#WAISworkshop

WAIS

West Antarctic Ice Sheet Workshop

Abstract Booklet

October 15–18, 2019

Camp Cedar Glen

Julian, CA

WAIS Workshop 2019 Agenda
Camp Cedar Glen
Julian, CA USA

Tuesday, October 15

2:00 pm – 8:00 pm	Registration: Pick up badges (registration on Wednesday and Thursday will be available during breaks in the agenda)	Assembly Hall
4:30 pm	WAIS Workshop Steering Group Meeting	Griffin Hall
6:00 pm	Icebreaker (cash bar) and pizza dinner	Dining Hall

Wednesday, October 16 (All oral sessions are in Griffin Hall)

Breakfast: 8:00 am – 8:30 am (Dining Hall)

Session 0	Opening Business	Presenter
8:30 am	Welcome to WAIS Workshop 2019	Helen Fricker & WAIS Committee
8:40 am	View from NSF [video]	NSF
8:50 am	View from NASA [video]	Thorsten Markus

Session 1	Dynamics across the Grounding Line	Presenter
9:00 am	Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks [slides][video]	Eric Larour
9:15 am	Seasonal ocean temperature influence on glacier velocities: Observations and model experiments beneath Dotson Ice Shelf, West Antarctica [slides][video]	Andrew Hoffman
9:25 am	Early Holocene Retreat and Late Holocene Re-advance of the Grounding Line in the Ross Sea Sector [slides][video]	Sarah Neuhaus
9:35 am	On the combination of factors that influenced the post-LGM grounding zone positions in eastern Ross Sea [slides][video]	Philip J. Bart
9:45 am	Impact of Ross Ice Shelf basal melting on mass loss from West and East Antarctic ice sheets [slides][video]	Cyrille Mosbeux
9:55 am	Contrasting outlet glacier responses to ocean vs. interior forcing [slides][video]	John Erich Christian
10:05 am	Discussion [video]	All

Coffee Break: 10:30 am – 10:50 am

Session 2	Community Health	Presenter
10:50 am	Changing Academic Culture: The Why, When, Who, and How [video]	Jane Willenbring

ECR Mentoring Program Meet & Greet: 12:20 pm – 12:40 pm (Assembly Hall)
Lunch: 12:20 pm – 1:30 pm (Dining Hall)

Session 3	Will the Snowflakes Save Us?	Presenter
1:30 pm	Reconstructing winds in the Amundsen Sea using paleoclimate data assimilation [slides][video]	Gemma K. O'Connor
1:40 pm	Large-Scale Atmospheric Drivers of Snowfall on Thwaites Glacier [slides][video]	Michelle L. Maclennan
1:50 pm	Will the pore space save us? The role of firn on ice shelf stability in West Antarctica [slides][video]	Brooke Medley
2:00 pm	Discussion [video]	All

Session 4	Science Communication	Presenter
2:30 pm	From WAIS Workshop to the World – Perspectives on Successful Outreach and a Plan for the WAIS Community [slides][video]	Marlo Garnsworthy
2:40 pm	An Exploration of Co-Creation on a Subglacial Lake in Antarctica [slides][movie trailer][video]	Kathy Kasic
2:50 pm	Discussion [video]	All

Break: 3:10 pm – 3:30 pm

3:30 pm	Poster lightning introductions	Griffin Hall
4:15 pm	Poster Session	Poster Hall

Dinner: 6:30 pm at Julian Beer Company (Directions: https://bit.ly/2n4gXyo)

Thursday, October 17 (All oral sessions are in Griffin Hall)

Breakfast: 8:00 am – 8:45 am (Dining Hall)

Session 5	The Great Glacier Conveyor: A John Nye & Wally Broecker Memorial Session	Presenter
8:45 am	The association of subglacial meltwater with grounding-line retreat [slides][video]	Lindsay Prothro
8:55 am	Thickness of the divide and flank of the West Antarctic Ice Sheet through the last deglaciation [slides][video]	Perry Spector
9:05 am	Subglacial Sediments Spanning Scales: A Process-To-Paleo Perspective	Ryan Venturelli
9:15 am	Searching for subglacial evidence of past West Antarctic Ice Sheet collapse – 1: Exposure history of a subglacial bedrock core [slides][video]	John Stone
9:25 am	Searching for subglacial evidence of past West Antarctic Ice Sheet collapse – 2: Ice sheet modeling [slides][video]	Trevor Hillebrand
9:35 am	Constraints on lower-than-present WAIS elevations from cosmogenic nuclides in subglacial bedrock at the Ohio Range [slides][video]	Robert Ackert
9:45 am	Discussion [video]	All

Coffee Break: 10:15 am – 10:30 am

Session 6	From The Sea	Presenter
10:30 am	Sea level and circulation in the Southern Ocean [slides][video]	Tom Armitage
10:45 am	Why now? Evidence for an anthropogenic component to West Antarctic ice loss [slides][video]	Eric Steig
10:55 am	Diffusive Convection controls basal melting of Antarctic ice shelves [slides][video]	Madelaine G. Rosevear
11:05 am	Could increased melting from East Antarctic ice shelves trigger runaway melting beneath Filcher-Ronne Ice Shelf? [slides][video]	Matthew Hoffman
11:15 am	Pliocene to Recent record of West Antarctic history from the Amundsen Sea continental rise: Initial Results from IODP Expedition 379 [slides][video]	Reed Scherer
11:25 am	How increasing WAIS meltwater and earlier springtime opening may flip the Amundsen Sea polynya from carbon sink to source. [slides][video]	Patricia L. Yager
11:35 am	The Bellingshausen Sea at the confluence of the West Antarctic ocean circulation system [slides][video]	Andrew Thompson
11:45 am	Discussion [video]	All

Lunch: 12:15 pm – 1:30 pm (Dining Hall)

Session 7	Processes Beneath	Presenter
1:30 pm	Vulnerability of the Antarctic ice sheet to basal thermal regime change: Integrating observations and models [slides][video]	Eliza Dawson
1:40 pm	Young Carbon beneath the West Antarctic Ice Sheet: A Unique Carbon Cycle Perspective from Mercer Subglacial Lake [slides][video]	Brad E. Rosenheim
1:50 pm	A new look at the Whillans Ice Plain stick-slip cycle: Tidally regulated precursory sliding affects unstable slip onset location and seismic wave radiation [slides][video]	Grace Barcheck
2:00 pm	Basal to bedrock: magnetotelluric imaging of an active subglacial hydrologic system [slides][video]	Chloe Gustafson
2:10 pm	Airborne ElectroMagnetics (AEM) as a powerful tool for efficient mapping of subglacial and englacial conditions along ice sheet margins [slides][video]	Slawek Tulaczyk
2:20 pm	Discussion [video]	All

Break: 2:50 pm – 3:30 pm

3:30 pm	Poster Session	Poster Hall

Dinner: 6:00 pm (Dining Hall)
ECR Mentoring Program Discussion: 7:15 pm – 8:00 pm (Assembly Hall)

Friday, October 18 (All oral sessions are in Griffin Hall)

Breakfast: 8:00 am – 8:45 am (Dining Hall)

Session 8	The Leading Edge 1	Presenter
8:45 am	From observations at the glaciers' margins to ice sheet model projections: progress in understanding ice sheet/ocean interactions in Greenland [slides][video]	Fiamma Straneo
9:00 am	Glacial Earthquakes and Precursory Seismicity Reveal Thwaites-Glacier Calving Behavior [slides][video]	Paul Winberry
9:10 am	Vulnerability of Antarctica's ice shelves to meltwater-driven fracture [slides][video]	Ching-Yao Lai
9:20 am	A poro-damage approach to simulating hydrofracture of glaciers and ice shelves [slides][video]	Ravindra Duddu
9:30 am	Discussion [video]	All

Break: 9:50 am – 10:00 am

Session 9	The Leading Edge 2	Presenter
10:00 am	ICESat-2 Bathes The World In Soothing Green Light [slides][video]	Benjamin Smith
10:15 am	Modelling Active Subglacial Lakes [slides][video]	Aaron Stubblefield
10:25 am	Spatial distribution of englacial layer slope as a constraint on ice sheet basal conditions. The case for subtemperate sliding. [slides][video]	Elisa Mantelli
10:35 am	The internal deformation regime of Thwaites Glacier [slides][video]	Felicity McCormack
10:45 am	Discussion [video]	All

Break: 10:05 am – 10:15 am

Session 10	The Leading Edge 3	Presenter
11:15 am	Geostatistically Simulating the Topography and Geology of the Amundsen Sea Embayment [slides][video]	Emma J. MacKie
11:25 am	Contextualizing the slow-down of Whillans Ice Stream using swath radar topography and ICESat-2 [slides][video]	Nicholas Holschuh
11:35 am	Using radar sounding observations to improve numerical models' estimates on ice sheet temperatures in West Antarctica	Winnie Chu
11:45 am	Electrical Resistivity Measurements of the McMurdo Ice Shelf, Antarctica, Reveal Seawater Intrusion in New Detail [slides][video]	Neil Foley
11:55 am	Prospecting for Gold: Finding the optimal site for a deep ice core at Hercules Dome, Antarctica [slides][video]	T.J. Fudge
12:05 pm	Discussion [video]	All

12:25 pm	Conference Feedback	WAIS Committee

Boxed Lunches: 12:30 pm

Community College Educators Session: 1:00 pm – 4:00 pm (location TBD)

Poster Presentations

Title	Presenter
Time-dependent freshwater fluxes from deep and shallow meltwater sources under Antarctica's large ice shelves	Susheel Adusumilli
Reanalysis of Greenland temperature and precipitation over the last 20,000 years using data assimilation	Jessica A. Badgeley
An overlooked ice-shelf calving process for accelerating Antarctic Ice Sheet loss	Maya K. Becker
Inferring Temperature Distribution in Shear Margins using an ApRES and Software Defined Radio in a Bistatic Configuration	Nicole L. Bienert
A 3D Model of Antarctic Ice Shelf Hydrology	Sammie Buzzard
Physical and chemical characterization of sediments from Mercer Subglacial Lake, West Antarctica	Timothy D. Campbell
Englacial Layers in Radar Sounding Data Modeled from Ice Core Electrical Stratigraphy	Riley Culberg
A Method for Quantifying Meltwater Volume Using ICESat-2 Laser Altimetry and High-Resolution Planet SkySat Imagery	Rajashree (Tri) Datta
WAIS Deglacial Dynamics and Confusing Ice Core Records	T.J. Fudge
Into the Last Glacial Maximum: The Timing of Ice Growth in Marie Byrd Land, Antarctica	Brent Goehring
Southern Ocean Storm positions and intensity estimated with seismic observations in the Ross Ice Shelf	Momme C. Hell
An 'extended' Stefan problem with applications for slush formation in glacier boreholes	Benjamin H. Hills
Calm, cool and collected: post-LGM conditions under the central Ross Ice Shelf, Antarctica	Christina Hulbe
Thwaites Glacier's recent meltwater signature recorded in ice shelf proximal sediment cores	Allison Lepp
Flexural gravity wave simulations and seismic observations constrain flexure near the ice edge of the Ross Ice Shelf	Ben Mullet
A New Project Catalog for the United States Antarctic Program hosted at the USAP-DC	Frank O. Nitsche
Tipping Points in Antarctic Climate Components	Svein Østerhus
Elevation Bias from Surface Roughness using Operation IceBridge	Thomas Overly
Acoustic Full Waveform Inversion to Recover Seismic Velocity of Firn [poster]	Emma Pearce
Passive radio sounding using the Sun as a signal to monitor subsurface processes	Sean Peters
Local basal melt rates near the Ross Ice Shelf front: Interaction of bathymetry, ocean heat fluxes, and ice damage history	David Porter
Characterization of subglacial sediment properties beneath Thwaites Glacier from seismic surface wave and receiver function analysis	Maeva Pourpoint
Surprises in the sediments collected from Mercer Subglacial Lake	SALSA Science Team

Title	Presenter
Pliocene to Recent record of West Antarctic history from the Amundsen Sea continental rise: Initial Results from IODP Expedition 379	Reed Scherer
Constraining model estimates of Antarctic surface mass balance, using satellite gravimetry and altimetry	Nicole Schlegel
Seismic Evidence for Pervasive Surface Fracturing Near the Grounding Line of the Ross Ice Shelf	Em Schnorr
Geological origins and tectonic inheritance of West Antarctica, with bearing on cryosphere processes	Christine S. Siddoway
Sinuous grounding lines often point to large retreat events to come	Lauren Simkins
A tale of two lakes – contrasting biogeochemical weathering regimes in proximal subglacial Antarctic systems.	Mark L. Skidmore
Sensitivity of submarine melting of 79N glacier to ocean forcing	Lars Smedsrud
Ice-shelf secondary flow counteracts the growth of sub-shelf basal channels	Martin Wearing
Integrating englacial reflectors across the Amundsen Sea Embayment: A progress report	Duncan A. Young
Diagnosing the sensitivity of grounding line flux to changes in sub-ice shelf melting	Tong Zhang
Laboratory produced unstable glacial slip	Lucas Zoet

Constraints on lower-than-present WAIS elevations from cosmogenic nuclides in subglacial bedrock at the Ohio Range

Robert Ackert[1], Jennifer Middleton[2], Zachary Mason[3,4], Sujoy Mukhopadhyay[3], Aaron Putnam[5], Seth Campbell[5], David Pollard[6], and Robert DeConto[7]

[1] *Harvard University, United States*
[2] *Lamont-Doherty Earth Observatory, Columbia University, United States*
[3] *University of California, Davis, United States*
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[5] *University of Maine, United States*
[6] *Pennsylvania State University, United States*
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Sea level data indicate that sea level during the last interglacial period was ∼5 m higher than present implying significant ice loss from the Antarctic Ice sheets with the WAIS the likely source. Even higher paleo-shorelines suggest complete loss of the WAIS at times during the Pliocene. Geologic evidence of past ice elevation can provide constraints on WAIS geometry over a wide range of climatic conditions. However, direct evidence for reduced WAIS extent is scarce due to cover by the extant ice sheet. Drilling through the ice is required to sample subglacial bedrock. We provide new data and proof of concept from multiple subglacial bedrock cores obtained through shallow drilling with the Winkie Drill that document frequent lower-than-present WAIS elevations at the Ohio Range in the Transantarctic Mountains during the Pleistocene.

Cores recovered from granite bedrock accessed by drilling through 10–30 m of ice, contain cosmogenic ^{10}Be, ^{26}Al, and ^{21}Ne. The cosmogenic nuclide concentrations closely follow spallation dominated depth profiles, indicating significant periods of ice-free exposure to cosmic irradiation. However, ^{26}Al/^{10}Be ratios indicate significant periods of burial by ice as well. A simple two-stage scenario provides limiting constraints on the duration of bedrock exposure and ice burial. The data indicate that bedrock surfaces 20–30 m below present-day ice levels experienced more ice-free exposure (250 kyr – 2 Myr) than ice cover (100 – 200 kyr) over the past ∼2 Myr. Thus, the subglacial bedrock data show that Pleistocene WAIS elevations at the Ohio Range were often >25 m lower than present-day. The results imply interior WAIS elevations during glacial periods were often thinner than present, likely reflecting lower accumulation rates. This is consistent with previous work that indicates maximum ice elevations in the WAIS interior occurred in the early Holocene, not the LGM. The Pollard and Deconto ice sheet models predict lower cosmogenic nuclide concentrations and lower ^{26}Al/^{10}Be ratios for bedrock at the subglacial sample elevations in the Ohio Range, indicating that modeled ice elevations are often too high. These results demonstrate the viability of using rock cores obtained by ice drilling to constrain lower than present WAIS elevations using cosmogenic nuclides.

Time-dependent freshwater fluxes from deep and shallow meltwater sources under Antarctica's large ice shelves

Susheel Adusumilli[1], Helen Amanda Fricker[1], Brooke Medley[2], Laurie Padman[3], and Matthew R. Siegfried[4]

[1], *Scripps Institution of Oceanography, United States*
[2]*NASA Goddard Space Flight Center, United States*
[3]*Earth and Space Research, United States*
[4]*Colorado School of Mines, United States*

Recent mass loss of Antarctic grounded ice is driven primarily by a decrease in buttressing as the floating ice shelves downstream lose mass by calving and basal melting in excess of steady state values. Large-scale observations of ice shelf melt rates and corresponding freshwater fluxes are difficult to make using in situ techniques, but can be inferred using satellite and airborne observations combined with output from atmospheric and firn models. We estimated height changes from CryoSat-2 radar altimetry (2010 to present) for all ice shelves at 1 km resolution averaged over the mission duration, and interpreted these results in the context of estimates of annual basal melt rates at 25 km resolution for ice shelf regions up to 81.5°S from the 25 year record (1994 to present) obtained from the ERS-1, ERS-2, Envisat, and CryoSat-2 missions. We converted ice shelf height changes to basal melt rates using vertical strain rates from satellite-derived ice velocity and a new, high-resolution (12.5 km) atmospheric and firn densification model. For the three largest ice shelves (Amery, Filchner-Ronne, and Ross), we partitioned basal melting into deep melting associated with inflows of High Salinity Shelf Water (HSSW) and shallow melting from inflows of modified Circumpolar Deep Water and seasonally warmed Antarctic Surface Water. The deep freshwater sources contribute to Antarctic Bottom Water formation, and the shallow sources feed freshwater into the upper coastal ocean where they affect ocean-atmosphere interactions, sea ice evolution, and primary productivity. The 25-year time series of meltwater production at deep and shallow sources show distinct spatial and temporal signatures that we use to examine oceanic and atmospheric drivers of melting and ocean response.

