to both foehn winds and synoptic atmospheric circulation patterns. These winds are influenced by the Southern Annular Mode (SAM), with periods of positive SAM leading to more frequent warm, dry, and strong down sloping winds on the leeward side due to the orographic lifting of polar westerlies over and across the Antarctic Peninsula. Resulting surface air temperatures above 0ºC can extend spatially over 100 km from the peninsula mountain range, likely contributing to extensive sea ice melt. These results are confirmed using a 15-year, daily time series from the Argentinean research station at Matienzo on the Larsen Nunatak. This analysis indicates that foehn winds play a key role in the regional weather of the northeast Antarctic Peninsula, with influences on both the cryosphere and marine ecosystem.

Evidence of rapid subglacial water piracy under Whillans Ice stream

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The subglacial water system of the lower Whillans Ice Stream on the Siple coast contains numerous connected subglacial lakes in three hydrological basins (northern, central and southern). We use ICESat data to derive estimates of lake volume change and regional thickness changes. By combining these results with a water budget model, we show that a uniform, localized thickness increase perturbed the hydropotential, resulting in a change in course of a major flowpath within the system in 2005. Water originating from upper Whillans and Kamb ice streams that previously supplied the southern basin became diverted toward Subglacial Lake Whillans (SLW). This diversion led to a ten-fold filling rate increase of SLW. Our observation suggests that water piracy may be common in the Siple Coast region, where the gentle basal relief makes the basal hydropotential particularly sensitive to small changes in ice thickness. Given the previously inferred connections between water piracy and ice stream slowdown elsewhere in the region, the subtle and complex nature of this system presents new challenges for numerical models.

Reflection-based C-axis Measurement of Ice Crystals

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We report initial results in the development of a reflection-based method to determine the c-axis orientation in ice crystals. The current state-of-the-art for measuring crystal orientation in ice is the Wilen stage method [1-2] based on older Rigsby stage techniques [3]. In Wilen's method, a thin section of ice is sliced from a core and placed between crossed polarizers in four sequential orientations. In each orientation the polarizers are rotated while light is transmitted through the slice, and the light intensity is measured. This method produces an accurate and complete measurement of fabric, but at the expense of destroying the local region of the core and requiring a dedicated laboratory for measurement. A technique that could utilize optical reflection instead of transmission would be non-destructive and could be built into field instrumentation used in boreholes. This abstract describes a first step towards direct measurement of c-axis orientations in ice cores and boreholes using backscattered light from trapped bubbles.

Similar to the Wilen stage, we solve for two angles, ϕ and θ, and their corresponding degeneracies in a sequence of four measurements. We tested our proposed method on crystals from a vertical thin section from WAIS Divide at a depth of 420 meters (courtesy of Dr. Joan Fitzpatrick and Dr. Don Voigt). With a bare silicon wafer placed behind glass-mounted thin section to serve as test reflector, a sequence of four measurements was performed with a 1.7 mW 675 nm fiber-coupled laser and a pair of crossed polarizers at different orientations as illustrated in Fig.1. In stage 1, the two possible values for ϕ are determined by looking for light extinction while rotating the thin section with respect to the optics. Stage 2 resolves the degeneracy for ϕ by observing the polarizers orientation for extinctions. Stage 3 and 4 determine θ in a similar fashion. From the measurements as shown in Fig.2 and Table.1, ϕ was found to be -46° and θ was found to be -80°, which deviates slightly from Dr. Voigt's data at -46.60° and -75.62° respectively. Ten other crystals have been measured at stage 1 showing similarly good matching with traditional c-axis techniques.

Currently the technique requires measurement of each point individually, but work is in progress to use bubbles within the ice as the "back reflector" to eliminate the need for ice slices and eventually to automate the measurement so that data can be taken from many points simultaneously.

[1] Wilen, L. A. "A new technique for ice-fabric analysis." *Journal of Glaciology* 46.152 (2000): 129-139.
[2] Hansen, Dirk P., and Larry A. Wilen. "Performance and applications of an automated c-axis ice-fabric analyzer." *Journal of Glaciology* 48.160 (2002): 159-170.
[3] Langway, Chester C. "Ice fabrics and the universal stage." *Department of Defense, Department of the Army, Corps of Engineers, Snow Ice and Permafrost Research Establishment,* 1959.

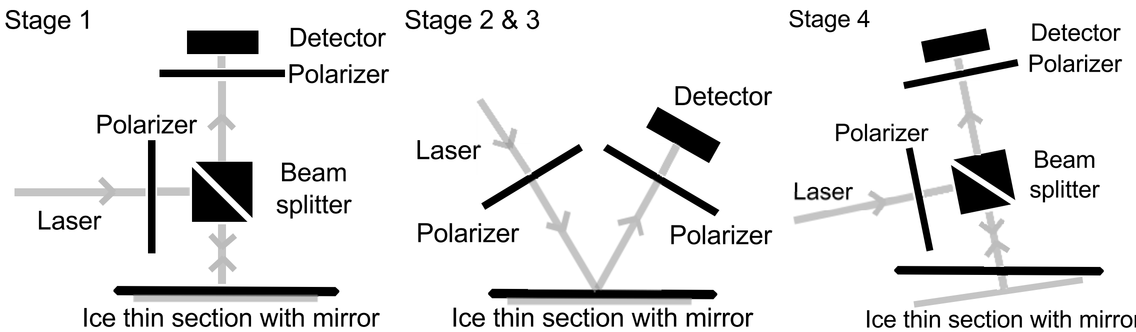

Fig.1 Optical setups, viewed from the side, for single point c-axis measurement. In all stages the polarizers rotate in unison, remaining crossed at all times. The ice thin section was backed by a bare silicon wafer which acted as a mirror.

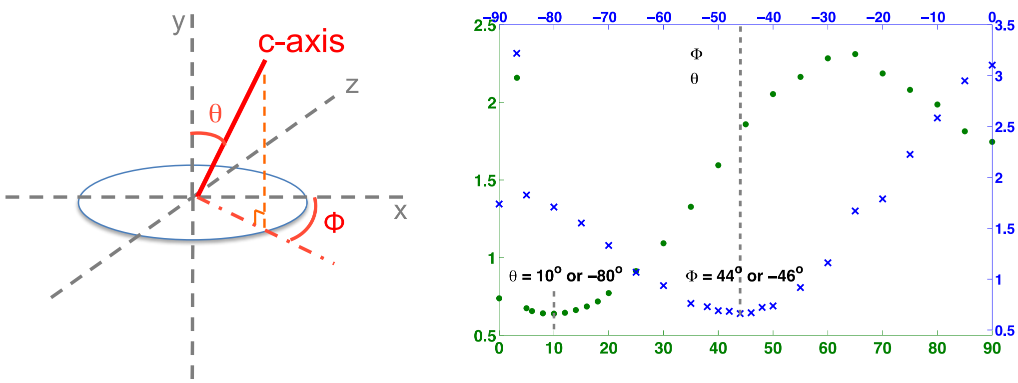

Fig.2 (a) For an ice crystal in the x-z plane, the c-axis can be determined by the angles ϕ and θ. (b) Determining angles ϕ and θ by rotating a pair of crossed polarizers through 0° to 90°. For clarity, the rotations for resolving degeneracies (stages 2 and 4) are not shown.

	Step 1	Step 2	Margin of error	Angle from Dr. Don Voigt
ϕ	44° or -46°	-46°	+/- 1°	-46.5982
	Step 3	Step 4	Margin of error	Angle from Dr. Don Voigt
θ	10° or -80°	-80°	+/- 2°	-75.6162

Table.1 Summary of c-axis determination experiment using back reflections. The error margins stem from the angular resolution of the equipment available in our laboratory.

Investigating the effect of subglacial lakes on the force balance of Byrd Glacier

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Byrd Glacier is an outlet glacier where ice drainage transitions from sheet flow to shelf flow. It has one of the largest catchment basins in Antarctica and drains approximately 20.5 km^3 of ice into the Ross Ice Shelf annually. Previous studies indicate that the main restive force controlling Byrd Glacier's flow dynamics is due to basal drag. Spatial calculations of the force balance produce smaller regions of higher basal drag, known as "sticky spots". There have been several studies into the dynamics of sticky spots found on ice streams, but very little literature exists on those on outlet glaciers. In recent literature, it has been hypothesized that sticky spots cause water to collect in smaller regions and form a subglacial lake. Other studies posit that the low values of hydro-potential around subglacial lakes are the cause of sticky spots. In the basin of Byrd Glacier, both of these theories potentially describe the cause and effect of the sticky spots. There are five regions in the basin where surface elevation changes have been recorded from altimeter LiDAR. These surface elevation changes are believed to be the result of water filling into, or draining from subglacial lakes. Two of the lakes in the catchment of Byrd Glacier were recorded draining accompanied by a 100 m/yr increase in ice velocity. Analysis of the bed topography, hydro-potential data, and other possible subglacial lake locations in this region show that these lakes likely are nourished by water sources upstream. In addition, there are other, much smaller lakes within the basin. These smaller lakes are isolated in the lower regions within areas of high relief and the hydro-potential results provide no indication that these lakes are filling from remote water sources. In this study, the effect of subglacial lakes on Byrd Glacier's force balance ("sticky spots") is being investigated. We are also exploring the possibility of lake formation due to basal melt by analyzing localized basal melt around the. It is hypothesized that these smaller lakes form from local basal melt due heat produced by friction heat. Our investigations use a combination of force balance and geothermal heat flux modeling. The spatial patterns of the results will be used to assess the correlations of high basal drag values and areas of potential bed melt.

Subglacial water and sediment transport across the grounding zone of Whillans Ice Stream, West Antarctica

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Much of the threshold behavior of marine ice sheets is thought to result from processes occurring in the grounding zone, where the ice sheet transitions into the ice shelf. At short timescales (decades to centuries), grounding zone behavior is likely to be influenced by processes not included in the current generation of ice sheet models. Here we report on two such processes: the flow of subglacial water beneath the ice sheet, and the associated transport, and deposition, of sediment. We present a ground-based geophysical study across the grounding zone of a major West Antarctic Ice Stream (Whillans Ice Stream (WIS)). Using a combination of active-source seismology and radio-echo sounding (RES) data, we image the outlet of a large subglacial drainage system. The geophysical data indicate that the grounding zone in this area of WIS is an estuary, which consists of a hydropotential low upstream of the grounding zone, which is linked to the ocean by a hydropotential trough and a large subglacial channel. Pressure differences along the trough axis are within a range that can be overcome by tidally-induced processes, making the interaction of subglacial and ocean water likely. The ocean water column within the embayment is everywhere less than 12 m thick, implying that the estuary is well mixed by tidal processes. RES reflectivity indicates that subglacial deformation, subglacial water flow, and the ocean water column likely transport sediment along the base of the ice sheet and eventually the ice shelf. These findings have implications for the evolution of grounding zones and the basal melt of ice shelves and their proper inclusion in whole-ice-sheet models.

