Student Awards Form

#WAISworkshop
WAIS West Antarctic Ice Sheet Workshop

WAIS Workshop 2021 Agenda (*all times EDT*)

Algonkian Regional Park
Sterling, VA USA

Monday, September 20

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

Tuesday, September 21 (All oral sessions are in the Loudoun Room)

Breakfast: 7:30 am – 8:30 am (Loudoun Room)

Session 0	Opening Business	Presenter
8:30 am	Welcome to WAIS Workshop 2021	WAIS Committee
8:40 am	View from NSF [video]	NSF
8:50 am	View from NASA [video]	NASA

Session 1	WAIS in the Community	Presenter
9:00 am	Community Building Efforts around Justice, Equity, Diversity, and Inclusion (JEDI) within the International Thwaites Glacier Collaboration (ITGC) [video]	Betsy Sheffield
9:10 am	Women's representation in the glaciological literature and the challenge of participation [video]	Christina Hulbe
9:20 am	Best practices in Glaciology: Building inclusivity through cryospherecollective.org [video]	Malisse Lummus & Jessica Mejia
9:30 am	Climate Ninja goes south! An outreach project involving Lego, school children and climate scientist [video]	Elin Darelius
9:40 am	Discussion [video]	All

10:00 am	One minute in-person poster teaser talks [video]	

Coffee Break: 10:30 am – 11:00 am

Session 2	Community Health	Presenter
11:00 am	Mental health, well being, and WAIS	Dr. Desiree Dickerson

Lunch: 12:30 pm – 1:30 pm (Loudoun Room)

Session 3	Marine Ice Sheet Sensitivity	Presenter
1:30 pm	Sensitivity of the West Antarctic Ice Sheet to +2 °C (SWAIS 2C) [video]	Molly Patterson
1:45 pm	Response of the Antarctic continental shelf heat budget to WAIS meltwater [video]	Ruth Moorman
1:55 pm	Rapid mass loss from WAIS may increase magmatic CO_2 flux to the atmosphere and geothermal heating [video]	Fiona Clerc
2:05 pm	High geothermal heat flow beneath Thwaites and Pope glaciers inferred from Curie depth analysis of a new aeromagnetic grid compilation [video]	Ricarda Dziadek

2:15 pm	Modeling ocean circulation in the Bellingshausen Sea [video]	Shuntaro Hyogo
2:25 pm	A generalized theory for layered subglacial seawater intrusion under grounded ice and implications for marine ice sheet retreat [video]	Alexander Robel
2:35 pm	Quantitative analysis of the maximum rate and minimum duration for a 200-km step-wise retreat of the Bindschadler Ice Stream at ~11.5 cal. kyr BP [video]	Matthew Kratochvil
2:45 pm	West Antarctic archipelago covered by cool-temperate forests during early Oligocene glaciation [video]	Johann P. Klages
2:55 pm	Discussion [video]	All

In-person Coffee break: 3:20 pm – 4:00 pm (Loudoun Room)
Virtual coffee break with the program managers: 3:20 pm – 4:00 pm (Zoom)

4:00 pm	Virtual Lightning Poster Session [video]	Zoom!

Dinner: 5:30 pm – 7:00 pm

Wednesday, September 22 (All oral sessions are in the Loudoun Room)

Breakfast: 7:30 am – 8:30 am (Loudoun Room)

Session 4	Beyond MISI Part I	Presenter
8:30 am	Antarctic Atmospheric River Climatology and Impacts in West Antarctica [video]	Jonathan Wille
8:45 am	Climatology of West Antarctic Atmospheric Rivers and their Impacts on Thwaites Glacier Surface Mass Balance [video]	Michelle Maclennan
8:55 am	Evaluating Antarctic precipitation-circulation relationships in CESM2 and what they mean for our understanding of historical and future snowfall trends [video]	David Schneider
9:05 am	Through-ice-shelf drainage of surface meltwater lakes and its implications for ice shelf stability [video]	Philipp Arndt
9:15 am	Mechanism for the Subglacial Formation of Cryogenic Brines [video]	Sarah Neuhaus
9:25 am	Quantifying glacial meltwater inventory in Pine Island Bay from 1994–2020 using seawater δ^{18}O isotopes [video]	Andrew Hennig
9:35 am	Discussion [video]	All

Coffee Break: 10:00 am – 10:20 am

Session 5	Beyond MISI Part II	Presenter
10:20 am	Marine ice sheet retreat: are we taking the MICI? [video]	Nick Golledge
10:35 am	Investigating basal thaw as a driver of mass loss across Antarctica [video]	Eliza Dawson
10:45 am	Subglacial abrasion energy expenditure during basal slip [video]	Jeremy Brooks
10:55 am	Frozen fringe growth and its effect on basal slip [video]	Dougal Hansen

11:05 am	Reconsidering multi-decadal ice-margin sliding deceleration associated with rising meltwater supply: Insights from alpine glacier analogues [video]	Nathan Stevens
11:15 am	Inward Migration of the Shear Margins at Thwaites Glacier in Response to Thinning [video]	Paul Summers
11:25 am	Riftquakes: Recording and Modeling Seismic Signals of Rifting at Pine Island Glacier [video]	Seth Olinger
11:35 am	Discussion [video]	All

Lunch: 12:00 pm – 1:00 pm (Loudoun Room)

Session 6	Greetings from the Future Part I	Presenter
1:00 pm	High-fidelity modeling of marine ice-cliff instability shows mixed-mode ice-cliff failure and stabilisation from mélange [video]	Anna Crawford
1:15 pm	Modeling the control of iceberg calving on decadal-scale retreat of Thwaites Glacier [video]	Trevor Hillebrand
1:25 pm	Circulation-Melt Interactions within Glacial Fjords [video]	Ken Zhao
1:35 pm	Development of a fixed-wing UAV for ice-penetrating radar data collection [video]	Dennis Woo
1:45 pm	Glaciological Constraints on Link Budgets for Orbital Radar Sounding of Earth's Ice Sheets [video]	Dustin Schroeder
1:55 pm	Snowfall Climatology and Extremes over Antarctica: First Results from a Variable-Resolution CESM2 [video]	Rajashree Datta
2:05 pm	Evidence of Recent Ocean-Driven Grounding Zone Retreat at Kamb Ice Stream Grounding Zone [video]	Peter Washam
2:15 pm	Discussion [video]	All

Coffee Break: 2:40 pm – 3:10 pm

Session 7	Greetings from the Future Part II	Presenter
3:10 pm	Closing the frequency gap between remote sensing and in situ observations [video]	Brent Minchew
3:25 pm	Radar polarimetry at Hercules Dome reveals ice fabric as it changes along the triple divide [video]	Benjamin Hills
3:35 pm	A Multi-frequency Radar Sounder and Integrated Radiometer for Measuring Ice Sheet Englacial and Basal Conditions [video]	Anna Broome
3:45 pm	Streamlined bedform sensitivity to bed characteristics from deglaciated landscapes [video]	Marion McKenzie
3:55 pm	Calibrating flow law parameters and uncertainties over Antarctic ice shelves with physics-informed neural networks [video]	Bryan Riel
4:05 pm	Discussion [video]	All

4:30 pm	In-person and Virtual Poster Session	Both Rooms & Zoom

Dinner: 6:00 pm (Loudoun Room)

Thursday, September 23 (All oral sessions are in the Loudoun Room)

Breakfast: 7:30 am – 8:30 am (Loudoun Room)

Session 8	**Piecing the Puzzle Together Part 1**	**Presenter**
8:30 am	Glacially derived sediment sources of iron fueling productivity in the Amundsen Sea [video]	Lisa Herbert
8:45 am	Sensitivity of the relationship between Antarctic ice shelves and iron supply to projected changes in the atmospheric forcing [video]	Michael Dinniman
8:55 am	Tracking Circumpolar Deep Water: Foraminifera as a proxy for oceanic conditions offshore Thwaites Glacier, Antarctica [video]	Asmara Lehrmann
9:05 am	Stable channelized subglacial drainage modeled beneath Thwaites Glacier, West Antarctica [video]	Alexander Hager
9:15 am	Insights from Thwaites and IPY on Building Large Collaborative International Programs [video]	Robin Bell
9:25 am	Thwaites Glacier Research at the mid-point of ITGC [video]	Ted Scambos
9:35 am	Discussion [video]	All

Coffee Break: 10:00 am – 10:30 am

Session 9	**Piecing the Puzzle Together Part II**	**Presenter**
10:30 am	What lies beneath: Using sub-ice archives to assess the Holocene (in)stability of the West Antarctic Ice Sheet [video]	Ryan Venturelli
10:45 am	Tectonic Influence on Bed-Character Variability under Thwaites Glacier, West Antarctica [video]	Louise Borthwick
10:55 am	Resolving solid earth properties through co-location of high-resolution ice load histories and GNSS measurements in West Antarctica [video]	Jamey Stutz
11:05 am	AntArchitecture goes west: towards an age-depth model of the WAIS from radiostratigraphy [video]	Robert Bingham
11:15 am	Can international consortia support pan-Antarctic observational networks? [video]	Terry Wilson
11:25 am	The US Antarctic Program Data Center (USAP-DC) — data archive and project catalogue for Antarctic Sciences [video]	Kirsty Tinto
11:35 am	Discussion [video]	All