Sea level and circulation in the Southern Ocean

T. Armitage[1], R. Kwok[1], A. Thompson[2], and G. Cunningham[1]

[1] *Jet Propulsion Laboratory, Pasadena, CA, United States*
[2] *California Institution of Technology, Pasadena, CA, United States*

Sea level has been poorly observed in the Southern Ocean due to a lack of tide gauge records, poor coverage by conventional altimeters, and because large areas are seasonally or perennially covered by sea ice, where conventional altimeter processing fails. Recently, this has changed, as specialized processing techniques to extract sea level in openings in the ice cover have become more commonplace. We present a sea level record combining Envisat and CryoSat-2 radar altimetry, that provides monthly basin-wide coverage of the Southern Ocean since 2003. We find that the Antarctic Slope Current has a significant seasonal cycle and that sea level exhibits several wind-driven modes of variability, in particular, we find a significant response of sea level to both the Southern Annular Mode and El Niño Southern Oscillation climate modes. We discuss the implications of our work for sub-surface ocean variability and ice sheet-ocean interactions.

Reanalysis of Greenland temperature and precipitation over the last 20,000 years using data assimilation

Jessica A. Badgeley[1], Eric J. Steig[1], Gregory J. Hakim[1], and T. J. Fudge[1]

[1] *University of Washington, United States*

Reconstructions of past temperature and precipitation are fundamental to modeling paleo ice-sheets and to contextualizing observations of ice-sheet change. While there are numerous reconstructions of temperature, there is a paucity of information about past precipitation. Ice-sheet models commonly address this by estimating precipitation using a simple thermodynamic scaling. While thermodynamic scaling may be reasonable for glacial-interglacial timescales, a number of studies using proxies from Greenland and Antarctica have shown that it is inappropriate on shorter timescales. We reconstruct Greenland temperature and precipitation using paleoclimate data assimilation and ice core data. Data assimilation leverages the available proxy data and dynamically interpolates using spatial relationships derived from climate model simulations. For evaluation, we use out-of-sample statistical tests and compare to previously-published reconstructions. We find that thermodynamic scaling is consistent with our reconstructions for the last 20,000 years on 50 to 5000-year timescales; however, this relationship is significantly in error for shorter time periods. We obtain spatial variations in the temperature-precipitation relationship that may have implications for reconstructions of the paleo Greenland ice sheet. By reconstructing past temperature and precipitation for Greenland, we showcase the strengths that data assimilation will bring to paleoclimate reanalysis for Antarctica.

A new look at the Whillans Ice Plain stick-slip cycle: Tidally regulated precursory sliding affects unstable slip onset location and seismic wave radiation

Grace Barcheck[1], Emily E. Brodsky[2], Patrick M. Fulton[1], Matt A. King[3], Matthew R. Siegfried[4], and Slawek Tulaczyk[2]

[1] *Cornell University, United States*
[2] *University of California, Santa Cruz, United States*
[3] *University of Tasmania, United States*
[4] *Colorado School of Mines, United States*

We report new GPS observations of precursory sliding before Whillans Ice Plain (WIP) unstable slip events. On the Siple Coast of West Antarctica, the WIP flows into the Ross Ice Shelf by a unique stick-slip style of sliding, in which hours-long periods of slow stable ice sliding are punctuated once or twice daily by sudden acceleration of ∼0.5 m in ∼30 minutes. Timing of these "unstable slip events" is modulated by tides beneath the Ross Ice Shelf. Previous work shows that the main "dynamic" phase of unstable slip starts in one of two regions, or "epicenters": a "central" area near the upstream end of a ∼30 km wide "locked" area of strain accumulation, and a grounding zone (GZ) region, where there is no apparent strain accumulation in GPS observations, but which may ephemerally accumulate strain due to tidal flexure. Despite a number of excellent previous WIP observational campaigns, questions remain about why unstable slip switches epicenters and what role the tides play in triggering the events. To address these questions, we use GPS stations deployed ∼5km from each epicenter and on floating ice for 59 days in 2014 (85 slip events), which allow for a direct comparison of ice movement at each epicentral area before and during unstable slip.

Our GPS observations reveal that most WIP unstable slip events during this period exhibit precursory sliding of 1s to 10s of cm over 1s to 10s of minutes at one epicenter or the other before the main phase of "dynamic" (fast) unstable slip. Which epicenter has precursory sliding is strongly affected by tidal phase: precursory sliding at the GZ GPS nearly always occurs in a 2 to 5 hour window after high tide near the GZ epicenter, while precursory sliding at the central GPS occurs randomly with respect to tide. We also compare timing of peak velocity and acceleration at each GPS to demonstrate that the main dynamic slip phase typically begins first at the opposite epicenter from precursory sliding, suggesting that precursory slip at one epicentral area loads and eventually triggers dynamic slip at the opposite area. Finally, GZ precursory sliding reduces peak velocity and acceleration at that GPS and eliminates seismic wave radiation observable at a far-field seismometer, while precursory sliding at the central GPS has little impact on local peak velocity or acceleration.

Our results show that most WIP slip events begin with precursory sliding at one epicenter, which likely propagates slowly across the ice stream and triggers dynamic unstable slip at the other epicenter. We attribute this systematic precursory process to slip expansion in a heterogeneous ice stream strain field generated by variable ice-bed locking and tidal loading, in which insufficient strain energy causes precursory slip to begin expanding at a slow pace until it reaches a highly strained area. Tidally controlled sliding events comparable to the GZ precursory slip likely occur at other ice stream grounding zones and may be revealed by high-rate GPS observations. These results also offer new insight into tectonic earthquake nucleation processes.

On the combination of factors that influenced the post-LGM grounding zone positions in eastern Ross Sea

Philip J. Bart[1] and Matthew DeCesare[2]

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[2] *Department of Geosciences, Auburn University, United States*

Following the Last Glacial Maximum (LGM), the Bindschadler Ice Stream (BIS) in eastern Ross Sea experienced at least two major grounding line position still stands. The first occurred between ~15 and 11.5 cal kyr BP with grounded ice being relatively stationary within approximately 70 km of the continental shelf edge. The BIS grounding line was stabilized downstream of a bottleneck between the Hayes and Houtz Banks that border the Whales Deep Basin. The still stand occurred despite elevated insolation, rapid sea-level rise, intermittent intrusion of Circumpolar Deep Water and an ice-shelf breakup. Accelerated ice-stream discharge (following the ice-shelf breakup at ~12 cal kyr BP) caused rapid grounding zone sedimentation, which created a foredeepened subglacial profile. These factors in combination with rapid sea-level rise triggered an abrupt 200 km retreat. The second grounding line still stand established shortly thereafter at Roosevelt Island. Ice stream flow was evidently re-buttressed on the middle continental shelf adjacent to this broad shallow bank until 3.2 kyr BP. Since the end of the Roosevelt-Island grounding still stand, the extent of grounded ice has contracted another 500 km. The absence of sea-level rise, elevated insolation or evidence of other external forcing in the late Holocene suggests that this major retreat was a consequence of internal controls perhaps coupled with the lack of significant pinning points below this sector of the Ross Ice Shelf. It is not known how the late Holocene retreat progressed or whether the modern grounding line position constitutes a third stillstand or an ongoing retreat (within a geological context). This synthesis of the available data shows that since the LGM, the paleo-BIS experienced at least two millennium-long intervals with relatively stationary grounding zone positions. Both the outer-continental-shelf and Roosevelt-Island stillstands were followed by major retreat of grounded ice (≥200 km). These oscillations of the paleo-BIS appear to have been a complex response to multiple external and internal factors coupled with specific topographic boundary conditions.

An overlooked ice-shelf calving process for accelerating Antarctic Ice Sheet loss

Maya K. Becker[1], Helen A. Fricker[1], Laurie Padman[2], Matthew R. Siegfried[3], Cyrille Mosbeux[1], and Till J. W. Wagner[4]

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[3]*Colorado School of Mines, United States*
[4]*University of North Carolina Wilmington, United States*

Nearly half of the melting below each of Antarctica's two largest ice shelves, Ross (RIS) and Filchner-Ronne (FRIS), and a significant portion of the melting below its third-largest ice shelf, Amery (AIS), occurs within 100 km of their ice fronts from the intrusion of seasonally warmed upper-ocean waters. This melting process contributes to a broad region where surface elevation declines smoothly toward the ice front. In some places along the ice front, thermal and physical erosion near the waterline leaves behind a submerged bench of ice whose buoyancy pushes the seaward edge upward, generating a flexural depression typically within a kilometer of the ice front. This stress imbalance induces an additional extensional stress at the ice base, facilitating widening of basal crevasses and, eventually, leading to a relatively small, front-parallel calving event. Here, we investigate the distribution of this "rampart-moat" surface morphology across the RIS, FRIS, and AIS fronts with repeat-track satellite laser altimetry from the Ice, Cloud and land Elevation Satellite (ICESat) and airborne laser altimetry from ROSETTA-Ice and Operation IceBridge. ICESat data reveal the existence of the feature on all three ice shelves and enable us to examine the evolution of ice-front surface profiles during ICESat's operational period (2003–2009). Several ICESat tracks that cross the ice-shelf fronts show a cycle of calving and subsequent rampart-moat redevelopment. We discuss observed spatial patterns in ice-front evolution and geometry in the context of the regional oceanography and sea-ice variability that influence seasonal warming of the upper ocean near the ice front. Combining these observations with satellite imagery and insights from elastic and viscous ice-shelf models, we estimate the amount of mass loss due to this calving process and speculate about how this mass-loss term might increase in future climates.

Inferring Temperature Distribution in Shear Margins using an ApRES and Software Defined Radio in a Bistatic Configuration

Nicole L Bienert[1], Dustin M Schroeder[1,2], Sean T Peters[1], Matthew Siegfried[3], Emma Mackie[2], and Eliza Dawson[2]

[1]*Department of Electrical Engineering, Stanford University, United States*
[2]*Department of Geophysics, Stanford University, United States*
[3] *Department of Geophysics, Colorado School of Mines, United States*

The physical processes controlling the location and stability of shear margins are poorly understood when topographic controls are absent. Recent modeling studies have indicated that shear margin behavior may be controlled by elevated temperatures and water content in the bottom half of the shear margin, while other studies predict that ice shear margins exist over concentrated subglacial water channels. Radio echo sounders can provide measurements of englacial water storage and subglacial conditions, but existing radar sounding techniques cannot measure the distribution of temperature and water to test these hypotheses. Monostatic radar measurements only discern depth averaged attenuation accurately, and due to the poor signal-to-noise ratio (SNR), bistatic systems have been unable to attain the large antenna separations necessary to resolve a temperature gradient. To address this challenge, we develop and apply a bistatic system that overcomes the SNR challenge of large antenna separations through coherent summation of phase re-aligned signals without relying on synchronization. The experiment is designed to minimize cost to glaciology community members by utilizing a common instrument, the ApRES, as a transmitter for the bistatic receiver which is a Software Defined Radio (SDR). The system's basic functionality has been verified at Siple Coast, West Antarctica with up to 1.3 km antenna separation. Recent data from Store Glacier, Greenland will be presented with complimentary simulations to determine if varying basal conditions and ice thickness are significant enough to require monostatic measurements in conjunction with bistatic. The measurement technique is planned for deployment to the eastern shear margin of Thwaites Glacier, West Antarctica in November 2019. By mapping the temperature distribution of shear margins, our bistatic measurement technique provides an observational method to test the hypotheses that temperature and water distribution influence a shear margin's evolution.

A 3D Model of Antarctic Ice Shelf Hydrology

Sammie Buzzard[1] and Alex Robel[1]

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The accumulation of surface meltwater on ice shelves can lead to the formation of melt lakes. Melt lakes have been implicated in crevasse propagation and ice shelf collapse, causing a loss of ice shelf buttressing, leading to an acceleration in glacier discharge and contributing to sea level rise. The Larsen B ice shelf on the Antarctic Peninsula was observed to have a large amount of melt lakes present on its surface just before its collapse in 2002.

Recent observations suggest that surface hydrology processes on ice shelves are more complex than previously thought, and that lateral transport of meltwater across ice shelves, ice shelf flexure and surface debris all play a role in the spatial distribution of meltwater and its influence on ice shelf stability.

We present a new 3D model of Antarctic ice shelf hydrology. The model code is based on updates made to the Buzzard et al. (2018) mathematical model of melt lake formation on an idealized ice shelf. The previous model incorporated a calculation of the surface energy balance of an ice shelf, heat transfer through the upper ice shelf, the production and percolation of meltwater into the firn, the formation of ice lenses in the firn and the formation, development and refreezing of surface melt lakes on the ice shelf, all in one dimension. In the new 3D modeling framework, we can incorporate key processes such as the lateral transport of surface meltwater, viscoelastic ice shelf flexure under loading and ice erosion by water flow. We discuss the model architecture, challenges for application to real ice shelves, and the prospect for model validation with new high-resolution data products.

Physical and chemical characterization of sediments from Mercer Subglacial Lake, West Antarctica

Timothy D. Campbell[1], Molly O. Patterson[2], Mark L. Skidmore[1], Amy Leventer[3], Alexander B. Michaud[4], Brad E. Rosenheim[5], David Harwood[6], John E. Dore[1], Martyn Tranter[7], Ryan A. Venturelli[5], and the SALSA Science Team

[1]*Montana State University, United States*
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[4]*Bigelow Laboratory for Ocean Sciences, United States*
[5]*University of South Florida, United States*
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More than 400 subglacial lakes are known to exist beneath the Antarctic Ice Sheet. These lakes serve as archives of landscape evolution, harbor microbial ecosystems, and in part control ice sheet dynamics. Despite their importance, little is known about Antarctic subglacial lake sedimentary depositional processes and subsequent structures. The Siple Coast ice streams of the West Antarctic Ice Sheet (WAIS) are underlain by a variable sedimentary cover including subglacial till. We propose that subglacial lakes in this region of the WAIS receive sediment from the melt out of debris entrained in the overlying ice sheet with additional input from hydrological transport of suspended material from upstream environments. Here, we present data on the physical and mineralogical characteristics of sediment cores collected from Mercer Subglacial Lake (SLM) during the 2018–2019 austral field season in order to evaluate the sedimentology and sedimentological processes occurring in the subglacial environment of West Antarctica. Short cores (0.3–0.5 m) were collected using a multicoring device which captured an undisturbed sediment-water interface, while longer cores (1–1.7 m) were collected using a free-fall gravity corer. The sediment record from SLM shows stratigraphic variability in terms of grain size distribution, clast abundance, mineralogical composition, and water content. These variations may reflect unique lithofacies associated with different subglacial depositional systems and processes. This suggests that the geologic history of this area may include temporal variations archived in the sediments. These results provide important information on the substrate properties beneath this hydraulically active Antarctic subglacial lake (only the second such lake ever sampled) and enhance our understanding of the history and dynamics of the West Antarctic Ice Sheet.

Contrasting outlet glacier responses to ocean vs. interior forcing

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The dynamic behavior of marine-terminating outlet glaciers is a key uncertainty in the cryosphere's response to a warming climate. Many outlet glaciers have accelerated and/or retreated, but observed changes differ between glaciers, and the variety of glacier geometries and climate forcings complicates comparisons across settings. Additionally, short observational records make it difficult to view recent changes in the context of the relevant climate history and dynamic response of the full outlet glacier, from grounding zone to ice-divide. While further observation is critical for characterizing the behavior of these systems, progress can also come from studying fundamental, general constraints that govern their dynamics.