ENSO and SAM Relationships Across the Antarctic Peninsula in Contrast to West Antarctica

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Recent analysis has suggested that the warming trends in West Antarctica and the Antarctic Peninsula are primarily of tropical origin, through atmospheric teleconnections. There is a strong seasonality to these connections, and the relationship also varies in space in time. Here, connections with tropical (specifically, the El Niño-Southern Oscillation, ENSO) and hemispheric circulation patterns (specifically, the Southern Annular Mode, SAM) are contrasted across the Antarctic Peninsula and West Antarctica. We note that during austral winter and spring, ENSO has a persistent relationship across the western Antarctic Peninsula temperatures, while SAM has a persistent relationship with temperatures across the northeastern Antarctic Peninsula. Meanwhile, the ENSO relationship with temperatures across the northeastern Antarctic Peninsula, and the SAM relationship with temperatures along the western Peninsula vary in time, especially in austral spring. In contrast, the relationship of these two climate patterns and temperatures across West Antarctica is more complicated and less persistent. Using the newly reconstructed Byrd temperature time series, we find significant relationships with SAM and temperatures across West Antarctica, but only in certain seasons. The ENSO relationship is weaker and statistically insignificant and varies in time and season as a function of the location and magnitude of the teleconnection to the South Pacific. Together, these results suggest that linking the warming across both the Antarctic Peninsula and West Antarctica to either changes in ENSO or SAM requires careful consideration of temporal and spatial variations in the atmospheric response in the Amundsen-Bellingshausen Seas associated with these patterns.

Bathymetry beneath the Abbot Ice Shelf from IceBridge gravity data: Implications for ocean-ice interactions

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Floating ice shelves surround much of the Antarctic continent and play an important role in stabilizing the Antarctic ice sheets. Some ice shelves have experienced rapid thinning attributed to interactions between the ice and warm Circumpolar Deep Water (CDW) circulating beneath. Knowledge of the bathymetry beneath ice shelves is important for assessing their vulnerability and modeling ice-seawater interactions. The Abbot Ice Shelf, located between Thurston Island and the Eights Coast of West Antarctica, shows a positive mass balance unlike nearby ice shelves in the Amundsen Sea Embayment. We inverted NASA Operation IceBridge (OIB) airborne gravity data over the Abbot Ice Shelf to obtain its underlying bathymetry. The morphology reveals a series of asymmetric fault-bounded basins to the west of 94°W. East of there, the sub-ice bathymetry is relatively shallow with no evidence of tectonic activity. South of the Abbot Ice Shelf, a rift basin is also found to the west of 99°W under the Cosgrove Ice Shelf. The shallowest constriction on our ten profiles is ~450 m and the sub-shelf basins north of 73°S appear to be interconnected. Thus, barring an uncharted blocking sill, water above that depth can circulate beneath the ice shelf.

Two CTD casts near the western ice front show the presence of warm CDW at depths below ~400 m. Temperatures are >3° above the melting point of ice at those depths, and the overlying thermocline is >1° above freezing up to depths of ~200-250 m. CDW thus has access to the cavity beneath the ice shelf. Melting by seawater that flows beneath the ice shelf will be limited by variability in the thermocline depth and by the relatively shallow ice draft, which is less than 275 meters below sea level (mbsl) throughout much of the cavity. The base of the ice is deeper along the Eights Coast east of 97°W where the grounding line depth varies from ~275 to 475 mbsl on our profiles. Those flight lines consistently show a variety of possible sills, pinning points and enclosed basins interpreted as formed by the uplifted footwall rims of south-facing normal faults. However, the high observed melting rate of the Abbot ice shelf indicates that those features do not fully restrict penetration of warm seawater to the deepest ice.

Response of ice motion to bold tidally influenced subglacial hydraulic systems discussed in large Arial Font

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Numerous studies using ground-based and satellite techniques show evidence for active water drainage beneath much of Antarctica. Along ice streams, data indicate hydraulically conductive flow paths with water moving between the overlying ice and underlying bed. Furthermore, data from sites near grounding lines show that flow of ice streams is tidally influenced. For some ice streams, areas of water drainage and tidally influenced flow overlap. These are areas known to be underlain by subglacial deformable till. Field studies, lab experiments, and theory all demonstrate that subglacial water is essential for the weakening of basal till. Weakening of till is critically dependent on effective pressure. Changes in tidal height alter the pressure of a subglacial hydraulic system. Thus, it is possible that changes in water pressure weaken basal till and aid ice slip.

Here, we show how tides affect subglacial till using mathematical and numerical models of subglacial water flow. Tides modulate effective pressure that, under certain circumstances, aids in till failure and slip. The critical parameter for tidal influence on slip is the compressibility of the water system. The compressibility is linked to the amount of water stored along the ice--bed interface. Observations show two starkly different tidally-modulated behaviors. In one case, Rutford Ice Stream has a smoothly varying displacement with the tides. Whillans Ice Stream, however, shows discrete stick-slip events. We show how both of these types of behaviors can be related to hydraulic weakening of the slip interface and discuss implications of this phenomenon.

Improved elevation change records for Antarctic ice shelves from satellite radar and laser altimetry, 1992-2012

Fricker, Helen A.[1]*, Fernando S. Paolo*[1]*, Geir Moholdt*[1]*, Laurie Padman*[2]

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We have been working to increase accuracy, resolution and record length of satellite radar and laser altimetry over ice shelves to provide an improved data set of elevation change for studies linking ice-shelf change to oceanic- and atmospheric-forcing variability. Here, we report our recent findings, focusing on the large Filchner-Ronne (FRIS) and Ross (RIS) ice shelves. In our satellite radar altimetry (RA) analysis we use improved procedures to integrate data from multiple satellite RA missions (ERS-1, ERS-2, and Envisat) to derive long-term (~20 years) continuous records of surface elevation changes for most of Antarctica's ice shelf area. There is considerable variability in the elevation change signal on the ice shelves both in space and time, with large interannual signals that mask the long-term trend when data from only a few years are considered. In our laser altimetry analysis, we have developed a new method that uses InSAR-based velocity fields to account for ice advection between overpasses of the ICESat laser altimeter. This allows us to monitor elevation changes in a "Lagrangian" reference frame, i.e., following specific locations on the ice shelf as they advect downstream. The Lagrangian approach reduces the noise level of the derived elevation changes and reveals clearer spatial patterns that can be transferred into basal melt/accretion rates after accounting for ice shelf strain, surface accumulation, firn air content and hydrostatic compensation. For the RIS and FRIS, we find that basal melt rates are highest around the grounding lines and near the ice shelf fronts, in agreement with oceanographic models. The maps show significant basal accretion over the central parts of FRIS, and much less basal accretion on RIS, consistent with previous studies. Although both these ice shelves are relatively stable at present, the differences in their spatial structure of basal mass balance and temporal response of dh/dt (from RA) implies that they may respond quite differently to similar large-scale changes in ocean state. We note that the spatial distribution of standard ("Eulerian") RA estimates of dh/dt from Envisat for the period 2003-2008 resembles that of the Lagrangian analysis of ICESat laser dh/dt, suggesting that over short time periods the RA dh/dt values might be biased by advection of ice elevation gradients.

Consequences of a Deeper Bed for Marie Byrd Land Stability

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Stability of the West Antarctic Ice Sheet (WAIS) has been a subject of much research since the marine ice sheet instability was proposed. Data collection and analysis have focused primarily on the Amundsen Sea embayment and the Siple Coast, coastal regions whose retreat will ultimately provide the avenue for ice loss from the continent's interior. Despite having only limited geophysical data collected inland from the coast, Marie Byrd Land (MBL) has been treated as a regional high in bed topography in all major mapping efforts of Antarctica. This high reduces the long term variability of ice over MBL; models using the currently prescribed bed show little change in ice volume or its spatial distribution on MBL in the last 5 million years. RES data collected by Operation Ice Bridge during the 2009-2010 Antarctic field season show ice thicknesses that locally exceed previous estimates by more than a kilometer, and indicate a much deeper and more complex bed for the region surrounding the Executive Committee Mountains. Improved ice thickness measurements indicate an additional 19,400 km^3 of ice (4.94 cm SLE) within WAIS. Using new bed topography generated from these data, along with the model outlined in Pollard and DeConto (2012), we refine the estimates of ice retreat into Marie Byrd Land, providing new insight into the sea-level contribution of WAIS in the event of complete collapse.

What Basal Crevasses Reveal About Stress State at the Ice-Ocean Interface of Whillans Ice Stream

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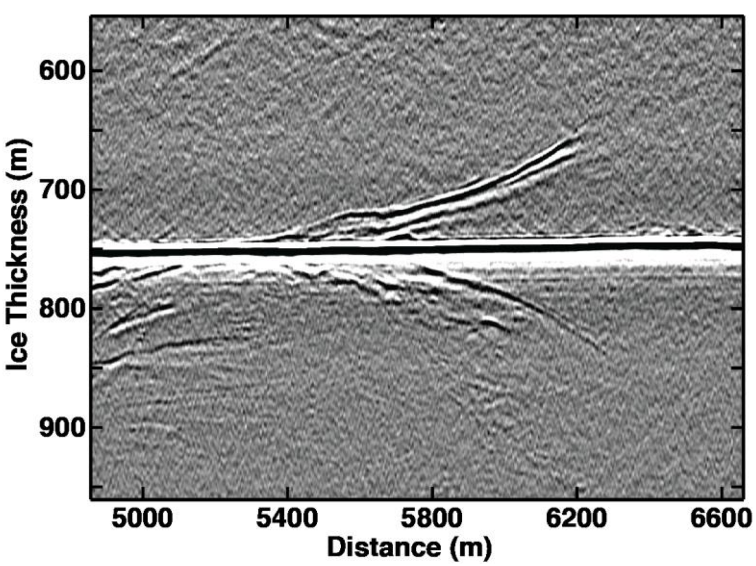
The transition from limited- or no-slip conditions at the base of grounded ice to free-slip conditions beneath floating ice occurs across the few-kilometers-wide grounding zone of ice sheets. This transition is either an elastic flexural transition from bedrock to hydrostatically supported elevations (often tidally influenced), or a transition from thicker to thinner ice over a flat bed, or some combination of these. In either case, ice must flow across a changing stress field, often resulting in brittle deformation manifested as basal crevassing at the ice sheet base and tidal strand cracking on the ice surface. Thus the position and morphology of basal crevasses reveal important information about the stress state across this transition where ice and ocean interact.

We acquired gridded ground-based radar surveys at two locations on the Whillans Ice Stream grounding zone, one over a subglacial peninsula where the transition to floatation is abrupt and the second over a subglacial embayment where several dynamic subglacial lakes drain to the ocean, likely resulting in episodic high sediment and water flux across the grounding line. Our surveys indicate a complex pattern of basal crevasses; some are related to basal topography, but others are more likely associated with ice flexure across the basal channel carrying water and sediment to the ocean. Due to the high reflectivity of seawater and the relatively shallow ice thickness, we image many off-nadir crevasses where the radar energy is first reflected from the ice-water interface and then from the crevasse, producing an echo signature with a delayed arrival time and reversed phase due to the second reflection. In several cases these crevasse echoes appear to mimic the geometry of a sub-ice "wedge" dipping into the sediment, while in reality the radar never penetrates below the basal interface. Elsewhere we image pairs of crevasses from either side of a channel incised into the bed that produce curious signatures in the radar profile showing a high degree of symmetry at both shorter and longer arrival times than the nadir bed echo (image). Our results indicate that basal crevasses offer a rich, but unexploited, dataset for diagnosing stress state and salient processes across grounding zones where ice and ocean interact, and that special care is needed when interpreting subglacial returns in radar data.



Symmetric crevasse signatures from the margins of a basal channel imaged simultaneously from fore and aft of the radar.

