WAIS Workshop 2012, Abstracts

Analyzing the Sensitivity of Grounding-Line Dynamics in Response to Periodic Forcing

E. Aykutlug and T. K. Dupont

Ice sheets undergo various cyclical external forcing. Numerous efforts have analyzed the response of the grounding line to different forcings, e.g., buttressing (Dupont and Alley 2005), sedimentation (Alley et al. 2007), basal melting (Walker et al. 2008), oceanic warming (Walker et al. 2009), orbital-scale climate cycling (Parizek et al. 2010), basal friction (Pattyn et al. 2012). It has been shown that numerical modeling plays a key role in analyzing grounding-line dynamics accurately, (Vieli and Payne 2005, Gladstone et al. 2010, Docquier et al. 2011, Pattyn et al. 2012). Here we analyze grounding-line dynamics under periodic forcing of system parameters, such as basal conditions or climate forcing. Simple 1D experiments are performed by finite-element models (FEMs), where the grounding line is determined within the partially grounded elements using the FEM basis functions. Preliminary results exhibit asymmetric advance/retreat of the grounding line. Combined perturbations may lead to smaller or larger oscillations depending on the phase. Different bed topographies are also considered to analyze various ice sheet geometries.

Ice stream stick-slip, sticky spots and rate-and-state friction

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The Whillans ice plain is highly unusual in that it is nearly stagnant during most of the day, but lurches forward twice daily by nearly half a meter during short-lived stick-slip events. These highly repeatable sliding events are choreographed to the rhythmic waxing and waning of the ocean tides. This behavior presents an interesting, but significant challenge to ice sheet models for two reasons. First, the stick-slip of the WIS requires elastic deformation of the ice with viscous flow of the ice only playing a secondary role. Second, the stick-slip behavior of the WIS is inconsistent with the array of sliding laws conventionally used in ice sheet models ? stick-slip requires resistance from friction that decreases with increasing velocity. Most sliding laws, in contrast, are velocity strengthening. These inconsistencies hint that simulations of ice sheet evolution may require models that not only include viscoelasticity, but are also capable of resolving individual stick-slip events. In this study, I use an elastic slider block model to show that rate-and-state friction laws, analogous to those used in earthquake studies, are consistent with stick-slip and tidally modulated ice stream flow. In this model stick-slip corresponds to slight velocity weakening, roughly consistent with rock-on-rock contact as would be the case if basal debris entrained within the ice is rubbing again exposed bedrock. Tidal modulation, in contrast, is consistent with slight velocity strengthening consistent with laboratory experiments in which sliding occurs through till deformation. Both velocity strengthening and velocity weakening sliding laws can be tuned to mimic more conventional sliding laws (and vice versa), but the distinction between velocity weakening and strengthening is crucial when examining the response of individual ice streams to perturbations. While these results remain speculative, it suggests that basal friction does not remain constant in time and understanding how friction evolves over time is likely to be both critical and difficult to predict.

Subglacial volcanism beneath the West Antarctic Ice Sheet in the West Antarctic Rift System, from aeromagnetic and radar ice sounding - Thiel Subglacial Volcano as possible source of the ash layer in the WAISCORE

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Radar ice sounding and aeromagnetic surveys reported over the West Antarctic Ice Sheet (WAIS) have been interpreted as evidence of subglacial volcanic eruptions over a very extensive area (>500,000 km^2!) of the volcanically active West Antarctic rift system interpreted as caused by subglacial volcanic rocks. Several active volcanoes have shown evidence of eruption through the WAIS and several other active volcanoes are present beneath the WAIS reported from radar and aeromagnetic data. Five-kilometer spaced coincident aeromagnetic and radar ice sounding surveys since 1990 provide three dimensional characterization of the magnetic field and bed topography beneath the ice sheet. These 5-50-km-width, semicircular magnetic anomalies range from 100->1000 nT as observed ~1 km over the 2-3 km thick ice have been interpreted as evidence of subglacial eruptions. Comparison of a carefully selected subset of ~400 of the >1000 high-amplitude anomalies in the CWA survey having topographic expression at the glacier bed, showed >80% had less than 200-m relief. About 18 high-amplitude subglacial magnetic sources also have high topography and bed relief (>600 m) interpreted as subaerially erupted volcanic peaks when the WAIS was absent, whose competent lava flows protected their edifices from erosion. All of these would have high elevation above sea-level, were the ice removed and glacial rebound to have occurred. Nine of these subaerially erupted volcanoes are concentrated in the WAIS divide area.

Behrendt et al., 1998 interpreted a circular ring of positive magnetic anomalies (Fig. 1a) overlying the WAIS divide as caused by a volcanic caldera. The area is characterized by high elevation bed topography (Fig.1b). The negative regional magnetic anomaly surrounding the caldera anomalies was interpreted as the result of a shallow Curie isotherm. High heat flow inferred from temperature logging in the WAISCORE (G. Clow 2012, personal communication; Conway, 2011) and a prominent volcanic ash layer in the core (Dunbar, 2011) are consistent with the magnetic data. A prominent subaerially-erupted subglacial volcano, here named Mt Thiel, about 100 km distant to the NE, at approximately 78^o 25’ S, 111^o 20’ W, may be the source of the ash layer. This peak is characterized by a ~400-nT positive magnetic anomaly which Behrendt el, 2004, modeled as having apparent susceptibility contrasts of .034 and .15 SI (Fig. 2). From its appearance (and the moat surrounding it), Mt. Thiel has subsided somewhat since initial eruption as is the case for Mt. Erebus and the Hawaiian Island chain. I suggest that Mt Thiel, about 100 km distance from the WAISCORE, may be the source of the ash layer. The present rapid changes in the WAIS resulting from global warming could be accelerated by subglacial volcanism. These results are discussed in Behrendt et al., 2012; Figs. are from this paper.

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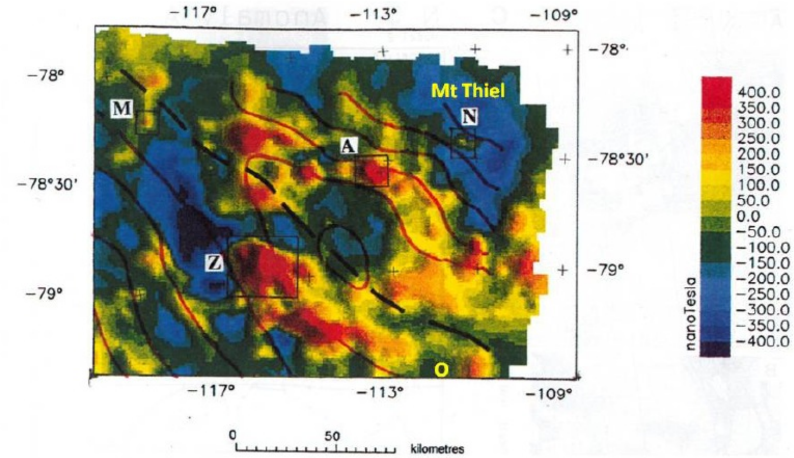

Fig. 1 (a) Shaded relief aeromagnetic anomaly map and bed maps of WAIS divide area from Behrendt et al., 2012. Circular group of anomalies define the interpreted caldera. Anomalies N, M, and N (Mt. Thiel) are modeled as shown in that paper. Anomaly A is modeled as shown in Behrendt et al., 2002. Location of WAISCORE is indicated by "o". WAIS divide (dashed black line) and 50-m snow surface contours are indicated; the dome elevation is 1800 m. Anomaly N overlies the subaerially erupted volcano Mt Thiel.

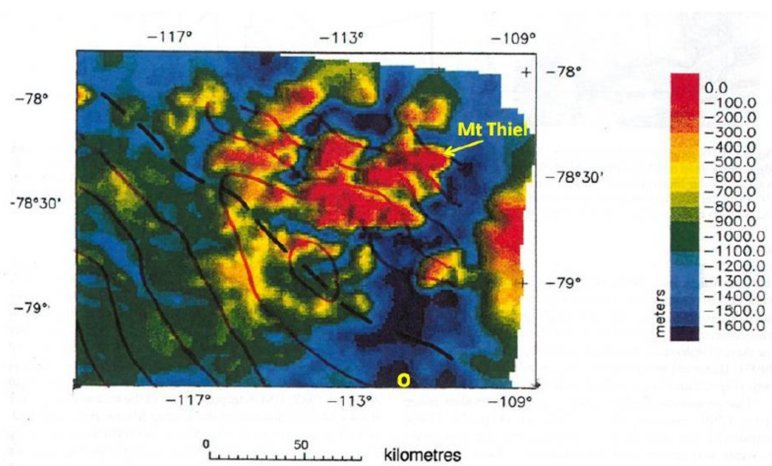

Fig. 1b. Shaded bed relief of WAIS divide area, from Behrendt et al., 2012. Note smoothed caldera rim. Detailed bed topography of Mt. Thiel (bed elevation ~440 m; bed relief ~1800 m) is shown in Fig. 2. Other features as in (a).

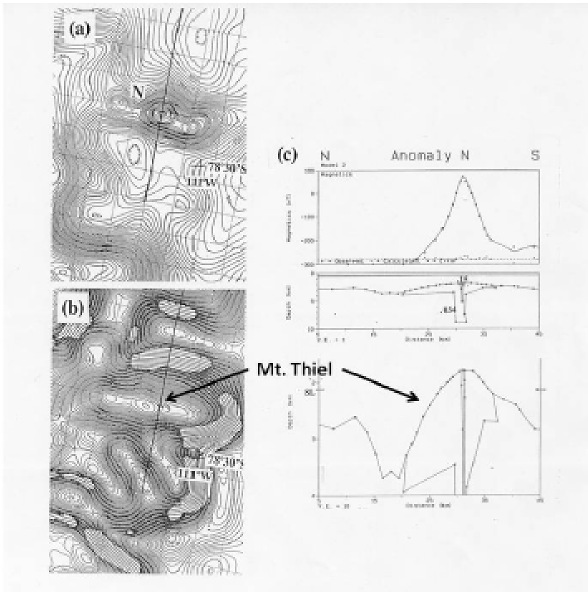

Fig. 2. Aeromagnetic (a) and bedrock elevation (b) maps of area of anomaly N (Mt. Thiel). Note the suggestion of a "moat" bordering the base of Mt.Thiel. (c) Theoretical 2 1/2 D model fit to aeromagnetic profile for anomaly N. Central body has strike length of 2.5 km to west and 2 km to east. Outside body has strike length of 8 km to west and east respectively. Note the surrounding magnetic "low" resulting from the inferred shallow Curie isotherm here and in Figs. 1a .Contour interval 10 nT. Grid survey lines are spaced at 5 km, and the long edges of the map trend true north. Location of modeled profile is indicated. (b) Bedrock elevation in area of anomaly N. Contour interval (CI) 20 m. Grid lines are the same as in (a). Location of modeled profile is shown. (c) Theoretical 2 1/2 D (two-and-one-half-dimensional, a special case of three-dimensional model in common usage) model fit to aeromagnetic profile for anomaly N. Apparent susceptibilities indicated in SI. VE= vertical exaggeration.