Lunch: 12:00 pm to 1:00 pm

Community College Educators Session: 1:00 pm – 3:00 pm

Virtual Lightning Posters

Title	Presenter
Inferring Antarctic Ice Sheet Elevation Change from Temperature Sensitive Ice Core Records	Jessica Badgeley
How Strong is a Sticky Spot? New Constraints on Healing and Shear Strength Beneath Whillans Ice Plain	Grace Barcheck
Disentangling the roles of natural variability and anthropogenic forcing in driving rapid outlet glacier retreat	John Erich Christian
Flexing the Explanatory Power of Plane Strain in a Grounding Zone Shear Margin	Martin Forbes
Known unknowns: The characteristics of the ice-ocean interaction of the Ronne Ice Shelf — Presenting the Ronne Ice Shelf Project (RISP)	Coen Hofstede
Is material strength expressed in geophysical properties of the glacial substrate?	Nicholas Holschuh
Icequakes measure friction and slip at the bed of Rutford Ice Stream, Antarctica	Tom Hudson
Damage control: forming stable ice shelves in simulations with damage mechanics	Samuel Kachuck
A thermomechanical model for subglacial frozen fringe	Colin Meyer
The Antarctic Meteorological Research and Data Center	David Mikolajczyk
Inverting ice surface elevation and velocity for bed topography beneath Thwaites Glacier	Helen Ockenden
Application of machine learning methods to identify glacial seismicity in a Distributed Acoustic Sensing dataset from Store Glacier, West Greenland	Andrew Pretorius
Flow Laws for Ice Sheet Modelling: Experiments tell us that n $\sim$ 4 not 3?	David Prior
Ice loss from asymmetric melting at Thwaites Glacier grounding zone	Britney Schmidt
Stability of Marine Ice Sheets in the Presence of Feedbacks	Olga Sergienko
Evidence for Temperate Ice in Shear Margins of Antarctic Ice Streams from Airborne Radar Surveys	Paul Summers
A synthesis of ice-ocean interface observations from the underwater vehicle Icefin	Peter Washam
The three-dimensional overturning circulation of the West Antarctic shelf seas	Andrew Thompson
Stability of Surface/Basal Crevasses in Marine Ice Shelves	Maryam Zarrinderakht

In-person Posters

Title	Presenter
Examining ice shelf grounding zone change with repeat, high-resolution elevation models and altimetry	Allison Chartrand
Evidence for simultaneous 20th century ice shelf changes of Thwaites and Pine lsland glaciers	Rachel Clark
Flow-Driven Boundary Conditions on the Wilkins Ice Shelf Firn Aquifer	Riley Culberg

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Title	Presenter
Durations of Grounding-zone Stillstands on the Ross Sea Outer Continental Shelf	Matthew Danielson
Deciphering the Role of Meltwater in the Formation of Muddy Antarctic Sediments	Nicole Greco
Grain-size evolution controls the accumulation dependence of modeled isothermal firn thickness	Jonathan Kingslake
An Observationally Based Investigation of Co-variability in the West Antarctic Atmosphere, Sea Ice, and Ice Sheet Surface Mass Balance	Jessica Kromer
Geostatistical simulation reveals subglacial hydrologic and geologic boundary conditions in the Amundsen Sea Embayment	Emma MacKie
Laser Cutting to Collect Ice Samples in Boreholes	Merlin Mah
$n=4$	Joanna Millstein
Hunt Fjord Ice Shelf: Insight into a Northern Greenland Ice Shelf	Naomi Ochwat
Feedbacks between ice deformation and ice rheology	Meghana Ranganathan
Does grounding line sinuosity drive ice shelf rifting on tidal timescales? Evidence from eastern Thwaites	Kiya Riverman
Observing connected subglacial lake drainage at Slessor Glacier, East Antarctica, using ICESat-2 laser altimetry	Wilson Sauthoff
Investigating persistent polynya structure and variability at Pine Island Glacier, West Antarctica, using seal-borne measurements and thermal remote sensing	Elena Savidge
Eastern Thwaites basal channel outflow inferred from persistent polynya variability	Tasha Snow
Wave propagation on Pine Island Glacier, West Antarctica, quantified with remote sensing	Erik Tamre
Simulation of flexural-gravity wave response of geometrically complex ice shelves to ocean waves and tides	Nurbek Tazhimbetov
Ice thickness interpolation with physics-informed neural networks	Thomas Teisberg
The Impact of Elevation-SMB Feedbacks on the Evolution of Thwaites Glacier, West Antarctica	Hannah Verboncoeur
The Automatic Weather Station Network	Lee Welhouse
Sedimentary and Bathymetric Structure Near the Grounding Line of Totten Glacier, East Antarctica	J. Paul Winberry

Observations of widespread through-ice-shelf drainage of surface meltwater lakes across Antarctica

Philipp Arndt[1], Dr. Helen Amanda Fricker[1]
[1]*Scripps Polar Center*

Surface melt is a small contribution to the total Antarctic Ice Sheet mass balance, but many of its floating ice shelves experience it to a significant degree. It is generally assumed that the vast majority of meltwater produced each melt season re-freezes in the winter, so surface runoff is deemed negligible for the net surface mass balance. Individual events of direct surface meltwater loss to the ocean have been documented, but were thought to be rare. We present evidence of widespread through-ice-shelf drainage of surface meltwater lakes, observed across various ice shelves around Antarctica. We show that supraglacial meltwater can accumulate on the surface of ice shelves in often buried lakes for many melt seasons before draining into the sub ice shelf ocean cavity nearly instantaneously. Such drainage events are observed year-round and likely occur via a through-cutting crevasse formed at the base of the meltwater lake by hydrofracture. The removal of a large load from the top of the floating ice shelf results in flexural uplift in the region around the drained lake basin. The associated surface elevation changes can be monitored using modern high-resolution WorldView satellite stereo imagery and ICESat-2 laser altimetry. Data from before and after the drainage events make it possible to estimate the total volume of meltwater lost to the ocean, whereas long-term observations can document the gradual viscoelastic response of the ice shelf to drainage and unloading and thus help constrain parameters used in modeling studies. Ice shelf surface elevation changes related to lake drainage have the potential to lead to significant local changes in surface meltwater routing, which may ultimately determine an ice shelf's long-term resilience in a warming climate.

Inferring Antarctic Ice Sheet Elevation Change from Temperature Sensitive Ice Core Records

Jessica A. Badgeley[1], Dr. Eric J. Steig[1], Dr. Marina Dutsch
[1]University of Washington, [2]University of Vienna

Temperature fluctuations preserved in paleoclimate records result from changes in climate forcing and elevation. Disentangling these two processes is valuable for reconstructing the past evolution of climate and land masses, including ice sheets. Previous efforts to estimate past elevation have paired paleo-temperature records that are thought, a priori, to have experienced the same climate change and different elevation changes. It is assumed that the difference between the two records can be simply converted to elevation with a lapse rate. Though this method is based on the first law of thermodynamics, the resulting elevation estimates are prone to error. We use an ensemble of existing climate simulations to quantify this error for estimates of Antarctic Ice Sheet elevation change from the last glacial maximum (LGM) to the pre-industrial (PI). We run three additional climate simulations to separate the effects of elevation and other climate forcings on the LGM-to-PI temperature change. These simulations allow us to identify the sources of error and their contribution to each elevation estimate.

How Strong is a Sticky Spot? New Constraints on Healing and Shear Strength Beneath Whillans Ice Plain

Dr. Grace Barcheck[1], Allan Brewer Cappellin[2], Dr. Slawek Tulaczyk[2], Dr. Bruno Sansó[2], Dr. Susan Schwartz[2]
[1]Cornell University, [2]University of California, Santa Cruz

Ice stream bed shear strength is difficult to measure, simply because of the remoteness and inaccessibility of the ice stream bed. Yet, basal traction is a key parameter affecting the velocity and mass balance of Antarctic ice streams. Whillans Ice Plain is known for its tidally-modulated stick-slip cycle and is experiencing a multi-decadal slow down that may be caused by an increase in basal traction. Here, we use in situ seismic and GPS observations to estimate the magnitude of basal shear stress at the start of unstable slip events on the Whillans Ice Plain sticky spot. These data also provide evidence for healing of the ice-bed interface between slip events.