Changes in the ASAID Basal Stress Boundary along the Antarctic Peninsula Coastline Observed over 30 years of LANDSAT observations

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Landsat image sequences of the Pine Island Bay area collected from online sources during the period 1972 through 2003 were analyzed and teams of researchers discovered a dissipating ice shelf that once occupied what is now known as *Elizabeth City State University Bay* [1]. The research was made possible by the definition of a Basal Stress Boundary (BSB) developed from the Antarctic Surface Accumulation and Ice Discharge (ASAID) project [2]. Similar changes are known to have occurred along the coastline of the western Antarctic ice sheet [3]. In particular, the Larsen Ice Shelf (LIS), occupying the northernmost extent of the Antarctic Peninsula, has shown similar significant glaciological changes [4, 5, 6]. Here we report the results of research and analysis to determine the existence of detectable variations in the Basal Stress Boundary (BSB) along the coastline of the Antarctic Peninsula, over the approximately 30-year record of Landsat observations. Changes in the BSB may have a direct correlation to historic ice-sheet mass loss. Images were gathered from online sources of the peninsula. ENVI 5.0 and ENVI 4.7 were used for image processing and overlaying the basal stress boundary vector file to visually represent any changes that occurred. LIS-C is the largest remaining component of the Larsen Ice Shelf complex. LIS-A and LIS-B having both disappeared starting in 1995. Evidence indicates that ice shelves retard the advance of great ice streams into the ocean where subsequently melt contributing to sea level rise. The cumulative collapse of ice shelves over time may play a role in accelerating sea level rise. All changes in LIS-C area based on the USGS Landsat archived 30+ year record of observations seen to have occurred at a scale greater than one square kilometer are reported.

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Sensitivity of Thwaites Glacier to Ice Shelf Melting

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Strong thinning as ice streams have sped up along the Amundsen Coast produces ice loss well in excess of that from other regions of Antarctica. Much of the increases in speed appear to be caused by the loss of buttressing as ice shelves have thinned in response to warmer ocean water and subsequent loss of basal traction as the grounding line has retreated. We have developed a finite-element implementation of a prognostic shallow-shelf ice stream/shelf model, which we have applied to Thwaites Glacier, Antarctica. We have conducted a number of numerical tests to examine the glacier's sensitivity to increased melting and surface accumulation. For melt rates comparable to present, the glacier continues to lose mass at roughly its present rate. Extreme (fourfold increase) sub-shelf melt rates produce a stepped retreat of the grounding line by more than 40-km over 250 years. Examination of the annual thinning rates shows rapid evolution of the spatial distribution of loss over periods of several years (comparable to the length of a typical satellite altimetry mission). In particular, with each episode of grounding line retreat, a pattern of strong thinning initially develops near the grounding line that then diffuses inland over periods of several years. Only with increased surface accumulation and reduced melting does the glacier stabilize. Thus, it is likely that Thwaites glacier will continue to lose mass over the next several centuries at a rate largely determined by the amount of warm circumpolar deep water that makes its way to the grounding line.

Radar characteristics of an ice stream marginal crevasse zone: analysis of a high resolution, three-dimensional GPR dataset from the margin of Rutford Ice Stream, West Antarctica

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Narrow zones of intense crevassing characterise many ice stream margins where the stress regime exceeds some threshold value. Theories of formation and subsequent alteration of crevasses within the margin have generally been formulated based on plan views of the crevasse field and there are few observations of the three-dimensional shape of crevasses because the marginal zone is usually extremely difficult to access. Parts of the margin of Rutford Ice Stream, West Antarctica are well defined by bright reflectivity on RADARSAT images, indicating extensive crevassing, however visual satellite imagery of the same area shows few open crevasses, even though the flow speed differential is >210 m/a. These areas provide a rare opportunity to obtain dimensional data on crevasses within an ice stream margin.

Here we present closely-spaced grids of 200 MHz ice-penetrating radar profiles from a section of the Rutford margin where a two-person team on snowmobiles was able traverse the area safely and obtain grids of 100 x 200 m size with 10 m line spacing. The data were put through a basic processing sequence that included migration and then imported to a 3D interpretation software package for analysis. We will compare two grids spaced 20 km apart along the margin and set the metrics of the crevasses in the context of Landsat and RADARSAT imagery of the marginal zone. A key finding from this survey is that on this active margin crevasses are not generally open to the surface. This raises a question about the use of the depth of apices of hyperbolae in un-migrated GPR data as a reliable indication of a time of ice stream flow shut-down.

What goes down must come up: viscoelastic deformation in the Antarctic Peninsula

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Since 1995 several ice shelves in the Northern Antarctic Peninsula have collapsed and triggered ice-mass unloading, invoking a solid Earth response that has been recorded at GPS stations. The Palmer GPS time series, in particular, offers a rare opportunity to study the time-evolution of the low-viscosity solid Earth response to a well-captured ice unloading event. The previous attempt to model the observation of rapid uplift following the 2002 breakup of Larsen B Ice Shelf failed, being limited by incomplete knowledge of the pattern of ice unloading and possibly the assumption of an elastic-only mechanism.

We make use of a new high resolution dataset of ice elevation change that captures ice-mass loss north of 66°S to first show that non-linear uplift of the Palmer GPS station since 2002 cannot be explained by an elastic-only signal. We next apply a viscoelastic model with linear Maxwell rheology to predict uplift since 1995. We vary the thickness of the elastic lithosphere and upper mantle viscosity, and test the fit to the Palmer GPS time series showing that the observations may be closely fit with an upper mantle viscosity of less than 2×10^{18} Pa s, much lower than previously modelled. Comparison with vertical velocities from six GPS stations deployed after 2009 (the LARISSA network) verifies the results from the model. We show that variations in surface mass balance help to explain much of the residual inter-annual signal.

Despite the excellent model-data agreement, wider geophysical and laboratory studies suggest that a more complex rheological model may be required to correctly interpret the observed deformation. We report on preliminary investigations into adopting a power-law rheology, and discuss the constraints placed on such models by this dataset and the potential implication for understanding grounding line stabilization through solid earth rebound.

Histories of accumulation, ice thickness, and ice-divide position from Central West Antarctica

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In the vicinity of the WAIS Divide ice-core site we use radar-observed internal layers, an ice-temperature profile at the core site, accumulation-rate estimates, ice-surface velocities, and modern ice thickness to infer *histories* of accumulation rate, ice thickness, and ice-divide position. In this inverse problem we use available continuous layers that have been imaged by ground-based radar sounding, and these available layers can now be dated using the depth-age scale for the WAIS Divide ice core. Including additional layer data is an important new development because we rely on data and on applied constraints in order to stably find a unique solution. There are many solutions that may replicate the set of available internal layers, but there are few solutions that are physically reasonable and can satisfy other available data. The measured depth-age scale and the ice-temperature profile are valuable data that can help constrain this problem, and for the first time we use all currently available data together to solve our best construction of this inverse problem. We discuss the sensitivity of the solution to the data used, in particular the time separation of internal layers.

The WAIS Divide ice-core site is located on the flank of the modern ice divide in the interior of Central West Antarctica with a high accumulation rate and a strong accumulation gradient. In a span of ~45 km across the modern divide, the accumulation rate varies from ~33 cm/yr on the Amundsen Sea side to ~20 cm/yr on the Ross Sea side (e.g. Neumann et al., 2008). The high accumulation rate is an advantage for ice-core studies, but the constancy of the modern accumulation pattern and the stability of the ice divide are unknown. While transients in accumulation and in ice flow can drive ice-divide migration, it is likely that dynamical changes initiated near the ice-sheet margin control ice-divide position. Margin changes can rapidly affect interior ice, and in Central West Antarctica this has been observed upstream of outlet-glacier systems draining to the Amundsen Sea and to the Ross Sea. In addition to rapid and recent changes in ice flow, the interior ice-sheet geometry may still be adjusting to changes in sea level and accumulation from the end of the last glacial. Conway and Rasmussen (2009) reported that the modern ice divide here is thinning by ~8 cm/yr and is migrating toward the Ross Sea at 10 m/yr. While this is a significant modern signal, it is unknown whether these changes are a response to decadal-, centennial- or millennial-scale forcing. We address: How long has the divide been migrating? How has ice thickness changed during the Holocene?

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Glacial History of Ferrero Bay (eastern Pine Island Bay): A polar comparison to Antarctic Peninsula fjords

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Ongoing research in the Antarctic Peninsula (AP) indicates that glacial response to Holocene climate events differed in timing and magnitude throughout the region, likely due to local forcings on glacial stability (e.g. oceanography, orography, drainage basin size and elevation). Primary sites include restricted bays and fjords that yield high-resolution marine sediment records and have been analyzed for sedimentary, geochemical, and microfaunal assemblage proxies. These are compared with onshore records, including ice cores, lake studies, and exposure ages of erratics. Ferrero Bay, located in eastern outer Pine Island Bay (PIB), provides a key end member for our understanding of glacial response to climate events. It is the largest and southernmost bay to be included in the study, lies within a truly polar climate setting, and encloses Cosgrove Ice Shelf within the inner bay, which is restricted by King and Canisteo peninsulas.

Three Kasten cores and high-resolution multi-beam swath bathymetry data were collected from Ferrero Bay during the Oden Southern Ocean 2009-2010 cruise. The base of KC-15 yielded two radiocarbon ages which provide a minimum age of ice sheet retreat of 10,736 ± 219 cal yr BP at 1.3 mbsf, indicating low accumulation rates during the Holocene. Mean grain size decreases up-section from clayey sand (winnowed proximal glacimarine facies) to sandy clay (sub ice shelf facies) during deglaciation of outer PIB (Kirshner, et al., 2012). Variation from facies described in outer PIB is expected, as Ferrero Bay lies within a more restricted setting. Total organic carbon and nitrogen increase steadily, suggesting an increase in productivity as Ferrero Bay opened, with greatest productivity during the most recent open water phase. Diatom total abundance also increases, and the assemblage is dominated by sea-ice related taxa. Ongoing diatom assemblage analysis on KC-15 helps delineate changing environments during the Holocene, including recognition of ice shelf vs. sea-ice vs. open water facies, and other variables such as water temperature and nutrient availability. The combined results show a progressive change from more severe polar conditions during early deglaciation of the bay to the current setting and indicates relatively little response to Holocene climate events, such as the mid-Holocene warm interval, compared to more northern bays and fjords.

A method to derive and validate supraglacial lake volumes along the western margin of the Greenland Ice Sheet from WorldView-2 and Landsat 8 imagery

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The integrated effect of supraglacial lake drainage events and continued meltwater influx to Greenland's englacial and subglacial hydrology systems leads to periods of ice flow acceleration which can potentially impact annual ice flux in the coming years. In this regard, assessments of meltwater volume stored in or drained from these lakes are of great significance. While estimating the extent of supraglacial lakes using satellite imagery is rather straightforward, retrieving the depth and thus their volume is not. Several passive remote sensing approaches based on the interpretation of Landsat, ASTER, and MODIS imagery have been proposed to calculate depth. Although providing valuable insight on lake bathymetry, most of these methods either lack field validation or rely solely upon sparse point measurements to verify lake depths. Worldview-2 (WV-2) sensor captures spectrally, spatially and radiometrically detailed information over ice sheet surface features and provides an underutilized source of data for cryospheric studies. Specifically, the target-orientated nature of the satellite provides an opportunity to acquire both multispectral images of full lakes and high precision stereo imagery of the same lakes after drainage. In this study we explore the capabilities of the WV-2 instrument in retrieving depths over melt ponds to more comprehensively and accurately validate depth estimates. We tune the parameters for a radiative transfer model by using lake reflectance values from WV-2 visible channels and a high resolution WV-2 DEM over the same lakes when drained at the end of the melt season. The optimized model is then applied to WV-2 coastal blue (401.4-453.2 nm) and blue band (447.5-508.3 nm) imagery over seventeen large lakes (other than the ones used in model optimization) in western Greenland to determine depths. We validate the results against the drained lake DEMs and assess the uncertainties associated with the model. Furthermore, we optimize the same radiative transfer model for Landsat 8's Operational Land Imager (OLI) using concurrent depth and reflectance *in-situ* measurements. We apply the model to OLI imagery along the western margin of the Greenland ice sheet to derive supraglacial lake volumes, which has great implications for estimating total water storage on the surface of the ice sheet.