We focus on a principle common to all marine-terminating outlet glaciers: climate forcing can come from surface mass balance changes over the glacier's interior catchment, and/or via ocean forcing that affects ice discharge at the grounding line. We explore these two distinct forcing types using a numerical flowline model and a recently developed reduced model. The latter approximates an outlet glacier as a dynamical system with two fundamental modes: a fast mode associated with grounding zone evolution, and a much slower mode associated with the adjustment of interior ice. Simplified experiments on stable geometries show that, in comparison to surface mass balance forcing, ocean forcing elicits a much faster initial terminus response, and larger terminus fluctuations in response to stochastic variability. Including decadal persistence in the forcing variability, as would be expected for ocean forcing, increases the variance further still. The reduced model provides a simple interpretation: ocean forcing projects more strongly onto the glacier's fast dynamical mode than does surface mass balance forcing. However, for either type of climate forcing, the equilibrium response to a long-term change is dominated by the slow mode, which operates on multi-millennial timescales.

We conclude by discussing three key implications of these findings. Firstly, the slow mode requires that observed responses to anthropogenic forcing are a small fraction of the total committed response, especially for the case of surface mass balance forcing. Secondly, the sensitivity of grounding-line flux to ocean variability, and the persistence in the variability, determines the detectability of forced change on centennial timescales. Finally, if grounding line flux is sensitive to ocean forcing, pre-industrial ocean variability is imprinted on the glacier's preindustrial state, and should be considered for glacier reconstructions and model initialization to project future glacier behavior.

Using radar sounding observations to improve numerical models' estimates on ice sheet temperatures in West Antarctica

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Ice-sheet temperature, especially in the lower half of the ice column, influences ice flow strain rates and exerts a strong control on the deformation of ice. Presently, our knowledge about ice temperature is provided either by sparsely distributed borehole measurements or from numerical ice-sheet modeling. Numerical models can reconstruct the general continental-scale pattern of deep-ice temperature in Antarctica. However, at the glacier catchment scale, there is often significant disparity among such models on their depiction of the basal thermal regime. This problem is particularly pronounced in the Amundsen Sector in the West Antarctica Ice Sheet (WAIS), where accurate reconstructions of temperatures at the base of Pine Island and Thwaites Glaciers are essential to characterizing processes responsible for their motion and, thus, on their potential contributions to sea-level rise. Here, we demonstrate the potential of integrating NASA IceBridge radar-sounding data into the JPL/UCI Ice Sheet System Model (ISSM) to improve its performance on calculating the basal thermal regime. We present a methodology that reconstructs basal temperature using an inversion based on two cost functions that measure misfits between radar-observed and modeled englacial radio-wave attenuation rates and basal reflectivity coefficients. A comparison at the WAIS Divide ice core between the measured and modeled temperature profiles demonstrates a $\sim$9°C difference in basal temperature before the optimization. This difference is reduced to $\sim$1.4°C after integrating radar sounding data into the ISSM model. We also show how the radar data-model integration can be used to calculate the geothermal heat flux of West Antarctica.

Englacial Layers in Radar Sounding Data Modeled from Ice Core Electrical Stratigraphy

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Deep ice cores provide high resolution insight into the age structure and past climate parameters of ice sheets. Unfortunately, these records are inherently limited to point measurements. By contrast, airborne radar sounding can image the englacial structure over large areas, but does not provide direct information on the physical or chemical properties of the ice sheet. However, quantitatively linking radar stratigraphy with ice core electrical stratigraphy allows us to investigate the physical nature of the observed layers, as well as propagate age-depth relationships across large regions. We develop and apply a computationally efficient electromagnetic forward model which uses dielectric profiling or electrical conductivity measurements to simulate depth-power profiles from a chirped pulse radar of arbitrary center frequency and bandwidth. Our simulations show excellent agreement with radar surveys at those Antarctic and Greenland deep core sites where conductivity profiles are available. Based on differences between the modeled and observed profiles, we infer transition points in density variability within the ice column, as well as the possible onset of layer roughening which may contribute to the echo free zone. In many cases, peak-matching is possible between simulated and observed data, so radar layer age can be determined by direct association to dated conductivity peaks. Similarly, we match distinct layers across surveys by different radar systems without transect crossovers by attributing them to common portions of the core conductivity profile. Our model contributes to improved understanding of the expression of physical ice sheet structure in radar observables, and can be applied to combine englacial structure information from different radar systems with greater fidelity.

A Method for Quantifying Meltwater Volume Using ICESat-2 Laser Altimetry and High-Resolution Planet SkySat Imagery

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Here, we quantify surface meltwater volume in early June, 2019 over a swath of western Greenland crossing the flowline of Sermeq Kujalleq (Jakobshavn Isbræ glacier), one of the fastest-moving glaciers in Greenland.

We first use ICESat-2 laser altimetry to estimate lake depth from dual interface returns (air-water and water-ice). These depths are used to calibrate a spectrally driven depth estimate from Planet SkySat imagery (at a 1-m resolution), which is then used to estimate meltwater volume over the full image. The high spatial resolution of this imagery allows for the detection of small stream features and different bottom surface types. These estimates will also be compared with Sentinel -based estimates for meltwater depth/volume, allowing us to directly compare volumes calculated by both methods.

Future work will apply this method over the full Greenland melt season for multiple swath locations, taking advantage of the high revisit time of Planet SkySat. Additionally, this study will produce a testbed of melt pond types and states; i.e. both imagery and altimetry estimates before, during, and after the presence of a melt pond over grounded ice. This testbed can potentially be used to hone a method for estimating the presence and depth of short-lived or small surface meltwater features based on ICESat-2 estimates alone.

Vulnerability of the Antarctic ice sheet to basal thermal regime change: Integrating observations and models

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Glacial thermal processes are a fundamental control on ice flow, governing both the ice viscosity and frozen-to-thawed transitions at the ice-bed interface. In warming climate scenarios, glacier flow is projected to accelerate which could potentially cause previously frozen ice at the bed to thaw, creating a feedback to the glacier flow regime and changing the ice sheet surface profile. Given the importance of the basal thermal state on ice stream dynamics in Antarctica, a rapid change in the bed condition could accelerate retreat in parts of the Antarctic ice sheet. However, work in this area has been limited by the scarcity of direct temperature measurements and inadequate modeling of these processes. Here we introduce radar sounding as a powerful addition for understanding thermal processes since the englacial radar attenuation is sensitive to temperature. We utilize NASA Operation Ice Bridge (OIB) radar sounding measurements to provide critical information about the basal thermal regime across Antarctica and its variations in space and time. We develop a novel method using a combination of radar observations, 1D heat flow and numerical modeling (Ice Sheet System Model) of the basal thermal state to assess its role in driving ice flow. We provide assessments for what regions of West and East Antarctica could be most sensitive, and for those areas, we provide catchment scale estimates of volume change that could be expected if forced by warmer basal conditions. By introducing a new approach to analyze the role of the basal thermal state, this work adds to the conversation about expected ice loss and contributions to sea level rise from vulnerable regions of Antarctica.

A poro-damage approach to simulating hydrofracture of glaciers and ice shelves

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The dynamic ice mass loss from the Antarctic ice sheet into ocean is one of the greatest sources of uncertainty in predicting future sea level rise. The fracture and detachment of icebergs, that is, calving is an important control on the mass loss from the ice sheet, and is intricately linked to climate dynamics through processes such as hydrofracturing. It has been hypothesized that hydrofracturing of ice shelves followed by ice cliff failure in Antarctica could contribute to rapid sea level rise over the coming centuries. Simulating hydrofracture propagation using process-based models can provide a better understanding of the conditions enabling full depth crevasse penetration and calving. To this end, we develop a new, nonlocal continuum poro-damage mechanics (CPDM) approach to simulate the propagation of water-filled surface crevasses in idealized rectangular glaciers based on creep-damage-mechanics and poro-mechanics. Using idealized simulations studies on rectangular glaciers in two-dimensions (plane strain conditions), we compare the penetration depths of isolated and closely-spaced water-filled surface crevasses predicted by the CPDM model with those from existing crevasse depth models. We find that the CPDM model is in good agreement with the linear elastic fracture mechanics (LEFM) models for an isolated surface crevasse and with the zero stress model (to a lesser extent) for closely-spaced surface crevasses, except when the glacier is near-floatation. We also examine crevasse propagation in relation to ice rheology, fracture process zone size, and basal boundary conditions using sharp crack and damage mechanics models. Based on these simulations studies, we argue that floating ice shelves are more vulnerable than grounded glaciers due to the combination of meltwater-induced hydrofracture and plate bending. To conclude, we discuss the limitations of the creep damage mechanics model and directions for future work, including modeling shear-dominated failure under compression using strain-energy-based damage models.

Electrical Resistivity Measurements of the McMurdo Ice Shelf, Antarctica, Reveal Seawater Intrusion in New Detail

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Ice shelves provide significant buttressing back stresses to the Antarctic ice sheet, reducing flux of grounded ice to the ocean. The stability of ice shelves is therefore of great importance to ice sheet evolution and predictions of near-future sea level rise. An important factor is the structure of the ice shelf itself, which can be affected, particularly near the front, by fracture and infiltration of seawater. Here we present airborne electromagnetic (AEM) resistivity measurements of the McMurdo Ice Shelf, a complex and heterogenous fringing ice shelf next to the US McMurdo Station. Because of the resistivity contrast between nonconductive pure meteoric ice and highly conductive salty water and ice, EM techniques excel at imaging the infiltration of seawater and brine into ice and firn. In contrast to radar, a higher frequency technique which images easily through highly resistive meteoric ice, EM resistivity measurements can more easily penetrate through some conductive layers, allowing for complete imaging of ice shelf thickness even in the presence of briny, conductive horizons.

Our measurements reveal the complexity of processes that can weaken an ice shelf through seawater infiltration. Seawater appears to penetrate the McMurdo Ice Shelf both from below, via basal crevasses, and from the front, where it directly floods the permeable firn layer. Once stored in the firn layer, seawater can migrate along the ice-firn contact for kilometers. In the western part of the McMurdo Ice Shelf, the floating ice tongue of the Koettlitz glacier can be seen transforming into a mélange of more icebergs surrounded by saline ice. Finally, the contrast ice between the McMurdo Ice Shelf and the adjacent larger Ross Ice Shelf can be easily distinguished. The Ross Ice Shelf is thicker and free of seawater intrusion, except near the shear zone that separates them.

The extent of seawater intrusion into the ice shelf, and the processes by which it is accomplished, need to be incorporated into predictions of ice shelf stability and should be generalized for ice shelves across Antarctica. Seawater—through its density, ability to advect and conduct heat, and depression of the freezing point of ice—represents a potential threat to ice shelf stability. This new imaging expands the domain of ice shelf-seawater interaction to include the internal structure of the ice shelf. The AEM sensor system used by us is very suitable for efficient mapping of internal ice shelf structure given the fact that it can penetrate up to 600–800 m of glacier ice underlain by conductive seawater and can directly image marine ice layers and seawater-flooded horizons.

WAIS Deglacial Dynamics and Confusing Ice Core Records

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Unlike most deep ice cores, the Siple Dome core was drilled at a site selected to investigate ice dynamics instead of paleoclimate. The records revealed two time periods that still remain difficult to explain twenty years after the core was collected. A new chronology has been developed for Siple Dome that incorporates information from the more recent Roosevelt Island and WAIS Divide projects.

Using the new chronology, Siple Dome has a 3.5‰ jump in δ^{18}O at ∼22 ka and a 2‰ jump in δ^{18}O at ∼14.8 ka. There is also a loss of the normal stagnant air column in the firn at ∼14.8 ka. These features do not appear in the Byrd, WAIS Divide or Roosevelt Island cores. Chemical and gas records preclude an accumulation hiatus as the cause of these events. It is difficult to explain how a purely climatic phenomenon with the large amplitude seen in the Siple Dome core did not have sufficient spatial extent to influence the other core sites. This pushes us to search for an ice dynamics explanation for the anomalous features at Siple Dome.

At 14.8 ka, the Roosevelt Island core shows a sharp reduction in the accumulation rate, falling in half from approximately 0.2 m a^{-1} to 0.1 m a^{-1}. This is coincident within the dating uncertainty with the anomalous firn column and δ^{18}O increase at Siple Dome. While seemingly coincident in time, the expression is very different between the two cores: Roosevelt Island's firn column remains consistent with an accumulation rate of half the previous value, while Siple Dome's accumulation rate stays at previous levels after the disruption of the firn and abrupt change in δ^{18}O. The anomalous features at Siple Dome likely shortly preceded the rise in sea level known as Meltwater Pulse 1A, but it is not possible to make a definitive connection. An abrupt change in the locations and or elevations of the ice streams bounding Siple Dome may be responsible for the anomalous features in the core, but without additional information that is only speculation.

At 22.3 ka, the WAIS Divide core contained evidence of a subglacial eruption in central WAIS. This is within the dating uncertainty of the 22.2 ka event at Siple Dome. Siple Dome is bounded by Kamb and Bindschadler ice streams, while Roosevelt Island would have been bounded by Bindschadler and MacAyeal ice streams. A significant change in Kamb ice stream due to enhanced subglacial meltwater from a subglacial eruption could have affected Siple Dome, but not Roosevelt Island. However, without corroboration at Roosevelt Island and a precise timescale match, any connection remains speculative.

There are four other periods of abnormal firn gases. The Siple Dome core is most likely recording the local response to large changes in the ice dynamics around Siple Dome, but the details remain elusive. The Siple Dome record is a reminder that we still have a lot to learn about the processes involved when WAIS adjusts to new climate conditions.

Prospecting for Gold: Finding the optimal site for a deep ice core at Hercules Dome, Antarctica

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Hercules Dome has been identified by the US ice-core community as the next deep drilling target. Here we present results from the first of three field seasons of a detailed site-selection radar survey. Hercules Dome is a ∼100 x 100 km complex with two distinct topographic ridges connecting three flow centers termed West, East, and South domes based on their map positions. Two new ground-based radar transects were acquired at both West and East Domes.

West Dome has undisturbed internal layering to within tens of meters of the bed. The divide position appears controlled by a ∼100 m bedrock high on an otherwise flat bed. The ice is 1600 m thick. Ice-and-heat flow modeling and englacial radar-attenuation rates suggest the bed is frozen and a continuous climate record from the Last Interglacial (130 ka) is preserved.

The US-ITASE 2002–2003 traverse crossed the flank of East Dome. Our new radar transects confirm the presence of thick ice and undisturbed stratigraphy; however, due to logistical limitations, the radar lines were not oriented across the divide and three-dimensional flow appears to affect the thickness of layers at mid-depths.

Field work at Hercules Dome will occurring in the upcoming two austral summers. Additional data is being collected with a suite of ground-based radar systems, GNSS receivers, thermistors, and shallow cores. These data sets will better constrain the internal stratigraphy, basal conditions, englacial and surface velocities, and surface conditions of mean annual temperature and accumulation rate. Together, this work will identify the optimal location for a deep ice core.

From WAIS Workshop to the World—Perspectives on Successful Outreach and a Plan for the WAIS Community

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Accelerating changes in the West Antarctic Ice Sheet, an alarming greenhouse gas emission trajectory, and a deficiency of political action to combat Climate Change make it clear that vigorous, targeted, and coordinated science communication must be among the top priorities of the WAIS community. With a range of media ever competing for the public's attention, capturing the layperson with easily understood and scientifically accurate information is particularly challenging. While the seriousness of polar melting is gradually seeping into the public consciousness via mainstream media and the sci-comm efforts of individual scientists and independent communicators, we will achieve greater engagement and more quickly by adopting a unified Outreach strategy.

I explore what the WAIS community can learn from a successful Outreach program and discuss my ideal Outreach plan for the WAIS. This includes: a range of easily accessible tools, shareable resources, and best practices for reaching an expanded audience; sharing the latest research and amplifying the efforts of individual science communicators; and making science communication far easier and less time-consuming for the WAIS community.

The Onboard Outreach Program (OOP) aboard the JOIDES Resolution sets the gold standard for science communication and Outreach, providing engaging, clear, and accurate information for a broad, global audience, and it is an excellent instructional model. I examine the success of the OOP's multifaceted approach to public engagement and education, including: an accessible, visually appealing, and easy to navigate centralized information source; coordinated social media platforms; downloadable educational resources; and live broadcasts. I discuss how the WAIS community might benefit from adopting a similar approach, additions to the OOP model that would enhance a WAIS strategy, and the components of an ideal Outreach plan for the WAIS.

A successful Outreach program also offers opportunities for growth of the scientist as communicator and nurtures an individual's unique communication skill set. Providing scientists with the training and resources they need to become better science communicators is an integral part of this ideal Outreach plan. Polar researchers, together with dedicated communicators and creatives, are on the vanguard in this battle to capture the public's imagination and combat misinformation and disinformation, and with a cohesive, unified strategy and fast, easy access to the right tools and resources, we can expand the reach of our work and inspire individual, group, and political action.