Our primary observation is that, at two neighboring locations on the ice plain, surface GPS motion at the start of unstable slip precedes the start of basal seismic wave radiation by several minutes. At these sites, basal seismicity is strong evidence for basal sliding, and lack of basal seismicity for the first few minutes of the event suggests that local sliding has not yet begun. We hypothesize that this lag between GPS motion and basal seismicity occurs when the ice base is strong enough to remain locked for several minutes while the ice column begins to deform due to loading from neighboring sliding ice. Eventually, the shear stress exerted on the bed due to deformation of the ice columns exceeds the local bed strength and sliding and basal seismicity begin.

We measure the magnitude of GPS displacement up to the point of basal seismicity onset for dozens of unstable slip events, finding ice surface displacements of ~10-30 cm. For 800 m thick ice, this corresponds to average shear strains in the ice column of ~1e-4 to ~4e-4, consistent with the maximum strain that geologic materials generally can experience before failing. Additionally, the magnitude of the shear strain increases when more time has elapsed since the previous unstable slip event. This is a unique geological signal of healing, or an increase in the critical threshold for failure with hold-time.

We estimate the shear stress on the ice stream bed at the moment when sliding starts. Assuming linearly elastic ice, these strains imply a basal shear stress at failure of ~200-1,000 kPa, values that are improbably high for an ice stream bed. Using a simple viscoelastic Burgers model driven by GPS-measured surface displacement, we calculate more-reasonable basal shear stress at failure in the range of ~50-200 kPa, with the high-end values observed only for longer (>17 hours) inter-event times. In addition, spectrograms generated from the high frequency seismic data reveal variation in ice stream tremor behavior relative to GPS-measured surface velocity for events occurring after short versus long inter-event times.

These observations provide new insights into the rate of healing for the Whillans Ice Plain basal slip surface and provide estimates for the basal shear strength of the primary sticky spot, which may help to understand the mechanism of decadal basal strengthening that is driving Whillans Ice Plain to slow down.

Insights from Thwaites and IPY on Building Large Collaborative International Programs

Dr. Robin Bell[1]
[1]*Lamont-Doherty/Columbia University*

Now is a unique time for the WAIS community and Cryosphere science. The scale of Cryosphere science is beyond the capacity of any individual investigator or even a single nation. The urgency of society's demands for answers. The U.S. National Academy of Sciences and its Polar Research Board have played an important role to launch these programs. The Academy's role in Polar Science goes back to the 1950's when much of the planning of the original Antarctic science and publication of the results from traverses to cruises was coordinated through the Academy. For the International Polar Year (2007-9) the Polar Research Board took the initiative and began the planning process that fostered the international collaborations. The results of the IPY ranged from the formation of APECs to POLENET to the Gamburtsev Mountains Expedition (AGAP). These programs were only possible due to the international collaboration. The Thwaites initiative emerged from a Polar Research Board study funded by NSF to set the priorities for Antarctic and Southern Ocean Research. Again this study dovetailed well with the priorities emerging from the UK and have led to the Thwaites program. Both these efforts brought new funding and new programs to our community. This is a unique moment to look to begin planning the next major programs.

AntArchitecture goes west: towards an age-depth model of the WAIS from radiostratigraphy

Professor RG Bingham[1], Dr Julien A. Bodart[1], Dr David W. Ashmore[2], Dr Duncan A. Young[3], Dr Nanna B. Karlsson[4], Dr Neil Ross[5], Professor Olaf Eisen[6], Dr Joseph A. MacGregor[7], AntArchitecture Consortium[8]

[1]School of GeoSciences, University of Edinburgh, [2]School of Environmental Sciences, University of Liverpool, [3] Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, [4]Geological Survey of Denmark and Greenland, [5]School of Geography, Politics and Sociology, Newcastle University, [6]Alfred Wegener Institute, [7]NASA Goddard, [8]Scientific Committee for Antarctic Research

Throughout the Quaternary Antarctica's ice cover has waxed and waned, inducing concomitant rises and falls in global sea level. It is critical to understand the rates and drivers of these past oscillations in order to contextualise current observations of persistent and accelerating losses of ice from contemporary Antarctica, and thereby project as accurately as possible the rates at which future global sea-level rise fuelled by ice melt will occur. The evidence for past Antarctic ice-sheet fluctuations has been derived predominantly from drilling into sediments deposited offshore around the continent and into the ice itself at ice divides and blue-ice exposures; these endeavours have supplied the palaeoclimate records that underpin all numerical modelling reconstructions of past and present ice-sheet extents and which are then used to project how this may evolve into the future together with implications for global sea levels. Complementary data that directly record past ice conditions, and hence indirectly record past climate conditions – but, uniquely, in a spatially continuous form all across the ice sheet - have been acquired from ice-penetrating radar (IPR) surveys acquired by multiple groups over the last >50 years across Antarctica. Although primarily motivated to sound the ice-sheet bed and thereby measure ice thickness and volume, the majority of IPR surveys have also sounded numerous internal-reflecting horizons that have remained under-utilised to date.

In summer 2018, an international initiative was established to coordinate international efforts in the lodging and scientific applications of Antarctica's "radiostratigraphy", ultimately to develop a continent-wide age-depth model of Antarctica's ice which can, for example, be used to link deep ice cores, and ultimately help to reconstruct past accumulation, ice dynamics and basal melting. Invoking the concept that radar-sounded englacial layering reflects the internal architecture of Antarctica, the initiative has collectively been termed AntArchitecture, and is presently funded as an international Action Group by the Scientific Committee for Antarctic Research.

An expanded outline of AntArchitecture and its timeline of activities can be accessed here: https://www.scar.org/science/antarchitecture/about/

This presentation provides a status report of activities and achievement of AntArchitecture to September 2021. Here we focus predominantly on the progress we have made to date in tracking a consistent set of internal-reflecting horizons across the WAIS, giving approximate age-depth constraints over the last 16.5 k.a.

Tectonic Influence on Bed-Character Variability under Thwaites Glacier, West Antarctica

Louise Borthwick[1], Atsuhiro Muto[1], Kirsty Tinto[2], Sridhar Anandakrishnan[3], Robin Bell[2], David Porter[2], Caitlin Locke[2]
[1]Temple University, [2]Lamont-Doherty Earth Observatory, Columbia University, [3]Pennsylvania State University

Of the parameters controlling flow of glaciers and ice-sheets, subglacial topography and bed character are influential. At an area of upper Thwaites Glacier, West Antarctica, reflection-seismic studies have shown variations in the subglacial topography and bed character. These occur in an along-flow direction, with flatter “lowland” areas containing continuous soft bed and the more elevated, rugged “highland” areas containing a mix of hard and soft beds. Here, we model upper crustal structures to assess their relationship with the previously found bed-character variability. Our study site centers around the location of the previous reflection-seismic study at an area 230-km inland of the current grounding line. We use long-offset reflection/refraction-seismic data over a ~40-km section and extend the section to ~220-km using airborne gravity and magnetic data. We find a sedimentary basin under the continuous soft bed of the lowland area with its downstream edge aligning with the transition from lowland to highland area, indicating the basins existence could be related to the formation of the subglacial topography. The basin is ~11-km long, ~400-m deep and has a half-graben shape, suggesting influence of rifting in its formation potentially associated with the West Antarctic Rift System. As the location of the basin aligns with bed-character variability and subglacial topography, there is potential tectonic influence on the basal conditions of Thwaites Glacier, which will have a resulting impact on the glacier flow.

Subglacial abrasion energy expenditure during basal slip

Jeremy Brooks[1], Dougal Hansen[1], Lucas Zoet[1]
[1]*Department of Geoscience, University of Wisconsin-Madison*

Variable bed conditions recently discovered beneath West Antarctic ice streams highlight the need to consider hard-bed physics when estimating catchment-wide erosion rates. Bedrock promontories cleared of till on their stoss sides remain in constant contact with basal ice and entrained debris, which will erode the surface through the process of abrasion. Basal drag for ice streams is highly sensitive to bed rheology and basal topography; therefore understanding how quickly rigid bedrock highs can be eroded or shaped is important for predicting long-term sliding dynamics. Energy expended through abrasion detracts from the overall available energy budget, with implications for landscape evolution beneath ice sheets and glaciers on glacial-interglacial timescales. However, the amount of basal sliding energy dissipated by subglacial abrasion is poorly constrained. Pioneering attempts to quantify abrasion energy dissipation in alpine catchments estimated that approximately 30% of basal sliding energy was consumed by abrasion, but these estimates have large uncertainties, warranting the need for a detailed investigation to constrain this energy expenditure. To this end, we conducted a suite of experiments, using both a direct shear and a cryogenic ring shear device, to simulate the process of abrasion during basal slip under a range of glaciological conditions for beds of two lithologies (limestone and marble). The magnitude of the contact force between entrained clasts and the bed is set by the melt rate at the ice-bed interface, which we vary between experiments, and basal drag is continuously recorded. We precisely quantify the abraded volume by scanning all resultant striations with a white light interferometer, capable of nm-scale vertical resolution, and constrain grain size distribution of the gouge particulate using laser diffraction analysis. From these metrics, we calculate the energy consumed by subglacial abrasion and compare it to overall basal sliding energy. Preliminary results indicate that less than 10% of energy is dissipated by subglacial abrasion, which is substantially less than previous estimates.