Potential Antarctic contributions to future sea level through the eyes of the SeaRISE Project

Robert Bindschadler and the SeaRISE Project Team

The SeaRISE (Sea-level Response to Ice Sheet Evolution) project addressed a major weakness in sea-level projections identified in the IPCC Fourth Assessment Report in 2007: the inability of then-current ice sheet models to credibly project contributions to future sea level from the dynamic response of ice sheets. SeaRISE used ten ice sheet models to study sensitivity of the Greenland and Antarctic ice sheets to a wide range of prescribed changes to their surface mass balance, the melt rate beneath their floating margins and to the rate of basal sliding. Results exhibited a large range in their contributions to global sea level change. Somewhat surprisingly, in most cases dependence of the ice volume lost on the strength of the forcing was close to linear. Thus, combinations of forcings could be closely approximated by summing the contributions from single forcing experiments. Greenland proved to be more sensitive than Antarctica to likely atmospheric changes in temperature and precipitation, while Antarctica was seen to be most sensitive to basal melting of its ice shelves. An experiment approximating the IPCC's RCP8.5 scenario produced first century contributions to sea level of 22.3 and 6.6 cm from Greenland and Antarctica, respectively, with a range among models of 62 and 17 cm, respectively. By 200 years, these projections increased to 53.2 and 20.5 cm, respectively, with ranges of 80 and 62 cm.

The presentation will focus on the Antarctic contributions especially from West Antarctica which most models indicated was the region most vulnerable to large ice losses. The spatial patterns will be examined to illustrate both broad similarities across the suite of models, as well as the manifestations of differences in how the models interact with the surface, basal and oceanic environments. The end result is a clear demonstration of the importance of having accurate representations of the oceanic influence on the fringing ice shelves of Antarctica.

An observed negative trend in West Antarctic accumulation rates from 1975 to 2010: evidence from new observed and simulated records

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Snow accumulation rate observations from five new firn cores show a statistically significant negative trend over the past several decades across the central West Antarctic ice sheet. A negative temporal trend in accumulation rates is unexpected in light of rising surface temperatures as well as model simulations predicting higher accumulation rates for the region. Both the magnitude of the mean accumulation rates and the range of interannual variability observed in the new records compares favorably to older records collected from a broad area of the West Antarctic ice sheet, suggesting that the new data may serve as a regional proxy for recent temporal trends in West Antarctic accumulation rates. The observed negative trend in accumulation is likely the result of a shift in low pressure systems over the Amundsen Sea region, dominated by changes in the austral fall season. Regional-scale climate models and reanalysis data do not capture the strong negative accumulation rate trend observed in these firn cores. Nevertheless the models and reanalyses agree well in both accumulation rate means and interannual variability, with no single model or dataset standing out as significantly more skilled at capturing the observed magnitude of and trend in accumulation rates in this region of the West Antarctic ice sheet.

Subglacial lakes and logical extensions thereof

Sasha P. Carter, Helen A. Fricker, Matthew Siegfried

With the repeat track satellite-based laser altimetry from the GLAS / ICESat mission of 2003 – 2009, it is now commonly known that subglacial lakes that periodically fill and drain underlie many of the fastest flowing ice streams and outlet glaciers of the Antarctic Ice Sheet. This finding has raised two questions for modeling subgalcial hydrology: 1. How do subglacial lakes fill and drain? 2. What effect does subglacial lake activity have on the mass balance of the ice streams in which they are found?

Using surface elevation timeseries data from GPS sensors placed over two connected subglacial lakes, Mercer (SLM) and L78, we have extended this record of volume change from the end of the ICESat mission in 2009 to early 2012. Models for flood initiation indicate that outflow from SLM commences before the lake attains maximum value. L78 appears to swell up during times of high discharge from SLM upstream, quickly subsiding following the cession inflow. At the end of the 2011 – 2012 field season the rate of volume change for SLM, which had been filling, decreased substantially. At this same time L78 appeared to increase in volume. This along with our modeling efforts indicate that at the time of this talk, SLM and the area downstream of it are in full flood stage with water from this system entering the southernmost portion of the Ross Sea.

Changing Influences on the Climate of West Antarctica and the Antarctic Peninsula during Austral Spring

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Recent studies have demonstrated a marked warming of West Antarctica over the last 50 years that is maximized during austral spring. The warming trend is consistent with changes in sea ice concentrations / extent in the nearby Amundsen-Bellingshausen Seas, and also is likely tied to changes in tropical forcing. Other influences on this warming trend are examined in this presentation, with a particular focus on temporal changes in potential mechanisms. It will be demonstrated that in austral spring a) the Amundsen-Bellingshausen Seas Low (ABSL) is becoming stronger over the last 30 years; b) cyclones in the Ross Sea are becoming stronger in the last 30 years, consistent with the sea ice changes and warming in West Antarctica; c) the El Niño – Southern Oscillation influence on both the ABSL and the climate of West Antarctica and the Antarctic Peninsula is strongly related to the magnitude and sign of the Southern Annular Mode (SAM); d) and the 1988 La Niña / negative SAM event had a profound and unique impact on the regional climate, notably different than typical La Niña events. The results suggest that understanding the austral spring changes in the West Antarctic and the Antarctic Peninsula climate is complex, and many factors and their temporal changes must be considered.

Systematic analysis of the resolution of inversions of airborne gravity data for bathymetry beneath floating ice

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The size and geometry of the water cavity beneath floating ice provides important constraints on ice-water interactions and therefore on possible ice shelf thinning and grounding line retreat. NASA's Operation IceBridge has carried out airborne surveys over a large number of glaciers and ice shelves in both Antarctica and Greenland. Collection of gravity data on these flights along with coincident lidar and radar data allows inversion of the gravity data to determine the bathymetry beneath floating ice and the bed in areas where radar cannot image it. Gravity inversions for bathymetry have been published for Thwaites Glacier (Tinto and Bell, 2011) and the Larsen C Ice Shelf (Cochran and Bell, 2012). Since the bathymetry in these areas is not directly observable, it is difficult to evaluate how well these inversions match the actual bathymetry. The few places where the inversions can be compared with measured bathymetry suggest a resolution of about 50 m. In order to assess the resolution and accuracy of gravity inversions, we simulated an inversion for bathymetry beneath an ice shelf by inverting gravity anomalies obtained from forward modeling of a detailed bathymetric survey just seaward of the Dotson Ice Shelf in West Antarctica

The gravity anomalies were sampled along simulated flight lines with a spacing characteristic of an OIB survey (5 km) and filtered with the filter (9.8 km spatial filter equivalent to a 70 second temporal filter) used for OIB data. The resulting simulated gravity profiles were inverted using two different approaches that have been used with OIB data.

1) The gravity anomalies were gridded and the gridded anomalies were inverted using the Parker-Oldenburg technique. This technique assumes that the anomalies arise from variations on a single interface (water/rock) and is appropriate where the ice is floating.2) The bathymetry along the individual profiles was determined by iterative forward modeling of the individual gravity lines. The resulting bathymetric profiles were then gridded to obtain the bathymetric grid. This technique is appropriate where ice is grounded in part of the survey area and also allows variations in bed density and the presence of sediments to be modeled.

In our experiment, the two methods give similar results. For relatively closely spaced lines (5 km) the inverted bathymetry is within about 25 m - 35 m of the actual bathymetry when it is filtered with the same 9.8 km filtered that is applied to the gravity measurements. In other words, the small-scale, short-wavelength relief is not recovered, but bathymetry is well reproduced at wavelengths greater than about 10-15 km. As the line spacing increases to 10 km or more, the shape of the bathymetry is reproduced, but the inferred depths deviate more from the actual filtered depths. The deviation is greater midway between the gravity lines. This is due to the gridding process and the need to fit a surface over more broadly spaced lines.

Grounding Zone Heterogeneity on Whillans Ice Stream, West Antarctica

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Grounding zones of ice sheets are critical to understanding marine ice sheet dynamics as processes here determine the mass flux from grounded to floating ice, and thus eventually to the ocean. Furthermore, basal hydrological processes at the grounding zone are critical to understanding inland ice sheet hydrology and the flux of subglacial water and sediment to the ocean. Despite this importance to ice sheet dynamics, comprehensive ground-based geophysical data over ice sheet grounding zones are sparse. Here we present the most comprehensive ground-based geophysical survey ever collected across an ice sheet grounding zone. Our data consist of over 1000 km of kinematic GPS data, over 650 km of ice-penetrating radar data, and approximately 50 km of active-source seismic data collected over the grounding zone of Whillans Ice Stream. These data show that grounding zones that have significantly different surface expressions (in the form of either differing surface slopes, recent grounding line behavior, or grounding zone width) also have significant differences in basal features and processes which are important to capture in ice flow models. Here we contrast a grounding zone embayment (an area where subglacial water from several subglacial lakes is suspected to drain to the ocean) with a grounding zone promontory (characterized by steep surface slopes). Our results indicate that the embayment is characterized by less dramatic surface and basal slopes and less basal reflectivity contrast across the grounding zone. This suggests that there is less of a barrier to seawater intrusion into, and possibly, upstream, of the low-tide grounding line. In contrast, data collected over the promontory depict steep surface slopes, dramatic ice thinning across the grounding line, and a strong contrast in basal reflectivity. This indicates that the grounding zone in this promontory is likely a strong barrier to seawater intrusion and thus to grounding zone retreat. These results suggest the need to include better parameterization of grounding lines into ice sheet models based on the most salient processes operating at the ice/bed interface in a specific geographical area. Thus current ice sheet models that use a single depiction of an ice sheet grounding zone over a wide geographical area are likely inadequate to simulate accurate ice sheet behavior, especially in response to a warming ocean or wind-induced changes in ocean circulation. In addition to presenting these new geophysical data, we also suggest changes to treatment of grounding zones in ice sheet models that may more accurately simulate ice sheet behavior.

Late Cenozoic glacial history of Shackleton Glacier, Antarctica

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The extent and volume of the Antarctic ice sheet at the Last Glacial Maximum (LGM), as well as the timing of subsequent deglaciation, remains poorly known. However, it is important to constrain these factors in order to understand better the dynamics of the ice sheet and therefore the potential for catastrophic ice-sheet collapse and future sea-level rise. We focus here on the ice sheet that filled the Ross Sea Embayment during the LGM. Drifts alongside outlet glaciers that extend through the Transantarctic Mountains (TAM), from the East Antarctic Ice Sheet to the Ross Sea, record changes in ice elevation and can be used to improve our understanding of the dynamics of the Ross Sea ice sheet at and since the LGM. Fieldwork in the central TAM at Shackleton Glacier, including the mapping and dating of Late Quaternary ice extents, revealed that ice midway up glacier remained close to the LGM limit until at least 10,500 to 9,000 cal yr BP. These preliminary ages suggest that most ice thinning occurred during the Holocene, a result consistent with a reconstruction of Ross Sea ice-sheet retreat (Conway et al., 1999). When complete, the chronology of ice fluctuations at Shackleton Glacier will improve our understanding of Ross Sea ice-sheet behavior, which in turn will help in interpretations of Antarctica's contribution to deglacial meltwater pulses, such as Meltwater Pulse 1A.

Detailed basal topography of the floating portion of Pine Island Glacier, West Antarctica

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In January 2009 the underside of Pine Island glacier's floating ice shelf, in West Antarctica, was imaged along three 30 km tracks using an upward-looking multi-beam echo-sounder mounted on an autonomous underwater vehicle. At 4-m resolution with a 300-m wide swath, these observations reveal with unprecedented detail the presence of channels oriented along and across the direction of ice flow. Many of these channels are characterized by basal crevasses above their apex and successive 200-500 m wide, 10-20m high terraces on their flanks. A near coincident, high resolution airborne radar survey confirm the widespread nature of these features. The oceanographic and glaciological conditions of Pine Island glacier are discussed to shed light on the processes leading to their formation and maintenance. For comparison, observations of terraces in a different setting, but in a similar oceanographic context in Greenland are also presented.