Into the Last Glacial Maximum: The Timing of Ice Growth in Marie Byrd Land, Antarctica

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We present constraints on the timing of ice thickening culminating in the Last Glacial Maximum, broadly defined, in the Ford Ranges of Marie Byrd Land. Excess of the in situ cosmogenic nuclide carbon-14 in bedrock relative to that predicted from independent knowledge of the deglaciation age allows for the determination of when ice advanced or thickened enough to cover a site. Beryllium-10 exposure ages of erratic cobbles from the Ford Ranges region suggest a mid- to late-Holocene deglaciation [Stone, J. O., et al., 2003. Holocene Deglaciation of Marie Byrd Land, West Antarctica. Science, 299, 99-102.] following the Last Glacial Maximum. Exposed bedrock surfaces generally preserve long-lived nuclides through multiple glacial cycles. We measured in situ carbon-14 in samples from three sites (Mt Atwood, Mt Van Valkenburg, Mt Darling) along the upper Boyd Glacier, 50–75 km from the modern grounding line, and an additional site (Migmatite Ridge, informal name) further down-flow, but not directly adjacent to Boyd Glacier, to determine the timing of ice thickening. Results indicate that ice thickening began 22–20 ka at the lowest elevation sites closest to the modern ice surface. Maximum ice thickness is not reached until between 12 and 8 ka at the highest elevations. Furthermore, maximum ice thickness is generally reached at progressively more recent times up-glacier. Ice thickening in Marie Byrd Land began late in the Last Glacial Maximum relative to the northern hemisphere ice sheets and in some cases was at its maximum thickness for no more than a few millennia. Initial ice thickness changes beginning around 20 ka occurred during a period of low accumulation observed in the Siple Dome ice core. Thickening during low accumulation implies grounding line forcing, possibly tied to a fall in relative (eustatic) sea level at that time. However, we cannot rule out control by ocean temperatures at the grounding line or complicated grounding patterns given the topography/bathymetry of Sulzberger Bay. Maximum ice thickness between 12 and 8 ka correlates with maxima in Siple Dome accumulation rate around 12–10 ka in spite of increasing eustatic sea level.

Basal to bedrock:
Magnetotelluric imaging of an active subglacial hydrologic system

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Antarctic subglacial hydrologic systems modulate ice sheet dynamics, influence grounding line stability, host microbial communities, and deliver freshwater and nutrients to the Southern Ocean. Repeat satellite altimetry measurements over the last 15 years have identified active subglacial lakes and highlighted the dynamic and potentially cyclic nature of these systems. In West Antarctica, Whillans Ice Plain hosts a series of interconnected active subglacial lakes that undergo filling and draining cycles, which have been linked to changes in ice acceleration. While satellites can detect changes in subglacial water, the total volume of water and the mechanisms by which water is stored and transported remains unknown, even after detailed seismic and radar surveying. Geophysical methods capable of sensing hydrologic variations in at least the upper kilometer of the basal environment are necessary in order to address this ambiguity and constrain the dynamics of sub-ice hydrology. Here we present the first magnetotelluric (MT) survey of an active subglacial hydrologic system. We build on previous geophysical and direct access studies of Whillans Subglacial Lake (SLW) and the grounding zone where SLW is thought to drain into the Southern Ocean beneath Ross Ice Shelf. We collected 27 MT soundings over SLW and 16 soundings over the grounding zone to investigate two prevailing hypotheses: 1) SLW is underlain by a deep saline groundwater reservoir and 2) subglacial freshwater and sub-ice-shelf ocean water mix in an estuarine-like environment at the grounding zone. Our MT data show lateral variations in the subglacial hydrology both at SLW and in the grounding zone, providing the first insight into the deeper groundwater systems of West Antarctica.

Southern Ocean Storm positions and intensity estimated with seismic observations in the Ross Ice Shelf

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Antarctic Ice Shelves are impacted by swell waves originating under extra-tropical cyclones over the Southern and North Pacific Oceans. Swell waves are long period ocean waves that are generated by strong surface winds. The gravity wave spectra contain characteristic information about storm wind speed, fetch size, and intensity. Modern optimization (machine learning) techniques are applied to two years of seismic observations of dispersed swell waves collected near the Ross Ice Shelf front to trace the origins of wave events in the Southern Ocean with an accuracy of 110 km and 2 h from a hypothetical point source. The observed wave spectra attenuate within sea ice and in the ice shelf, but retain characteristics that we compare to parametric spectral wave models. Comparisons with the MERRA2 and ERA5 reanalysis products suggest that about 60% of the observed wave events cannot be matched with Southern Ocean high wind events. The reanalysis cyclones and winds are often miss placed by about 450 km (corresponding to $\sim$6 hours) in both reanalysis products when compared to the most likely position inferred from the seismic data. This method (Hell et al., JTech, 2019) can be applied to any coastal or near-front ice shelf seismic observations around Antarctica that receives swell waves , and will be used to characterize impacts of swell and infragravity waves on the RIS, and also tested to estimate critical sea-ice properties, such as ice thickness and wave attenuation during all seasons.

Searching for subglacial evidence of past West Antarctic Ice Sheet collapse – 2: Ice sheet modeling

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Measurements of cosmogenic nuclides in subglacial bedrock at the Pirrit Hills, West Antarctica show that the ice there has not thinned by 150 m or more relative to present during the last 2–3 million years. To determine the relationship between ice thickness at the Pirrit Hills and the size of the ice sheet, we ran a large ensemble of 3D ice sheet model simulations of the West Antarctic Ice Sheet (WAIS). We used the Pennsylvania State University ice sheet model in a nested configuration. In this approach, the entire continent is first modeled at coarse (40 km) resolution. This output is then used to establish time-varying boundary conditions for higher-resolution (20 km) simulations of the WAIS. We modeled the ice sheet through three of the warmest interglacial periods of the latter half of the Pleistocene: Marine Isotope Stages 31 ($\sim$1.1 Myr BP), 11 ($\sim$400 kyr BP), and 5e ($\sim$125 kyr BP). We explore 90 parameter combinations for each interglacial period by varying the isostatic rebound timescale, sub-ice-shelf melting parameterization, slipperiness of the modern seafloor, and coefficients of ice shelf hydrofracture and ice cliff failure (including zero). We find that ice thickness at the Pirrit Hills predicts on average $\sim$70% of the variance in ice sheet volume above floatation. In our simulations, full WAIS collapse (i.e., a seaway connecting all three sectors) only occurs when using the most aggressively destabilizing parameter combinations, and then only during Stage 31. The modeled ice sheet around the Pirrit Hills thins by >150 m in almost all simulations during Stages 31 and 5e, which is inconsistent with the subglacial bedrock data. During Stage 11, modeled Pirrit Hills ice thicknesses approach the 150 m threshold, but do not cross it by a significant margin. Some simulations do not predict any significant deglaciation of the Pirrit Hills during Stage 11. In these cases, a large and stable ice shelf persists in the Weddell Sea through the interglacial, preventing ice sheet drawdown at the Pirrit Hills. This indicates that a large, buttressing ice shelf may have been present in the Weddell Sea during interglacial periods for the 2–3 million year duration of continuous burial of the Pirrit Hills drill site. Our results cannot exclude the possibility of a deglaciation initiated in the Amundsen Sea sector that leaves the large ice shelves intact, such as that modeled by Feldmann and Levermann (2015). The Pirrit Hills are not significantly deglaciated in their simulation, despite a 3 m sea-level contribution from the WAIS. Future recovery and analysis of subglacial bedrock from throughout West Antarctica is necessary to constrain the minimum extent of the ice sheet during the Pleistocene.

An ‘extended’ Stefan problem with applications for slush formation in glacier boreholes

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Glacier boreholes are drilled for englacial and subglacial access, with the intent of either retrieving material from the bed or for down-hole experimentation. Water-filled boreholes refreeze in a matter of hours or days, and prior attempts to maintain boreholes with antifreeze have historically resulted in a plug of slush effectively freezing the hole even more quickly. Here, we use a cylindrical Stefan model with thermal and molecular diffusion to represent this slush formation and run a parameter-sensitivity test with the intent of mitigating the process. We find that slush always forms in cases where the dimensionless Lewis number (thermal over mass diffusivity) is greater than one. Thus, the slush process is driven by solute accumulation near the borehole wall as it freezes back in, effectively suppressing the solution temperature in a supercooled zone near the wall. With the goal being slush avoidance, or at least minimization, we find that antifreeze should be added to the hole soon after drilling to avoid freeze-back of the hole all together.

Seasonal ocean temperature influence on glacier velocities: Observations and model experiments beneath Dotson Ice Shelf, West Antarctica

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Remote-sensing observations from the Amundsen Sea Embayment (ASE) suggest that marine ice-sheet instability may well be underway; however, the pacing of ice loss and ensuing sea-level contribution in the coming decades remains highly uncertain, in part, due to variance in predicted glacier response to ocean heat content variability. Recent advances in satellite and moored ocean observations show unequivocally that ice-sheet-ocean interactions take place across a broad range of spatial and temporal scales with global implications for overturning circulation and sea-level rise. Until now, however, limited sub-annual observations (particularly in ice-shelf cavities where the ice and ocean actually meet) have restricted studies to broad interannual and decadal syntheses, and identifying robust causal links between changes in ice dynamics and variability in ocean heat content has proven challenging. Here we present the first sustained, continuous observations made by Seagliders and EM-APEX floats in and around the Dotson and Crosson ice-shelf cavity from January 2018 until March 2019. The data gathered during the year-long campaign suggest: (i) the observed variability in amplitude of seasonal ocean temperature in the year 2018 is similar to the amplitude of multi-year temperature variability over the previous 10 years; (ii) mesoscale exchanges between the open ocean water and the ice-shelf cavity drive large spatiotemporal temperature variability across the ice-shelf calving front; and (iii) near the ice-ocean interface, water properties (i.e. salinity, temperature, eddy covariant structure) and stratification vary spatially and evolve sub-annually. Using a higher order ice-flow model, we simulate the influence of seasonally and spatially-variable ocean heat content on grounding-line migration and ice velocity. To connect our observations to the broader climatic setting, we also examine links between variability in sub-annual ice-shelf cavity ocean heat content and regional oceanic and atmospheric conditions.

Could increased melting from East Antarctic ice shelves trigger runaway melting beneath Filcher-Ronne Ice Shelf?

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The Filchner-Ronne Ice Shelf (FRIS) presently experiences modest basal melt rates, but model studies have highlighted the potential for an order of magnitude increase in melt rates should relatively warm modified Circumpolar Deep Water (mCDW) reach beneath the ice shelves. Models and observations have indicated that redirection of a coastal current by changes in sea-ice cover and wind stress has the potential to transport mCDW beneath FRIS and initiate melt instability there. We investigate this FRIS melt instability using the Energy Exascale Earth System Model (E3SM) run in a global low-resolution configuration that includes ocean circulation beneath Antarctic ice shelves with fixed geometry and prognostic calculation of freshwater and heat fluxes from ice-shelf melting. We demonstrate the potential of an additional mechanism for FRIS melt instability by freshening and increasing stratification due to high meltwater fluxes from nearby ice shelves in East Antarctica. We see this behavior in partially-coupled simulations with only active ocean and sea-ice, as well as in fully-coupled simulations that also include active atmosphere and land components. Freshening from ice-shelf meltwater reduces ocean density on the continental shelf, shoaling isopycnals near the shelf break and allowing sustained flow of mCDW from offshore onto the continental shelf and into the cavity beneath Filcher Ice Shelf. However, when ice-shelf melting is disabled from neighboring ice shelves in East Antarctica, the melt instability at FRIS is avoided, identifying meltwater from these ice shelves as another potential contributing trigger for this instability. While E3SM indicates the possibility of such a domino effect in ice shelf-melting, we identify biases in the E3SM simulations that precondition the ocean for FRIS melt instability. Reducing these biases through increased regional resolution and improved ocean model tuning is the focus of ongoing work.

Contextualizing the slow-down of Whillans Ice Stream using swath radar topography and ICESat-2

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The slowdown of Whillans Ice Stream is likely driven by thermal and hydrologic processes occurring at the ice-stream bed. Characterizing the stress distribution requires capturing the subtle details of the ice-sheet surface and bed, because low amplitude or spatially confined topographic features can exert substantial influence on the uniquely low-stress Whillans Ice Plain. In this study, we reprocess airborne ice-penetrating radar data collected during the 2013/14 austral to produce a seamless (∼20 m posting) resolution bed topography for comparison with satellite records recording the slow-down and thickening of Whillans, characteristic of ice-stream stagnation.

In addition to reprocessing ice-penetrating radar data over Whillans Ice Plain, we use ICESat-2 data to (a) extend the dh/dt time series, and (b) calibrate photogrammetry-derived DEMs (REMA strips) to produce the best available surface topography and surface change map to date. These data allow us to test the hypothesis of subglacial hydrologic reorganization over the last 16 years, in an effort to determine if a slowing of Whillans Ice Plain is related to variability in lake drainage cycles observed over the last decades. Ultimately, we examine the possibility of a positive feedback between regional-dewatering of the till, thickening ice, and accelerated stagnation that could drive a long-term reorganization of ice-flow across the Siple Coast.

Calm, cool and collected:
Post-LGM conditions under the central Ross Ice Shelf, Antarctica

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Direct observation of ice and ocean conditions, together with sea-floor sediment coring, indicates a central Ross Ice Shelf environment characterised by long quiescent periods but capable of rapid change. The site has been persistently ice covered since grounding line retreat. There is no evidence of either persistent re-freezing or melting at the ice shelf base along the flow band.

Our evidence comes from two boreholes drilled using hot water at a site ~320 km upstream of the present-day calving front (~80°39' S, 174°28' E), in the glacier-left of a flow band originating in Liv Glacier. Over 2 weeks in December 2017, we made repeated temperature, salinity, current, and turbulence measurements through the ~428 m water column, collected 11 sea-floor sediment cores, and sampled sediments from within the ice shelf. Low frequency radar soundings were made to provide glaciological characterisation of the site.

Ocean conditions are similar to those observed 4 decades ago at J9. The ice-ocean boundary layer is cold (~ -2.12°C), relatively fresh (32.4 to 32.5 psu) and a few 10s of m thick. This layer is separated from a ~50 m high salinity (34.7 to 34.8 psu) benthic boundary layer by a more variable intermediate layer. A few cm of platelet ice was observed at the base of the ice.

A ~60 m thick basal layer of bubble-poor ice containing unevenly distributed sediment was observed at both boreholes. The contact between the overlying bubbly glacier ice and the basal layer is abrupt and steep. The englacial sediment chemistry is consistent with a Transantarctic Mountains source and no diatoms were recovered from the ice. It is thus not marine and must instead have been accreted in the terrestrial environment and preserved over the ~800 years since the ice entered the shelf.

Most of the sea floor sediment record is of near-grounding line conditions. A compacted basal diamict is overlain by ~47 cm of granule-sized mud pellets and capped by ~7 cm of mud. Dropstones on the sea floor indicate minor Holocene basal melting (but not proximity to the calving line). The sediments contain reworked late Miocene to early Pliocene diatom fragments in an assemblage that appears similar to that at J9. Magnetic fabric analysis indicates a gradual decline in current strength and an episode of re-grounding within the till pellet facies.

This research was facilitated by the New Zealand Antarctic Research Institute (NZARI) funded Aotearoa New Zealand Ross Ice Shelf Programme. Drilling was supported by the Victoria University of Wellington. Logistics support was provided by Antarctica New Zealand.

An Exploration of Co-Creation on a Subglacial Lake in Antarctica

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The SALSA (Subglacial Antarctic Lakes Scientific Access) project was an immense undertaking in one of the most remote locations on Earth. The SALSA Education and Outreach (E&O) not only allowed for substantial public access to science, but it also built on practical and theoretical research within the discipline of film. SALSA took a transmedia approach to the creation and dissemination of the research, including a documentary for PBS, short science films, a social media campaign, a museum installation and PBS Learning Media modules for K-12 students. Furthermore, the collaborative academic model built the E&O team within the SALSA science team rather than as an ad hoc external team. This approach developed an atmosphere of co-creation from logo and website development to film production and distribution. During this presentation, Kasic and Collins will discuss the combined traditional and non-traditional approaches the project took to E&O, from conception to completion.