A Multi-frequency Radar Sounder and Integrated Radiometer for Measuring Ice Sheet Englacial and Basal Conditions

Ms. Anna Broome[1], Dr. Dustin Schroeder[2]
[1]Department of Electrical Engineering, Stanford University, [2]Department of Geophysics and Department of Electrical Engineering, Stanford University

Radar sounding is a powerful tool for investigating englacial and subglacial conditions of ice sheets and glaciers. Radar echoes reflected off the bed directly measure ice sheet basal conditions including thermal state, material, and roughness, as well as englacial conditions such as density and temperature. Each of these glaciological conditions has a nonunique effect on the echo power, creating ambiguity in interpretations of radar sounding data. Existing ice-penetrating radar sounders are unable to disambiguate the contributions of these different effects, which makes it challenging to comment on ice sheet basal conditions with confidence. We are developing a multi-frequency ice-penetrating radar sounder, which will be able to separate basal material and basal roughness effects by leveraging the frequency dependence of scattering from a rough surface and the frequency independence of basal reflection coefficients. We are also developing the capability to simultaneously acquire ground-based radiometer data that when used in conjunction with the radar data will allow us to constrain and/or correct for ice-sheet temperature and attenuation signals. Our system thus removes two significant sources of ambiguity in the interpretation of ice sheet basal conditions from radar sounding data. Here we will present details on system development and calibration, as well as discuss survey design and system performance considerations for studies to characterize basal hydrology, thermal state, roughness, and material for both grounded and floating ice.

Examining ice shelf grounding zone change with repeat, high-resolution elevation models and altimetry

Ms. Allison Chartrand[1], Dr. Ian Howat[1]
[1]Byrd Polar & Climate Research Center - The Ohio State University

Ice shelves control the stability of ice sheets and regulate ice sheet contribution to sea level rise by buttressing ice flow. Most of Greenland's ice shelves have already been lost, and many ice shelves around Antarctica are thinning and retreating, with the most significant changes occurring in West Antarctica. Many factors influence ice shelf stability both spatially and temporally, including changes at the grounding line, basal melt, variable strain rates and stress transfer, and the incidence and advection of surface and basal features. The relationships between these processes, and their implications for ice shelf stability, remain largely unknown due to the lack of observations of sufficiently high spatial and temporal resolution. We aim to elucidate how changes in elevation, thickness, and geometry at the grounding zone relate to the evolution of ice shelf features such as sub-shelf meltwater channels, rifts, and crevasses for several ice shelves in West Antarctica. Further, we intend to investigate how these processes impact overall ice shelf stability, defined as the persistence of ice shelf area necessary to maintain a "safety band", or sufficient buttressing force, against grounded ice. We use high temporal and spatial resolution digital elevation models (DEMs) from REMA and laser altimetry from ICESat-2 to map and track the positions of ice shelf structures (e.g. rifts; surface depressions of sub-shelf channels) as well as to quantify elevation and thickness changes at the grounding zone. Where time-evolving grounding line position data are sparse, we use the DEMs to track the boundary of hydrostatic equilibrium, which we use as a proxy for changes in grounding line position in order to investigate changes in ice shelf geometry. Based on our preliminary results, we hypothesize that rapidly evolving sub-ice shelf melt channels are associated with high rates of change in the grounding zone. We also expect to use velocity maps, in concert with surface elevation, to correlate downstream structure evolution with earlier changes in the grounding zone, as our temporal range of observations allows. This work is integral to assessing past and future ice shelf stability and to obtaining more accurate estimates of ice flux across the grounding zone, which will improve estimates of the contribution of Antarctica to sea level rise.

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Disentangling the roles of natural variability and anthropogenic forcing in driving rapid outlet glacier retreat

Dr. John Erich Christian[1,2], Dr. Alexander Robel[1], Dr. Ginny Catania[2]
[1]Georgia Institute of Technology, [2]University of Texas at Austin

Many marine-terminating outlet glaciers in Greenland and Antarctica have retreated in recent decades, but the role of anthropogenic forcing remains uncertain. One challenge is that the forcing acting on glaciers is noisy. Glacier retreats have been tied to local atmospheric and ocean anomalies, which are in turn influenced by known modes of internal climate variability. For example, recent analyses show that atmospheric variability in the tropical Pacific paces the submarine melt anomalies at glaciers terminating in the Amundsen Sea. Similarly, Atlantic climate variability modulates melt anomalies in Greenland.

An additional challenge for attributing retreats comes from the fundamental dynamics of marine-terminating glaciers. Many of the largest observed retreats have occurred on reverse-sloping bed topography, which implicates the marine-ice-sheet instability. This instability means that, if sufficiently perturbed, marine-terminating glaciers may retreat irreversibly between topographic highs, or collapse entirely. These threshold dynamics complicate efforts to attribute glacier changes to natural vs. anthropogenic forcing. In the context of internal climate variability, an attribution assessment must evaluate the anthropogenic role against the possibility that that natural variability alone could push termini past topographic thresholds. Recent studies have clarified the anthropogenic component of climate anomalies that affect glaciers, but formal attribution statements have not yet been made for the glacier retreats themselves.

We propose a probabilistic attribution framework that asks: what is the likelihood that variability alone could have triggered glacier retreat, and how has anthropogenic forcing changed that likelihood? We demonstrate the framework using large ensembles of models forced with independent realizations of climate variability. Synthetic experiments over a range of parameters clarify the major controls on the probability of retreat, and show that estimated probabilities can be sensitive to uncertainties in boundary conditions and the glaciers' preindustrial state. However, a century-scale external forcing trend robustly increases the probability of retreat, even if the trend is small compared to the natural variability. This is a simple consequence of the timescales over which glacier dynamics integrate forcing, and suggests that the full history of anthropogenic forcing is important for outlet glacier attribution, even for recently-initiated retreats.

Evidence for simultaneous 20th century ice shelf changes of Thwaites and Pine Island glaciers

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Today, Circumpolar Deep Water (CDW) is flowing onto the Amundsen Sea shelf and melting marine-based ice at the grounding zone and at the base of floating ice shelves. In recent years, this melting has resulted in net mass loss for Pine Island Glacier and neighboring Thwaites Glacier. It is unknown when this trend initiated for Thwaites Glacier since satellite and airborne radar data only extend back to the 1970s. The marine sedimentary record around the Thwaites Glacier calving margin can be used to investigate ice-ocean dynamics over the past centuries and millennia. In 2019 and 2020, two research cruises, aboard the RV Nathaniel B. Palmer, sailed to the Amundsen Sea continental shelf to survey the seafloor around Thwaites Glacier and recover marine sediment cores across a range of water depths and distances from the ice-shelf margin. The cores were analyzed continuously downcore for magnetic susceptibility and density, and discrete sediment samples were investigated for a range of proxies, including grain size and grain shape. The radioactive isotope 210Pb was measured on the uppermost sediments (ca. 5-40 cm) to calculate sediment accumulation rates and approximate ages of deposition over the past century. Several cores were selected for computed tomography (CT) scanning to aid the visual identification of sedimentary structures. We used this information together with the other multi-proxy data to identify and map sedimentary facies across the study area, with a particular focus on cores collected from local depressions atop large bathymetric highs or ridges to investigate recent glacier history and dynamics. In general, the sediment facies changes sharply from gravel-rich muds into fine-grained laminated clayey. This change is linked to the unpinning of the ice shelf from the seafloor and expansion of the ice-shelf cavity above these bathymetric highs. Based on 210Pb geochronology, unpinning initiated in the mid twentieth century. This timeline is similar to the ice shelf unpinning that Smith and others (2017) documented in sediment cores collected under the Pine Island Glacier ice shelf. While additional proxies and analyses are required to investigate when CDW flow underneath Thwaites Glacier ice shelf intensified, this initial work suggests this incursion occurred with similar timing at both glaciers. This finding is consistent with geological data from the outer Amundsen Sea shelf suggesting increased CDW advection onto the shelf between the 1940s and 1970s (Hillenbrand et al. 2017).

References: Hillenbrand, C.-D. et al. 2017: West Antarctic Ice Sheet retreat driven by Holocene warm water incursions. Nature 547, 43-48. Smith, J.A. et al. 2017: Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier. Nature 541, 77-80.