Along-stream evolution of melt under the Pine Island Glacier ice shelf, West Antarctica

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Thinning ice in West Antarctica, resulting from acceleration in the flow of outlet glaciers, is at present contributing about 10% of the observed rise in global sea level. Pine Island Glacier in particular has shown nearly continuous acceleration and thinning throughout the short observational record. The floating ice shelf that forms where the glacier reaches the coast has been thinning rapidly, driven by changes in ocean heat transport beneath it. However details about the ice-ocean interaction in such dynamical environments remain largely elusive. Here, high resolution space- and air-borne ice surface velocity and digital elevation models are used to estimate melt rates under the ice shelf and the associated dynamical adjustment of the ice flow. At the ice shelf scale, melt rates up to 100 m/yr dominate near the grounding line, tapering down to 10 m/yr 15 km downstream. At smaller scales, a network of sinuous sub-glacial channels originating upstream from the grounding line, typically 500 m to 3 km wide, and up to 300 m high, is coupled with the melt. Melting enhances the sub-glacial channel signatures where the ice goes afloat and diminishes it downstream. Bridging stresses in the ice smooth the surface expression of sub-glacial melt, but near grounding line dynamical adjustments are visible in observations of surface ice velocity where convergences (divergences) coincide with channel crests (keels) as ice columns sink under the melt-induced loss of hydrostatic support.

The dynamic response of Pine Island Glacier to a calving event inferred from Elmer/Ice

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Pine Island Glacier is known as the weak underbelly of the West Antarctic Ice Sheet. During the last 30 years, it has undergone a dramatic acceleration along with a retreat of its grounding line. In the ice shelf, the ice shrink and the rift boarding the main ice stream extended upstream to reach the grounded part of ice. Since records are performed on Pine Island Glacier, calving events have been taking place frequently, however the recent enlargement of the crevasses area questions the possibility of larger calving events to occur in the future. Pine Island Glacier being potentially unstable as it lies below sea level on an upward sloping bedrock, is thus of high importance to assess the potential impact of calving events on the ice stability.

In this presentation, the 3D full-Stokes model Elmer/Ice is used to investigate the dynamic response of Pine Island Glacier, West Antarctica, to various calving scenarios. The flow problem takes into account surfaces evolution, migration of the grounding line, and an inverse analysis to infer basal drag and ice viscosity. Various mesh refinement were tested showing that such modeling require sub kilometric resolution at the grounding line to compute consistently its migration in a short time scale of a few decades. We show that the current calving event initiated at the end of 2011 will not induce any significant acceleration of ice or a retreat of the grounding line. However, the model predicts that a calving event taking place further upstream would rapidly induce large dynamic changes, since doubling the amount of ice loss is sufficient to result in a significant increase of the ice discharge, along with a fast retreat of the grounding line.

Ice mechanics, basal water and the stagnation of Kamb Ice Stream, Antarctica

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Several of the ice streams that move ice from the interior of the West Antarctic Ice Sheet (WAIS) to the Ross Ice Shelf are documented to stagnate and reactivate on multi-century time scales. Once such event may now be underway on the downstream ice plain of the Whillans Ice Stream (WIS), a stream that stopped and started between about 850 and 450 years ago. Kamb Ice Stream (KIS) ceased its rapid flow about 150 years ago in an event that appears to have initiated in the downstream reach of the ice stream. These switches from fast to slow and back again produce major changes in mass balance of the ice sheet and ice shelf system.

Ice stream stagnation must in some way involve changes in the basal water that facilitates fast flow. Here, transients in ice thickness and surface slope, which together steer basal water, are examined in the context of the recent stagnation of KIS. Transients have both regional—changes in WIS flux and in Crary Ice Rise, for example—and local causes. A mechanical analysis of high-resolution surface elevation and ice velocity data sets on the now-active WIS is used as a proxy for past conditions on KIS and an ice flow model is used to place those local conditions in a regional context. We argue that thickness transients associated with stagnation of WIS required the KIS grounding line to retreat far upstream of its present location while reactivation of WIS led to regional thickening, grounding of floating ice, and advance of the KIS grounding line toward its present location. The present work examines the role of lateral margins near the grounding line, in particular the broad, flat, "Duckfoot" on the right lateral side of the KIS outlet and Lake Englehardt, which occupies the same position at the outlet of WIS. Lake Englehardt diverts water away from the main trunk of the ice stream. In the past, the Duckfoot may have played a similar role and that diversion may have been associated with KIS stagnation. Overall, our aim is to understand the interaction among regional and local transients in ice thickness and surface slope and flow events on the downstream ends of ice streams.

High Basal Melt at the WAIS-Divide ice-core site

T.J. Fudge, Gary Clow, Howard Conway, Kurt Cuffey, Michelle Koutnik, Tom Neumann, Kendrick Taylor, and Ed Waddington

We use the depth-age relationship and borehole temperature profile from the WAIS-Divide ice core site to determine the basal melt rate and corresponding geothermal flux. The drilling of the WAIS-Divide ice core has been completed to 3400 m depth, about 60 m above the bed. The age of the deepest ice is 62 ka, younger than anticipated, with relatively thick annual layers of ~1 cm. The borehole temperature profile shows a large temperature gradient in the deep ice. We infer a basal melt rate of 1.5 (±0.5) cm yr^{-1} using a 1-D ice flow model constrained by these data sets. The melt rate implies a geothermal flux of ~230 mW m^{-2}, three times the measured value of 70 mW m^{-2} at Siple Dome.

We compile radio-echo sounding data sets to assess the spatial extent of high melt. Deep internal layers are the most useful for inferring spatial patterns of basal melt. Unfortunately, the IceBridge WAIS-core flight and two site-selection surveys did not image consistent reflectors deeper than Old Faithful (2420 m and 17.8 ka). A ground-based survey by CReSIS (Laird et al., 2010) was able to image consistent layers as deep as 3000 m, but the survey is not oriented along the ice-flow direction making interpretation more difficult. There is no obvious draw down of deep internal layers that would indicate an area of localized melt. While this suggests a uniform melt rate within the survey, it might also indicate that other factors (e.g. accumulation gradients, rough bed topography) obscure the influence of basal melt on the internal layer depths.

The role of subglacial drainage and basal freeze-on for ice streams

Marianne Haseloff, Christian Schoof

The Siple Coast ice streams are major discharge routes for ice in the West Antarctic. Observations suggest that their fast flow is due to sliding along a water-saturated bed, with variations in velocities and ice stream width on decadal to centennial time scales. These variations include the migration of ice stream margins, where the fast flow slows down to the speed of the surrounding ice, which in contrast appears to be frozen to the underlying bed.

Using a coupled ice-sediment model we investigate the roles of basal freeze-on, subglacial drainage, and feedbacks between fast flow and heat dissipation for ice-stream evolution. The ice is modeled as a vertically uniform plug flow. The sediment model allows for lateral motion of melt water in the sediment and changes in the thickness of the water-saturated sediment layer due to melting and freezing processes. Dynamical feedbacks in the energy balance include both frictional heating along the bed and lateral shear heating.

We study the evolution and possible steady states of ice streams, which are typically reached on timescales of several hundreds of years. We find that no steady-state ice stream configurations are possible in the absence of subglacial drainage. Moreover, the bed outside of the fast flowing region will eventually freeze onto the ice, which prohibits outward migration of ice stream margins due to subglacial drainage. Possible steady state configurations are investigated in detail.

Hence, subglacial drainage must play an important role for ice stream behaviour, but drainage-driven margin migration is possible to a limited extent only, as the margin is believed to coincide with the boundary between a frozen and temperate bed.

Glacial Geomorphology of the Pensacola Mountains, Weddell Sea Sector, Antarctica

<u>Matthew Hegland</u>, Michael Vermeulen, Claire Todd, Greg Balco, Kathleen Huybers, Seth Campbell, Howard Conway, Chris Simmons

We mapped glacial geologic features in the Thomas, Schmidt, and Williams Hills in the western Pensacola Mountains. The three nunatak ranges are adjacent to the Foundation Ice Stream (FIS), which drains ice from the East and West Antarctic Ice Sheets (EAIS and WAIS), into the Filchner-Ronne Ice Shelf. Glacial deposits in the Pensacola Mountains record changes in the ice thickness of the FIS and provide insight into ice sheet history. Glacial scour on Mount Hobbs, Williams Hills suggests maximum ice thickness was at least 562 m greater than today and striations atop Martin Peak, Thomas Hills suggest ice here was at least 675 m thicker. Glacial striations oriented transverse to topography indicate that ice was thick enough to flow unconstrained over topography and suggest increased contribution from the EAIS. In the Schmidt and Williams Hills, depositional landforms are sparse with occasional highly weathered erratics found over 100 m above the modern ice surface and relatively unweathered erratics deposited beside them below 100 m, suggesting preservation of older erratics in a cold-based environment. Upstream in the Thomas Hills, a highly-weathered till is present at all elevations; this deposit (a) contains lots of clay, indicating wet-based ice, (b) has a highly-oxidized surface layer, and (c) includes highly-weathered surface boulders, indicating long-past thick ice cover. This till is sparsely covered at a range of elevations by erratics with different degrees of weathering. At low elevations, greater depositional volume is observed in preserved moraines and relatively unweathered till that indicate multiple ice surfaces 20 - 100 m higher than today; these features likely post-date the last glacial maximum. Preliminary numerical modeling of ice surfaces in the Thomas Hills suggest elevation changes could be attributed to local variations in ablation in addition to surface elevation changes in the FIS.

Changes in Pine Island Glacier from Time Series of ICESat GLAS Data

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The importance of changes in Pine Island Glacier and their relationship to the stability of the WAIS may not need any introduction in this community. The center of this presentation are the analysis of laser altimeter data collected over Pine Island Glacier, discussion of mathematical approaches to interpolation, roughness analysis and simulation at several scales, and geophysical conclusions. We use Geoscience Laser Altimeter System (GLAS) data collected during the ICESat Mission (2003-2009) and Airborne Topographic Mapper (ATM) data collected since 2002 (in recent years, as part of Operation IceBridge).

(1) *Interpolation:* Using all data collected over Pine Island Glacier, its catchment area and its ice shelf, time series of elevation maps and elevation-change maps are derived. This part of the analysis includes separation of geophysical signals and artifacts that may affect laser-data values. (2) *Surface roughness:* Features of the ice surface, such as flow bands and crevasses fields, influence the received laser signal (error source), but on the other hand may serve as an additional source of geophysical information. The second part of the talk presents results derived from roughness analysis. (3) *Scale-dependent simulation:* Results of roughness properties at highest resolution and large-scale elevation models are integrated into a scale-dependent elevation model, which is generated using an approach to conditional simulation that allows inclusion of realistic (data-derived) spatial properties at every scale. This may serve as input in scale-dependent modeling as well as geophysical interpretation

Discussion: In previous work, we have reported that the spatial distribution of surface lowering in Pine Island Glacier suggests an attribution of the changes to an internally forced process in the glacier. Thinning rates increased since 2003, which indicates an increase in the magnitude of changes in Pine Island Glacier. We discuss indications of processes that initiate from changes in the ice shelf versus processes that start internally in the glacier.