Vulnerability of Antarctica's ice shelves to meltwater-driven fracture

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Atmospheric warming threatens to accelerate the retreat of the Antarctic Ice Sheet by increasing surface melting and facilitating 'hydrofracturing', where meltwater flows into and enlarges fractures on ice shelves. Hydrofracturing in turn could trigger ice-shelf collapse. The collapse of ice shelves that 'buttress' the upstream ice sheet increases discharge from the ice sheet and accelerates sea-level rise. Despite progress in modelling hydrofracture, there is limited understanding of the extent to which ice-shelves are vulnerable to hydrofracturing, which is currently described simplistically in continent-scale ice-sheet models, hindering predictions ice-shelf collapse. Here we provide a new theoretical framework, based on Linear Elastic Fracture Mechanics, to predict fracture locations and for the first time quantify vulnerability to hydrofracture across Antarctica's ice shelves. To test theoretical predictions, we train a deep convolutional neural network (DCNN) to identify fractures in continent-wide satellite imagery, and demonstrate close agreement between the distribution of fracture and our model, without the need to tune any model parameters; 89% of 28000 locations identified by the DCNN as fractures across Antarctic ice-shelves lie in regions where our theory predicts fracture formation. We find that many regions regularly inundated with meltwater in the present climate are resilient to hydrofracturing. On the other hand, large regions that resist ice discharge (i.e., which provide significant buttressing to upstream grounded ice) are susceptible to hydrofracture if covered with meltwater. Our findings suggest that as the Antarctic atmosphere warms, increased meltwater production will generally only trigger hydrofracturing if water is formed in or flows into the vulnerable regions we identified. Our new theoretical framework could be included in ice-sheet models to improve predictions of Antarctica's response to atmospheric warming and impact on sea-level rise.

Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks

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We present a new investigation of the complex interactions between global relative sea-level (RSL) changes and local ice-sheet dynamics in Antarctica, with special focus on the grounding line. There is indeed heightened interest in negative feedbacks caused by solid-Earth effects. For example, Barletta et al, 2018 modeled GPS data, combined with an ice retreat scenario, to strongly argue for an ongoing negative feedback induced by solid earth deformation in West Antarctica. This type of fast deformation is not always incorporated into contemporary sea level projections. Here, we present a state-of-the-art global spherical ice-sheet/RSL simulation that accounts for fast grounding line dynamics and local RSL feedbacks such as self-attraction and loading (SAL) and vertical elastic land motion. We demonstrate that by far, elastic land motion provides the largest negative feedback, contributing to nearly 30 years delay in RSL projections, or an overall reduction of 25–30% in grounding line retreat at 2300 , and responsible for an uplift rate of up to 45 cm/a by 2500 . We also find that SAL interactions with grounding line migration contribute an additional 10% negative feedback on grounding line dynamics. Our approach shows that offline ice-sheet simulations currently overestimate RSL change by 1–2% by 2100 , 28.5% by 2350 and 10% by 2500.

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration's Cryosphere Science Program.

Thwaites Glacier's recent meltwater signature recorded in ice shelf proximal sediment cores

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Thwaites Glacier, located in the Amundsen Sea Embayment, is a leading contributor to ice volume loss across the continent [1,2,3]. Recent satellite surveys show sectors of the Florida-sized glacier's shelf are retreating as rapidly as 1.2 km year^{-1} [4]. Thwaites alone has the capacity to contribute 0.6 m to global sea level rise [5], and it has been suggested the collapse of Thwaites may trigger larger destabilization of the West Antarctic Ice Sheet [6].

Subglacial meltwater plays a vital role in glacial dynamics and grounding line stability [7] and has been evaluated by integrating such methods as ice-penetrating radar sounding and imaging [8], swath bathymetry surveys on deglaciated margins [9], and coupled geomorphologic and sedimentological studies [10,11]. Stratigraphic analysis seaward of neighboring Pine Island Glacier has identified episodic meltwater discharge events that coincide with rapid grounding line retreat [12]. Reconstructing history of meltwater activity of Thwaites may thus have implications for projections of ice sheet behavior.

Here we present a multi-method analysis of two marine sediment cores retrieved during the first Thwaites Glacier Offshore Research (THOR) cruise (NBP1902). KC04 was collected from a bathymetric high directly seaward of the modern Thwaites ice tongue. The other, KC08, comes from a deep and broad NE-SW trending trough $\sim$10 km seaward of the Thwaites Western ice shelf. We employ x-ray fluorescence, magnetic susceptibility, and grain size analysis to examine downcore variations in sediment origin and identify deposits characteristic of meltwater plumes. Additionally, we consider concentrations of D and ^{18}O isotopes in porewater as a possible indicator of intensive meltwater activity. This ongoing research will integrate age models determined from Pb-210, supplemented by ^{14}C dates where available, to constrain the timing and frequency of Thwaites meltwater discharge events.

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Geostatistically Simulating the Topography and Geology of the Amundsen Sea Embayment

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The topographic and geologic conditions in the Amundsen Sea Embayment are a major source of uncertainty in ice sheet retreat projections. Observations of subglacial geology from seismic data are difficult to gather at a large scale, so these conditions are poorly constrained. We use novel geostatistical techniques to simulate subglacial topography and predict the geology by integrating paleo-observations from the Pine Island Bay seafloor. We generate topographic realizations using multiple-point direct sampling, an interpolation technique that uses training data to preserve the spatial statistics of the observations. HiCARS, PASIN, OIB, and MCoRDS radar bed picks across the Amundsen Sea Embayment are used to generate these realizations. Multiple realizations are generated in order to quantify uncertainty. Sediment core and acoustic data throughout Pine Island Bay are used as training data to make geological predictions at subglacial locations. Through regression analysis, the topographic roughness of these known bedrock and sediment regions is used to map sediment and bedrock throughout the region. Our results show that the inner trough of Thwaites Glacier is predominantly underlain by sediment. The topographic and geologic maps produced by this study can be used in ice sheet models to assess the stability of the West Antarctic Ice Sheet.

Large-Scale Atmospheric Drivers of Snowfall on Thwaites Glacier

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High snowfall events on Thwaites Glacier are a key influencer of its ice mass change. In this study, we diagnose the mechanisms for orographic precipitation on Thwaites Glacier by analyzing the atmospheric conditions that lead to high snowfall events. A high-resolution regional climate model, RACMO2, is used in conjunction with MERRA-2 reanalysis to map snowfall and associated atmospheric conditions over the Amundsen Sea Embayment. We examine these conditions during high snowfall events over Thwaites Glacier to characterize the drivers of the precipitation and their spatial and temporal variability. Then we examine the seasonal differences in the associated weather patterns and their correlations with the position and strength of the Amundsen Sea Low and the Southern Annular Mode. Understanding the large-scale atmospheric drivers of snowfall events allows us to recognize how these atmospheric drivers and consequent snowfall climatology will change in the future, which will ultimately improve predictions of accumulation on Thwaites Glacier.

Spatial distribution of englacial layer slope as a constraint on ice sheet basal conditions: The case for subtemperate sliding

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Englacial layers are an ubiquitous indicator of internal deformation within ice sheets, as well as a common finding in radio echo sounding data. In spite of this, placing direct constraints on present or past ice flow through englacial layers remains, to date, a challenging task. Our work leverages recent advances in the processing of airborne radar sounding data along with modelling work to address this challenge. Here we present an application to the case of an abrupt change in basal friction due to a transition from frozen to temperate basal conditions, which we seek to detect from radar sounding data through its signature in englacial layer geometry. We first formulate a boundary layer problem for ice flow across an abrupt change in basal friction, and use it to quantify expected anomalies in layer geometry. Then we exploit a recently developed layer-optimized, unfocussed SAR processing technique that automatically estimates layer slopes with high accuracy to look for this signature in the onset region of Institute Ice Stream (West Antarctica). Even though layer geometry clearly reflect the pattern of basal acceleration, we find that observed slopes are incompatible with an abrupt sliding initiation. Our results instead provide evidence for the existence of an extended region of subtemperate sliding, where basal lubrication would occur as a result of basal premelting with a basal energy budget approximately in balance.

The internal deformation regime of Thwaites Glacier

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Internal deformation is the main process controlling ice flow in ice shelves and in slow-moving regions of polar ice sheets where the ice is frozen to the bed. However, the contribution of internal deformation to flow in ice streams and fast-flowing regions is typically poorly constrained in ice sheet models. The current standard description of internal deformation used in most large-scale ice sheet models - the Glen flow relation - is limited by its failure to capture the tertiary flow of anisotropic ice that prevails in polar ice sheets. Here, we compare the flow regime of Thwaites Glacier as simulated by the Glen flow relation with a recent flow relation for anisotropic ice - the ESTAR (Empirical Scalar Tertiary Anisotropy Regime) flow relation. With ESTAR, internal deformation contributes a factor of three times more to overall flow in the Thwaites Glacier ice streaming zone than when using the Glen flow relation. Using temperature dependent flow rate parameters with a stronger physical basis along with the ESTAR flow relation together provide the best match to observed surface velocities, but parameter selection and "matching" (i.e. via inversion) can significantly alter the predicted flow regime. Our results have implications for ice sheet evolution and stability, and may provide insight into an improved picture of basal sliding parameterizations.

Will the pore space save us?
The role of firn on ice shelf stability in West Antarctica

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Recent concern over the stability of the West Antarctic Ice Sheet revolves around the hypothesized marine ice cliff instability (MICI). This mechanism for dramatic grounding line retreat relies on the rapid disintegration of buttressing ice shelves, which is hypothesized to occur under enhanced surface melt conditions that lead to an increased likelihood of hydrofracture. While observations of surface lakes, streams, and runoff suggest the ingredients for hydrofracture are already available over several ice shelves, evidence of meltwater infiltration and refreezing indicate that the firn has the potential to absorb meltwater, diminishing the likelihood of hydrofracture and ultimately MICI.

Here, we present the evolution of the firn air content over West Antarctic ice shelves from 1980–2019 in order to evaluate (1) the total volume of pore space available to absorb surface melt, (2) its evolution in time, and (3) the drivers of change. We provide simple metrics of stability by relating total firn air volume to modern day melt and snow accumulation rates in order to estimate the time to instability (i.e., complete saturation of the firn pore space with refrozen melt). Perhaps most interestingly, we investigate the opposing processes of snowfall and melt on firn air content to determine which ice shelves (if any) are most vulnerable to hydrofracture and what that means for the future of the West Antarctic Ice Sheet.

Impact of Ross Ice Shelf basal melting on mass loss from West and East Antarctic ice sheets

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Mass loss from the Antarctic Ice Sheet is increasing, accelerating its contribution to global sea level rise. Interactions between the ice shelves (the floating portions of the ice sheet) and the ocean play a central role in this mass loss. The large (∼480,000 sq km) Ross Ice Shelf, while presently stable, buttresses grounded ice equivalent to about 12 m of global sea level, and geological evidence points to large and sometimes rapid past changes. Recent studies show that seasonal inflows of warmed upper-ocean water under a thin-ice corridor from Ross Island to Minna Bluff can produce locally high melt rates each summer, suggesting that future increases in net summer ocean warming north of the ice front could accelerate ice-shelf flow speed and mass loss. This modeling study aims to quantify how these previously overlooked changes on Ross Ice Shelf could affect the grounding line ice flux and the contribution of the region to sea-level rise. We used an ice sheet model (shallow shelf implementation of the finite element model Elmer/Ice) to investigate the seasonal to interannual response of Ross Ice Shelf and the surrounding grounded-ice basins to perturbations in basal melting based on ocean/ice-shelf simulations with the Regional Ocean Modeling System (ROMS). We assessed the sensitivity of the model response to the basal melt pattern, the viscosity of the ice, and to the choice of friction law. Our results suggest that an increase in melting in the area of Ross Island and Minna Bluff would accelerate grounded-ice loss from both East and West Antarctic ice sheets.

Flexural gravity wave simulations and seismic observations constrain flexure near the ice edge of the Ross Ice Shelf

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Ocean surface gravity waves incident on ice shelves cause flexure and bending stresses that possibly contribute to rifting and calving. The wave energy that is transmitted from the incident ocean wave to the ice shelf and ice-covered water depends on the properties of the ice shelf and characteristics of the incident wave, particularly its frequency content. Chen et al. (2019, in press) recently reported an empirical transfer function for the Ross Ice Shelf based on observations from a broadband seismic array and ocean bottom hydrophones. The transfer function is the ratio, in the frequency domain, of the vertical displacement of a point on the ice shelf to the open-water wave amplitude (as indirectly determined from seafloor hydrophone pressure measurements). Here we utilize numerical modeling of flexural gravity waves to explain many of the pertinent features of the transfer function. Our 2-D (vertical cross-section) flexural-gravity wave model (Mattsson, Dunham, and Werpers, 2018) assumes that the ice shelf acts as a thin elastic plate, accounting for both elastic restoring forces and inertia. The velocity potential in the water is characterized with Laplace's equation, fully capturing dispersion of short wavelengths. Matching the observed transfer function primarily constrains the bending stiffness of the ice shelf as 3.8e15 to 1.1e16 Pa m^3. Because thicker ice is more stiff, the model exhibits trade-offs between the ice elastic modulus and thickness to appropriately match the bending stiffness. The resulting calibrated model can quantify bending stresses near the front of the Ross Ice Shelf.

Early Holocene Retreat and Late Holocene Re-advance of the Grounding Line in the Ross Sea Sector

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Knowledge of past ice sheet configurations is important because it can inform predictions of future ice sheet behavior and be utilized in calibrating ice sheet models. Much of the past research on geometric evolution of the West Antarctic Ice Sheet (WAIS) has focused on reconstructing its decay from its Last Glacial Maximum (LGM) to the modern configuration. Until recently it was assumed that the current outline of the WAIS is the smallest since the LGM. However, new evidence suggests that the grounding line along the West Antarctic Ice Sheet retreated further back than its current position within the past 10,000 years and is now advancing (Kingslake et al., 2018). We further re-examine the timing of this retreat and re-advance in the Ross Sea Sector of Antarctica through modeling constrained by radiocarbon concentrations in sediments collected below the ice sheet, as well as through modeling basal ice temperatures measured by Engelhardt (2004). The observational evidence is best fit by scenarios which assume a quick retreat early on in the post-LGM deglaciation combined with a very recent re-advance of the grounding line.

A New Project Catalog for the United States Antarctic Program hosted at the USAP-DC

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The US Antarctic Program funds a wide variety of research projects that collect and produce valuable, unique datasets that are archived in a range of different, often discipline specific repositories. In order to (1) provide a central resource for information about USAP projects and access to the associated datasets in these distributed repositories and (2) better assist PIs in their life-cycle data management, the USAP-DC has launched a new Project Catalog. The Project catalog is designed to host a project page for each single or collaborative award. Project pages include links to associated datasets together with other project relevant information. PIs can register their project for an NSF award or collaborative award, by filling out a simple web form on the USAP-DC web site. It is recommended to create the project page early in the award period, so that the USAP-DC projects catalog reflects ongoing projects as well as an inventory of completed projects. Once created PIs will be able to update these project pages and add new information such as links to datasets or publications as they become available.

Datasets can be archived at various, established disciplinary repositories including the USAP-DC repository (which is also the disciplinary repository for NSF-funded glaciology data). Based on the information provided through the project registration and update process, USAP-DC will also create and update entries (DIF records) in the Antarctic Master Directory (AMD), which continues to serve as an international registry and catalog of Antarctic datasets and projects from other US agencies and SCAR member countries. In accordance with the introduction of the project catalog, the USAP-DC has launched a new search tool that allows searching and browsing for projects and datasets in the USAP-DC database and includes various filter options. We will present an overview of the updated USAP-DC workflow and guidance for PIs and users on how to the submit project and dataset information, as well as the use of our search tools to discover projects and datasets.

Reconstructing winds in the Amundsen Sea using paleoclimate data assimilation

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Ice shelves in the Amundsen Sea sector of West Antarctica are melting from below due to upwelling of warm Circumpolar Deep Water. The amount of upwelling is enhanced by westerly wind events occurring at the continental shelf break (e.g., Dutrieux et al., 2014). It is virtually certain that melt rates have increased since the mid 20th century, which suggests that there has also been an increase in westerly wind events. Recent climate model experiments show that greenhouse gas forcing may have gradually increased the prevalence of westerly wind events through the 20th century (Holland et al., 2019). However, since direct observations of climate in this region begin only in 1979, there has been no empirical evidence to support this hypothesis.

Here, we use ice core records and other proxy data to provide an empirical assessment of whether westerly winds have changed significantly in recent decades. We reconstruct wind anomalies over southern high latitudes through the 20th century, using an Ensemble Kalman filter data assimilation technique to combine paleoclimate observations with the dynamical constraints of climate models. The proxy data provide all information about the time variations in climate, while the climate model, used as a prior for the climate state, provides information about the spatial covariance. We experiment with subsets of the proxy data and several different climate model priors to evaluate the robustness of the results.