Rapid mass loss from WAIS may increase magmatic CO2 flux to the atmosphere and geothermal heating

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The rapid retreat of ice sheets decreases pressures in Earth's mantle, enhancing mantle melt generation[1]. Enhanced melting can result in increased volcanic activity[2], which in turn may incite the release of CO_2 and aerosols into the atmosphere and the acceleration of glacier flow by geothermal heating. Previous scalings of eruptive records suggest the global deglacial release of CO_2 influences climate[3] [4]. Yet these estimates exclude areas currently under ice (i.e., W. Antarctica) or hydrothermal systems (i.e., Yellowstone). We model the enhancement in mantle melting due to the deglaciation of the Yellowstone ice cap. We find a 19-fold enhancement in melting and estimate the associated CO_2 released may have increased the modern global volcanic CO_2 flux by ~23–39%. More broadly, we suggest magmatically-active continental systems may experience enhanced mantle melting in response to deglaciation. Tectonic similarities between the West Antarctic Rift System and Yellowstone include volcanic activity[5], relatively thin (60–110 km) continental lithosphere[6], possible existence of a mantle plume[7], and extensional lithospheric stresses. During some interglacials, paleo proxies[8] and models[9] suggest rapid mass loss from the West Antarctic Ice Sheet (WAIS), which when combined with the horizontal extent of WAIS, imply deglacial unloading will generate larger rates of decompression at asthenospheric depths compared to our calculations for Yellowstone. Finally, while the total flux of CO_2 from West Antarctic volcanism is unconstrained, other continental rift systems are important CO_2 emitters[10] and sections of the West Antarctic mantle are rich in CO_2 (ref. 11). Thus, rates of mantle melting and associated CO_2 fluxes released into the atmosphere may be greatly enhanced during WAIS collapse and could drive a positive feedback with climate warming. As modern elevated GHF already influence ice flow (e.g., ref. 12), deglacially enhanced melting may further impart heat to the base of the WAIS and accelerate its collapse. Understanding the magnitude of deglacially enhanced melting beneath West Antarctica has implications for global carbon budgets, climate, and the evolution of the WAIS over millennial time scales.

1. Jull & McKenzie, JGR (1996); 2. Maclennan et al., G3 (2002); 3. Huybers & Langmuir, EPSL (2009); 4. Watt et al., ESR (2013); 5. De Vries, et al. (2018) ; 6. An et al., JGR (2015); 7. Behrendt et al. (1992); 8. Scherer et al., Science (1998); 9. Pollard & DeConto, Nature (2009); 10. Werner et al. (2019); 11. Giacomoni et al., Lithos (2020); 12. Blankenship et al., Nature (1993)

High-fidelity modeling of marine ice-cliff instability shows mixed-mode ice-cliff failure and stabilisation from mélange

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Immense ice-cliffs could be exposed at the periphery of the Antarctic Ice Sheet (AIS) following ice-shelf loss and the retreat of glacier grounding lines. An ice cliff will be susceptible to structural failure when it reaches a height at which glaciostatic stress exceeds the yield strength of ice. If increasingly tall ice cliffs are exposed following each cycle of failure, then the rapid retreat process of marine ice-cliff instability (MICI) will initiate. It is challenging yet necessary to adequately represent ice-cliff failure in AIS simulations and projections of global sea level rise. In this study, we investigated ice-cliff failure by conducting a series of idealised simulations with a suite of high-resolution 3D glacier models that consisted of the full-Stokes continuum model, Elmer/Ice, the Helsinki Discrete Element Model (HiDEM), and a second, brittle visco-elastic implementation of HiDEM. We found that structural ice-cliff failure can transpire through a range of modes that can be described by the interactions of viscous deformation, brittle failure and shear-band formation. The simulations also showed that retreat rates and instability rapidly increase with cliff height, though the transition to self-sustaining MICI retreat may be averted depending on initial thickness of calving fronts and viscous deformation rates. A simple retreat rate law for ice-cliff failure was derived from the most conservative failure mode. This power-law equation is intended for use in continental-scale ice sheet models that will also need to represent mélange, which can suppress ice-cliff failure if sufficient resistive force (4.2e6 to 5.7e7 N m-1) is exerted on a calving face. Regions with over-deepening basins > 1 km in depth are particularly vulnerable to collapse via MICI and research conducted as part of the DOMINOS project of the International Thwaites Glacier Collaboration is now looking at how ice-cliff failure and MICI could unfold at susceptible locations (e.g., Thwaites Glacier).

Flow-Driven Boundary Conditions on the Wilkins Ice Shelf Firn Aquifer

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Perennial firn aquifers are formed by the infiltration and storage of surface meltwater in porous firn in areas with sufficient annual accumulation to insulate the subsurface water from seasonal refreezing. On the Greenland Ice Sheet, aquifer boundaries and large-scale flow are controlled by a combination of melt-to-accumulation ratio, surface topography, and stress regime, with some aquifers likely draining to the bed through downstream crevasses. Perennial firn aquifers have also recently been identified on several current ice shelves and ice shelf remnants in the Antarctic Peninsula, including the Wilkins Ice Shelf. An ice shelf environment potentially exerts a more complex set of controls on aquifer boundaries as compared to ice sheets, particularly in inlets where the physical and thermal state of the firn is affected by the convergence of ice from tributary glaciers, the long-term dynamics of suture zones on the shelf, and localized surface mass balance variations like föhn-induced sublimation of snow and surface melting.
We use ice penetrating radar, visible and SAR satellite imagery, firn saturation estimates derived from satellite L-band microwave radiometry, ice velocity derived from satellite optical feature tracking, and RACMO climate model outputs to investigate the sharp transition from surface ponding and dolines to subsurface storage within perennial firn aquifers in the Hayden inlet of the northern Wilkins Ice Shelf. We have identified a combination of aquifer drainage to the ocean from troughs developed above basal crevasses, intermittent subsurface refreezing, and brine infiltration where the faster-flowing (~500 m/yr) Gilbert Glacier merges with the slower-flowing (<~100 m/yr) shelf, suggesting that ice dynamics may have a strong influence on meltwater pathways to the ocean as well as ice shelf stability at ice shelf aquifer–tributary glacier boundaries. Similar processes can be inferred at the aquifer-tributary glacier boundaries on the northern George VI Ice Shelf and the former Wordie Ice Shelf.

Durations of Grounding-zone Stillstands on the Ross Sea Outer Continental Shelf

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Seismic mapping of grounding-zone wedges (GZWs) on the Ross Sea continental shelf has been used to reconstruct the grounding-zone locations at and after the last glacial maximum (LGM). There now exists an extensive grid of regional seismic data across Ross Sea that are primarily hosted at the Antarctic seismic data library system (SDLS) by the Italian National Institute of Oceanography and Applied Geophysics (OGS). The last regional study of Ross Sea was conducted by Anderson et al. (2014). Within the context of GZWs identified in that study, we are using over 500 seismic transects with a total line coverage of ~54,000 km to map the sediment volume of major GZWs in each of the Ross Sea trough basins complementing Perez et al., 2021. The mapping includes complexes interpreted to be of LGM and post-LGM ages. Previous studies have shown that the Bindschadler Ice Stream deposited 5.2 x 10^{11} m^3 of GZW sediment on the outer continental shelf of the Whales Deep Basin in eastern Ross Sea. Chronologic control indicates that this unusually large volume represents deposition during an ~3000-year-long grounding zone stillstand. This corresponds to an average erosion rate of 0.7 mm a^{-1} averaged over the entire drainage area. At the other extreme, our preliminary analyses shows that LGM GZW sediment volume in the Pennell Trough is significantly smaller suggesting that the erosion rates were either much lower or that the stillstand was of a shorter duration. In this ongoing study, a combined interpretation of the subsurface mapping and geomorphological mapping serves two goals: 1) the creation of updated isopach and time-structure maps of grounding-zone sediments deposited in each trough and 2) an evaluation of a relative grounding-stillstand history of the West Antarctic Ice Sheet (WAIS) in Ross Sea. Time-structure maps are being created for each trough and depth-converted using velocity control from sonobuoy data acquired during multiple previous expeditions. Since the deposition of seismically resolvable GZWs occurs during grounding line stillstands, we present stillstand durations calculated using sediment volumes derived from sediment flux estimates. These duration estimates for grounding-zone stillstands are significant because they further refine the regional-scale reconstruction of WAIS retreat in Ross Sea.

Climate Ninja goes south! An outreach project involving Lego, school children and climate scientist

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Climate Ninja - a Lego figure - has so far joined climate researchers P. Langebroek and E. Darelius to fieldwork in EastGRIP and on an icebreaker in the Weddell Sea. His adventures have been documented in photo novels, that are currently available online (Flickr). The stories are guided by Ninja's curiosity, and the reader learns about our science while getting insight into life on a research station and vessel.
In a newly funded project, we are to collaborate with "climate clubs" in local schools and libraries to turn our stories about Climate Ninja into science based children books.

Snowfall Climatology and Extremes over Antarctica: First Results from a Variable-Resolution CESM2

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Both the quantity and characteristics of snowfall over Antarctica are a critical component of uncertainty in sea level rise estimates, especially as snowfall over Antarctica is projected to increase with global temperature in the future. Earth System Models can provide valuable information for understanding current Antarctic snowfall as well as providing predictions in future scenarios.