Bathymetry and geological structures beneath the Ross Ice Shelf at the mouth of Whillans Ice Stream, West Antarctica, modeled from ground-based gravity measurements

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New gravity data reveal important geologic controls on the location and behavior of the grounding zone of Whillans Ice Stream (WIS), West Antarctica. Grounding zones of ice sheets and contiguous ice shelves are important for understanding ice-sheet dynamics, as key processes that influence the grounded ice and its discharge into the ocean occur in these regions. Here we model the bathymetry and shallow geological structures beneath the Ross Ice Shelf in an embayment of the WIS grounding zone using gravity data collected on the ground, in conjunction with seismic and radar data. We find that the region of shallow ocean water (<~50 m) is extensive; oceanographic models suggest grounding zones exhibiting thin ocean cavities with gently sloping ice-ocean interfaces are likely to be tidally well-mixed, leading to slower basal melting than would occur in a thicker, stratified water column. Beneath the ocean water column, we model a fault and a sedimentary basin in a half-graben, filled with two layers of sediments. The total thickness of the sediment layer is 900 to 1250 m in the half-graben, and 600 to 800 m on the upthrown block, and the basement depth is no more than 2000 m. We observe that the upper, softer sediment is thinnest near the modern grounding line and may possibly pinch out near our grid, and that the modeled fault is roughly parallel to part the grounding. We therefore hypothesize that the WIS grounding line stabilized in its current location in part due to the subglacial geology.

SIA vs Higher Order: Greenland tests, and thoughts on Antarctica

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With large spatiotemporal uncertainties remaining in controlling variables, processes, and boundary conditions, ensemble simulations are often utilized to provide a range of possible outcomes and to assess ice-sheet sensitivity to combinations of poorly constrained parameters. Due to their computational efficiency, models based on the traditional shallow ice approximation (SIA) enable whole ice sheet glacial-cycle runs as well as large suites of perturbation experiments. However, with the development of higher-order and full-Stokes physics cores, the validity and continued utility of SIA ice sheet models are increasingly questioned. This motivates the need to gain a better understanding of the impact of incorporating more accurate, but less-efficient, higher-order physics on model results. To this end, we conducted a suite of five Greenland stepped-warming experiments ($\Delta T = 0, 3, 4.5, 6$, and 12 K) with both a SIA and higher-order model. In settings such as this, we find that: i) process inclusion matters as much as the physics core, ii) higher-order physics initially delays volume loss for more moderate warming and accelerates loss with additional warming, and iii) the rate and magnitude of warming matter not only to the quantity of mass loss, but also to the rate of loss.

The Neglected Middle Child - Snow, Firn, and Water Storage in the Ice Sheet Percolation Zone

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Bright radar reflections within the firn are typically interpreted as the top of a local water table, and that all pore space below this depth to the firn-ice transition is saturated with water. We use an enthalpy formulation of the 1-D conservation of energy equation to show that this interpretation is not always valid, especially in the percolation zone. Our model suggests that under certain conditions, layers of water-saturated firn can persist between layers of cold, dry firn. Two key requirements for a thermally layered percolation zone are relatively high accumulation (to increase downward advection) and relatively high – but not too high – surface melt in the summer (to slow the refreezing of meltwater).

We use conservation of enthalpy because it allows us to track both the temperature and water content. A key assumption is that the effective vertical diffusivity of water is much smaller than the diffusivity of heat. Figure 1 shows the layered structure for an extreme high accumulation rate site (7m/yr), such as found in British Columbia. The left side of the figure shows the firn column when there is less surface melt: all surface meltwater refreezes and the entire firn column is below the freezing point. The right side of the figure shows the firn column when there is higher surface melt: the firn is all temperate with layered variations in enthalpy corresponding to differing amounts of water storage.

We present model results for a range of surface conditions, including those found in WAIS, supporting four key conclusions:

1. Enthalpy transport between winter and summer layers is limited by the ability of the cold ice to conduct heat away from the warm wet layers, slowly freezing the water. Therefore, even a temperate firn column, variations in the amount of liquid water can persist.

2. Differing densification rates for cold and warm firn suggests two bubble close-off depths. The warm wet firn reaches bubble close off higher in the column than the cold dry firn. Because densification reduces the ability of warm firn to hold water, the water becomes concentrated at the upper boundary of the warm layer where it meets the overlying colder (less dense) layer. This process likely results in the bright radar reflector we observe.

3. Finally, our model shows that daily random noise superimposed on a steady state seasonal surface enthalpy results in structure in the enthalpy profile much deeper than 10 meters for both cold and temperate ice. *This has implications for inferring past surface temperatures from*

borehole temperatures in cold sites and for inferring firn water storage from radar for temperate sites.

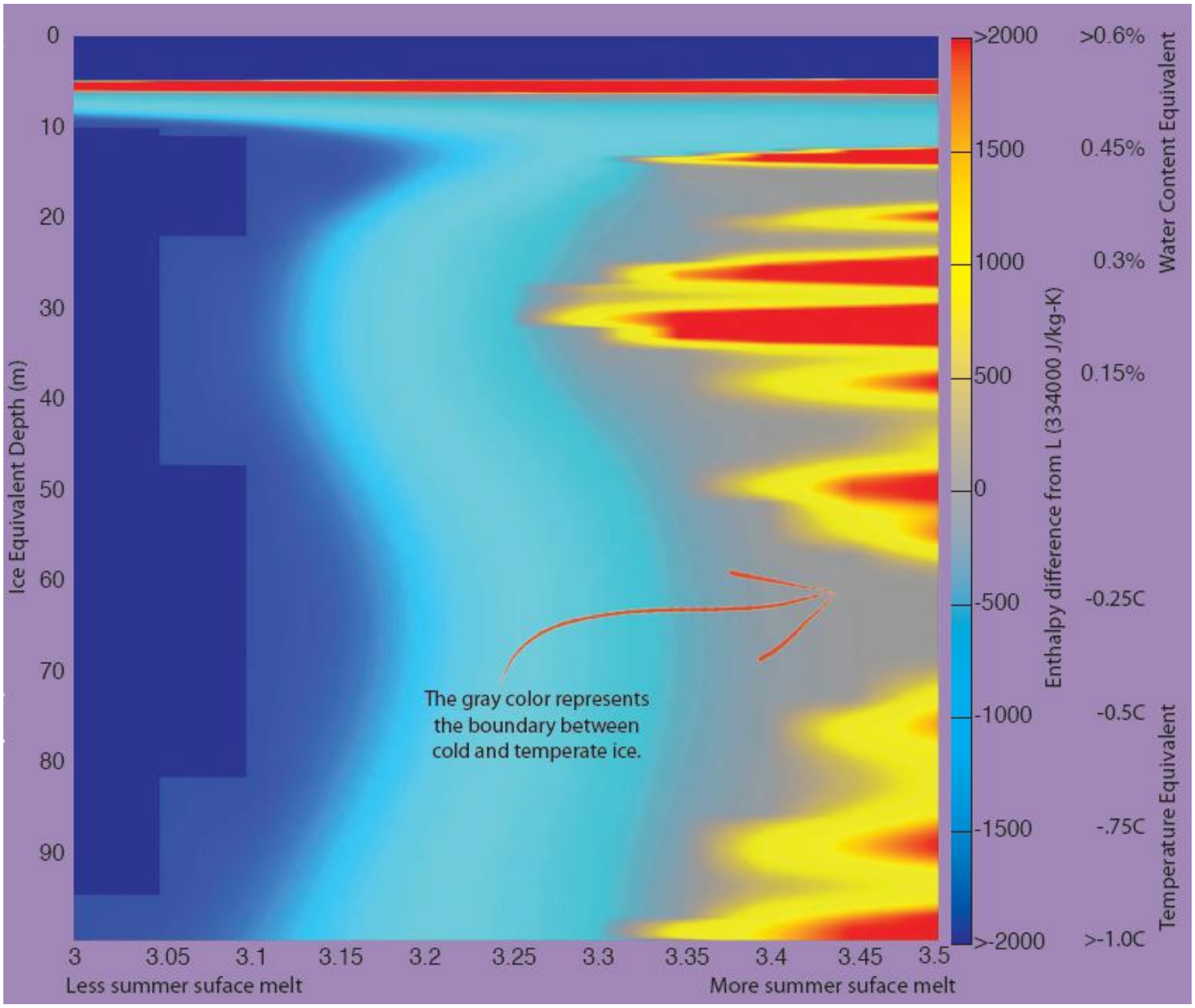

Figure 1: Enthalpy as a function of depth for the top 100m for a site with 7m/yr accumulation. An enthalpy difference of zero is equal to ice at 0^{o}C without any liquid water present. The x-axis is a proxy for the surface melt. All model runs are steady state and use the same surface data (including noise) with daily timesteps.

Nested ice-sheet modeling of long-term variations in the Pine Island-Thwaites Glacier basins

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Recent observations of thinning, acceleration, and grounding-line retreat of the Pine Island and Thwaites Glaciers (PIG/THW) identify this sector of West Antarctica as particularly vulnerable to future climate change. To date, most modeling of these glaciers has focused on recent and modern calibration, and few-hundred-year future timescales. As an alternate approach, we apply a hybrid ice sheet-shelf model to ice retreat in this sector from the Last Glacial Maximum (~15,000 yr BP) to present, and make use of geologic data of grounding-line position, shelf extent and other records to calibrate the model.

The model is run on a 5-km grid spanning the PIG/THW drainage basins and continental shelves, with lateral boundary conditions from a prior continental-scale run with the same model. The goal is to use large-ensemble techniques varying multiple model parameters, and to assess parameter ranges using objective scoring methods vs. geologic data. Here, preliminary results are shown, varying just two model parameters involving oceanic forcing, and using one basic scoring method.

A further goal is to use the validated model to simulate possible future envelopes of retreat on ~thousand-year time scales. Preliminary projections with crude future climate forcing consistently show dramatic grounding-line retreat into the interior of West Antarctica within ~2000 years, contributing +2 to 3 m of global sea-level rise.

Applications of Landsat 8 to Ice Sheets

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Landsat 8 (formerly the Landsat Data Continuity Mission, LDCM) is the newest satellite in the Landsat series. It was launched on 11 February 2013, with operational imagery available starting on 12 April 2013. Onboard are two instruments – the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS).

OLI bands have a nominal spatial resolution of 30 m, plus a visible-only panchromatic band (500-680 nm vs. ETM+'s 520-900 nm) with 15 m resolution. An improvement over Landsat 7's ETM+, OLI has two additional bands in the "coastal/aerosol" (427-459 nm) and "cirrus" (1341-1410 nm) ranges. Imaging deep blues, the coastal/aerosol band will be of interest for a range of applications, including (potentially) estimating the depth of supraglacial lakes. The cirrus band will improve the cloud-detection capabilities of OLI, a task which is often tricky over bright, cold glaciated areas. In addition, OLI mission requirements specify a higher signal-to-noise ratio than the ETM+ and data from all bands are quantized to 12 bits (as opposed ETM+'s 8-bit data). This enhanced radiometric resolution improves OLI's ability to image low contrast surfaces (such as ice sheet topographic variations) as well as simultaneously image scenes with both dark and light areas of interest (e.g. coastal areas) without sacrificing either area.