All reconstructions show an increase in the strength of the circumpolar westerly wind belt through the 20th century, in agreement with previous work (e.g., Abram et al., 2014). We also find that all reconstructions show excellent agreement with the Holland et al. simulation of zonal winds at the Amundsen Sea shelf break during the latter half of the 20th century. However, different reconstructions show different wind anomalies during the first half of the 20th century, resulting in considerable uncertainty in the long-term trends. Using the same model as Holland et al. (the NCAR tropical "PaceMaker" simulation, from Schneider and Deser, 2018) as our prior, we find a small but significant positive trend at the continental shelf break, providing an observationally-constrained result consistent with the hypothesis that westerly winds have become more prevalent in the Amundsen Sea region in recent decades. In contrast, reconstructions in which other climate-model simulations are used as the prior show a weakly negative trend. The difference in trend lies in the details of the covariance between regional Amundsen Sea winds and the larger-scale climate. Ongoing work is exploring the potential for reducing the ambiguity of our findings by accounting for issues such as model bias, frequency dependence, and the nonlinearity of proxy versus climate relationships.

Tipping Points in Antarctic Climate Components

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In our new Horizon 2020 project "Tipping Points in Antarctic Climate Components" (TiPACCs) we will investigate the probability of sudden and large changes in the sea-level contribution from the Antarctic Ice Sheet that would result from passing tipping points in the marginal seas and at the grounding lines of the floating ice shelves that fringe the ice sheet. A comprehensive study of the triggering processes will reveal the likelihood of reversibility, while the study of ice-ocean feedbacks will provide insight into the threat of sudden sea-level rise. Modelling work will deliver parameter estimates of safe operating spaces, and linking these with Southern Ocean observations will contribute to the launch of early-warning indicators for dangerous levels of ocean-induced basal melting of the ice shelves. We will achieve these objectives using a suite of state-of-the art ocean-circulation and ice-flow models, greatly enhancing confidence in the results. The combination of numerical work with existing remote sensing and in-situ observations and paleo-reconstructions is ideal for defining the proximity of the simulated tipping points. With this work, we aim to provide a better understanding of key processes controlling the climate-Earth system that are critical for further improvement in climate projections and reducing uncertainty in climate sensitivity calculations. We will also assess more accurately the impacts of climate change related to the proximity, rate, and reversibility of tipping points in Antarctic climate components. Furthermore, future climate projections will benefit from our combined use of numerical models and paleo-reconstructions as they allow a better understanding of how the climate system worked during abrupt climatic transitions and under warmer or colder than present-day conditions. Thus, the project will dramatically improve our knowledge of sudden sea- level rise caused by tipping points in Antarctic climate components.

Elevation Bias from Surface Roughness using Operation IceBridge

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Topographic surface roughness studies describe roughness in terms of deviation from an average surface. Snow surface roughness in the polar regions results from wind eroding snow into centimeter to meter-scale longitudinal dunes called sastrugi. Surface roughness impacts radar interaction with snow, sea-ice, and ice sheets, and therefore plays an important role in radio-glaciology. Surface roughness modifies signal backscatter, scattering at different wavelengths, and surface dielectric properties with implications for altimetry on ice sheets. Climate models use surface roughness in part when determining heat exchange between the ice sheet surface and atmosphere. At present models use spatially coarse values of surface roughness, a critical parameter for predictive numerical runoff models. Potential exists to improve understanding of the relationship between surface roughness and radar backscatter, thereby improving altimetry. We use NASA's Operation IceBridge Ku-band retrieved radar backscatter combined with surface roughness from laser altimetry to estimate range-biases around 88°S. We re-track the air–snow interface from Ku-band radar using a waveform fitting method to obtain a surface elevation, and then calculate the elevation offset. We validate our results with GPS surface elevations from the 88°S traverse, then extend our methods to select flightlines across West Antarctica.

Acoustic Full Waveform Inversion to Recover Seismic Velocity of Firn

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The transformation of snow into ice is a fundamental process in glaciology. The yearly accumulation of fresh snowfall increases the overburden pressure, changing the snow's properties such that it transitions into firn and pure glacier ice thereafter. Therefore, firn characteristics provide a tool for evaluating past and present climate conditions relating to the amount of snow accumulation, melt, temperature conditions and the subsequent preservation of the snow. Due to the importance of relationships between firn and other glaciological processes (e.g., settling, sublimation, recrystallization and other deformation processes) it has not been possible to develop a theoretically-based model which accurately predicts firn properties with depth. Therefore, methods of measuring firn are either intrusive or rely on (potentially unreliable) empirical conversions. Full Waveform Inversion (FWI) may offer a new standard for glaciological seismic modelling, mitigating issues within current seismic modelling techniques and paving the way for the recovery of elastic properties, including density. Using seismic datasets obtained from Pine Island Antarctica, we show how FWI can mitigate the dependence on borehole/core techniques and empirical relationships. Using seismic refractions, we are able to arrive at an estimate for subsurface acoustic seismic velocity, which when compared to ground truth data, show an improvement from current seismic techniques.

Passive radio sounding using the Sun as a signal to monitor subsurface processes

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Traditional radar sounders can characterize the subsurface conditions of ice sheets but are limited by the need to transmit their own electromagnetic signal. If one could eliminate the need to actively transmit a signal for radio-echo sounding, this could significantly reduce the overall design complexity, power consumption, cost, and logistics of glaciological measurements. To address this, we describe our implementation of a passive radar technique that uses ambient radio waves, such as the Sun, as a source for radio-echo sounding of ice. Our software-defined radio receiver sits on the surface of the ice sheet and records the Sun's direct path and its path that propagates through the ice and is reflected off the basal interface. We then use an autocorrelation-based method to extract the amplitude and delay time between the direct and reflected Sun signal, which maps to an ice thickness measurement. Here, we present the results of our field testing in Store Glacier, West Greenland, where we have demonstrated passive radio sounding using the Sun as a source for echo detection to measure ice sheet thickness. In addition to measuring ice sheet thickness, we evaluate the potential for a passive radar using the Sun to perform a variety of ice sheet measurements, such as bed topography, basal melt rates, reflectivity time series, vertical velocities, and englacial water storage. We conclude by discussing the spatio-temporal resolutions and scales that are achievable with this technique, and highlighting the geographic regions, particularly on the West Antarctic Ice Sheet, where these observations can best be performed.

Local basal melt rates near the Ross Ice Shelf front: Interaction of bathymetry, ocean heat fluxes, and ice damage history

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Recent observations show that increased basal melt rates near the Ross Ice Shelf (RIS) front can influence ice shelf stability and the loss of grounded ice from both West and East Antarctic catchments. Ice shelf basal melt depends on the complicated long-term interactions between the ice base, ocean cavity, and underlying geology. We use a combination of historical and recent observations of the ice, ocean, and potential fields along the RIS front near Roosevelt Island to demonstrate how such processes interact to determine ice shelf mass loss processes in this region, towards developing a better understanding of RIS stability in a changing climate. Here, we focus on a region of thin ice at the RIS front near Hayes bank, where radar observations from ROSETTA-Ice project have mapped a 25 km wide region of localized thin ice, and bright reflectors consistent with basal melt. Ross Sea cruises spanning nearly 4 decades, near-front moorings in the 1980s, and autonomous profiling floats deployed by ROSETTA-Ice, have all collected hydrographic data near this thin-ice area, allowing for estimation of southward mCDW heat flux and identifying fresh ice shelf meltwater outflow. Hayes Bank is where mCDW extends southwards under the ice front; the southern extent of the sub-ice-shelf bank controls the maximum penetration of mCDW heat into the cavity. Circulation depends on water column thickness and so the relative locations of thinned ice and submarine ridges matters. New gravity-derived bathymetry from ROSETTA-Ice shows Hayes Bank extends less than 100 km under the RIS, suggesting that mCDW inflow to the west of Hayes Banks does not extend far into the back of the RIS cavity, limiting its melting potential to a small region near the front, mostly within a region of minimal buttressing (Furst et al., 2016). Upstream of this region lies the Steershead Ice Rise, where re-grounding and basal shear stress impart damage that travels and evolves along flow to the front. Ocean melting interacts with these damage features altering calving characteristics at the front and instigating a positive feedback between thinning ice, increased access for mCDW. Over scales of thousands of years, the permanence of these banks (e.g.. depositional versus tectonic origins) shows how geology can alter the interplay between globally-sourced ocean waters and the ice sheets.

Characterization of subglacial sediment properties beneath Thwaites Glacier from seismic surface wave and receiver function analysis

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The West Antarctic Ice Sheet is undergoing rapid changes across the Amundsen Sea Embayment where increased ice-mass loss and acceleration of grounding line retreat have been reported over the last few decades. Thwaites Glacier is of particular concern because of its size and overdeepened bed configuration, making it prone to catastrophic collapse. The potential for Thwaites Glacier to experience unstable retreat strongly depends on basal conditions upstream of the grounding line which, in turn, depend on subglacial properties including basal lithology and water distribution. Thus, constraining these properties and understanding their control on ice flow dynamics is critical to accurately model the ice-sheet evolution and its contribution to sea-level rise. Here we use passive seismic data recorded by the POLENET and UKANET seismic networks to investigate localized variations in sediment properties across Thwaites Glacier. We image shallow subglacial structure beneath each station from a joint Monte Carlo inversion of receiver function, ambient noise derived Rayleigh and Love wave dispersions, and Rayleigh wave horizontal-to-vertical (H/V) amplitude ratio. Variations in modeled shear wave velocity with depth allow us to locally distinguish between soft (saturated, deforming) and hard (consolidated) sediments. Constraints on sediment thickness come from the sensitivity of receiver function and H/V ratio curve to vertical impedance contrast across layer boundaries. We find that bed properties are spatially variable across Thwaites Glacier, with regions of primarily hard bed juxtaposing regions of more complex bed stratigraphy comprising accumulation of soft dilated till material overlying consolidated sediment. Sediment thickness appears, however, to correlate with basal topography and with regions of faster ice flow, with the thickest sedimentary layers being resolved across the Byrd subglacial basin, the Bentley subglacial trench and at stations closest to the grounding line. Results from this study show the promising use of receiver function and surface wave data for high resolution mapping of subglacial sedimentary units which we discuss in light of previous studies of bed type distribution across Thwaites Glacier.

The association of subglacial meltwater with grounding-line retreat

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The movement of subglacial meltwater has been found to be both common and capable of affecting the behavior of overlying ice. Our recent and ongoing work demonstrates the effects of subglacial meltwater on ice margin stability and large-scale grounding-line retreat during the Holocene. Using the paleo record in the Ross Sea, Pine Island Bay, and Marguerite Bay, we demonstrate associations of meltwater activity with grounding-line retreat and identify a sedimentological marker of ice sheet instability. We compare these observations with examples of modern meltwater activity on Antarctic margins across Antarctica, including the Pine Island/Thwaites system, to identify signs of impending instability. The most complete analogue to the Thwaites/Pine Island system is in Marguerite Bay, where geomorphology of the continental shelf reveals that the bay was once occupied by an ice stream that was underlain by an extensive network of meltwater channels and basins. Existing geomorphic data suggest an embayment formed during initial retreat from the continental shelf edge, but the timing is not well-constrained. Previous records of grounded ice retreat through Marguerite Bay were based only on minimum ages, but we have updated the chronology and produced more definitive grounding-line retreat ages by using a new sediment facies model to guide us in selecting intervals for radiocarbon dating. We show that grounding line retreat occurred sometime well prior to 14 cal ka BP, with the ice shelf retreating to the middle continental shelf by 13 cal ka BP. Grounding-line embayments and the ice shelf gradually retreated through the deep portions of Marguerite Bay through 11 cal ka BP. By 10 cal ka BP, inner Marguerite Bay was nearly ice-free, corresponding to a 9.6 cal ka BP drawdown of nearby terrestrial ice. Meltwater deposits are found only within the basins of the rugged bedrock and not in cores on the shallower outer continental shelf, suggesting sediment was expelled within plumes at high enough velocities or sediment concentrations to prevent plumes from becoming hypopycnal. This meltwater activity occurred in association with the deglaciation beginning at 13 cal ka BP until just prior to the major 10 cal ka BP ice retreat. Marguerite Bay may be a particularly useful model for estimating the future of the unstable Pine Island/Thwaites Glacier system, which is also underlain by an active hydrological system that produces sediment-laden meltwater plumes today.

Young Carbon beneath the West Antarctic Ice Sheet: A Unique Carbon Cycle Perspective from Mercer Subglacial Lake

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A major focus of the Subglacial Antarctic Lakes Scientific Access (SALSA) project was providing an integrated understanding of subglacial carbon cycling. During the 2018–2019 field season, the SALSA field team accessed Mercer Subglacial Lake (SLM) 1092 m beneath the surface of the Mercer Ice Stream using clean-access hot water drilling, subsequently collecting water and sediment samples from the lake (15 m deep, 169 km^2), as well as imagery of the basal ice and the lake bed sediments. Here, we present the first results of analysis of these sediments from a carbon isotope perspective. Radiocarbon dates from multiple components of the SLM system indicate that sedimentary organic matter has more radiocarbon (is "younger") than inorganic carbon in the lake water, porewater, and sediment. Stable carbon isotope values suggest a marine source for the sedimentary organic matter, however few marine diatoms are observed in the sediment including no diatoms that are age-diagnostic of the Pleistocene. We observe low rates of metabolic activity and evidence of ammonia-oxidizing bacteria and archaea, but the carbon isotope systematics suggest that observed metabolic pathways do not explain the relatively high radiocarbon content of the sediments. We explore these surprising contradictions in an unprecedented sedimentary archive that preserves the sediment-water interface and penetrates several meters into SLM sediment. The sediment archive suggests that processes not synoptically observed during clean access of SLM must be invoked to explain the radiocarbon age of the sediments.

Diffusive Convection controls basal melting of Antarctic ice shelves

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The Southern Ocean drives mass loss from the Antarctic Ice Sheet by melting its fringing ice shelves. However, the processes by which the ice and ocean interact are poorly sampled and understood, impeding projections of how the ice sheet will contribute to global sea level in the future. In this study we examine the ocean-driven melting of a horizontal ice shelf by using high resolution Large Eddy Simulations. We perform the first geophysical-scale simulations of the ice-ocean boundary layer, bridging the scales between molecular diffusion and oceanic mixed layer formation. We find that Diffusive Convection is the primary control on the initiation and evolution of basal melting, and sets the depth and properties of the oceanic mixed layer adjacent to the ice. Results, which are are put into the context of new observations made near the grounding line of the Ross Ice Shelf, demonstrate the importance of Diffusive Convection at realistic ocean conditions. Diffusive Convection will produce significantly different basal melt rate predictions when included in ice/ocean parameterisations. Our finding therefore has significant potential implications for ice sheet models that rely on ocean melt rate parameterisations to predict the evolution of the Antarctic Ice Sheet.

Surprises in the sediments collected from Mercer Subglacial Lake

The SALSA Science Team

Sediments collected at Mercer Subglacial Lake (SLM) during the 2018–2019 field season exhibit a suite of sedimentary facies that suggest dynamic and changing controls on sedimentation beneath Mercer Ice Stream. This observation is surprising given that all previously recovered subglacial sediments have been described as diamicton or till, with no apparent grading or bedding, and no stratigraphic variability. During the Subglacial Antarctic Lakes Scientific Access (SALSA) project, SLM, a 15 m deep lake under 1092 m of glacial ice, was accessed via clean hot-water drilling. The team collected 10 short sediment cores 0.45 m maximum length, with a modified Uwitek multicorer, and two free-fall gravity cores, 0.97 and 1.78 m length. Two multicores from the first cast and both free-fall cores were returned to the Marine and Geology Repository at Oregon State University, where whole-core CT-scans revealed stratigraphic variability that guided subsequent sampling of the split cores. The upper 10–15 cm of the multicores are characterized as greenish gray muds with high water content and few clasts, which are primarily associated with thin clast-rich layers. These alternating layers may represent fill drain cycles within the lake. Underlying a sharp contact is a more cohesive dark greenish gray massive unit with higher but variable clast content, interpreted as a diamicton likely deposited under grounded ice. The longer free-fall cores, which over-penetrated the lake sediment surface and missed collection of the uppermost unit, are mostly diamict, but contain a third unit, a 5 cm thick greenish gray, clast-free mud, bounded by sharp upper and lower contacts. Several thinner lenses, $<$ 1 cm thick, of this lower-density, clast free unit are observed above the 5 cm thick unit; these layers can be correlated in detail between the two free-fall cores. Sedimentologic, geochemical and micropaleontologic analyses will be used to define these facies and their depositional settings, and to address larger scale questions of how these changing facies relate to changes in movement and extent of the overlying ice.