The open-source Community Earth System Model version 2 (CESM2) has been used extensively over polar regions for present-day, paleoclimate and future scenarios. A new, variable-resolution version of CESM (VR-CESM) balances the extensibility of a global model with the high computational costs of a high-resolution regional climate model by nesting a higher resolution grid within a coarser-resolution global grid. Here, we introduce a new VR-CESM grid (ANTSI) with a 0.25° resolution over the Antarctic ice sheet and surrounding oceanic regions within a 1° global grid typical for the default CESM2. Enhanced spatial resolution models better capture complex surface mass balance processes, including orographic lifting when air masses interact with the ice sheet topography.

This grid was designed to capture maximum mean sea ice extent in the modern era, thus potentially applicable for a wide array of simulations (e.g. paleoclimate runs). Runs were performed with an active atmosphere and land model, forced by observed sea surface temperatures and sea-ice concentration (1979-2020). . We compare our VR-CESM results with lower-resolution CESM2 simulations forced by the same observed sea ice and SST, to isolate the effect of enhanced resolution. In addition, we compare our results to the fully-coupled CESM2 Large Ensemble.. All simulations are compared to in situ observations and ERA5 reanalysis to assess overall biases.

Outputs produced at a high temporal-resolution from VR-CESM ANTSI will be used to calculate the frequency and effects of atmospheric rivers, to be compared with the ERA5-derived catalogue. Our results will allow us to characterize how well Antarctic climate, and especially snowfall, is captured by this first historical simulation of VR-CESM ANTSI, and provide a baseline for future climate simulations.

Investigating basal thaw as a driver of mass loss across Antarctica

Ms Eliza Dawson[1], Dr Dustin Schroeder[1], Dr Winnie Chu[2], Dr Elisa Mantelli[3,1], Dr Helene Seroussi[4]
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Contemporary mass loss from Antarctica primarily originates from the discharge of marine terminating glaciers and ice streams. The rate of mass loss is influenced by warming ocean and atmospheric conditions, which lead to subsequent thinning or disintegration of ice shelves and increased outflow of upstream grounded ice. What's less clear is how the basal thermal state of upstream grounded ice could evolve in the future and thereby have an effect on mass loss as well. Here, we use the Ice-sheet and Sea-level System Model to investigate the impact of basal thawing on the Antarctic Ice Sheet over 100yr simulations and find that it can be a significant driver of mass loss across the ice sheet. Notably, we find that if localized patches of frozen bed were to thaw, that could be enough to transition from a stable mass balance configuration to mass loss in some regions. We supplement this work with analysis of ice penetrating radar data with the goal of discerning transitions in the basal thermal state using characteristics of the radar bed reflectivity. In combination, our work provides constraints on where the ice-bed interface could be frozen but vulnerable to thawing and estimates of possible mass loss due to thaw.

#WAISworkshop

Sensitivity of the relationship between Antarctic ice shelves and iron supply to projected changes in the atmospheric forcing

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Previous studies showed that correlations of satellite-derived estimates of chlorophyll a in coastal polynyas over the Antarctic continental shelf with the basal melt rate of adjacent ice shelves are a result of upward advection or mixing of iron-rich deep waters due to circulation changes driven by ice shelf melt, rather than a direct influence of iron released from melting ice shelves. A 5-km resolution ocean/sea ice/ice shelf model of the Southern Ocean is used to examine the effects of projected changes in winds, precipitation, and atmospheric temperatures on this relationship. The atmospheric changes are added as idealized increments to the forcing. Modifying the winds alone leads to a 50% increase in the total ice shelf basal melt with changes being heterogeneously distributed around the continent. Increasing the precipitation has little impact on the basal melt, but adding an increase in air temperature to the other changes gives a total 83% increase in basal melt compared to the base state. When all the atmospheric changes are added, the total dissolved iron supply to the surface waters over the continental shelf increases by 62%, while the surface iron supply due just to basal melt driven overturning increases by 48%. However, even though the total increase in iron supply is greater than the increase due to the ice shelves, the ice shelf driven supply becomes relatively even more important in some locations, such as the Amundsen and Bellingshausen Seas. Along with the increase in micronutrient supply to the surface, the atmospheric changes also lead to a reduction in summer sea ice extent and a shoaling of the summer mixed layers. All these changes point to a relief of light and nutrient limitation for phytoplankton blooms over the Antarctic continental shelf and perhaps an increase in annual production in years to come.

High geothermal heat flow beneath Thwaites and Pope glaciers inferred from Curie depth analysis of a new aeromagnetic grid compilation

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Variations in geothermal heat flow at the Earth‘s surface are a result of different tectonic and magmatic processes. High heat flow in the polar regions has been debated to play a significant role in affecting ice sheet dynamics. This is in particular relevant for the West Antarctic Ice Sheet which is largely underlain by thin crust of the West Antarctic Rift System causing a submarine setting for most of the ice sheet basis. Previous Antarctic continental-scale indirect heat flow estimates often have a low spatial resolution and yield large discrepancies between different models. In this study, we analyse integrated onshore and offshore aeromagnetic data to estimate geothermal heat flow in the Amundsen Sea sector of West Antarctica. We performed a detailed Curie depth analysis based on this new magnetic anomaly grid compilation, which reveals variations in lithospheric thermal gradients. Our analysis infers that the rapidly retreating Thwaites and Pope glaciers in particular are underlain by areas of largely elevated geothermal heat flow. These areas of high heat flow relate to the so far known tectonic and magmatic history of the West Antarctic Rift System in the Amundsen Sea sector. Our results imply that the behavior of this vulnerable sector of the West Antarctic Ice Sheet is strongly coupled to the dynamics of the underlying lithosphere.

Flexing the Explanatory Power of Plane Strain in a Grounding Zone Shear Margin

Martin Forbes[1], Holly Still[1], Prof. Christina Hulbe[1], Prof. Dave Prior[1]
[1]*University of Otago*

Shear margins are important sources of resistive stresses in the force budgets of glaciers, ice streams and ice shelves. As sites of large, localised deviatoric stresses, shear margins are exciting targets for field studies of ice deformation (and challenging sites in which to conduct such studies). The true-left margin of Priestley Glacier, a few kilometers downstream of the grounding line, is a relatively rare location in which both deformation and safe access coincide. The area is often scoured free of snow. In the austral summer of 2019-20, a New Zealand lead international team, collected ice core samples, and collected active seismic and phase sensitive radar through a transverse section across the shear margin. The primary aim was to investigate ice fabric, however, the suite of high quality surveying data used to provide kinematic context for that work is interesting in its own right.

Over the course of 3 weeks, the positions of a camp base station and a modest network of survey marks were observed using continuous GNSS (at the camp) and a total station. As expected, ice motion in the study area is tidally modulated in both the along- and across-flow directions, with along-flow velocity peaking on the falling tide. Such patterns have elsewhere been attributed to tidal modulation of glacier flow upstream of the grounding line or, where two velocity peaks are observed per cycle, tidally modulated increases in effective stress in the margin. Here, we use precise, high-resolution measurements across a tidally-forced shear margin to consider these two alternatives. We arrive at a third conclusion.

We simulate plane strain elastic bending across the glacier with a 2D finite element model implemented with FEniCS (opensource!) libraries. Bending is forced using pressure on the underside of the floating ice, following a coastal tide prediction. Lateral margins are fixed. We use a fit to the combination of vertical and horizontal displacement to calibrate Young's modulus as a homogeneous property of the ice. The across-flow motion is well described by this straightforward model. Similarities in both the magnitude and the timing of the along- and across-flow velocity variations lead us to conclude that at this site, elastic deformation alone explains flow response to tide forcing.

We would also like to note that with optical surveying techniques, you too could be measuring strains between $1/10^4$ and $1/10^5$.

Marine ice sheet retreat: are we taking the MICI?

Nicholas Golledge[1]
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The broad spread of simulated future global mean sea level trajectories is primarily associated with process-level deep uncertainty relating to the behaviour of the West Antarctic Ice Sheet. Traditional (diffusion-based) models are mature and well-tested across a range of environments and time scales, yet recently there have been suggestions that these models underestimate rates of ice sheet collapse. It has been proposed that non-analog modes of brittle ice failure also need to be incorporated, in order for both past reconstructions and future projections to be reliably simulated. In this talk I will briefly review the reasons why this new view has arisen, and the ways in which the approach has been implemented. Using examples from both past and future simulations I'll suggest some areas where future modelling effort could be focused, in order to clarify our process understanding and perhaps reduce projection uncertainty.