Effects and feedbacks of the basal sliding parameter on ice and water flow beneath an ice-stream

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Relatively short timescale elevation anomalies - on the order of 2 to 3 years - observed in a number of locations along west Antarctic ice-streams are interpreted as being subglacial ponds filling or draining in response to subglacial hydrologic conditions. We hypothesize that the ponds' formation is associated with response to local variations in basal traction that has a dual effect on the subglacial water. On the one hand, locations with high basal traction act as a source of melt water, on the other hand, variations in the basal traction affect ice flow and its thickness, these in their turn determine locations of water ponding. We investigate how the ice and water flow may affect one another when treated as a coupled system. Here we present the results of work in which the effect of varying the basal sliding parameter is investigated relative to the flow and distribution of subglacial water as well as the potential feedbacks that could be created in the coupled system.

Near-continuous monitoring of Antarctic ice shelf and sub-ice shelf ocean temperatures

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During the Austral spring of 2011, two instrumented boreholes were completed through the McMurdo Ice Shelf (MIS) at Windless Bight to test rapid drilling and continuous monitoring methods. The boreholes were drilled using an approach combining ice coring for the upper portion of the borehole, with a new hot-point method for the final penetration through the iceocean interface. Each borehole was drilled through 190 m of ice to the ocean using two-person drilling team. The core drilling provided a 130mm diameter open borehole that remained dry through the drilling period. A hot point drill was used to penetrate into the ocean, and provided a 40 mm diameter borehole. The boreholes were instrumented with distributed temperature sensing (DTS) fiber-optic cables temperature measurements within the ~190m thick ice shelf and into the ocean below. The boreholes were also instrumented with traditional thermistors both in the ice shelf and in the ocean column and pressure transducers all attached to the armored DTS cables. Borehole BH1 is instrumented with fiber optic temperature sensing cable through the ice shelf and extending 30m into the ocean below. BH2, located 40 north of BH1, was used to test measurements to depths of 800m and also to demonstrate the potential for multiple independent installations through the same borehole. BH2 is completed with one DTS cable extending 600m below the ice/ocean interface, a logging pressure transducer and thermister located 450m below the ice/ocean interface and four additional logging thermistors. Temperature measurements are made every 1 meter along each optical fiber. The measurements are repeated hourly through the summer, and 4 times per day in winter months to conserve power. Data are transmitted off site via satellite link. After 3 months of operation (February 2012), there has been warming trend (~0.5^{o}C) in the upper ocean column that began in late December, consistent with previous measurements in the vicinity.

Bed topography of the Byrd Glacier trunk from airborne radar soundings of the ICECAP Project

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Byrd Glacier has one of the largest catchments in Antarctica and delivers more ice to the Ross Ice Shelf than any other ice stream. The geometry of its trunk has implications for subglacial water activity, glacier flow history and ice sheet response to climate change. Byrd Glacier's massive ice flux is channeled through a fiord of only ~20 km width, resulting in severe convergence and crevassing that has posed a challenge to radar sounders. Combined with logistical issues and a lack of directed airborne campaigns over Byrd until recently, this has resulted in subglacial topography and ice thickness being constrained by a single profile acquired by the NSF/SPRI/TUD surveys of the 1970's; furthermore, the radar data for that profile were apparently lost. The ICECAP project has successfully acquired new radar sounding data over the main trunk of Byrd Glacier during the course of four field seasons, resulting in multiple definitive profiles of bed topography. The data show a basin within the trunk approx. 2.5 km below sea level, located ~75 km upstream of the grounding zone. This depth is largely consistent with the deepest detected echoes in the NSF/SPRI/TUD soundings; however, those data contained only sporadic returns in the deep zone and it is likely that some cross-track echoes were misinterpreted as bed returns for a portion of that single profile. Also, significant variations in bed topography, both across and along the trunk, are now evident with multiple profiles. These new radar soundings were accomplished using the University of Texas Institute for Geophysics (UTIG) High Capability Radar Sounder (HiCARS) operating at 60 MHz with a 15 MHz bandwidth.

Big or little? Patterns of change on the Ross Ice Shelf

<u>Christina Hulbe</u>, Ted Scambos, Jennifer Bohlander, Choon-Ki Lee

Comparison of surface velocities measured during the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS, 1973 to 1978) and velocities measured via feature tracking between two Moderate-resolution Imaging Spectroradiometer (MODIS) mosaics (compiled from 2003-4 and 2008-9 images) reveals widespread slowing and minor areas of acceleration in the Ross Ice Shelf (RIS) over the ~30 year interval. The largest changes (-13 ma^{-2}) occur near the Whillans and Mercer Ice Streams grounding line in the southernmost part of the ice shelf. Speed has increased over the interval (up to 5 ma^{-2}) between the MacAyeal Ice Stream grounding line and the shelf front, and along the eastern part of the shelf front. Here, a well-tested model of the ice shelf is used to discern between longer and shorter time scale transients in ice shelf flow. Changes in ice thickness observed using ICESat laser altimetry are used to test various model outcomes. The observed transients represent a combination of ongoing response to ice stream discharge variations and resulting shelf thickness changes over the past millennium and while faint impressions of past events are evident, the modern signal is dominated by shorter time scale events, including the stagnation of Kamb Ice Stream ~160 years ago, recent changes in basal drag on the Whillans Ice Stream ice plain and, apparently, iceberg calving. Details in embayment geometry, for example the shallow sea floor below Crary Ice Rise, modulate the spatial pattern of ice shelf response to flow perturbations.

Linkage between Grounding Line Dynamics and Geological Observations in the Weddell Sea Sector of Antarctica

Kat Huybers

Surface-exposure dating is a potentially a powerful technique to constrain Antarctic ice-sheet thinning from the Last Glacial Maximum to its present state. In the austral summers of 2010-2011 and 2011-2012, our research team (led by Greg Balco and Claire Todd) collected erratics near the grounding line of the Foundation Ice Stream in Antarctica's Weddell Sea sector. Using surface-exposure dating techniques, these erratics detail thickness maxima and exposure rates along nunatak elevation transects. These points in space and time constrain the local ice elevation and rate of thinning -- but what can they tell us about the history of the interior ice stream's elevation profile?

The elevation profile of the interior ice is strongly controlled by the position of the grounding line, which, in turn, depends on sea level, accumulation, and the ice stream/shelf's physical characteristics. We use an idealized flowline model to assess the relative importance of different aspects on modeling ice stream thickness profiles. We divide these aspects into two general categories: model physics, and environmental factors. Model physics include the sliding law, and the calculated flux at the grounding line, where the ice transitions from grounded stream to floating shelf. Environmental factors include climate, basal topography, sliding efficiency, sea level, ice softness, and lateral shelf stresses. Presently, we do not account for the potentially important effects of isostatic rebound and the gravitational pull of the ice-sheet on ocean water (e.g. Gomez et al., 2010).

Preliminary findings show that the position of the grounding line controls the elevation at the exposure sites; and that sub-glacial and sub-marine basal topography, together with the assumed form of the grounding-line flux, dominates the grounding-line sensitivity to change. We also show that the ice-flux necessary to hold the grounding line at a fixed point is very sensitive to the lateral stresses along the sides of the ice shelf. Consequentially, the ice surface elevation predominantly reflects regional-scale ice sheet behavior rather than the climate local to the ice-stream catchment.

History of the Ross Sea Ice Sheet in Salmon Valley During the Last Glaciation

Margaret S. Jackson, Brenda L. Hall, George H. Denton

During the Last Glacial Maximum, grounded ice fed by both the West and East Antarctic Ice Sheets filled the Ross Sea Embayment. Understanding the history and extent of this former Ross Sea Ice Sheet (RSIS) is crucial to addressing Antarctica's contribution to global sea level since the LGM, as well as the future stability of the West Antarctic Ice Sheet (WAIS). Salmon Valley, in the Royal Society Range, is a dry valley that opens to McMurdo Sound. During the LGM the valley was dammed by the intruding RSIS, and glacial deposits record the movement of ice across the landscape. Preliminary radiocarbon dates of algae from prominent moraines along the coastal headlands suggest the RSIS was at or near its maximum between ~17,000 yr BP and ~14,000 yr BP, when it reached an elevation of ~290 m. On the southern headland, dates from a moraine range between 17,180 - 360 yr BP and 14,829 - 371 yr BP. A secondary ridge ~10 m below yields ages of 13,967 - 272 yr BP and 14,038 - 222 yr BP. On the northern headlands, dates range between 14,680 - 443 yr and 14,222 - 337 yr BP. Dates from perched lacustrine deltas on the valley floor indicate ice was extensive enough to dam a proglacial lake in the valley to an elevation of 261 m at 16,388 - 529 yr BP and to an elevation of 131 m at 13,902 - 145 yr BP. These results call into question the likelihood of any significant contribution by the RSIS to MWP-1A at 14.6 kyr BP.

Model-Based Analysis of Ice Sheet Thinning in the Amundsen Sea Embayment

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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 examine this response for Pine Island and Thwaites glaciers using models constrained by satellite data. Our earlier work reproduced the transient response on Pine

Island Glacier and predicted that strong near thinning near the grounding line should abate, but that overall losses should remain high as thinning diffuses inland. Here we find that this conclusion is supported by new IceBridge data, which show recent reduction of near grounding-line thinning as speeds have leveled off. On Thwaites Glacier, we conducted a series of numerical experiments to investigate sensitivity of ice flow to ice-shelf loss and grounding-line retreat. The model suggests that recent changes in speed are the result of enhanced rifting that weakened the ice shelf followed by retreat of the grounding line. In response, surface slopes have thinned causing the speedup to migrate inland. We also use a prognostic model to investigate whether such thinning will continue over the next century.

Propagation of an active rift in the Ross Ice Shelf, Antarctica

Christine LeDoux

Understanding propagation behavior of large rifts in ice shelves is important for understanding shelf adjustments to change and for parameterizing calving in models. We use satellite images and a comparison of two epochs of the MOA (MODIS Mosaic of Antarctica) to study the propagation of an active rift within a rift system near the western front of the Ross Ice Shelf. Between 1992 and 2012, the most upstream rift within the rift system propagated over 90 km. We observe large jumps and two types of episodic propagation. We use a numerical model to study recent propagation behavior of test fractures within a stress field. Our observations and model simulations support findings on the Ross and other large ice shelves regarding the importance of lateral propagation and the roles of transverse compressive stress, fracture length, and material inhomogeneity in controlling propagation behavior.

Increased melting of Pine Island Ice Shelf: cause or effect?

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Previous interpretations of Pine Island Ice Shelf (PIIS)'s rapid thinning have attributed observed increases in basal melting to increases in ocean heat content. However, the discovery of large-amplitude bedrock topography underneath the ice shelf suggests a role for glaciological and/or coupled processes. Here, as an outgrowth of a calibrated ensemble projection project spanning a wide range of glaciological and oceanic parameter space, we investigate changes in basal melting and ice shelf shape following perturbations in ice flux and/or ocean heat content. Increases in ice flux comparable to those observed in PIIS give increases in the area-averaged basal melt rate similar to those resulting from large increases in ocean temperature, and larger than those resulting from a shoaling of the thermocline. Though the final steady state achieved following an increase in ice flux is often characterized by a thicker ice shelf, local thinning may persist for decades. Using idealized representations of bedrock topography, we then show that the evolution of ice shelf shape and melt rates following removal from pinning points is strongly governed by this fast flux/melting feedback. Although we do not rule out the role of a change in ocean heat content as a trigger for PIIS's rapid retreat, we find that the transient melt rate and ice shelf shape is only weakly dependent upon the magnitude of oceanic perturbations.