Pliocene to Recent record of West Antarctic history from the Amundsen Sea continental rise: Initial Results from IODP Expedition 379

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The Amundsen Sea sector of Antarctica has long been considered the most vulnerable part of the West Antarctic Ice Sheet because of the great water depth and retrograde slope at the grounding line, the observed incursion of warm Circumpolar Deep Water onto the shelf, and the lack of substantial buttressing ice shelves. Notably, ice flowing into the Amundsen Sea embayment is undergoing rapid changes, including substantial grounding line retreat over recent decades. International Ocean Discovery Program (IODP) Expedition 379 accomplished two successful drill sites on the continental rise of the Amundsen Sea in January-March 2019, the first from this sector, despite significant logistical limitations, including persistent sea ice that prevented access to all proposed continental shelf sites and abundant mobile icebergs that forced loss of $\sim$50% drilling time.

Both sites recovered sediments spanning Upper Miocene to Pleistocene, with greater than 90% recovery in the upper Pliocene to Holocene section and no evidence of significant unconformities. Site U1532 is located on a large sediment drift, dubbed the Resolution Drift, and penetrated to a depth of 794 m below seafloor. Site U1533 reached 383 m below seafloor in a more condensed sequence from the lowermost flank of the same sediment drift. The cores from both sites contain unique records of cyclicity interpreted as reflecting ice sheet advance and retreat processes as well as ocean-bottom circulation and water mass changes. Excellent chronostratigraphic control will allow very high-resolution, sub-orbital scale climate change studies of the previously sparsely sampled region.

Coarse-grained sediments, interpreted as ice-rafted debris (IRD), were identified throughout all time periods recovered. Documented sedimentary cycles alternate between microfossil-rich facies with common to abundant IRD, including notable “pulses” of West Antarctic derived clasts, and gray, laminated, rapidly deposited terrigenous muds, especially in Pliocene successions. A notable difference between Pliocene and Pleistocene cycles is evident in the succession, with significantly higher production of terrigenous sediment during the Pliocene, reflecting higher erosion rates. Lower rates of Pleistocene erosion may be due to colder ice and ice flow across already deeply incised glacial landscapes.

These cores contain the most complete Pliocene to Recent sedimentary record ever recovered from the circum-Antarctic continental margin. Being situated offshore from the Amundsen Sea Embayment, the cores offer an unparalleled record of WAIS history spanning the last several million years, offering new insights into pre-anthropogenic WAIS advance and retreat behavior.

Constraining model estimates of Antarctic surface mass balance, using satellite gravimetry and altimetry

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The surface mass balance (SMB) of the Antarctic Ice Sheet (AIS) constitutes a significant portion of the ice sheet's mass budget and mass balance (MB) uncertainty. The rest is determined by the discharge (D) of ice at the grounding line, and depends on grounding line ice thickness and ice velocity. Understanding variability in D and SMB is key to improving our knowledge of the processes responsible for current ice sheet change and those that could drive future AIS sea level contribution. New remote-sensing products allow us to quantify D and MB regionally at high (monthly) temporal resolutions, and consequentially to estimate AIS SMB at a basin scale. These types of data offer us the opportunity to evaluate model-based estimates of historic SMB. Using the new ERA-5 reanalysis as forcing, we model AIS SMB, using the glacier and energy mass balance (GEMB) surface radiation model, now integrated into the Ice Sheet System Model (ISSM). Here, we take advantage of new remote-sensing derived estimates of regional SMB in order to evaluate variability, and trends and assess uncertainty in the new product. This work is performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration's Cryosphere, Sea Level Rise, and MAP Programs.

Seismic Evidence for Pervasive Surface Fracturing Near the Grounding Line of the Ross Ice Shelf

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Data collected from a dense seismic array near the grounding line of the Whillans Ice Plain (WIP) reveals an abundance of tidally-modulated seismicity that is temporally correlated with falling tide. Our analysis indicates that the source of this seismicity is surface fracturing due to ice shelf flexure under tidal forcing. We suggest that passive seismic monitoring and characterization near ice shelf grounding lines may be a practical strategy for tracking ice shelf strength and damage evolution. We examined the grounding zone (GZ) events over five consecutive field seasons from 2012–2016 to investigate their source and tidal dependence. The seismograms are strongly dominated by surface waves, and show very little body wave energy. Because picking P and S waves was impractical given their low amplitudes, we located event sources using beamforming techniques. The resulting event locations were then used to compute synthetic seismograms for the specific geometry and velocity structure of the WIP. Event source depth was then constrained by comparing the surface-to-body wave ratios of the computed seismograms with that of the recorded seismograms. The GZ events were located near the grounding line, and constrained to shallow depths of no more than 30 meters. The observed seismicity's temporal correlation with low tide and location characterization strongly indicate that the source is likely tensile fracturing at the surface in the form of strand cracks or buried crevasses. Our result implies that despite the odd ice flow geometry at this location (i.e. ice flow being parallel to the grounding line), and the lack of surface expression, the changing ocean height is sufficient to produce fracturing on diurnal timescales. Additionally, we note the distinct importance of not only low tidal height to induce seismicity, but also the speed at which the tide is falling. The observed GZ seismicity begins at peak falling tide velocity and ceases at maximum low tide. This observation is consistent with the findings of similar studies conducted elsewhere on the Ross Ice Shelf, and laboratory experiments indicating the rate-dependent fracture toughness of ice.

Geological origins and tectonic inheritance of West Antarctica, with bearing on cryosphere processes

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Geophysical remote sensing of the concealed Antarctic bedrock, and provenance studies of marine sediments recently cored by IODP, bring new understanding of the physical characteristics and geotectonic context of the crust of West Antarctica. The subglacial extent of varied crustal domains, and the positions of faults that may localize heat flow or hydro/geothermal anomalies, are being mapped. The spatial correspondence of geological province boundaries with prominent physiographic features such as the Transantarctic Mountains, Ross Embayment, Marie Byrd Land dome, and the Thwaites Glacier/Pine Island troughs, can be assessed and verified, or corrected.

This presentation provides the contemporary view of the geological development and crustal characteristics of the West Antarctic rift system (Ross Embayment through Marie Byrd Land and Amundsen Sea) drawing upon direct observations from rock exposures in West Antarctica, magnetics and gravity anomalies from airborne surveys, subglacial topography and modeled bathymetry obtained from airborne data, and Paleozoic-Mesozoic tectonic reconstructions of the accretionary margin of East Gondwana. It will share perspectives gained from the examination of coarse clastic material within IODP Expedition 379 drill cores, for sedimentary provenance. Crystalline rock clasts are a constituent of coarse detritus, interpreted as ice-rafted debris, that is present throughout the Upper Miocene to Pleistocene sediments that were recovered.

This synthesis suggests that the prevailing view of West Antarctica as a collection of independent microcontinental blocks, or terranes, may have delayed the process of geological attribution of the subsided crust of the Pacific sector of Antarctica. The geological makeup and tectonic inheritance have a bearing on crustal heat production, localization of volcanic centers, erodibility of subglacial bedrock, and development of topographic relief that factor into cryosphere research questions, including the initiation and expansion of the West Antarctic ice sheet, the timing and duration of fluctuations in ice sheet extent, and isostatic/glaciostatic responses.

Sinuous grounding lines often point to large retreat events to come

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Progressive sediment deposition at grounding lines acts as a self-stabilizing feedback due to the construction of relief at the ice-bed interface and reduction in the ice thickness needed to hold grounding lines in place. A first-order control on grounding line landform growth is sediment availability, and a second-order control is duration of grounding line occupation. Many grounding line landforms display longitudinal sinuosity (i.e., perpendicular to ice flow) that imply heterogeneity in formative processes and challenge the validity of thinking about grounding lines in 2-dimensional space, parallel to ice flow direction. Non-uniformity in processes, such as spatial variability in sediment flux, tidally induced sediment compaction, and channelized meltwater drainage, can result in grounding line sinuosity that ultimately increases ice-ocean contact and potentially sensitizes grounding line sectors to processes that drive retreat.

I compare hundreds of grounding line landforms on the deglaciated Antarctic continental shelf, marking post-LGM retreat of the Antarctic Ice Sheet, with contemporary grounding line geometries derived from the MeASURES differential satellite synthetic aperture radar interferometry (DInSAR) dataset. The paleo-landforms indicate that sinuosity scales with landform size and thus arguably with longevity of grounding line occupation. Additionally, relatively sinuous grounding lines are commonly associated with large (10s of kilometer) retreat events. Across the margins of individual ice streams and outlet glaciers, sinuosity is up to two-fold higher for contemporary grounding lines than paleo-counterparts and highly sinuous grounding lines experiencing 300% more exposure to the ocean than if they were linear. Longitudinal grounding line geometry and processes controlling kilometer-scale sinuosity should therefore be further explored and incorporated in numerical models to more realistically assess marine-ice sheet behavior.

A tale of two lakes – contrasting biogeochemical weathering regimes in proximal subglacial Antarctic systems

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Lakes that underlie the Siple Coast Ice Streams of West Antarctica are hydrologically active on sub-decadal time scales. Two of these dynamic lakes, Mercer Subglacial Lake (SLM) and Whillans Subglacial Lake (SLW), located beneath adjacent ice streams Mercer and Whillans respectively, have been accessed in recent years using clean drilling techniques, and water and sediment samples have been collected. The catchment basins for these two subglacial lakes span contrasting geologic substrates. SLW is sourced only from West Antarctica, whereas SLM has potential sources from both West and East Antarctica. SLW was sampled during the austral summer of 2012-13 and geochemical analysis of the lake water revealed it is freshwater with mineral weathering as a significant solute source, with a minor contribution from sea water. SLM was sampled during the austral summer of 2018-19. SLM is also freshwater, but with a contrasting chemical composition to that of SLW. Sediment cores collected from SLM were longer than those collected at SLW and exhibited more variable sedimentary structure than those from SLW. Here, we present the biogeochemistry of the lake waters and sediment pore waters from SLM and characterize the likely solute sources for these waters. We will contrast these data with those generated from SLW for an improved understanding of physical and biogeochemical weathering processes beneath ice streams in West Antarctica, and for better definition of the potential impact that solute and sediment exported from beneath the ice streams may have on the fertilization of coastal ocean systems.

Sensitivity of submarine melting of 79N glacier to ocean forcing

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The Nioghalvfjerdsbræ (79NG) is a floating ice tongue on Northeast Greenland draining a large part of the Greenland Ice Sheet. A CTD profile from a rift on the ice tongue close to the northern front shows that Atlantic Water (AW) is present in the cavity below, with maximum temperature of approximately 1°C at 610 m depth. The AW present in the cavity thus has the potential to drive submarine melting along the ice base. Here, we simulate melt rates from the 79NG with a 1D numerical Ice Shelf Water (ISW) plume model. A melt water plume is initiated at the grounding line depth (600 m) and rises along the ice base as a result of buoyancy contrast to the underlying AW. Ice melts as the plume entrains the warm AW. Maximum simulated melt rates are 50 – 76 m/yr within 10 km of the grounding line. Melt rates drop rapidly to 6 m/yr within the first 10–20 km from the grounding line. Further downstream, melt rates are between 15 m/yr and 6 m/yr. The melt-rate sensitivity to variations in AW temperatures is assessed by forcing the model with AW temperatures between 0.1–1.4 °C, as identified from the 10 ECCOv4 ocean state estimate. The melt rates increase quadratically with rising AW temperature, and overall mean melting changes from 10 m/yr to 21 m/yr with the changes in ocean forcing. The corresponding freshwater flux ranges between 11-30 km^3/yr (0.4–1.0 mSv). If the 79NG has gone from steady state to the warm AW forcing between 2012 and 2016 it accounts for approximately 9% of the recent freshwater discharge from the ice sheet. Our results show that submarine melting of the marine-terminating 79NG is sensitive to changes in ocean temperature.

ICESat-2 Bathes The World In Soothing Green Light

Benjamin Smith[1], Tom Neumann[2], Nathan Kurtz[2], Lori Magruder[3],
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The Ice, Cloud and land Elevation Satellite-2 (ICESat-2 to you and me) launched on 15 September 2018, and has been collecting science quality data since 14 October 2018, just over a year ago. Data continue to be delivered to the community through the National Snow and Ice Distributed Active Archive Center (NSIDC). I hope that we will be able to report that everything continues to operate smoothly with the Advanced Topographic Laser Altimeter System (ATLAS) and the spacecraft that carries it from 88 degrees north to 88 degrees south some 15 times a day. (Everything is fine as of this writing in any case!)

In this presentation, we will give a mission update including the status of ATLAS, an overview of the data products of interest (specifically ATL03—the geolocated photon cloud that will eat your hard drive space, ATL06—the product for ice sheet enthusiasts, and ATL09 in case anyone care about the atmospheric conditions at the time the data was collected), upcoming and recent data releases and what is new in those products - release 002 should be out right in time for this meeting, and an assessment of the overall data quality.

The excellent coverage of the WAIS by ICESat-2 will hopefully form not only a reference elevation data set, but allow for measurement of fine spatial and temporal scales of change. With this presentation, we hope to show off ICESat-2 to interested parties and point people towards the tools and tricks that will help get them on the way to using the data. We're also happy to take any feedback from data users about what works, what doesn't, and what would make ICESat-2 data better.

Thickness of the divide and flank of the West Antarctic Ice Sheet through the last deglaciation

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We report cosmogenic-nuclide measurements from two isolated groups of nunataks in West Antarctica: the Pirrit Hills, located midway between the grounding line and the divide in the Weddell Sea sector, and the Whitmore Mountains, located along the Ross-Weddell divide. At the Pirrit Hills, evidence of glacial-stage ice cover extends up to ∼320 m above the present ice surface. Subsequent thinning mostly occurred after ∼14 kyr B.P., and modern ice levels were established some time after ∼4 kyr B.P. At the Whitmore Mountains, cosmogenic C-14 concentrations in bedrock surfaces demonstrate that ice there was no more than ∼190 m thicker than present during the past ∼30 kyr. Combined with other constraints from West Antarctica, the C-14 data imply that the divide was thicker than present for a period of less than ∼8 kyr within the past ∼15 kyr.

At the Pirrit Hills, ice levels appear to have lowered monotonically following the last glacial maximum despite the deglacial increase in snowfall, which suggests that the dominant glaciological process was thinning induced by retreat of the grounding line downstream in the Weddell Sea. In contrast, the divide at the Whitmore Mountains appears to have initially thickened following the LGM due to increased snowfall, and only thinned once the dynamic effects of margin retreat began to outpace the thickening from snowfall.

We use these results to evaluate five recently-published ice-sheet simulations at the Pirrit Hills and Whitmore Mountains. We find that most of the models we consider do not match the observed timing and/or magnitude of thickness changes at these sites. However, the model of Pollard et al. (JGR Earth Surf., 122, 2124-2138; 2017) performs well at both sites, which may be, in part, due to the fact that the model was calibrated with geological observations of ice thickness change from many sites in Antarctica.

Why now?
Evidence for an anthropogenic component to West Antarctic ice loss

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Recent ice loss from the West Antarctic Ice Sheet has been caused by ocean melting of ice shelves in the Amundsen Sea (1). Variability in the winds at the shelf break causes significant variations in the import of warm Circumpolar Deep Water onto the Amundsen Sea continental shelf, which creates transient melting anomalies (2). The dominant driver of the wind variability is the state of the tropical Pacific, which varies on interannual and decadal timescales as part of the natural El Niño-Southern Oscillation cycle (ENSO) (3,4). This raises the question of why WAIS ice loss has probably increased over the last century: if the main forcing is ENSO, and there is no trend in ENSO, then what has driven the change in ice sheet loss? In other words, why are such losses occurring now? A new analysis by Paul Holland and colleagues (5) provides a credible explanation. Climate model simulations suggest that although interdecadal variability related to ENSO has dominated the ice-sheet-relevant wind variations over the last century, this variability is superimposed on a small but significant long term trend that has caused the shelf-break winds to become increasingly westerly over the last century. This implies warm anomalies in the Amundsen Sea have gradually become more prevalent in the last century. Importantly, the simulate trend begins prior to the 1970s, and is largely attributable to greenhouse gases rather than ozone depletion. Existing climate model projections show that strong future greenhouse-gas forcing creates persistent mean westerly shelf-break winds by 2100, suggesting a further enhancement of warm ocean anomalies.