TIRS has two thermal infrared bands (10.6-11.2 and 11.5-12.5 μm) at a nominal spatial resolution of 100 m. While previous Landsat sensors featured only one thermal band (e.g. ETM+: 10-12.5 μm), TIRS' two thermal bands will allow for potential application of a split-window technique for more accurate measurement of surface temperature. However, in dry areas such as the Antarctic, a second band may be more appropriately used to simply validate temperature retrievals. TIRS data may be interesting for applications to ice sheet-marginal sea ice dynamics, supraglacial lake evolution, and polar night ice sheet monitoring, for example tracking the behavior of the large iceberg (B-31) recently calved from Pine Island Glacier.

This poster will present case studies which showcase the abilities and cryospheric applications of Landsat 8 data. We will also present the Landsat 8 acquisition plan for the Greenland Ice Sheet and gather suggestions and feedback for an Antarctic acquisition plan.

Rapid grounding line migration induced by internal variability of a marine-terminating ice stream

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Numerous studies have found significant variability in the velocity of ice streams to be a prominent feature of geomorphologic records in the Siple Coast (Catania et al. 2012) and other regions in West Antarctica (Dowdeswell et al. 2008). Observations indicate that grounding line position is strongly influenced by ice stream variability, producing rapid grounding line migration in the recent past (Catania et al. 2006) and the modern (Joughin & Tulaczyk 2002).

We analyze the interaction of grounding line mass flux and position in a marine-terminating ice stream using a stretch-coordinate flowline model. This model is based on that described in Schoof (2007), with a mesh refined near the grounding line to ensure accurate resolution of the mechanical transition zone. Here we have added lateral shear stress (Dupont & Alley 2005) and an undrained plastic bed (Tulaczyk et al. 2000). The parameter dependence of ice stream variability seen in this model compares favorably to both simpler (Robel et al. 2013) and more complex (van der Wel et al. 2013) models, though with some key differences.

We find that thermally-induced internal ice stream variability can cause very rapid grounding line migration even in the absence of retrograde bed slopes or external forcing. Activation waves propagate along the ice stream length and trigger periods of rapid grounding line migration. We compare the behavior of the grounding line due to internal ice stream variability to changes triggered externally at the grounding line such as the rapid disintegration of buttressing ice shelves. Implications for the Marine Ice Sheet Instability are discussed.

Evolving Toward the Next Antarctic Ice Shelf Disintegration: Recent Ice Velocity, Climate, and Ocean Observations of the Larsen B Ice Shelf Remnant at Scar Inlet

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Ice shelf / ice tongue retreats have a major effect on glacier mass balance, and nowhere has this been more evident than in the northern sections of the Larsen Ice Shelf in the Antarctic Peninsula. Glacier ice flux in this region surged 2- to 6-fold after the 1995 and 2002 ice shelf disintegration events, driven by a group of processes based on the presence of extensive surface melt lakes. However, precursor changes in the ice shelves beginning more than a decade before the events have been identified. A new assessment of these provides insight on the earliest causes of ice shelf change.

Ice flow speed on the central Scar Inlet Ice Shelf has increased 60% between 2002 and 2012 (425 to 675 m/yr), and 20% (540 to 660 m/yr) at the grounding line of Flask Glacier, a tributary. In late 2002, and again in late 2012, major new rifts formed on the southern portion of the Scar Inlet shelf, and the northwestern shear zone has rapidly evolved. The ice speed increase and the new rifts are inferred to be due to significant structural changes in the ice shelf shear margin on its northern side (concentration of shear motion and disruption of the shelf margin area).

Weather data collected under LARISSA highlights the importance of foen winds in causing both surface melting and reducing sea ice at the ice shelf fronts, and show that specific weather patterns lead to frequent foen events. Oceanographic data from CTD casts show that deep ocean water near the Larsen Ice Shelf region retains a small capacity for inducing melt in the shelf cavity. At Seal Nunataks, ICESat detects surface lowering at 0.25 m/yr, but the implied shelf thinning rate is similar to that observed at adjacent Robertson Is. due to melt runoff.

An examination of satellite imagery spanning 1963 to the present shows that shear margins on the Larsen B and Scar Inlet were essentially unchanged through 1986. Following that time, ice shelf shear zones show significant evolution, including increased and expanded areas of rifting, concentration of shear, and ice flow speed increases. These changes are the initial events leading to effects described in Glasser and Scambos, 2008 J. Glaciol., Vieli et al., 2007 EPSL, and Khazendar et al., 2007 GRL. These early changes, occurring prior to shelf area loss, suggest either increased ocean-driven basal melt or effects of increased meltwater on the shelf and tributary glaciers are the cause of early shelf weakening that led to disintegration.

WISSARDs and GLIDErs: Season Recap and Forecast

WISSARD Project Members Reed Scherer, Presenter*

**See http://www.wissard.org/ for authors & affiliations*

The WISSARD (Whillans Ice Stream Subglacial Access Research Drilling) project successfully penetrated and sampled Subglacial Lake Whillans in January, 2013, using a new hot water drill system utilizing full clean-access protocols. In situ measurements, water sampling, and sediment coring were successfully performed, as well as remote sensing and geophysical surveying.

The lake, a catchment area on the downstream portion of the ice stream, is shallow (~1.5m deep) and is characterized by a surprisingly diverse and abundant microbial community. The sediments are muddy diamicton with sedimentary and micropaleontological evidence of extensive shear strain, consistent with highly deformed till, similar to materials previously recovered from beneath the Upstream B (Whillans) and C (Kamb) camps. Micropaleontologic evidence indicates dominantly Miocene marine source rocks, with older and younger (Pliocene and Quaternary) contributions.

The 2013-14 field season will include access and sampling at the grounding zone, where the sub-ice shelf marine cavity interfaces with grounded ice, ca. 50 km from Lake Whillans.

Proposed work for future seasons include exploration of the sub-ice shelf cavity, with an anticipated greater influence of sub-ice shelf ocean circulation.

Ice Velocity Mapping in Antarctica – Achievements, Challenges and the Way Forward

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Ice sheets are acknowledged by the World Meteorological Organization and the United Nations Framework Convention on Climate Change as an Essential Climate Variable needed to make significant progress in the generation of global climate products and derived information. Ice velocity is a crucial geophysical parameter that can be measured using spaceborne Synthetic Aperture Radar (SAR) data. Here, we report on a NASA funded effort to generate Earth System Data Records (ESDR) of ice velocity in Antarctica based on data from a suite of spaceborne SAR sensors and provide analyses results based on these products.

Building on the first complete mapping of the flow of ice surface over the Antarctic continent using data predominantly acquired during IPY, we are now working on a series of regional time series by processing available data from several different epochs. The analysis of velocity changes between discrete measurements requires even more careful data processing in order to be able to accurately measure subtle changes. We provide example results of several studies we conducted. Results on Ross Ice Shelf show for the first time the spatial extent of the more subtle changes in the region. Our analysis of velocity changes in the Amundsen Sea Embayment region between 1996 and 2013 shows changes propagating over a large portion of the drainage basin. Using ice velocity amongst other information we evaluated ice shelf melt water production of Antarctic ice shelves and compared it to iceberg calving. Our results indicate that basal melt exceeds a calving flux, making ice-shelf melting the largest ablation process in Antarctica.

In an effort to improve our ice velocity ESDRs, we also request feedback from the community on the products already available. Data continuity is a crucial aspect to our work, particularly in light of the fact that four SAR missions have ceased operations since IPY and all available missions have a primary mandate that is not scientific data collection. We are working with the science community and the Polar Space Task Group (PSTG), a coordinating body of international space agencies. In 2013 the Canadian Space Agency committed RADARSAT-2 to a large scale Antarctic data acquisition campaign. In addition, the German Space Agency and the Italian Space Agency acquire high resolution SAR data in high priority sites.

Data analysis and ESDR production is conducted at the Department of Earth System Science, University of California Irvine under a contract with the National Aeronautics and Space Administration's MEaSUREs program. Spaceborne SAR data are made available for this project courtesy of the Polar Space Task Group.

What Can Radar Scattering Tell Us About the Relative Character of Past and Future Retreats in the Amundsen Sea Embayment?

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The morphological, lithological, and hydrological basal boundary conditions of ice-sheets and glaciers can exert strong, even dominating, control on their behavior, evolution and stability. However, the scales at which the physical processes and observable signatures of this control occur are typically smaller than the spatial resolutions achievable using ice penetrating radar. Further, the strength of calibrated radar bed echo returns is a combination of both the material (i.e., relative permittivity, conductivity) and geometric (i.e., rms height, rms slope, auto correlation length) properties of the ice/bed interface. This ambiguity in the relative contribution of material and geometric bed properties, along with uncertainty in englacial attenuation from underconstrained ice temperature and chemistry, also makes definitive assessment of basal conditions from echo strengths extremely difficult.

To address these challenges in interpreting geometric and material bed properties at glaciologically relevant scales, we apply a new algorithmic approach to measuring the radar scattering function of the ice/bed interface by performing range-migrated SAR focusing using multiple reference functions spanning different ranges of Doppler frequencies for the bed. We parameterize this scattering function in terms of the relative contribution of angularly narrow specular energy and isotropically scattered diffuse energy. This specularity content of the bed echo is insensitive to englacial attenuation and is a measure of both the angular distribution of returned echo energy and the geometry of the ice/bed interface at the sub-azimuth-resolution scale.

We present the application of this technique to a gridded airborne radar survey over the entire catchment of Thwaites Glacier, West Antactica. We show how this information can be used to constrain the morphology of basal bedforms and infer the distribution of deformable sediments and crystalline bedrocks across the catchment. We compare this distribution to offshore bedforms and sediment records on the deglaciated inner continental shelf of the Amundsen Sea Embayment. We also discuss the potential implications for the processes and timing of previous, contemporary, and potential grounding line retreats in the region.

Rib-like patterns in basal shear of ice streams

Olga Sergienko

GFDL/Princeton University

The direct observations of the basal conditions under continental-scale ice sheets are logistically difficult. A possible approach to estimate conditions at the ice - bed interface is from surface observations by means of inverse methods. The recent advances in remote and ground-based observations have allowed to acquire a wealth observations from Greenland and Antarctic ice sheets. Using high-resolution data sets of ice surface and bed elevations and surface velocities, inversions for basal conditions have been performed for several ice streams in Greenland and Antarctica. These inversions reveal the presence of rib-like spatial structures in basal shear in many locations. The analysis of the hydraulic potential distribution shows that these rib-like structures co-locate with highs of the gradient of hydraulic potential. This suggests that subglacial water plays a role in the development and evolution of the basal shear ribs.

Controlling mechanisms of fast flowing glaciers in West Antarctica

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Ice shelves play a major role in the stability of fast flowing ice streams in Antarctica, by exerting buttressing on inland ice and controlling the discharge of ice into the ocean. However, the mechanisms at work remain poorly understood and interactions between floating and grounded ice need to be better characterized in order to estimate the impact of climate change on the ice sheets. Glaciers in West Antarctica experienced significant changes over the past decades.
Pine Island Glacier, for example, has been thinning and accelerating since the 1970's at least and its grounding line has been retreating inland at a rate of about 1 km/yr. Initiation of these changes is usually attributed to warmer ocean waters in the Amundsen Sea affecting the floating part of Pine Island. By buttressing grounded ice flow and controlling the discharge of inland ice to the ocean, the ice shelf of Pine Island plays a major role in the stability of the glacier. Thwaites Glacier features a small and heavily fractured ice shelf that provides limited back stress pressure on inland ice but is pinned on the eastern part on a prominent ridge. Contrary to Pine Island Glacier, Thwaites Glacier has maintained a consistently high velocity and negative mass balance for at least 20 years. Recent observations show a widening of its fast flowing area as well as a sustained acceleration since 2006 and a rapid retreat of its grounding line in the center of the glacier.