Deciphering the Role of Meltwater in the Formation of Muddy Antarctic Sediments

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Flocculation of fine sediment is pervasive in particle-rich nearshore hypopycnal plumes. Floc formation is seen in field studies of northern-hemisphere fluvial margins, deltas, and meltwater-rich fjords. Comparable studies are rare for Antarctica, but indicate lateral transport of fine sediment, likely as flocculated material implying a meltwater role in their formation. The fluvial introduction of suspended sediment into marine waters creates flocs, the quantity of which scales positively with water and sediment discharge. Subglacial meltwater discharge may contain fine sediment, which can rapidly flocculate and settle to the seafloor along with single grains of silt and sand transported in the turbulent plume discharge. Clay mineralogy also plays an important role in flocculation and settling velocity of sediment in the water column. The platy structure of clay minerals (<4 μm diameter) and their charge imbalances stimulate cohesion and flocculation. Curran et al. (2004; doi: 10.1111/j.1365-3091.2004.00647.x) infer the flux of flocculated and single-grain sediment to the seafloor with an inverse model applied to disaggregated grain size distributions (DIGS). I am applying the same model coupled with sediment mass accumulation rates to quantify the mass flux of flocculated mud in glacimarine environments. I am also performing bulk- and clay-mineral XRD analyses to account for sediment mineralogy. Published and newly acquired grain-size distributions are from terrestrial tills, sub-ice stream and sub-ice shelf cores, and grounding line proximal marine sediment cores. Observed meltwater discharge varies from minor (Ross Sea and East Antarctic Ice Sheet) to voluminous (Svalbard, Greenland, Alaska). Modeling is within context of published glacimarine facies to control for termini position on texture. The working hypothesis is that increasing meltwater abundance leads to increased floc formation, accumulation, and hydrodynamic sorting of single-grain silt sub-populations, but sediment minerology can also affect floc formation. I observe that sub-ice stream and terrestrial till deposits are extremely poorly sorted and polymodal, often with discrete modes in the clay-size fraction; no evidence of flocs exists. Suspended sediment DIGS from N. Hemisphere fjords are primarily floc with secondary single-grain fine-silt components. Similar distributions are seen in multicore sediments from Disenchantment Bay, Alaska, but show increased single-grain silt contributions having narrow modal size distributions, which we attribute to hydrodynamic sorting during subglacial and plume transport. Antarctic sediments contain both floc and single-grain silt fractions, but floc component is reduced, and my measurements of sediment mineralogy show lower clay mineral abundance relative to meltwater-rich settings. Single-grain modes also are more poorly sorted. I attribute both to minimal hydrodynamic sorting from reduced transport in meltwater prior to deposition relative to temperate settings. Floc accumulation rates are orders of magnitude larger in meltwater-dominant settings reflecting elevated glacial erosion rates that produce more sediment.

Stable channelized subglacial drainage modeled beneath Thwaites Glacier, West Antarctica

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Subglacial hydrology is a leading constraint on basal friction and ice dynamics. At low discharge, subglacial water flows through high-pressure, sheet-like systems that lubricate the glacier bed; however, at high discharge, subglacial water melts the overlying ice into localized channels that efficiently remove water and increase basal friction. Recent observations have suggested channelized subglacial flow exists beneath Thwaites Glacier, yet it remains unclear if stable channelization is feasible in West Antarctica, where surface melting is nonexistent and water at the bed is limited. Here, we used the MPAS-Albany Land Ice model (MALI) to run a suite of over 100 subglacial hydrology simulations of Thwaites Glacier across a wide range of physical parameter choices to assess the likelihood of channelization. We then narrowed our range of realistic simulations by comparing modeled water thicknesses to previously observed radar specularity content, an indicator of spatially extensive, water-saturated conditions at the bed. In all of our realistic simulations, stable channels reliably formed within 100–200 km of the grounding line, and reached individual discharge rates of 35–110 m^3/s at the ice-ocean boundary. No simulations matched specularity content when channelization was disabled. Our results suggest channelized subglacial hydrology has two contrasting consequences for Thwaites Glacier dynamics: amplifying submarine melting of the terminus and ice shelf, while simultaneously raising effective pressure within 100 km of the grounding line and buttressing against retreat.

Frozen fringe growth and its effect on basal slip

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Temperate ice overriding unconsolidated sediment (till) is a ubiquitous configuration for ice streams across the West Antarctic Ice Sheet (WAIS), but the character of the ice-till interface remains enigmatic. Layers of debris-laden basal ice (“frozen fringe”) have been observed in boreholes at WAIS, warranting consideration of its effect on both sliding dynamics and erosion rates. However, the spatial extent and growth rate of this fringe is poorly constrained, and the physics governing freeze-on remain an open debate. Classical understanding suggests that ice infiltrates basal sediment through regelation, a process in which ice melts in contact with till due to pressure melting and then refreezes around individual grains. However, this process neglects significant complexities undoubtedly present in natural systems and relies on questionable thermodynamic assumptions. Alternatively, new theory highlights the effects of premelting on ice-sediment interactions and postulates that the capacity for ice to infiltrate basal sediments is driven by surface energy at the interfacial contacts, indicating fringe growth depends sensitively on factors such as pore space geometry and effective stress rather than pressure melting.

Here we present results from two experiments designed to test the predictions of these models by growing frozen fringe in the laboratory under glaciological conditions and then testing its effect on drag induced during basal slip. Using a large-diameter, cryogenic ring shear apparatus, we slide temperate ice over saturated sediment beds with contrasting grain size distributions (a subglacial till and a loess). Once deformation reaches its critical state, we terminate ice motion and hold the system static under uniaxial compression at a constant effective stress for a prescribed period to facilitate fringe growth. We then resume shear while monitoring both basal drag and the orientation and geometry of the new failure surface. After the experiment ends, we dissect and characterize the ice-sediment interface to assess the extent and physical properties of any fringe. We track motion of the sediment bed using digital image correlation on a photographic time series captured through transparent walls, and pore geometry is estimated using a Monte Carlo approach that samples the pore space in synthetic sediments modeled after the measured grain size distributions of the loess and till. The rate and extent of fringe growth observed in these experiments provide a quantitative framework to weigh the predictions of both regelation and premelting theory for both parameters under well-constrained boundary conditions. Comparing the stress response and flow profile in the sediment beds for the case of clean ice against the presence of fringe offers insight into the mechanics dominating each.

Quantifying glacial meltwater inventory in Pine Island Bay from 1994-2020 using seawater δ18O isotopes

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The West Antarctic Ice Sheet (WAIS) has been identified as a potential tipping point for the Earth's climate system. WAIS Glaciers grounded below sea-level are responsible for most of the mass loss from Antarctica, today. Collapse of WAIS, driven by marine ice sheet instability (MISI) could lead to A rise in global sea level of up to 3.3 m. Mass losses in the Amundsen Sea sector occur in part where deep, warm, subsurface waters come into contact with ice shelves at and above their grounding lines. Glacial ice is highly depleted in $\delta^{18}O$ relative to other freshwater sources, and as such, paired $\delta^{18}O$-salinity measurements can be used to quantify the amount of glacial meltwater in the water column. The $\delta^{18}O$-salinity relationships reveal a relatively constant freshwater endmember isotopic value from 1994-2020 that can only result from glacial meltwater input. Calculations using $\delta^{18}O$ show a surprisingly constant mass inventory of glacial meltwater in Pine Island Bay between 1994 and 2020. Additionally, measurements of Modified Circumpolar Deep Water (mCDW) over the same period show a consistent multi-decadal decrease in seawater $\delta^{18}O$ while salinity remains relatively constant, pointing to increasing entrainment of glacial meltwater in the Antarctic Circumpolar Current (ACC) source waters of mCDW in the Amundsen Sea embayment. Measuring glacial meltwater using stable isotopes is a technique entirely independent from other methods of quantifying mass loss, and provide a means to measure the melt of coastal glaciers directly. Utilizing stable isotopes in conjunction with remote sensing methods of quantifying mass loss from ice sheets is crucial for understanding implications for future global sea level rise.

Glacially derived sediment sources of iron fueling productivity in the Amundsen Sea

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The Amundsen Sea hosts the highest primary productivity per unit area observed on the Antarctic continental shelf. Areas of high productivity are concentrated in coastal polynyas near the outlets of the fastest melting glaciers of the West Antarctic Ice Sheet. These polynyas are highly dynamic carbon sinks where production is controlled by light and the availability of iron (Fe). Previous studies indicate that most Fe in the polynya surface waters is delivered through upwelling of modified Circumpolar Deep Water that invades the deep shelf. The water mass eventually enters the ice shelf cavities, where it is injected into the upper water column by the addition of meltwater buoyancy (the "meltwater pump"). This altered surface water mass contains higher concentrations of Fe than the original water mass, suggesting that glacial inputs may be an important source of Fe to the surface water in the Amundsen through direct injection in glacial meltwater and/or remobilization of Fe phases from the seabed. While a remobilized Fe source from the seabed is suggested by observations and modeling to exceed a direct glacial meltwater source, the distribution and magnitude of the purported benthic Fe flux is unknown. To investigate the surface sediment biogeochemistry and the potential for a dominant benthic flux of Fe to the Amundsen Sea, sediment cores were collected at two sites close to the calving face of the Pine Island and Thwaites ice shelves in late summer 2020. Pore waters were analyzed for Fe and other trace elemental concentrations. Dissolved Fe fluxes were calculated from pore water gradients and porosity, revealing a spatially variable but potentially important input to the lower water column that could ultimately fertilize primary productivity in the polynyas. Fluxes of Fe from the benthos are supported by a combination of 1) reductive release during organic matter remineralization, and 2) a lithogenic source previously undescribed in the region, possibly linked to volcanic tephra observed in the sediments. These first-ever pore water metals data for the Amundsen Sea provide a basis for further investigation of Fe cycling and benthic-pelagic coupling in the region, which will likely be impacted by accelerating glacial melt and changes in productivity patterns resulting from ongoing climate change.