1. Jacobs et al, 1992
2. Jenkins et al, 2018
3. Steig et al., 2012
4. Dutrieux et al, 2014
5. Holland et al, 2019

Searching for subglacial evidence of past West Antarctic Ice Sheet collapse – 1: Exposure history of a subglacial bedrock core

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Cosmic ray exposure provides a direct and unambiguous method for determining whether subglacial bedrock has been deglaciated during climatic periods warmer than the present. During the 2016-17 Antarctic field season we attempted to drill two bedrock cores from different depths below the surface of the West Antarctic Ice Sheet (WAIS) in the Pirrit Hills. The first hole failed within a few meters of the bed due to hydrofracture of the basal ice, but the second produced 8 m of bedrock core overlain by 1 m of intact ice from a depth of 150 m. The core top was collected without exposure to light, to allow for luminescence dating. Cosmic-ray-produced Be-10 and Al-26 concentrations in quartz are low and uniform down the core, with the exception of the topmost meter, where there is a systematic increase in Be-10 up to ~1000 atom/g over the background level of ~4000 atom/g. These data indicate: (i) Average Pleistocene ice cover of ~200 m. (ii) One or more pre-Pleistocene deglaciations that exposed the core site for ~200–800 years in the Pliocene, or $>$ 800 years, in the Miocene. Infra-red stimulated luminescence (IRSL) dating shows the core top to be saturated, setting a minimum age for last exposure to sunlight $>$ 450 ka, consistent with the Be-10 and Al-26 data. Trapped atmospheric argon from 80 cm above the bedrock surface indicates an age for the enclosing ice $>$ 2 Ma (δAr-40/Ar-36 = -0.15 ‰). Together these results rule out any Pleistocene thinning of ice in the Pirrit Hills region by more than 150 m. However, implications for overall WAIS volume require model-based extrapolation from this single geographic datum. These implications, and estimates of the WAIS contribution to eustatic sea level during past climatic warm periods, will be explored in the accompanying presentation by Hillebrand et al. (this meeting). Supported by NSF awards NSF-ANT-1142162 and PLR-1341728.

From observations at the glaciers' margins to ice sheet model projections: Progress in understanding ice sheet/ocean interactions in Greenland

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Increased melting under Greenland's floating ice shelves and at the edge of its marine-terminating glaciers, associated with warming ocean waters, has emerged as a likely trigger for glacier speed up, making ice sheet-ocean interactions a scientific priority underlying efforts to improve predictions of climate change and sea level rise. This talk focuses on advances in our understanding of glacier/ocean exchanges based on observations made at the edge of Greenland's massive calving glaciers where melting is caused by intrusions of warm, subtropical waters into the fjords and enhanced by plumes of surface melt released hundreds of meters below sea level. Next, I show how understanding gained from observations and processed based models has been used to construct parameterizations of ocean forcing to be used by ice sheet models for IPCC climate scenario projections.

Modelling Active Subglacial Lakes

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Hundreds of subglacial lakes have been observed through satellite and aerogeophysical studies in Antarctica. Altimetry studies show that these lakes commonly inflate and deflate in response to water volume changes over time. Understanding how ice deformation above these lakes reflects changes in basal conditions is fundamental in assessing the state of the subglacial drainage system in many areas. However, the response of the ice surface to subglacial lake filling and draining has not been explored in sufficient detail with numerical models. Here we introduce a model for ice flow over a subglacial lake in order to characterize surface expressions of lake activity and quantify water pressure variations. We use a modified Stokes model where water volume is conserved via a Lagrange multiplier that in part determines the mean water pressure in the lake. Using this model, we study the evolution of the free surfaces over time for various volume change regimes. We quantify the departure of the mean water pressure from the ice overburden pressure in order to introduce an effective pressure approximation that may be used in simplified models of lake drainage. We use a simplified model to study filling-draining cycles in a system of two lakes that are connected by a subglacial channel. Complex oscillations in the downstream lake are driven by discharge out of the upstream lake. These include multi-peaked and anti-phase filling-draining events. We compare the results from both models with ice altimetry data from West Antarctic subglacial lakes to explore quantitatively the relationship between ice-surface deflection and changes in lake volume.

The Bellingshausen Sea at the confluence of the West Antarctic ocean circulation system

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The transport of warm Circumpolar Deep Water (CDW) towards the West Antarctic coast, extensively documented along the West Antarctic Peninsula (WAP) and in the Amundsen Sea, is largely responsible for the rapid thinning of ice shelves in this region. The Bellingshausen Sea (BS) has exhibited similar or even higher rates of ice shelf thinning, yet it remains remarkably under-studied compared to the WAP and the Amundsen Sea to the east and to the west, respectively. Here, we propose that the BS plays a critical role in the circulation system of West Antarctica due to unique water mass transformation processes that occur here. The BS not only connects circulation features between the WAP and the Amundsen Sea, but also contributes to setting water properties that circulate under ice shelves throughout the West Antarctic continental shelf. We also offer a new mechanism for the initiation of the Antarctic Slope Front (ASF) in the western BS that impacts the transport of heat across the continental shelf break in the Amundsen Sea.

We present observations from a hydrographic survey of the BS continental shelf completed in January 2019, complemented by historical data. Using CTD, Lowered ADCP, and ocean glider observations, we show that submarine troughs provide topographically-steered pathways for CDW from the shelf break towards deep embayments and under ice shelves in the BS. Warm, modified CDW (MCDW) enters the shelf in the Belgica Trough and flows onshore along the eastern side of the trough. Modification of these poleward-flowing waters can be detected from meltwater concentrations exiting along the western side of the Belgica Trough. These changes to MCDW are complemented by the formation of high salinity shelf waters in polynyas that are crucial to the establishment of the ASF. From our observations we estimate the strength ($\sim$1 Sv) and structure of the shelf overturning circulation. We present the magnitude and distribution of meltwater fractions within the BS, and will discuss the potential for the complex boundary current system observed over the continental slope to transport water mass properties to the Amundsen Sea.

Airborne ElectroMagnetics (AEM) as a powerful tool for efficient mapping of subglacial and englacial conditions along ice sheet margins

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High frequency radio-echo sounding (radar) has been the primary airborne geophysical tool for glaciological investigations since 1970s. Its great advantage is that it can penetrate kilometers into meteoric glacier ice, thanks to the fact that this material has very low electrical conductivity and, hence, long attenuation length scales for radar waves. However, radar imaging ends typically right at the ice bed, and sometimes even at the top of the more conductive accreted ice layers. This is because radar attenuation increases drastically in water- and solute-bearing materials. Time-domain ElectroMagnetic (TEM) surveying is a lower frequency EM technique. Propagation of EM energy is governed in TEM by a diffusion equation rather than by a wave equation. The technique relies on the fact that secondary EM fields are induced in subsurface conductors by the primary EM field imposed by a large antenna suspended under a helicopter. The time-rate-of-decay of magnetic field strength measured at the receiver coil can be inverted for vertical electrical resistivity structure down to >800 m. We will review the results of two TEM surveys which collected data over ca. 5000 km in the McMurdo Dry Valleys and surroundings. These surveys probed the resistivity structure of East Antarctic outlet glaciers, local mountain glaciers, and the McMurdo Ice Shelf. We will review the insights into subglacial and englacial structure of these systems gained from the AEM data. The AEM can clearly reveal subglacial water through up to 800 m thick glacier ice, including in locations where past radar surveys concluded that there was no water beneath ice.

Subglacial Sediments Spanning Scales: A Process-To-Paleo Perspective

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Research throughout the last decade has revealed a dynamic hydrological system of interconnected lakes and streams beneath the Antarctic ice sheet through which basal meltwater is transported from the interior of the continent to the ocean. Whereas almost two decades of multi-mission satellite observations have facilitated a modern understanding of subglacial lake fill-drain dynamics, the longevity of active subglacial lakes on longer (geologic) timescales, and thus the significance of these features as reservoirs of ice sheet history, has remained unclear. We present new biogeochemical evidence bound by Ramped PyrOx radiocarbon derived from sediment cores collected by the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD, 2013 & 2015) and Subglacial Antarctic Lakes Scientific Access (SALSA, 2018–2019) projects. Sedimentary radiocarbon records from the Whillans Ice Stream grounding zone provide in situ evidence for Holocene grounding line variability, while sediment cores collected upstream the of the grounding line at Mercer Subglacial Lake (SLM) reveal a more complex history characterized by three distinct sedimentary facies, including a laminated sequence providing preliminary evidence for past subglacial lake fill-drain cycles. Geochemical evidence from SLM sediment also indicate oceanic connectivity to WAIS subglacial environment within the radiocarbon record (last $\sim$60,000 years), however microfossil assemblages reveal no age-diagnostic taxa indicative of open-ocean conditions within that timeframe. These unique sedimentary records provide new insight into subglacial carbon cycling as well as the style and timing of past ice sheet variability along the Siple Coast, which could inform models of future ice dynamics of the West Antarctic Ice Sheet.

Ice-shelf secondary flow counteracts the growth of sub-shelf basal channels

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Ice-shelf basal channels form due to concentrated melting at the base of floating ice shelves. Basal channels are present in many Antarctic ice shelves and can reduce ice-shelf structural integrity, potentially incising through the entire ice-shelf thickness. We describe the viscous ice response to the presence of a basal channel—secondary flow—which acts perpendicular to the channel axis and is induced by the gradient in ice thickness across the channel. Owing to the large gradient in ice-shelf thickness, secondary flow cannot be approximated accurately using the Shallow Shelf Approximation. We present an analytical higher-order approximation and show that secondary flow increases with channel height and the slope of channel sidewalls. Using a numerical ice-flow model, we test the analytical approximation and demonstrate how secondary flow reduces the rate of channel growth and increases the time until complete incision through the ice shelf. In some cases, a steady-state geometry can exist even while melt continues.

Our combined analytical and numerical approach allows us to conclude that despite vertical gradients in horizontal flow near a basal channel, well resolved surface velocities can be used to determine basal melt rates, as is commonly done in remote-sensing studies. However, the future growth of basal channels cannot be predicted by assuming a constant growth rate and the ice-flow response must be accounted for.

Glacial Earthquakes and Precursory Seismicity Reveal Thwaites-Glacier Calving Behavior

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We observe two large (~M_s 5) long-period (10–50 s) seismic-events that originate from the terminus of Thwaites Glacier, Antarctica. Serendipitous acquisition of radar satellite images display a calving event of Thwaites Glacier at this time and confirm that the seismic events were glacial earthquakes generated during the capsizing of icebergs. The glacial earthquakes were preceded by 6 days of discrete high frequency events with an increasing rate of occurrence, culminating in several hours of sustained tremor co-eval with the long period events. A series of optical satellite images collected during this precursory time-period show that the high frequency events and tremor are the result of accelerating growth of ancillary fractures prior to the culminating calving event. Although Thwaites Glacier is one of the largest sources of Antarctic ice-mass loss, the physics of the processes that control discharge into the ocean remains poorly resolved. This study indicates that seismic data have the potential to elucidate the processes by which Thwaites glacier discharges into the ocean, and improve our ability to constrain future sea-level rise.

How increasing WAIS meltwater and earlier springtime opening may flip the Amundsen Sea polynya from carbon sink to source

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The magnitude and direction of the Southern Ocean CO_2 flux is important to both the global carbon cycle and any potential feedbacks to climate change. Here we explore the climate sensitive nature of a carbon cycle 'hot spot' in coastal Antarctica that is impacted by the WAIS. The Amundsen Sea hosts the most biologically productive polynya in all of Antarctica, with its vibrant green waters visible from space, and an atmospheric CO_2 uptake density 10x higher than the Southern Ocean average. The region is vulnerable to climate change, however, experiencing rapid losses in sea ice, a changing icescape, and some of the fastest melting glaciers flowing from the West Antarctic Ice Sheet (WAIS). Currently, basal melt resulting from warm deep waters penetrating ice shelf cavities dominates mass losses of WAIS, contributing to sea level rise. These physical melting processes are being studied by the International Thwaites Glacier Collaboration (ITGC). The impact of melting on the marine ecosystem has also been explored, and we know that productivity is due in part to meltwater-associated micronutrient iron delivery, which underpins productivity in this otherwise high-nutrient, low chlorophyll region. We have shown previously how meltwaters impact the coastal ecosystem using observations as well as a high-resolution numerical model developed to simulate ocean circulation in the Amundsen Sea and its interactions with the WAIS. Melting ice shelves are crucial for supplying iron both directly and indirectly (via the "meltwater pump," or buoyancy-driven overturning circulation). Biogeochemical cycling is included in this 3-D model (St-Laurent et al. 2019), with parameterizations developed using a 1-D model version (Oliver et al. 2019). An important result is that the 1-D model (with no lateral advection) reproduced the bloom if provided a realistic Winter Water (WW) iron reserve. With this 1-D model, we will demonstrate here the importance of seasonal sea ice and the timing of polynya opening to the carbon sink, particularly under increasing meltwater flux. Since the buoyant iron- and meltwater-rich deep waters are also rich in CO_2, the polynya carbon sink depends very much on net photosynthesis in the well-lit surface waters. If sea ice melts just 2 weeks earlier, the bloom is enhanced by a lengthened growing season. Melting sea ice 6 weeks earlier, however, triggers deeper mixed layers and light-limitation, reducing biological productivity and increasing the opportunity for outgassing of carbon-rich waters, and reversing the flow of CO_2 from atmosphere-to-ocean, to ocean-to- atmosphere. We expect this reversal to intensify under conditions of increasing meltwater.

Oliver, H., P. St-Laurent, R. M. Sherrell, and P. L. Yager (2019). Modeling iron and light controls on the summer Phaeocystis antarctica bloom in the Amundsen Sea Polynya. Global Biogeochem. Cyc. doi:10.1029/2018GB006168 St-Laurent, P., P. L. Yager, R. M. Sherrell, H. Oliver, M. S. Dinniman, and S. E. Stammerjohn (2019). Modeling the seasonal cycle of iron and carbon fluxes in the Amundsen Sea Polynya, Antarctica. J. Geophys. Res: Oceans. doi: 10.1029/2018JC014773

Integrating englacial reflectors across the Amundsen Sea Embayment: A progress report

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The AntArchitecture project is a multinational inititutive to construct a cohesive englacial stratigraphy for the Antarctic Ice Sheet, using ice penetrating radar. This compliation will require integrating data from radar systems with differing center frequencies, bandwidths and processing approachs, from multiple institutions and surveys with different science goals. Early work on such intercomparisons has focued on Dome C in East Antarctica. Here we discuss progress on performing these intercomparisons in West Antarctica, in the vicinity of Thwaites Glacier and Pine Island Glacier. Using oil industy seismic packages, UTIG and the University of Edinburgh have performed extensive mapping of key glacial horizons through the catchments of Thwaites Glacier (with HiCARS) and Pine Island Glacier (PASIN). UTIG has mapped out six key horizons and connected them to the WAIS and Byrd ice cores, and performed a Bayisan analysis on the uncertainity in the age of four of these horizons. Edinburgh has identifed three horizons that span much of the southern catchment of Pine Island Glacier. Through flight lines that were shared between the surveys, we assess the corrspondance between the two stratigraphies.

Diagnosing the sensitivity of grounding line flux to changes in sub-ice shelf melting

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We look for an improved physical understanding for how ice dynamics link ice thickness perturbations, via changes in sub-ice shelf melting, to changes in ice shelf buttressing and grounding line flux. More specifically, we seek a connection among grounding line flux, ice shelf buttressing and basal melting. By studying the ice dynamics for both idealized (MISMIP+) and realistic (Larsen C) ice shelves, we find a strongly direction-dependent buttressing number that links local changes in ice shelf thickness and dynamics with changes in the integrated grounding line flux. From these two examples, this buttressing metric, defined using the first principal stress, is better overall for quantifying changes in grounding line flux than a similar metric defined using the second principal stress or stress along the flow direction. This correlation is possibly controlled by the relative relationship of geometric/dynamic features between the perturbation point and the grounding line, indicating a dynamic (time evolving) sensitivity field of integrated grounding line flux to basal melt. We find this buttressing metric only shows a robust relationship with the integrated grounding line flux for regions near the center of an ice shelf; for points too near the grounding line or the calving front, no clear relationship exists. This motivates our exploration of an adjoint-based method for defining integrated grounding line flux sensitivity to local changes in ice shelf geometry.

Laboratory produced unstable glacial slip

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Glacial seismicity continues to provide insight into subglacial phenomena, but the underlying mechanics that control glacial seismicity from unstable slip remain speculative. Using a biaxial shearing apparatus that shears debris-laden ice over a bedrock asperity we have, for the first-time, generated laboratory "icequakes". By modifying and controlling the apparatus stiffness we generate stick-slip behavior during shearing that provides insights into unstable glacier slip for comparison with field seismological observations. We find that our laboratory-produced icequakes replicate several seismological field observations of glacier slip, such as slip velocity, stress drop, and stress drop recurrence-interval relationship. A positive correlation between sliding speed and stress drop was found, which is also consistent with observations from laboratory experiments of rock friction. Furthermore, we observe a velocity dependence of stable vs unstable sliding that confirms our prior predictions of slip stability from rate-and-state friction.

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