We use the Ice Sheet System Model (ISSM) and a three-dimensional higher-order model to simulate the evolution of the glacier for the next fifty years and assess the effect of changes in several climate forcings and model parameters, namely basal melting under the floating part, ice front position, atmospheric conditions and grounding line retreat. Simulation results show the dominant effect of basal melting and of grounding line retreat. Results also show that changes are not limited to the ice shelf and the grounding line area but propagate far inland, almost to the ice divide. We find that enhanced basal melting or grounding line retreat are each associated with a distinct pattern of ice thinning and acceleration. We compare the simulation results with remote sensing observations of velocity changes and grounding line evolution to elucidate which forcing is more likely to have caused the recent changes observed on these glaciers.

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory and the University of California Irvine under a contract with the National Aeronautics and Space Administration, Cryospheric Sciences and Modeling, Analysis and Prediction Programs

Measuring Changes to the Seal Nunataks Ice Shelf Remnant from Imagery and Altimetry

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Acquisition and analysis of a combination of repeated imagery and ICESat-1 altimetry has enabled the ongoing losses from the northern Larsen B ice shelf remnant to be visualized and measured. The northern remnant, the Seal Nunataks Ice Shelf (SNIS), has four ICESat tracks that cross it as well as a track that obliquely crosses adjacent Robertson Island (RI). The available altimetry data from ICESat (2003-2009) shows that elevation losses generally increase from west to east across the SNIS. In addition, the adjacent ice shelf thickness losses adjacent to Robertson Island are almost 1.5x the average elevation losses measured for the grounded ice suggesting a significant amount of basal shelf melting. Imagery analysis shows that ice area losses continued on both margins of SNIS with the largest losses occurring on the north side in late 2004 into 2005. New rifts that form on SNIS do not tend to fill with melt water and soon release icebergs. In contrast, RI has experienced relatively minor area losses suggesting that most of its ice is grounded and is less impacted by ocean interactions as compared to SNIS. This analysis is compatible with the analyses of Pritchard et al. (2012) and Rignot et al. (2013) and provides some insights about ongoing ice loss processes.

Subglacial flood event observed using *in situ* GPS data, CryoSat-2 altimetry, and MODIS image differencing on the Whillans Ice Plain, West Antarctica

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The Whillans Ice Plain (WIP), at the confluence of the Whillans and Mercer Ice Streams on the Siple Coast, West Antarctica, has been observed to have a dynamic subglacial hydrological system, including subglacial lakes that fill and drain on sub-annual to decadal cycles. The initial data from the ICESat mission (2003-2009) provided a precise, yet spatially and temporally discontinuous, time-series of lake activity for nine subglacial lakes in the area. Here, we use an array of moderate-rate GPS units to monitor the subglacial hydrology on WIP during and after the ICESat/CryoSat-2 altimetry gap, assess the efficacy of CryoSat-2's Synthetic Aperture Radar-Interferometric (SIN) mode data for investigating active subglacial lakes, and tie the ICESat and Cryosat-2 datasets together through these in situ observations. Simultaneous ice-surface elevation measurements over Subglacial Lake Mercer (SLM) from GPS data and SIN-mode data reveal a subglacial lake drainage event lasting from August 2012 until March 2013, which is independently confirmed through MODIS image differencing. This event is similar in magnitude to the only previously documented SLM lake drainage (~$30 m^3 s^{-1}$ sustained over 6-8 months in 2005), but the GPS (at 30-second intervals) and CryoSat-2 data (at monthly intervals) have improved the temporal resolution of previous observations of WIP subglacial floods by orders of magnitude. This increase in both the temporal and spatial resolution at which we map subglacial water allows for a better mechanistic understanding of the subglacial hydrological system on a decelerating ice stream, and enables us to track the movement of subglacial drainage water downstream.

Influence of subglacial conditions on ice stream dynamics: Seismic and potential field data from Pine Island Glacier

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A synthesis of geophysical and glaciological data sets are used to investigate the relationship between ice dynamics and the underlying geology at one location on Pine Island Glacier. We find correlations between subglacial geology and variations in flow of the overlying ice. Seismic reflection amplitudes indicate a layer of soft water-saturated sediment immediately beneath the ice. Beneath this, gravity and magnetic data indicate basement rocks containing a significant geological boundary, aligned in the ice-flow direction. Crossing this boundary, the ice velocity decreases whilst bed roughness and modeled basal drag both increase. The acoustic impedance of the soft sediments at the ice-bed interface shows no significant change across the boundary. The smoother glacier bed, overlying thicker (>100 m) sediments, appears to facilitate the fastest flow. Where the bed is rougher the soft sediment layer beneath the ice is very thin (≤10 m) and overlies basement rocks; we propose that the rough surface of the basement rocks beneath this thin sediment increases the basal drag on the ice, through the intervening soft sediment, without a detectable influence on the sediment's acoustic properties.

Changes in the sub-bed (i.e. deeper than the ice-bed interface) lithology appear to account for the contrasting basal drag and ice velocity patterns at this location. Repeated surveys would indicate whether this is a steady state, or whether subglacial erosion in the near future could remove the thin, soft sediment layer, perhaps leading to long-term changes in the glacier's flow.

Icequakes! Microseismic ‘Sticky Spots’ in Rutford Ice Stream, West Antarctica.

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Microseismic emissions from the base of Rutford Ice Stream, West Antarctica, were recorded over a 34-day period using ten three-component instruments on the surface of the ice stream. Around 3000 microseismic events were detected and located. Events are concentrated in spatial clusters that are likely to be ‘sticky spots’: areas of increased basal friction where shear stress is concentrated. The ‘sticky spots’ turn on and off over the recording period becoming inactive for a period of time before being re-activated in the same location. The constant nature of these locations indicates a temporal stability in the basal regime despite the fact that rapid changes have been seen at the bed in this area (erosion and drumlin formation). Furthermore, events in each location cluster have a consistent waveform at a given receiver and a consistent source mechanism determined by fault plane analysis.

The source mechanisms for these microseismic events show variation between clusters. Evidence of low-angled thrust faults in the ice flow direction suggest basal sliding is occurring in some regions and that in these regions basal flow is in the same orientation as surface flow, despite considerable bed topography. However, more complex source signatures in other regions indicate a spatial change in the basal processes over the survey area. An increased understanding of basal processes is fundamental in our ability to predict the evolution and future contribution to global sea level rise of ice sheets. Passive microseismic monitoring is proving to be an effective tool for investigating many aspects of this.

A PIG unknown: the first sediment cores recovered from beneath Pine Island Glacier

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To date, only a handful of studies have successfully recovered sediment samples from beneath Antarctic ice shelves. Published data is limited to short cores from beneath the Amery Ice Shelf, one 0.28m core from beneath the Novolazarskiy Ice Shelf and sediments recovered as part of major drilling efforts in the Ross Sea. The lack of data from these environments is surprising given their potential to reveal important information regarding ice shelf history (i.e., thinning and retreat), changes in ocean circulation through time, as well as much needed boundary information about sub-ice shelf sedimentation. The latter information is critical for determining periods of ice shelf presence and absence in the geological record.

Here we present preliminary data on sediment cores recovered from beneath Pine Island Glacier (PIG) during December 2012 and January 2013. Three drill sites (A-C) were established on PIG to access the ocean cavity for oceanographic measurement and sediment cores were successfully recovered at each site. Sites A and C were seaward of the prominent transverse seafloor ridge identified by Autosub, and Drill site B was located on the landward side of the ridge. Sediments were collected using a simple percussion corer, which proved to be enormously effective and simple to deploy. In total, 2.5m of sediment was recovered with a maximum penetration depth of 1.2m (Drill site B). Preliminary physical properties data (sediment density, P-wave velocity and magnetic susceptibility which provides a proxy for terrigenous vs. biogenic sediment as well as information on sediment provenance) and core data will be presented. Detailed investigation of the sediment is currently ongoing (lithological description, sediment provenance, and dating) and will shed light on the processes occurring at or very close to the grounding line (e.g., meltwater discharge, tidal pumping and sediment delivery). In addition, the cores also have the potential to provide a longer-term perspective on recent glaciological and oceanographic changes such as sub-ice shelf ocean circulation and timing of grounding line retreat.

Exposure history of West Antarctic nunataks

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There is strong evidence that the West Antarctic Ice Sheet has been thinner during the Pleistocene, however the timing, duration, and magnitude of past deglaciations are poorly known. Ice-sheet elevation changes over glacial and interglacial periods can be revealed by cosmogenic-nuclide measurements of bedrock surfaces. Whether ice was thinner during past warm climates can be tested by measuring cosmogenic nuclides in currently subglacial bedrock surfaces, provided that cold-based ice has protected the surfaces from erosion. During 2012-13, we visited three groups of small nunataks in West Antarctica with the intention of locating favorable drilling sites for the recovery of subglacial bedrock to look for evidence of thinner ice in the past. We traveled to the Whitmore Mountains, located near the ice-sheet divide, and the Pirrit and Nash Hills, nunatak groups located in the Weddell sector of West Antarctica at ~1300 and ~1500 m, respectively.

At the Pirrit Hills, fresh glacial erratics are evidence of thicker ice during the last ice age and indicate that ice levels were at least ~350 m, but less than ~510 m, above the present level. Despite thicker ice, bedrock at all three sites, extending down to the present ice level, is weathered and exhibits delicate cavernous forms, evidence of prolonged subaerial weathering prior to the last ice age. The preservation of these features, along with the lack of evidence for wet-based glacial erosion, indicates that former ice cover was cold-based and protected the underlying bedrock.

Cosmogenic ^{10}Be measurements of bedrock surfaces show that the majority of the Pirrit Hills have been exposed for over ~0.5 Myr and up to ~4.3 Myr. Even within a few meters of the present ice surface, two bedrock samples yield minimum exposure ages of ~230 and ~490 kyr. Paired ^{26}Al and ^{10}Be measurements from Pirrit Hills bedrock indicate that past episodes of ice cover thicker than the present were not long-lived and that the bedrock surfaces experienced very low erosion rates for at least the past ~0.5 Myr. Bedrock measurements from the Whitmore Mountains show even longer exposure and no evidence of prior ice cover.

Ice-penetrating radar surveys, conducted around minor nunataks of the Pirrit Hills, revealed detailed bedrock topography to depths of ~400 m (see accompanying abstract by Lewis et al.). Of particular interest is a gently-dipping ridge radiating from the small granitic outcrop of Harter Nunatak. Between 100 to 300 m below the ice surface, internal reflectors within the ice truncate against this ridge. Although this could result from basal melting, no evidence exists for wet-based ice, and basal melting is unlikely to occur at this shallow depth. The truncating reflectors appear to result from onlapping snow layers, implying exposure of the ridge during a time of thinner ice.

At the Pirrit Hills, evidence for past ice-free conditions and cover by cold-based, protective ice suggest that the cosmogenic-nuclide signal of prolonged exposure extends below the modern ice surface. This favors the Pirrit Hills as a potential site for future subglacial drilling to depths of a few hundred meters.