Subglacial till body underneath a contemporary grounding zone

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We report a subglacial wedge near the contemporary grounding line of an ice-rise (Derwael ice rise) surrounded by ice shelves along the Princess Ragnhild Coast in eastern Dronning Maud Land (DML), Antarctica. Three 2-MHz ground-based radar profiles were made together with kinematic GPS surveys aligned roughly parallel to the ice-rise's local ice-flow direction. The first two profiles face the outlet of Western Ragnhild Glacier, whereas the third profile is oblique to the regional shelf-ice flow. Along the two profiles facing the glacier outlet but 2.5 km away from each other, we discovered a subglacial wedge of 3 km long and 200 m high. The bed elevation at both sides is nearly equal. The wedge has a very steep slope (~20^{o}) at its landward side, a plateau for about 1 km, and a gentle slope (~2.5^{o}) at the seaward side. Analyses of both the radar power returned from the bed as well as the shape of the upper ice interface indicate that the ice becomes afloat less than 0.5 km seaward of this wedge. Therefore, this wedge is at least 2.5 km wide along the shore and locates within or immediately landward of the contemporary grounding zone. Such grounding zone wedge was found neither along the third profile oblique to the glacier outlet nor along other profiles across the grounding zone of another ice rise in the western DML, which do not face outlet of a fast-flowing glacier. We argue that this wedge is a till body that was developed when the ice sheet was extended beyond the Derwael ice rise.

A community model for transient thermo-mechanical evolution of firn density

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Firn density evolution is relevant for several lines of questioning in glaciology including mass balance and dating ice-cores. Mass-balance studies using laser altimetry must account for the density of the firn column. Interpretation of ice-core records is complicated by the difference in age (called delta age) between the air trapped in bubbles and the ice enclosing the air. Determining delta age requires understanding both densification of polar firn and gas transport through the firn. In the past individual research groups have developed independent models of firn densification and firn gas transport. As partners in the PIRE-ICEICS (*International Collaboration and Education in Ice Core Science*) project[1], we at UW are developing a web-based model of firn densification and gas transport that will combine the best features of those models and is freely accessible to research teams.

In the first and current online version, users can enter site-specific data (accumulation rate, temperature, surface density), and the model provides depth-density-age and delta-age results using the steady-state Herron and Langway[2] algorithm. Several measured density-depth profiles from sites in Greenland and Antarctica can be stored on the server, and can be compared graphically to the firn-density profiles computed with the user's parameters.

In addition to the web-based steady-state model, transient firn-densification and gas-transport models are under development. These models allow physical properties to evolve, resulting in more accurate delta-age approximations at times of rapid climate change in the past. These community models will be downloadable as open-source Python code. They will provide a framework for comparisons among datasets, or against other models. The models are modular, allowing users to choose preferred physical models and physical processes to include, based on available pre-coded options. Alternatively, users can adapt the code to include new or different physics. We hope that user-designed additions can then be added to the community model.

Here, we present results from the first web-based (Herron and Langway) model, and compare those results with measured firn-density profiles.

1. *http://iceics.science.oregonstate.edu*
2. Herron, M.M. and C.C. Langway. 1980. Firn densification: an empirical model. *Journal of Glaciology* 25(93), 373-385.

New, High-Resolution Spatio-Temporal Accumulation Rate Measurements and Their Validation of Climate Models and Implication for the Recent Sea-Level Contribution from West Antarctica

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Under a warming planet scenario, enhanced accumulation could potentially counteract the recent and future sea-level rise caused by increased ice discharge over the Antarctic continent. Several individual core accumulation histories show temporal trends, but their spatial significance is limited due to the small-scale variability in accumulation. Climate model and global reanalyses of the accumulation rate (i.e., surface mass balance) show insignificant temporal trends in accumulation over recent decades, yet the skill of these models has yet to be rigorously determined. This work presents a new, high-resolution spatio-temporal accumulation rate data derived from airborne CReSIS snow radar surveys flown between 2009 and 2011 as part of NASA's Operation IceBridge. The snow radar horizons are confirmed as annually repeating through comparison with several new and existing intermediate-depth ice core accumulation records, which allows us to date each horizon by manual count rather than core glaciochemistry. This discovery will expand use of the snow radar to more remote and inaccessible areas of the ice sheet, as little to no fieldwork is necessary to generate accumulation rate estimates. We find the radar is most capable of resolving an annual signal in areas that receive 0.3-0.6 m we yr^{-1} accumulation on average.

Based on model comparison with our spatio-temporal accumulation measurements, we find that the RACMO2 regional climate model is very capable (r = 0.88) of generating the spatial pattern of the 30-year average accumulation rates. The reanalyses have weaker spatial correlation, but more highly correlate (r > 0.90) with the annual variation in accumulation yet underestimate the overall *magnitude* of accumulation. Our accumulation results from Thwaites Glacier, West Antarctica, indicate that between 1980 and 2009 no significant trend in accumulation exists and is thus not counteracting the increasing trend in local ice discharge. Additional flight surveys are necessary before basin-wide annual net accumulation is estimated.

Sub-meter imagery status of WAIS

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Significant progress has been made in the past year in imaging the West Antarctic Ice Sheet using a constellation of 5 sub-meter resolution commercial satellites. We now have continuous coverage of the entire continent including repeat imagery for PIG and Thwates as well as other scientific and logistical targets. There is an increased understanding of the capacity for repeat mono and stereo imagery as well as a better understanding of yearly base imagery collection. The 2012-13 tasking plan, the current understanding of the licensing agreement and new imagery services will be presented.

Gravity survey on the Ross Ice Shelf at the mouth of Whillans Ice Stream, West Antarctica

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Grounding zones of ice sheets and contiguous ice shelves are important in understanding ice sheet dynamics, as key processes that influence the grounded ice and its discharge into the ocean occur in these regions. Ice-ocean interactions are controlled by the relatively poorly known bathymetry and the configuration of the cavity beneath ice shelves. In addition, knowledge of submarine geological structures and their distributions contributes to understanding the dynamic history of the glaciers and ice streams feeding the ice shelves. However, detailed geophysical surveys of these areas remain scarce due largely to the logistic difficulties of obtaining observational data about the subglacial environment beneath an ice shelf. In the austral summer of 2011-12, we conducted a ground-based gravity survey over the Ross Ice Shelf in an embayment at the mouth of Whillans Ice Stream with the aim of modeling the subglacial bathymetry and geological structures. The survey consisted of 82 sites scattered at 3 km spacing within a ~500 km^2 embayment that is roughly triangular in shape. We present preliminary results of 2-D modeling of bathymetry and geological structures along a few lines coincident with high-resolution active-source seismic and ice-penetrating radar data. The active-source seismic survey revealed a shallow water column (<15 m) and soft sediments approximately 15 km seaward of the grounding zone. We explore the extent of such water and sedimentary columns, and the density of the sediment in this embayment and discuss uncertainties in the presented models.

Sea-ice ocean interactions in a high-resolution global climate model

Emily Newsom

University of Washington

The physical processes regulating the stratification of the Southern Ocean are poorly understood in nature and important to global climate: the production of Antarctic Bottom Water (AABW) is important in moderating the global meridional circulation and ocean heat uptake; the rate of transport of Circumpolar Deep Water (CDW) onto the continental shelf is important in regulating the mass balance of the Antarctic Ice Sheet. Here, we seek to understand how the explicit resolution of oceanic eddies affects simulation of the Southern Ocean. To do so, we compare water mass production and stratification between standard (1 degree) and high (1/10 degree) resolution of ocean and sea ice in 150-year integrations of the Community Climate Model Version 3.5 (CCSM 3.5). The atmosphere and land components are at 0.5 degree resolution in both cases. High resolution generally improves the agreement in temperature and salinity between simulation and observations in the Southern Ocean, as several key features emerge in the eddy-resolving integration that are not captured at coarser resolution. At high resolution, the water mass similar to AABW is colder and more saline, sinks along steeper isopycnals, and contributes to a more vigorous deep overturning. At mid-depths, water comparable to CDW upwells at greater rates, and extends closer to the continent. We argue that resolving localized sea ice formation regions has improved the production of AABW, driving a more vigorous deep overturning circulation at high resolution. In addition to considering the effect of resolution on the unforced ocean mean state, preliminary results are presented from two perturbed experiments branching from the same control simulation. In one, integrations at peak (1960's) and minimal (2000) ozone levels are contrasted. In the other, $CO!$ is ramped by 1% per year until it doubles. Fine resolution alters how the ocean evolves when perturbed, especially at depth. Irrespective of resolution, however, ozone depletion and $CO!$ ramping cause an increase in surface westerlies, a warming of the surface waters and a decrease in sea ice.

Perspective on the West Antarctic warming from the reconstructed Byrd temperature record (1957-2012)

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Large uncertainty remains in our knowledge of the temperature changes in West Antarctica since the mid-20th century. Existing Antarctic temperature datasets show significant disagreement about the sign, magnitude and seasonality of the temperature trends, largely a result of the paucity of long-term observations in the region. Only one instrumental record, Byrd Station, in central West Antarctica, provides near-surface temperature observations from 1957 onward, yet its numerous gaps have largely precluded its use for long-term climate change assessment. Here, we present the results from a reconstruction of the Byrd temperature record in which the missing observations have been filled in with 2-meter temperature estimates from global reanalyses. The 1957-2011 temperature trends derived from this reconstructed dataset confirm earlier evidence of significant warming annually as well as in austral winter and spring, but suggest larger temperature increases than previously thought. In addition, our analysis reveals for the first time some significant warming occurring in summer, which has important implications for the West Antarctic Ice Sheet given the increased possibility of surface melting that it entails. The consistency of these results with recent analyses of the West Antarctic spring- and wintertime warming will be discussed. We will also propose some mechanisms accounting for the summer warming.

Ice-2-O: Interactions between ice shelves, sea ice and ocean

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The mass budgets of ice shelves, marine-terminating glaciers and the adjacent grounded ice sheets can change rapidly as the adjacent ocean state varies. The three water components – glacial ice, sea ice, and liquid ocean – interact in complex ways to affect not just the ice sheet mass balance, but also the production of dense water masses and the flux of sea ice northwards over the Southern Ocean. We use a model of the Ross Sea, including its ice shelf, to motivate a discussion of some climatically important interactions between these water components. We also consider the implications for mass loss mechanisms for large "cold water" ice shelves such as the Ross and Filchner-Ronne. We focus on the hypothesis that their future mass loss will be via frontal retreat caused by accelerated melting in, and associated calving of, the Ice Shelf Frontal Zone (ISFZ) rather than by thinning that is either concentrated near the grounding lines or broadly distributed under the ice shelf. The modeling points to the need to accurately represent the seasonality of sea ice production and advection when projecting ice sheet response to changing ocean state. Improved calving laws are also required to incorporate this potential mass loss process into projections of ice sheet mass change.

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

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Retreat of the West Antarctic Ice Sheet and consequent sea level rise in response to future warming is a serious concern. Recent observations of thinning, acceleration and grounding-line retreat of the Pine Island and Thwaites Glaciers (PIG/THW) identify this sector of the Amundsen Sea coast as particularly vulnerable. Here a hybrid ice sheet-shelf model is used to simulate past and future ice variations in this region. The model heuristically combines scaled equations for vertical shearing (stiffly grounded sheet) and horizontal stretching (stream and shelf) flow, and parameterizes ice flux across the grounding line as a function of local bedrock depth. For these experiments, the model is run on a nested domain centered on PIG/THW at 5 km resolution, driven at the boundaries by the results of a prior continental simulation.