Flow Dynamics of Byrd Glacier, East Antarctica

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Byrd Glacier is a fast-moving outlet glacier transecting the Transantarctic Mountains, funneling an estimated 20.6 Gt/yr of ice originating on the East Antarctic plateau into the Ross Ice Shelf through a fjord that is ~100 km long and ~20 km wide. The glacier has been the subject of glaciological investigations since the early 1960s, including a comprehensive assessment of balance of forces on the lower trunk by Whillans et al. (1989) using surface elevations and ice velocities derived from repeat photogrammetry in the late 1970s. That study, as well as subsequent more recent studies, was limited by lack of detailed information on the bed topography under the glacier. In 2011-2012 the Center for Remote Sensing of Ice Sheets (University of Kansas) conducted extensive airborne radar sounding for mapping the bed under Byrd Glacier, thereby allowing reevaluation of results from earlier studies and, in particular, to investigate the relation between "sticky spots" and basal relief. The present study aims to investigate flow dynamics and essentially represents an update of the study of Whillans et al. (1989).

Force-balance calculations reveal large variations in the along-flow component of driving stress that are muted by gradients in longitudinal stress such that basal drag is less variable spatially. The most pronounced sticky spot is located at the downstream end of a basal overdeepening, while smaller regions of high basal drag are co-located with a bed ridge transverse to the flow direction. On the large scale, gradients in longitudinal stress play a small role in balancing the driving stress, and flow resistance is partitioned between basal and lateral drags. Confirming earlier results, there is a significant component of driving stress in the across-flow direction resulting in non-zero basal drag in the direction perpendicular to ice flow. This is an unrealistic result and we propose that there are spatial variations in ice strength similar to those found on other glaciers.

The effect of geometry on ice-shelf ocean cavity ventilation: a laboratory experiment

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A laboratory experiment is constructed to simulate the density driven circulation under an idealized Antarctic ice shelf and to investigate the flux of dense and fresh water in and out of the ice shelf cavity. Our results confirm that the ice front can act as a dynamic barrier that partially inhibits fluid from entering or exiting the ice shelf cavity, apart from in two wall-trapped boundary currents. This barrier results in a density jump across the ice front and in the creation of a zonal current which runs parallel to the ice front. However despite the barrier imposed by the ice front, there is still a significant amount of exchange of water in and out of the cavity. This exchange takes place through two dense and fresh gravity plumes which are constrained to flow along the sides of the domain by the Coriolis force. The flux through the gravity plumes and strength of the dynamic barrier are shown to be sensitive to changes in the ice shelf geometry and changes in the buoyancy fluxes which drive the flow

Impurity Influence on Normal Grain Growth in the WAIS Divide 06A Ice Core, Antarctica

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High impurity loading leads to reduced grain growth rates in the WAIS Divide 06A ice core, West Antarctica, as shown by regression analysis of new data from this core. Grain sizes measured on thin sections cut from the core were compared to concentrations of soluble impurities and proxies of insoluble impurities measured on the remaining core over the same depth intervals. In general, samples with higher concentrations of several impurities, especially calcium, but also magnesium, sodium, and sulfate, showed smaller grain sizes. Physical understanding indicates that higher impurity loading reduces the grain growth rates.

What determines the differences in basal melt between ice shelves in the Amundsen Sea?

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The ice shelves of the Amundsen Sea are thinning faster than anywhere else around Antarctica but this mass loss varies substantially from one ice shelf to another. We examine the hypothesis that ice shelf geometry is the main cause of these differences. We employ a high-resolution (1.5km) 3-D ice shelf-ocean numerical model to simulate the mean basal melt rates of the Amundsen sector (interannual variability of the melt is not considered in this study). The model domain includes Cosgrove, Pine Island, Thwaites, Dotson and Getz ice shelves as well as parts of Crosson and Abbot ice shelves. The ocean and ice shelves are thermodynamically-coupled and the ice shelf geometry is assumed constant over the short period of time considered (5years). All ice shelf cavities are initialized with the same water temperature profile. On the continental shelf, the warm slope water is steered by large glacial troughs and circulates in a complex pattern controlled by the sea floor topography. This circulation particularly enhances the melt of Thwaites, Pine Island and Dotson ice shelves. We find however that the location of the glacial troughs plays a smaller role than ice shelf geometry in determining the differences in melt between the ice shelves.

Deformation-induced melting in the margins of the West-Antarctic ice streams

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The mass balance of the West Antarctic ice sheet depends primarily on the location and flow speed of arterial drainage routes called ice streams, which represent localized zones of rapid ice flow separated by ridges of comparatively stagnant ice. One main challenge in current models of ice streams is the treatment of the shear margin, which plays an important role in the force balance. The goal of this study is to shed new light on the interplay between mechanical deformation and deformation-induced melting in ice-stream margins and explore to what degree the processes in the shear margins affect ice-stream dynamics. To compare our modeling results with observational data, we specifically address the margin of Whillans ice stream B2, commonly referred to as Dragon margin, but argue that our insights may apply to ice streams more generally.

We devise a 2D anti-plane strain model of an ice stream moving over a plastic bed in steady state. Our approximation neglects small components of non-anti-plane deformation that must accompany the marginal melting and drainage that we infer. We include horizontal and vertical advection, latent heat of melting, and surface crevassing into our model. We strive for a realistic description of the rheology of ice entailing multiple deformation mechanisms dominant at different stresses and accounting for the temperature dependence of material properties. By coupling heat and mass flow, we are able to show that a temperate zone is likely to form in the shear margin, where the heat production from lateral deformation is most intense.

Our numerical results are in excellent agreement with observational data for the transverse profile of surface velocities across Dragon margin measured by Echelmeyer et al., 1994. The numerical solution also enables us to test how the extent of the temperate zone and the amount of melt water produced depends on the assumed model parameters, in particular the latent heat of melting, the advection of cold ice into the margin, and the extent of surface crevassing. The simulations including surface crevassing also lend themselves to a comparison with the temperature data by Harrison et al., 1998. While a perfect fit to the observed temperatures cannot be expected within the confines of a steady-state model, we are able to reproduce the key features of the temperature data.

We conclude that Dragon margin and potentially the other active shear margins in West Antarctica are likely to be partially temperate as first suggested by Jacobson and Raymond (1998) and studied in more detail by Perol and Rice (see http://www.waisworkshop.org/abstracts/2011/Perol.pdf). For Dragon margin, we estimate a temperate zone of 4km width and 180m height, entailing a meltwater production of approximately 5m^3/yr per meter in downstream direction. The presence of meltwater in ice-stream margins might have important consequences for the dynamics of ice streams, because the yield stress of glacial till is highly dependent on water content (e.g. Tulaczyk, 1999). Meltwater could also form a channelized drainage system with important ramifications for the stress and pore-pressure distribution at the bed (Perol and Rice, submitted 2012).

Using zigzags to quantify surface melt (in Greenland)

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Ice strata are exposed in the ablation zone at the margin of the Greenland ice sheet. Ice penetrating radar show that these strata dip at a low angle into the interior of the ice sheet. When the ice surface is incised by meltwater channels, these outcropping strata form large, km-scale zigzags across the surface. In geological mapping this simple zigzag effect is known as the "rule of Vs", where the amplitude of the zigzag is determined by the relative dip of the stratum and the surface topography. Over time, ice flow moves the ice sheet stratigraphy towards the margin, but surface melt moves the outcrop of this stratigraphy down dip, i.e. towards the interior of the ice sheet. By examining satellite imagery from the summer months, we are able to use the year-to-year displacement of the outcropping zigzag strata to compare the relative influence of ice flow and surface melt. In this way we use the rule of Vs to document increased surface melt over the last decade.

The Antarctic Glaciological Data Center provides support for NSF Antarctic Program Principal Investigators to share their snow, ice and related data

Sarah Tressel, T. Scambos, R. Bauer

Antarctic Glaciological Data Center

Data collected as part of an Antarctic field research project may have more than one story to tell. The data may take on new life years or even decades later, as new scientific uses for the data arise. In the changing ice, climate and ocean global system, data collected today become the foundation of change detection measurement tomorrow.

Antarctic Glaciological Data Center (AGDC) staff works closely with Principal Investigators funded by the National Science Foundation (NSF) Office of Polar Programs (OPP) Antarctic Glaciology and other Antarctic programs to quickly and easily make their data available to the scientific community.

The AGDC Web site and associated activities promote new data sets to the community for the benefit of ongoing and future research. AGDC data collections are widely used by researchers, and AGDC has a data citation policy that benefits the contributing Principal Investigators.

We invite you and your colleagues to participate with AGDC in preserving your data and fulfilling the NSF OPP data-sharing requirements.

Some Lessons on Basal Physics of Ice Motion from Flow Variability of Whillans Ice Plain: the WISSARD GPS Experiment (in a Shadow of a Borehole)

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Here we report preliminary results from the largest ever glaciological on-ice cGPS experiment, which is taking place as part of the WISSARD project (and a pre-WISSARD OPP-Antarctic Glaciology project) since late 2007 on Whillans Ice Plain (WhIP), a regional flow feature with approximate dimensions of 100km by 100km by 1km. Overshadowed by a borehole and a subglacial lake in the eyes of the media, this experiment is yielding a (discontinuous) high-resolution time series of ice velocity and strain rates from one of the most erratically behaving parts of the West Antarctic ice sheet.

The WhIP has been slowing down since at least 1963. Prior constraints on this slowdown were consistent with a constant long-term deceleration rate. Here we show that the deceleration rate varies through time, including on interannual timescales. For instance, between 2009 and 2012 WhIP decelerated at a rate that was double the multi-decadal average. To identify the mechanism/s responsible for this slowdown, we used force budget models as well as a higher-order inverse model. All model results support the conclusion that the observed deceleration is caused by an increase in basal resistance with magnitude of 10-40 Pa/yr. Subglacial processes which may be responsible for such strengthening include basal freeze-on, changes in subglacial water drainage, or increases in the area of resistant basal substrate through differential glacial erosion. The WISSARD cGPS experiment captured an episode of Subglacial Lake Whillans (SLW) filling and draining in 2008 and 2009. During this time period, ice surface elevation over the lake went up and down by up to four meters. This subglacial lake activity resulted in a regional, temporary acceleration by about 2% of ice surface velocity. This acceleration shows up on all cGPS stations, including the ones located over 50km away from SLW, suggesting that lake activity is correlated in time with regional changes in subglacial hydrology.

Differential melting of wAP glaciers by modified upper circumpolar deep water along a latitudinal gradient

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Glaciers in the western Antarctic Peninsula (wAP) have been retreating for the last 60 years from North to South. To understand the processes leading to this retreat, we estimated ocean influence through studies in 4 fjords in central and southern peninsula. There is a higher influence of Modified Upper Circumpolar Deep Water (MUCDW) on glacier melting further South. Comparing oceanographic properties in the the fjords, Barilari (65.5 S), Flandres (64.5 S), Andvord (64.3 S) and Brialmont Cove (63 S), we find the more negative delta18O concentrations in surface waters of Barilari, associated with lowest salinity, indicative of glacier meltwater input. An estuarine circulation is observed in this fjord, coherent with high subsurface melting, similar to Alaskan fjords, where deep warm water entering fjords melts the glacier face. The meltwater rises to the surface and leaves the fjord in a surface layer ~24 m thick. From modeling we estimate ~300 m y^{-1} of glacier ice is melted in Barilari Bay. Further North, the circulation is more complex: outflow is sometimes manifested as a diffuse surface layer and at other times as a subsurface meltwater plume. If subsurface, a plume is located below the summer mixed layer (23-30 m). This layer, salty and cold, is observed in Temperature-Salinity (TS) diagrams. Assuming UCDW has a delta 18O of ~0, fjord water has a high meltwater content of up to 8%, concentrated at the surface layer in Barilari and present from surface to depth in the other fjords further North. When integrating over the depth of the water column, Barilari has 5 m of meltwater in contrast to 9m-13 m in the central fjords. The difference is compensated by the residence time of seawater within fjords. We interpret the difference in processes of glacier melt along the latitudinal gradient to a decrease in oceanic influence towards the north where UCDW does not reach the glacier face.