Preliminary results are shown using various parameterized climates (modern, LGM, and future warm). Model parameter space is explored to obtain the best fits to the modern state, and to the much greater grounding-line extent at LGM reconstructed from geologic data across the continental shelf. The goal is to perform time-continuous experiments over the last 20 kyrs, validating against geologic data on deglacial retreat in this sector, and projecting these runs into the future.

Automated Production of High Resolution Commercial Imagery Mosaics of Antarctica

Claire C. Porter, Thomas Juntunen, Bradley G. Herried, and Paul J. Morin

As the amount of high-resolution commercial satellite imagery of Antarctica increases, the need for user-friendly access to the data for the scientific community has become urgent. The Polar Geospatial Center (PGC) developed a method of automatically sorting and overlaying the imagery in its archive to create tiled image mosaics with 50 cm resolution. Input images are orthorectified to a DEM to correct for terrain displacement and converted to top-of-atmosphere reflectance to color match images as much as possible. They are sorted by measurements of image quality, including cloud cover, sun elevation angle, off-nadir angle, and camera exposure settings. Lower quality imagery is removed from the final product in the merging stage. By eliminating redundant data caused by overlaps and by reducing the number of files, the final product is smaller, faster, more portable, and much easier for non-image scientists to use than the original imagery. The tiled mosaic product can be published as a web service, facilitating access to high-resolution imagery of remote areas by scientists and operations support staff with no GIS or remote sensing training. So far, 30% of West Antarctica has been mosaicked with this process on our compute cluster, at a rate of 50,000 square kilometers per day.

Influence of Ocean Circulation Patterns on Ocean Heat Transport to Ice Shelves

Pierre St-Laurent, John M. Klinck, Michael S. Dinniman
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Oceanic exchanges across the continental shelves of Antarctica play an important role in biological systems and the mass balance of ice sheets in West Antarctica. We focus in this research on the ocean heat transport to idealized ice shelves representative of the conditions encountered in Antarctica. In most shelf seas around the continent, the waters are close to freezing point and the mean circulation includes a westward flow at the shelf break (case 1). Conditions in the Amundsen and Bellingshausen seas (West Antarctica) are contrasted and include warm waters on the continental shelf and an eastward flow at depth at the shelf break (case 2). We examine the differences between these two cases by comparing process-oriented simulations conducted with a high-resolution (1km) 3-D ocean model (ROMS) coupled to a thermodynamically-active ice shelf. In both cases the cross-shelf exchanges of heat are initiated by corrugations at the bottom of the sea (troughs). However the magnitude of the onshore heat transport and the mechanism behind it are significantly different. This asymmetric response is explained by potential vorticity conservation and is compared to observational data recently acquired in the Ross and Bellingshausen seas. By assuming one large trough per 1000km of coastline, it is estimated that such flow-topography interaction provides 1GW of oceanic heat (relative to freezing point) per km of Antarctic coastline.

Mass Balance of the northern Antarctic Peninsula from image- and ICESat-based dH/dt

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An assessment of the most rapidly changing areas of the Antarctic Peninsula (north of 66DEGS) shows that ice mass loss for the region is dominated by areas affected by eastern-Peninsula ice shelf losses in the past 20 years. We combined satellite stereo-image DEM differencing and ICESat-derived along-track elevation changes to measure ice mass loss for the Antarctic Peninsula north of 66DEGS between 2001-2010, focusing on the ICESat-1 period of operation (2003-2009). This mapping includes all ice drainages affected by recent ice shelf loss in the northeastern Peninsula (Prince Gustav, Larsen Inlet, Larsen A, and Larsen B) as well as James Ross Island, Vega Island, Anvers Island, Brabant Island and the adjacent west-flowing glaciers. Polaris Glacier (feeding the Larsen Inlet, which collapsed in 1986) is an exception, and may have stabilized. Our method uses ASTER and SPOT-5 stereo-image DEMs to determine dh/dt for elevations below 800 m; at higher elevations ICESat along-track elevation differencing is used. To adjust along-track path offsets between its 2003-2009 campaigns, we use a recent DEM of the Peninsula to establish and correct for cross-track slope (Cook et al., 2012, doi:10.5194/essdd-5-365-2012 [adsabs.harvard.edu]; http://nsidc.org/data/nsidc-0516.html [nsidc.org]) . We reduce the effect of possible seasonal variations in elevation by using only integer-year repeats of the ICESat tracks for comparison. Total mass loss from the Peninsula north of 66DEGS is 22+/- 8 Gt (preliminary estimate), or roughly 20 to 35% of the total Antarctic mass imbalance. Little if any of the dynamically-driven mass loss is compensated by increased snowfall in the northwestern or far northern areas, but there is evidence of increasing accumulation in the southwestern portion of the study area. Mass losses are dominated by the major glaciers that had flowed into the Prince Gustav (Boydell, Sjorgren, Roehss), Larsen A (Edgeworth, Bombardier, Dinsmoor, Drygalski), and Larsen B (Hektoria, Jorum, and Crane) embayments. The pattern of mass loss emphasizes the significant and multi-decadal response to ice shelf loss along the eastern Peninsula coast. Areas with shelf losses occurring 30 to 100s of years ago seem to be relatively stable or losing mass only slowly (western glaciers, northernmost areas). The remnant of the Larsen B, Scar Inlet Ice Shelf, shows signs of imminent break-up, and its feeder glaciers (Flask and Leppard) are already increasing in speed as the ice shelf remnant decreases in area.

Antarctic Data at NSIDC: Continued Data Collection, Archiving, and Distribution of Results of NSF-OPP Funded Research in Antarctic Glaciology

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The Antarctic Glaciological Data Center (AGDC) at the National Snow and Ice Data Center (NSIDC) archives and distributes Antarctic glaciological and cryospheric system data collected by the U.S. Antarctic Program for the National Science Foundation.

The AGDC facilitates data exchange among Principal Investigators, preserves newly collected data useful to future research, gathers data sets from past research, and compiles continent-wide information for modeling and field work planning. The AGDC's data holdings include data sets collected by individual investigators on specific grants, and compiled products assembled from many different Principal Investigator data sets, published literature, and other sources. Data archived at AGDC include ice velocity, snow temperature, ice core data, geochemical composition, and snow pit data, among other topics. Data sets are available via our web site at http://nsidc.org/agdc/, where users can access data and documentation, citation information, locator maps, derived images, and references. We are also actively interested in data rescue efforts to recover data measurements from the pre-digital era. Old data reports, or old field books, may be archived at the NSIDC ROCS Analog Archive, digitized, and made available.

The NSF OPP Guidelines and Award Conditions for Scientific Data state that PIs should submit data collected as a result of their OPP grant to a designated data center as soon as possible, but no later than two years after the data are collected. The AGDC has an online submission form for scientists to use in contributing data to the AGDC. This submission process is intended to comply with the NSF OPP Data Policy, to satisfy the needs of the principal investigators, and to serve the broader scientific community. AGDC staff are ready, willing and able to assist Principal Investigators with their data submissions. Please contact Rob Bauer (robert.bauer@colorado.edu).

Thermal migration of ice stream shear margins

C. Schoof and M. Haseloff

Ice stream shear margins can be viewed as boundary layers connecting a Poiseuille-like shear flow in ice ridges with a membrane-like, lateral-shear dominated flow in the ice stream itself. The discharge of the ice stream is then highly sensitive to its width: with a Glen?s law rheology, ice velocity scales as the fourth power of ice stream width. A crucial question therefore is how the width of the ice stream evolves over time.

Existing, depth-integrated models of ice stream dynamics typically predict that the bed underlying an ice ridge should freeze over time, while the ice stream bed remains unfrozen, and the transition between the two should occur in the shear margin. Depth-integrated models however cannot describe the details of that transition, which would allow the rate of margin migration to be computed.

We consider this boundary layer problem in detail, focusing on an abrupt transition from free slip to no slip at the point where the bed temperature changes from temperate (i.e., at the melting point) to subtemperate (i.e., below the melting point). This engenders multiple singularities in both, stress field and hence volumetric heating rate, and in heat flux. We show that the strength of these singularities is controlled by the far field, and that one of the singularities in the heat flux must be alleviated in order to allow the ice stream to widen. In the process, we show that at least a small zone of temperate ice must also form above the transition between frozen and unfrozen ice.

We show that the alleviation of the heat flux singularity is possible only for specific combinations of the following quantities : i) the strength of shear heating in the margin dicated by lateral shear stress acting on the ice stream margin ii) the background temperature gradient dictated by surface temperatures and advection in the ice ridge and iii) the margin migration rate. More specifically, in the absence of significant advection from the ice ridge, we are able to show (by using the Wiener-Hopf technique) that margin migration rate is determined uniquely by lateral shear stresses and background temperature gradient.

Evidence for Ice-Flow-Coupled Subglacial Water Systems Beneath West Antarctica's Potentially Unstable Thwaites Glacier

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Subglacial water in various forms has been observed and theorized to accelerate the flow of overlying ice. The acceleration depends on the flux through the subglacial water system and whether the dynamic state is hydrologically “distributed” or “concentrated” . Marine ice sheets with landward-sloping beds are in an unstable configuration for which such accelerations can initiate or modulate grounding line retreat and ice loss. Thwaites Glacier (TG) is one the largest, most rapidly changing glaciers on earth and its landwardsloping bed reaches the interior of the marine West Antarctic Ice Sheet (WAIS) which impounds enough ice to yield meters of sea level rise. Despite the potential instability of this configuration, the subglacial water systems beneath TG and their control on ice flow have not been characterized by geophysical analysis. Although, the size of TG makes airborne radar sounding the only practical means of observation, previous radar analysis approaches have proven inadequate to characterize the dynamic state and geographic extent of its subglacial water systems. We use advanced processing to focus radarsounding data collected over TG and measure the angular distribution of energy returned from the bed. This allows us to characterize the meter-scale geometry and dynamic state of subglacial water systems across TG and validate our interpretations with meter-scale imaging. Our results show substantial water volumes ponding in a system of “distributed” canals upstream of a bedrock ridge that is breached and bordered by a system of “concentrated” channels. The transition between the “distributed” and “concentrated” systems is both co-located and physically consistent with increasing basal shear stress, surface slope, and water flux, indicating a strong feedback between the subglacial water and overlying ice. This feedback raises the possibility that variations in subglacial water flow could trigger a grounding line retreat in TG capable of spreading to the rest of the WAIS.

Ice shelves in cold and warm oceanic environments

Olga Sergienko

Antarctic ice shelves exist in a variety of oceanographic thermal regimes: from "cold" for Filchner-Ronne and Ross ice shelves, where sub-ice-shelf water masses are dominated by High Salinity Shelf Water, to "hot" for Pine Island Glacier or George VI ice shelves, where sub-ice-shelf water masses are dominated by Circumpolar Deep Water. Observations show that ice shelves in different oceanic environments experience a variety of basal conditions – from refreezing and mild melting on Filchner-Ronne and Ross ice shelves to strong melting on Pine Island Glacier floating tongue. Dynamic and thermodynamic aspects of the ice shelves and cavities underneath them are investigated with a one-dimensional, fully-coupled ice/ocean model. Model simulations show that ice shelves afloat in warm ocean waters have significantly colder internal ice temperatures than those that float in cold waters. This implies that ice shelves in a warm ocean environment are stiffer (less deformable) and are thus more prone to fracturing and crevassing than ice shelves afloat in cold waters. Sensitivity experiments show that ice shelves with faster flow across the grounding line (larger mass flux) experience stronger melting than ice shelves with weaker flow through the grounding line, and in the case of confined ice shelves, have configurations quantitatively similar to ice shelves floating in the ocean environments with increased heat content.

Quantifying Ice-sheet/Ice-shelf Dynamics and Variability with Meter-scale DEM and Velocity Timeseries

David Shean, Ian Joughin, Ben Smith, Zach Moratto, Claire Porter, Paul Morin

Both the Antarctic and Greenland ice sheets are losing mass at an increasing rate, although loss due to accelerating flow and dynamic thinning remains poorly understood. We are using complementary data from repeat satellite and airborne observations to investigate the relationship between ice-sheet/ice-shelf dynamics and geometry on seasonal to interannual timescales. High-resolution along-track stereo imagery from commercial satellite vendors DigitalGlobe and GeoEye provides unprecedented spatial (~0.5 m/px with ~17 km swath width) and temporal (weekly/monthly) resolution for these efforts.

We have developed an automated pipeline using open-source software to produce orthoimage, DEM, and surface velocity products from DigitalGlobe imagery. High-contrast surface texture (e.g. sastrugi, crevasses) visible at sub-meter resolution provides near-perfect image correlation (~99% success rate) during DEM and velocity map derivation. Elevation data from IceBridge ATM/LVIS, ICESat GLAS, and GPS campaigns are used to correct DEMs and perform accuracy assessment. Preliminary tests over exposed bedrock provide relative vertical accuracy estimates of <1-2 m for Worldview-1/2 DEMs. Velocity data from TerraSAR-X and GPS campaigns provide validation for surface velocity products, with horizontal error estimates of <10 m.

Velocity and elevation change products with 2-4 m/px spatial resolution allow for unprecedented 3D dynamic characterization of sub-km flow transition zones (e.g. grounding lines, shear margins), capturing both local and regional variations due to surface/sub-shelf melting and dynamic thinning. We present preliminary elevation/velocity timeseries for Pine Island Glacier from 2010-2012, and provide estimates for grounding line position and ice shelf thickness. These observations complement ongoing efforts to measure and model outlet glacier dynamics, with implications for future ice-sheet mass balance estimates.

A comparison of grounding zone features and flexure dynamics in two geometries over a 12-hour tidal range

<u>Matthew R Siegfried</u>, Helen Amanda Fricker, Lucas Beem, Knut Christianson, Huw Horgan, Slawek M Tulaczyk

The grounding zone (GZ) of an ice sheet, where meteoric ice transitions from fully grounded to freely floating, is a critical boundary where land ice interacts directly with the ocean. Since floating ice responds to tides while grounded ice does not, the GZ is a region of significant ice flexure, which can pump warm, saline seawater upstream beneath the ice sheet. The GZ can be mapped on large spatial scales with limited temporal sampling using satellite data, yet the GZ has never been studied continuously over a diurnal tidal cycle. Here we describe a high-rate, kinematic Global Positioning System (kGPS) survey experiment completed as part of the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project, collecting repeat surface-elevation profiles over a 12-hour tidal range of two ~20 km, along-flow transects across the GZ of the Whillans Ice Stream (WIS), West Antarctica. One transect crosses a bedrock promontory, representing a "typical" GZ (i.e. orthogonal to ice flow, steep surface slopes). The second is through a narrow embayment, over which ice flexure is supported both longitudinally and laterally (i.e. bridged). Bridged embayments are typical at subglacial water outlets, where outflow causes local grounding line retreat. We combine these kinematic GPS surveys with nearby continuous GPS data to map GZ features and contrast ice flexure mechanics between two types of GZs. These geometry-induced differences in GZ behavior are ignored in simple models, but must be incorporated to more realistically capture ice-ocean interactions in the GZ and upstream.

The Losers Next Door: Mass loss from Thwaites, Pope and Smith glaciers

Ben Smith, Ian Joughin, and David Shean

Headlines about mass loss from the Amundsen Sea sector are often dominated by the antics of Pine Island glacier. But just next door, three large glaciers have each made their own contributions to sea level. A synthesis of laser-altimetry and photogrammetry from ICESat, IceBridge, and Worldview, shows that Thwaites, Pope and Smith have together lost more mass since 2009 than PIG, and while the near-grounding-line thinning on PIG appears to be thinning, it has held steady over the last year on Smith Glacier. The cause of the large ice losses in these glaciers is probably ongoing changes near the grounding line. Visible-light and radar imagery reveals changes in crevassing patterns and in the configuration of ice rises near the fronts of all of these glaciers, suggesting that thinning ice shelves have lost some support from submarine peaks that once helped buttress them against ice flowing form upstream, while combined altimetry and ice-sounding measurement reveal changes in the extent of grounded ice.

At the same time, melt near the grounding lines has eroded contact between ice and rock. In some cases, the changes have been subtle, as in the Thwaites Ice Shelf, where the freeboard of nearly-floating ice has decreased, leading to patchy flotation; in the case of Pope Glacier, the change is not subtle at all: beneath the fastest-flowing part of the glacier, the ice has thinned by nearly 30 m/yr since early measurements in 2002, creating a dramatic new embayed area upstream of the grounding line. The extent to which these changes can continue will depend greatly on the future rate and pattern of marine melt, the specifics of which will be discussed in a companion presentation by Ian Joughin.

Insights on WAIS history from a high-resolution Eemian record collected at the Allan Hills Blue Ice Area, Antarctica

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The Allan Hills Blue Ice Area (AH BIA), located on the western flank of the Convoy Range of the Trans-Antarctic Mountains, has been suggested on the basis of meteorite terrestrial ages and ice flow modeling to contain ice of great antiquity. Here we present the first direct evidence that ice from the last (MIS 5 - Eemian) and penultimate (MIS 7) interglacials is exposed at the surface of the icefield. Ice age in the AH BIA was determined through stratigraphic correlation of two stable water isotope (δD) records from the area with established deep core records like EPICA Dome C (EDC). The first AH BIA δD record consist of measurements from samples collected every 10 m, from 5-7 cm depth, along an ~ 5.5 km transect through the main icefield; the second δD record is composed of 15 cm resolution measurements from a 225 m core drilled at the mid-section of the same transect. The correlation between these records and EDC is supported by trapped gas measurements, including $^{40}Ar_{atm}$ ages and $d^{18}O$ measurements from both the 225 m core and a series of ~15 m ice cores collected along the transect.

Preliminary glaciochemical data from four locations along the transect suggest that the chemical characteristics of glacial/interglacial climates has also been preserved in the ice. Trace element (S, Al, Ca, Mn, Fe, Co, Cu, Zn, Cd, La, Ce, Pr, Nd, Sm, Eu, To, Dy, Ho, Er, Yb, Lu, Pb) concentrations are highest in the sample collected near the glacial extreme of MIS 6 and lowest in the sample from MIS 7. Major ions ratios (SO_4^{2-}/Na^+, Ca^{2+}/Na^+, Cl^-/Na^+) from these samples also show differences that may be indicative of changing sea ice cover. The glaciochemical patterns, as well as secondary trends within the δD record, have the potential to increase our understanding of changes in Eemian sea ice extent and atmospheric circulation.

Long-term glacial history of the central Transantarctic Mountains

Perry Spector[1] and John Stone[1]
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Model simulations of past configurations of the Antarctic Ice Sheet are poorly constrained by geologic observations. Although extensive research has been devoted to unraveling the post-Last Glacial Maximum (LGM) deglacial chronology, constraints on prior episodes of the ice sheet's history are extremely rare. The history of ice thickness changes can be constrained by measurements of cosmogenic nuclides in bedrock surfaces. In 2010-11, we sampled an elevation transect of bedrock from Mt Hope, located in the central Transantarctic Mountains at the mouth of Beardmore Glacier and abutting the Ross Sea. Over glacial cycles, ice levels at Mt Hope would have been sensitive to thickness and grounding line changes of the West Antarctic Ice Sheet as well as ice elevation changes in East Antarctica that were communicated through the Transantarctic Mountains by Beardmore Glacier. Here we present a record of Quaternary exposure and ice cover from Mt Hope, derived from measurements of cosmic ray-produced ^{26}Al and ^{10}Be in bedrock surfaces.

Bedrock exposed during interglacial periods accumulates cosmogenic nuclides such as ^{10}Be and ^{26}Al. During glacial periods, thick ice cover shields bedrock from cosmic radiation, and differential nuclide decay rates (^{10}Be $t_{1/2}$ = ~1.4 Myr; ^{26}Al $t_{1/2}$ = ~0.7 Myr) leads to isotopic disequilibrium. In cases where bedrock has been protected by non-erosive, cold-based ice during glacial periods, the concentrations of these nuclides provide million-year records of exposure and ice cover. Although these measurements cannot date specific glaciations, for each sample we can determine: 1) lower limits on the cumulative exposure time and time ice covered and 2) upper limits on the proportion of time each sample has been ice-free.

Paired ^{26}Al-^{10}Be measurements from Mt Hope bedrock show that the proportion of time samples have been exposed increases with elevation, as expected. Results from the weathered bedrock that characterizes the upper slopes of Mt Hope show that, although the summit (827 m elevation) was overrun by ~250 m of LGM ice, these surfaces have been nearly continuous exposed for over 0.5 Myr and up to 2 Myr. This implies that highstands similar to the LGM have not been long-lived in this part of Antarctica. On the lower flanks of Mt Hope, striated and glacially-carved bedrock are evidence for subglacial erosion by warm-based ice. Surprisingly, isotopic data from this bedrock display substantial disequilibrium in $^{26}Al/^{10}Be$, indicating that, despite being repeatedly overrun by ice discharged from Beardmore Glacier, there was insufficient subglacial erosion to completely erase the record of prior exposure.

During the most recent deglaciation, a knoll on Mt Hope's north slope became ice free ~1-2 kyr prior to higher elevations on the mountain's prominent southeast ridge, based on ^{10}Be

measurements of glacial erratics. The paired ^{26}Al-^{10}Be record from Mt Hope bedrock show that this is not a phenomenon unique to the last deglaciation, for bedrock on the knoll has been exposed and ice covered (for at least ~300 kyr and ~250 kyr, respectively) longer than bedrock at higher elevations on the southeast ridge. This necessitates that bedrock below ~250 m elevation has been ice covered for much of the last half of the Pleistocene.

Significance of exceptional recent climate and glacier changes in West Antarctica

Eric Steig, University of Washington

The West Antarctic Ice Sheet (WAIS) has warmed significantly in the last 50 years, and sea ice concentrations have declined in the adjacent Amundsen and Bellingshausen Seas for at least the last three decades. Contemporaneously, outlet glaciers that drain the WAIS into the ocean have accelerated, leading to overall mass loss and a significant contribution to sea level rise. The rising temperatures and declining sea ice are linked with the glacier accelerations by changes in atmospheric circulation, which have enhanced the flow of warm Circumpolar Deep Water (CDW) onto the Antarctic continental shelf, resulting in thinning of floating ice shelves. Data from an array of ice core records from the WAIS show that recent conditions are likely unprecedented in at least the last 200 years, but are dominated by decadal variability. Similar conditions occur with a frequency of about once per century over the last 2000 years. The unusual climate in West Antarctica in recent decades can be attributed primarily to similarly unusual conditions in the tropical Pacific. Future changes in the tropics will need to be taken into account in projections of the Antarctic ice sheet contribution to sea level rise.

Physical Properties in Thin Sections from WAIS Divide Core WDC06A; Fabric, Bubbles, Grains and More

D.E. Voigt. R.B. Alley, J.M. Fegyveresi, J.J. Fitzpatrick, D. Laurel, E. Ligmanowski, M. Spencer, and N. Stevens

As part of the Physical Properties study (NSF 1043528) vertical thin sections from the WAIS Divide Core (WDC06A) were sampled in the field and thinned at the National Ice Core Lab (NICL).