Mapping Surface Roughness and Snow Grain Size across Antarctica with MISR images … a Work in Progress

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MISR is the Multi-angle Imaging SpectroRadiometer. This instrument was built at NASA Jet Propulsion Laboratory and is one of five scientific instruments aboard the EOS Terra satellite. It images Earth simultaneously from nine angles, collecting an image series of data along-track that can be used to distinguish different clouds, atmospheric particles, and land surface covers. For ice sheets, this angular information can be exploited to quantify surface roughness. The sensor has outstanding radiometric resolution (14-bits) in all bands, and the nadir camera provides this level of measurement for blue, green, red, and infrared channels. Thus a second application we are pursuing is a more accurate snow grain size mapping, building on previous work (Nolin et al., 2002; Nolin and Payne, 2007; Scambos and Bohlander, 2011). Both surface roughness and optical snow grain size have been shown to be related to climate condition and accumulation rate, particularly for East Antarctica.

We compute a normalized difference angular index from the 60° fore and 60° aft camera data. A previously completed pilot study (Scambos and Bohlander, 2011; see also Scambos et al., 2012) created a preliminary roughness mosaic of East Antarctica from this quantity. It revealed that seasonal variations in solar illumination geometry and the viewing geometry produce effects in addition to those of the actual roughness and grain size changes. The current project aims to examine seasonal variability of surface roughness and snow grain size distributions and adjust for varying illumination and viewing geometries. This starts with contruction of several shorter-term (early summer, for example) regional MISR mosaics spaced throughout a summer season, each providing more of a "snapshot" of the ice sheet surface. Additionally we will use the MODIS Mosaic of Antarctica (MOA) grain size band to validate our grain size derivation from the MISR nadir camera data.

Ultimately our goal is to create separate mosaics for grain size and for surface roughness that will support investigations into the relationships between surface slope, wind direction and accumulation rate for East and West Antarctica.A. Nolin, F. Fetterer, and T. Scambos, 2002, "Surface Roughness Characterizations of Sea Ice and Ice Sheets: Case Studies With MISR Data", IEEE Transactions on Geoscience and Remote Sensing, Vol. 40, No. 7, pp 1605-1615.

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Ice-shelf flexure and tidal forcing of Bindschadler Ice Stream

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Viscoelastic models of ice-shelf flexure and ice-stream velocity perturbations are combined into a single efficient flowline model to study tidal forcing of grounded ice. The magnitude and timing of ice-stream response to tidally driven changes in hydrostatic pressure and/or basal drag are found to depend significantly on bed rheology, with only a perfectly plastic bed allowing instantaneous velocity response at the grounding line. The model can reasonably reproduce GPS observations near the grounding line of Bindschadler Ice Stream (formerly Ice Stream D) on semidiurnal time scales; however, other forcings such as tidally driven ice-shelf slope transverse to the flowline and flexurally driven till deformation must also be considered if diurnal motion is to be matched.

The Structure and Seismicity of West Antarctica and Implications for the Evolution of the West Antarctic Ice Sheet

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New seismic results from the POLENET/ANET seismic deployment provide strong evidence that the solid earth structure of West Antarctica (WA) exerts important controls on the development of the West Antarctic Ice Sheet (WAIS). The POLENET/ANET deployment, begun in 2007, involved installation of 33 seismographs across West Antarctica and surrounding regions, including a 16 station transect from Marie Byrd Land (MBL) to the Whitmore Mountains during 2010-2012. The stations operated continuously over the Antarctic winter using insulated boxes, power systems, and modified instrumentation developed in collaboration with the IRIS PASSCAL Instrument Center. We analyze the data using several different techniques to develop high-resolution models of WA seismic structure. We use Rayleigh wave phase velocities at periods of 20-180 s determined using the two-plane wave analysis of teleseismic Rayleigh waves to invert for the three dimensional shear velocity structure. In addition, Rayleigh wave group and phase velocities obtained by ambient seismic noise correlation methods provide constraints at shorter periods and shallower depths. Receiver functions provide precise estimates of crustal structure beneath the stations, and P and S wave tomography provides models of upper mantle structure down to ~ 500 km depth along transects of greater seismic station density. Results show that topographic lows such as the Bentley Trench and Byrd Basin are characterized by slow uppermost mantle velocities and thin (20-25 km) crust. These results confirm previous suggestions that the basins represent Cenozoic rift systems. Slow seismic velocities in the shallow mantle indicate that the thermal perturbation associated with the rifting has not yet dissipated, consistent with the inference that these basins were active during the last phase of WA tectonism [Granot et al. 2010]. Thermal anomalies from late Cenozoic rifting may provide an explanation for extremely high heat flow values inferred from the nearby WAIS drilling site and suggests that anomalously high heat flow may exert a profound influence on WAIS evolution. Slow mantle seismic velocities beneath MBL at somewhat deeper asthenospheric depths suggest a major thermal anomaly, possibly due to a mantle plume. The entire WA region shows thin lithosphere and slow seismic velocities, suggesting high upper mantle temperatures and low mantle viscosity. Using realistic rheological models we infer several orders of magnitude difference in viscosity between East and West Antarctica, with lowest viscosities found beneath MBL and the WA Rift System. The low WA upper mantle viscosities suggest that GIA occurs very rapidly in WA and must be taken into account in developing ice sheet models from GPS and GRACE constraints.

We also find evidence for currently active subglacial volcanism in MBL. Swarms of volcanic deep long period (DLP) earthquakes at 25-40 km depth coincide with subglacial highs approximately 55 km south of Mt. Sidley and Mt Waishe in the Executive Committee Range and demonstrate the existence of deep magmatic activity in this region. Subglacial eruptions may routinely provide sudden release of large quantities of water at the ice sheet base far from the coastline, and perturb the hydrological and glaciological conditions within the hydrological catchments of several of the major ice streams.

Why Philosophy-of-Science Is Important When Assessing the Outlook for the Ice Sheets

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Managing and communicating uncertainty in policy-relevant scientific assessments is connected to deep philosophical issues. These issues can have important practical and ethical implications for society. It is therefore of high importance to discuss implicit assumptions and value judgments that are made in policy-relevant scientific assessments, such as the future contribution to sea level rise from the great ice sheets.
The view that science should be free of social and ethical considerations (sometimes called "the value-free ideal of science") is examined. It is showed that this view in itself assumes an ethical standpoint, which becomes particularly important when making scientific assessments that are policy-relevant.

An alternative to the value-free ideal for policy-relevant assessments is proposed, in which scientific assessments that are used to inform societal decision-making should try to anticipate applications and aim to construct statements that characterize knowledge and uncertainty in a way that are most useful for those anticipated applications.
This alternative ideal means that scientific assessments should take into account the context in which the information will be used. In particular, the recent development of decision-making tools that are able to work with great uncertainty, such as bottom-up" and "robust" decision-making frameworks, are presented. It is showed how these tools introduces new demands but also new opportunities for making policy-relevant scientific assessments of the future of the ice sheets.

Tidal Pacing, Stick Slip, and the Slow Down of the Whillans Ice Stream

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The Whillans Ice Stream (WIS) is major route for ice transiting from the interior of the West Antarctic Ice Sheet (WAIS) into the Ross Sea. It has been observed that the WIS has been slowing, contributing to a positive mass balance in the Ross Sea sector of the WAIS. Our examination of the velocity time-series for the ice stream reveals that the deceleration is not occurring at a steady rate, but varies at the sub-decadal time-scale. This unsteady deceleration modulates the temporal evolution of a broad (~50 km across) surface-elevation bulge forming at the junction between the relatively narrow upstream portion of the ice stream and broad ice-plain that constitutes the down-stream end of the WIS. Superimposed on this decadal-scale trend of deceleration, comparison of observations from 2003/04 and 2010/11 reveal significant changes in the tidally modulated stick-slip cycle that regulates motion on the ice plain. We observe that the timing of slip events has become less regular in response to decreased flow speed in the upstream portions of the ice stream. The reduced regularity of slip events has resulted in a less efficient release of stored elastic strain during slip events, increasing the rate deceleration, pointing toward non-linear feedbacks at the daily-scale that influence the decadal time-scale evolution of the ice stream

Dynamic Stick-Slip at the Base of Ice Sheets Generates Massive Internal Deformation

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Large basal structures that disturb the normally flat ice sheet stratigraphy and rise as high as 50% of the ice thickness have been observed in both Antarctica and Greenland. We propose that these structures may be formed by dynamic contrasts in basal slip. We use a thermomechanical ice sheet mode whose key features include water transport, freezing, and enhanced sliding when the basal temperature nears the melting point. Moving slip contrasts triggered by subglacial water produce large deformed stratigraphic structures, including synclines, anticlines, and overturned folds that resemble observations. Uplift caused by mobile slip contrasts can raise debris into the middle of the ice sheet, possibly delaying melt-out during Heinrich events. Dynamic changes in slip rate cause 100-1000 year long increases in model ice flux.

Deep troughs dissect the Marie Byrd Land subglacial highland: Initial results of the GIMBLE survey

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Due to its high relief and potential evolution over the Cenozoic, the subglacial highland underlying coastal Marie Byrd Land plays a critical role in the architecture of the West Antarctic Ice Sheet. This enigmatic region records of the extension of the West Antarctic Rift System and may potentially host elevated heat flow due to a proposed sub-lithospheric hotspot.
The GIMBLE (Geophysical Investigations of Marie Byrd Land Evolution) project will span two field seasons and is designed to understand the origin and evolution of the Marie Byrd Land subglacial highland. GIMBLE has migrated the DC-3T aerogeophysical platform developed for the East Antarctic ICECAP project to West Antarctica, operating from Byrd Surface Camp. Data collected include magnetics, coherent radar, gravity, and laser altimetry.
GIMBLE conducted four survey flights from Byrd Surface Camp toward the coast during late January 2013 to gain a reconnaissance view of the region. Further flights are planned for 2014-15 to provide a high-resolution view of the southern margin of the highland.
Initial results indicate that the core of the highland is in fact deeply dissected, with at least one major submarine valley connecting DeVicq Glacier directly to the interior of the West Antarctic Ice Sheet. Other major valleys extend from the Flood Range to the coast, and cut the southern margin as well. The deep ice in these valleys (with depressed pressure melting points) and the high heat flow implied by evidence of local volcanism could provide an additional source of subglacial melt water to both the grounding line and the interior of the West Antarctic Ice Sheet.

Calving events near the terminus of Thwaites Glacier, Antarctica

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Using The Polar Earth Observing Network's (POLENET) seismic array, Repeating seismic events at the terminus of Thwaites Glacier, Antarctica, likely caused by calving, were recorded on the Polar Earth Observing Network (POLENET) seismic array. Repeating events occurred in three separate episodes, with the majority of events occurring from March 1-3 2011. The events have a monochromatic signal. A seismogenic calving mechanism is proposed that would result in these observed 2 Hz signals through resonance ("ringing") of energy within a calving ice block. Calving generates broadband noise, but the block size and seismic velocity select for only those frequencies that constructively interfere.

The events are close to the surface near 75.09S 107.82W, where radar data indicate an ice thickness of ~420 m. For a shear-wave velocity of 1840 m/s, this yields a resonance at 2.2 Hz, in good agreement with the observed ~2 Hz signals, especially if the velocity is lowered slightly to include the effects of the firn. During repeating episodes the mean interevent time is 18 +/- 6 min with a mean magnitude of M_l=1.4. Satellite imagery is not available during the time of repeating ruptures; however, during other periods icebergs of both sizes have been observed to break of the calving front of Thwaites glacier.