Purpose: Coordinated interpretation of c-axis fabrics, grain sizes and shapes, and bubble characteristics are being used to learn about the history of ice flow, the processes of ice flow, and the softness of the ice for additional deformation. Bubble number-density is used to reconstruct temperature changes through the rest of the bubbly part of the core, providing important paleoclimatic data for earlier parts of the Holocene.

c-axis Fabric: Vertical thin sections were analyzed using the automated c-axis Fabric Analyzer (Wilen, 2000; Hansen and Wilen, 2002) located at Penn State University. The c-axis orientation at 420 meters depth is nearly random but by 965 m the c-axes have started to migrate until a very strong girdle fabric developes in the vertical plane. The presence of a persistent girdle fabric indicates stretching in the horizontal axis. The lack of a double girdle may indicate that the ice has undergone no strain induced recrystalization at these depths. This vertical girdle fabric persists to 3000 meters where the axes start to rotate towards the poles and the fabric begins to resolve into one indicating a regime of simple shear.

Bubble Number-Density: Bubble number-density measurements have been made from depths of 580 meters to 1120 meters in the WAIS Divide core. Notable variations are seen in the data, with interesting outliers that could be indicative of seasonal biasing. A depth-variable strain-rate model based on the most currently published depth-age scale is being employed to determine accumulation-rate history so that a paleoclimate reconstruction can be modeled and validated against recent ™18O data from the core. Ultimately, this reconstruction will also determine the viability of the bubble number-density technique through the brittle ice zone. To further investigate how seasonality affects the process of bubble trapping at WAIS Divide, bubble number-density is being measured along two continuous (~25 cm) ice samples that were recently prepared at NICL from the nearby WDC05A core. These samples represent at least two continuous seasons at the site.

Grain Growth and Zener Pinning: Grain geometry characterization has been completed for sections from the entire core as have area population statistics and 2-dimensional petrofabric analyses. Grain size and shape information are now being compared to other datasets, including data recovered from the drill system during drilling operations, to look for correlations and trends as well as grain characterizations from other core sites. Comparisons of grain-size and impurity trends will assess controls on grain growth. Dual mapping of grains and bubbles allows improved assessment of their interactions, including the effects of Zener pinning.

Visual Stratigraphy of the Core: Visual examination and logging has been completed for the entire core and a summary of these data will be discussed.

WAIS Divide Ice Core Project: How did we do?

D.E. Voigt representing the WAIS Divide Ice Core Community
Penn State University, Department of Geosciences
DRI, UNH, and many other institutions

The main borehole of the WAIS Divide Ice Core Project was completed in the 2011-2012 season at a depth of 3405 meters. Drilling of the WDC06A borehole started in the 2006-2007 season and production coring began the next season. In 2012-2013 replicate coring will complete the drilling at WAIS Divide.

This talk will present an overview of the WAIS Divide Ice Core Project and cover some of the early scientific highlights. Thanks to NSF for funding and constant support of this project.

Intermittent rift propagation in the Amery Ice Shelf

C. C. Walker, J. N. Bassis, R. J. Czerwinski, H. A. Fricker

The Amery Ice Shelf features five prominent rifts within 30 km of its calving front. Through observation using available MODIS and MISR data, we produce a time series of changes in rift length for the period 2002-2012. We find that all five are actively propagating, but with a complex spatio-temporal pattern of variability in which some rifts propagate in tandem while others appear to tradeoff. Temporal variability in rift propagation is dominated by large episodic bursts. These bursts, analogous to the much smaller propagation events detected from field observations, are not synchronous across all five rifts nor do the timing of propagation events exhibit any correlation with observed proxies for environmental forcing (e.g., atmospheric temperatures, sea-ice extent). However, we find that several propagation events take place after the predicted arrival from tsunamis originating in the Indian Ocean. This is especially apparent following the December 2004 Sumatra earthquake and three other earthquakes in the Sumatra/W. Indonesia area. This connection is bolstered by the observation of similar effects at other ice shelves, e.g., a large iceberg calving after the sudden propagation of two front-initiated rifts at Larsen C after the December 2004 tsunami. In comparing rift propagation at Amery with 67 rifts on 11 other ice shelves around Antarctica, we find that with the exception of the occasional tsunami triggered propagation event, the extreme variability on the Amery Ice Shelf is highly atypical. We postulate that the pronounced activity on the Amery is due to the fact that it last had a large calving event in 1963/64, and is approaching its pre-calved position. This suggests that the AIS is poised for another major calving event and the highly dynamic propagation we observe is the precursor to such an event.

Ice-shelf tidal flexure and subglacial pressure variations

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We develop a model of an ice shelf-ice stream system as a viscoelastic beam partially supported by an elastic foundation. When bedrock near the grounding line acts as a fulcrum, leverage from the ice shelf dropping at low tide can cause significant (?1 cm) uplift in the first few kilometers of grounded ice. This uplift and the corresponding depression at high tide lead to basal pressure variations of sufficient magnitude to influence subglacial hydrology. Tidal flexure may thus affect basal lubrication, sediment flow, and till strength, all of which are significant factors in ice-stream dynamics and grounding-line stability. Under certain circumstances, our results suggest the possibility of seawater being drawn into the subglacial water system. The presence of seawater beneath grounded ice would significantly change the radar reflectivity of the grounding zone and complicate the interpretation of grounded versus floating ice based on ice-penetrating radar observations.

The influence of stick-slip motion on the present deceleration 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. Superimposed on this decadal-scale deceleration is a tidally modulated stick-slip characterized by extended periods (6-24 hours) of minimal motion followed by brief periods (30 minutes) of rapid motion when the ice stream lurches forward by ~ 0.5 m. Comparison of new results collected during 2010-2011 with earlier measurements show that the deceleration has continued and the timing of slip events has become less regular, often slipping only once during a day instead of previously observations that documented two slip events daily. The reduced regularity of slip events has resulted in a less efficient release of stored elastic strain during slip events. These observations highlight non-linear feedbacks at the daily-scale that influence the decadal time-scale behavior of the ice stream.

Inferring the seasonality of past precipitation from ice core impurity records

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Impurity records from the WAIS Divide ice core, West Antarctica, have preserved seasonal information far back in time. These data contain information on the timing of past precipitation events: Each snowfall event leaves a chemical imprint in the ice core record, and the composition is controlled primarily by the time of year of deposition, because most chemical species measured in ice cores have seasonally varying sources. By means of a novel statistical approach with an origin in algorithms for machine speech-recognition, the inter-annual variability in snowfall seasonality can be inferred in a probabilistic manner. We will present the preliminary results when applying this method to chemistry data from the upper part of the WAIS Divide ice core.

Changes in seasonality of past precipitation have important influence on the ice core stable water isotope records. Inevitably, the isotopes only records paleoclimatic information during snowfall events, and consequently their mean values are biased towards the temperature at the time of year with most precipitation. Knowing how to disentangle the effect of precipitation seasonality in the ice core climate records will enrich our understanding of the isotopic signal in these, and allow for better estimates of e.g. past climate variability to be made. Such knowledge is likely to further our insights into the underlying mechanisms responsible for climate change, in the past as well as in the future.

Controls on the Geometry of Accretion Reflectors

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Basal accretion occurs when meltwater refreezes onto the base of an ice sheet. Thick (600-900 m) regions of accretion ice are identified in radio-echo sounding data as plume-shaped reflectors above the basal reflector and below isochronous layers of meteoric ice. In both Antarctica and Greenland accretion reflectors have been imaged at an elevation of 1/3-1/2 of the ice sheet thickness and extend in the flow direction as far as 100 km. Here we investigate the freezing rates and energy budgets of basal accretion processes using both simple scaling estimates and a two-dimensional thermomechanical higher order numerical flowline model coupled to a basal hydrology model.

Simple scaling estimates for the freezing rate can be derived by linking the observed height of the accretion reflectors, the size of the accreting region, and the known ice velocity or surface accumulation rate. These estimates imply freezing rates on the order of 10-100 cm/yr. Such rates require latent heat fluxes of 1-10 Wm^{-2}, orders of magnitude larger than typical conductive heat fluxes beneath continental ice sheets.

The mismatch between the latent heat flux required to maintain a large freezing rate and the conductive heat flux that can be removed from the ice sheet base implies two end-member possibilities. First is the supercooling possibility, where the freezing rates and latent heat fluxes are of the same order of magnitude as that implied by the simple scaling estimates. In this case the conductive heat flux is supplemented by glaciohydraulic supercooling. In supercooling the heat flux removed is proportional to the water throughput, allowing large heat fluxes to be removed if a large amount of water flux is focused through a small area. Second is the overriding possibility, where a thin layer of accretion ice has overridden a larger zone of deformed meteoric ice. In this possibility the accretion volume and freezing rates are much smaller than what is implied by simple estimates that assume that all the ice underneath the observed reflectors is accretion ice. If the freezing rates are small then conduction can remove the necessary heat flux, but a complex deformation pattern must be found other than normal ice sheet flow. This deformation pattern must be able to cause a thin layer of accretion ice to override meteoric ice to a height of 1/3-1/2 the ice thickness.

We use both simple scaling and our hydrology model to estimate the water flux required to reproduce the observed height of the accretion reflectors through glaciohydraulic supercooling. Under reasonable assumptions about bed and surface gradients, approximately 10^5 m^2a^{-1} of water throughput is required to reproduce the observed height of the accretion reflectors through supercooling. In addition, we use our ice flow model to search for a combination of boundary conditions that can cause a thin layer of accretion ice to override meteoric ice to the required height. We have been unable to find such a pattern so far, even including rapid changes in the basal boundary condition. This suggests, but does not prove, that supercooling is responsible for producing large accretion plumes.

GIMBLE: Geophysical Investigations of Marie Byrd Land Evolution: a new airborne survey of the linchpin of the West Antarctic Ice Sheet

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The Marie Byrd Land crustal block is the linchpin of the West Antarctic Ice Sheet, and has been an important geological target for its record of the evolution of the Mesozoic Antarctic margin, Cenozoic volcanism, and potential Neogene doming. However, despite significant geological expeditions and POLENET efforts, no comprehensive areogeophysical efforts have targeted the dome of Marie Byrd Land itself. A number of contesting hypotheses for the origin of Marie Byrd Land make predictions for the potential fields and the geomorphology of the underlying crust: that overlies an active mantle hotspot; that it represents the rift flank of an ancestral West Antarctic Plateau; or that it represents large scale dynamic topography related to Gondwana margin evolution.

We have proposed to perform a 16 flight, two year aerogeophysical survey of Marie Byrd Land with 4 key datasets: gravity, magnetics, radar data and laser altimetry. Gravity with collocated radar will be used to constrain the compensation state of Marie Byrd Land, leveraging NSF?s investment in the POLENET project; magnetics will be used to assess the potential for ongoing sub ice volcanism (and thus qualitatively assess heat flow); and ice penetrating radar will be used to map out at 5-km resolution the topography of the interior slope of Marie Byrd Land?s bedrock, to understand the evolution of erosion and thus regional topography. Laser altimetry will help constrain the state of Marie Byrd Land's outlet glaciers.

In this poster, we describe the plans for the coming season, and how they will be meshed with concurrent Ice Bridge operations. This work is supported by NSF's OPP, NASA's Operation Ice Bridge, and the Australian Antarctic Division.