Modeling the control of iceberg calving on decadal-scale retreat of Thwaites Glacier

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The retreat of Thwaites Glacier has the potential to drastically increase the West Antarctic contribution to sea-level rise, and rates of ice shelf calving could exert a primary control on the glacier's future evolution. We explore the controls of iceberg calving on the future retreat of Thwaites Glacier over decadal timescales using the higher-order MALI ice sheet model, with an optimized initial condition that solves for ice temperature and basal friction in 2014. We explore four calving parameterizations based on damage, stress, and strain rates: (1) ice exceeding a threshold degree of damage is removed, with damage evolving through ductile thinning and ocean melting; (2) calving rates are proporational to degree of ice damage; (3) calving rates proportional to von Mises tensile stress; and (4) calving rates proportional to principal strain rates (eigencalving). We tune these to observed calving rates along the eastern ice shelf and simulate the glacier's evolution to 2050 using climate forcings from CMIP5/ISMIP6 and a range of basal friction laws to explore potential feedbacks between calving and grounded ice velocity. Carefully tuned calving parameterizations from hindcasting analysis of recent changes on the Thwaites ice shelf could potentially reduce uncertainties in near-future changes at Thwaites Glacier.

Radar polarimetry at Hercules Dome reveals ice fabric as it changes along the triple divide

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Hercules Dome is uniquely situated in the bottleneck between East and West Antarctica. Its proximity to the West Antarctic Ice Sheet implies that a history of WAIS collapse could be preserved within the deep ice. Not only is the paleoclimate history preserved within the isotope record, but also ice flow history is preserved within the englacial stratigraphy, ice temperature, and crystal orientation fabric. Here, we explore the latter, using radar polarimetry to interpret fabric. We conducted quad-polarized (VV, VH, HH, HV) ApRES acquisitions for eight locations at Hercules Dome. Four sites form a transect along the east-west ridge, and five sites form a transect across the ridge at the central saddle location (with one site occupying both transects). At each site, the co-polarized (HH-VV) phase gradient with depth is used to constrain girdle fabric orientation and strength profiles. The westernmost site is the shallowest, it has bed-conformal stratigraphy, likely a frozen bed, and the fabric is an east-west girdle. The saddle sites are slightly deeper, again with an east-west girdle. Along the saddle transect, the girdle weakens from strong for acquisitions north of the ridge to almost no phase gradient for acquisitions south of the ridge. The easternmost site is significantly deeper, with complex stratigraphy, signs of a thawed bed, and a north-south girdle. Girdle orientations agree with the InSAR surface velocities, knowing that ice crystal c-axes rotate toward maximum compression. The surface velocities and topography show that Hercules Dome is a triple divide with predominant north-south extension in the west and east-west extension in the east. Now, our fabric interpretations imply that this present-day triple-divide flow regime is consistent with at least the near-term flow history. Future field campaigns will repeat acquisitions for vertical (ApRES) and horizontal (GNSS) velocities, a critical step to interpreting our polarimetry data more holistically.

Known unknowns: The characteristics of the ice-ocean interaction of the Ronne Ice Shelf — Presenting the Ronne Ice Shelf Project (RISP)

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Ice shelf stability, largely determined by interaction with the ocean, is crucial to determine the wider stability of ice sheets. Ocean cavities underneath ice shelves form a particular difficulty, their geometry is essential to understand ice shelf-ocean interaction but difficult to constrain. Where the Filchner Ice Shelf was thoroughly investigated by the successful Filchner Ice Shelf Project (FISP 2015-2017), comparable interdisciplinary studies on the Ronne Ice Shelf are missing. We therefore propose a long traverse to acquire ~ 800 km seismic profiles at the Ronne Ice Shelf, Antarctica using the fast and efficient vibrator-snowstreamer technique AWI successfully employs since 2009. Next to an accurate seabed topography we aim to reconstruct the glaciological and geological history of the Ronne Ice Shelf area. AWI is looking for collaborators acquiring different data sets (ApRES, ocean measurements such as CTD, sediment coring) essential to understand and model the ice shelf-ocean interaction in this huge unknown area. In short AWI is looking for interested collaborators to help make this essential project a success.

Is material strength expressed in geophysical properties of the glacial substrate?

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Early remote sensing efforts captured the state of the ice sheets for the first time, measuring the velocity structure, ice surface elevation, and (where radar data were available) ice thickness. Ice sheet models were then used to ingest those data and reproduce the observed state. But, the substrate rheology and bed strength, tuned to reproduce modern observations, are non-unique, leading to diverging projections of future sea level rise. As data availability increases, two types of data have been proposed as additional constraints on unknown ice sheet properties: (1) the measured transient response of the ice sheet from our growing remote sensing record, and (2) substrate geophysical properties measured using radar and active source seismic experiments (e.g., acoustic impedance, radar reflectivity, resolved roughness, and wave scattering characteristics). Both of these data sets are limited – modern thinning and acceleration is confined to the margins of Antarctica and Greenland, important regions for decadal sea level rise but too narrow to constrain centennial scale change, and the relationships between geophysical parameters and physical properties are themselves poorly understood. This work focuses on the intersection of these two datasets, in an effort to use the modern thinning pattern (measured using ICESat-2) to evaluate whether any subsurface observables are diagnostic of the bed rheology.

We focus specifically on the comparison between thinning and the spatial distribution of subglacial bedforms, where active till deformation is thought to be indicative of plastic deformation. Swath radar imaging over parts of Thwaites Glacier captured the scale and extent of bedforms present at fine resolution, but the same features are also apparent in nadir focused radar images collected in the flow direction. Bedforms appear as parallel, repeating reflections arriving after the ice bottom reflector. We explored the Center for Remote Sensing of Ice Sheets (CReSIS) radar archive to identify the size, distribution, and scale of bedforms in nadir images across Antarctica and Greenland. Within the CReSIS archive, 14% of all data collected in Antarctica was oriented with ±10° of the flow orientation (making it suitable for bedform imaging in this way), with 0.2% of the total archive containing evidence of bedforms. These were concentrated at Thwaites Glacier and Byrd Glacier. While relatively uncommon in the Antarctic data, 1% of all radar data in Greenland showed evidence of bedforms, most notably spanning Jakobshavn Isbrae and the Northeast Greenland Ice Stream. Where bedform fields approach regions of thinning and acceleration, we explore the thinning patterns expressed in ICESat-2 ATL11 data, to test the hypothesis that bedform fields are characterized by a plastic bed rheology, such that spatial gradients in the dh/dt field should be negligible.

Icequakes measure friction and slip at the bed of Rutford Ice Stream, Antarctica

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Glacier slip is the primary mechanism governing the migration of ice from land into the oceans, contributing to sea-level rise. Friction at the bed of a glacier fundamentally limits the speed at which this ice can slide. The frictional properties at the bed are controlled by a number of factors, including bed material, effective normal stresses, and the presence and development of basal hydrological systems. However, basal drag remains poorly understood or constrained by observations. Here we show the first direct observations of both frictional shear stress and slip at the bed of an ice stream. We quantify these parameters using 100,000 repetitive stick-slip icequakes at the bed of Rutford Ice Stream, West Antarctica, in combination with a rate-and-state friction model. The source properties and repetitive nature of these earthquakes allow us to calculate temporal and spatial variations in effective normal stress, total frictional shear stress, bed shear modulus, slip and slip-rate at hundreds of sticky patches on the bed. We observe frictional shear stresses of 10^4 to 10^7 Pa and slip-rates varying from 0.2 to 1.5 m day^{-1} over the order of hours. This spatial and temporal variation in friction and slip is likely caused by bed heterogeneities in combination with an active hydrological system. Our results demonstrate that friction at the bed of an ice stream can vary by orders of magnitude over durations of hours and distances of 10s metres, and that a rate-and-state friction model can describe ice stream friction behaviour. Our findings have implications for ice dynamics models of West Antarctica used to inform sea-level rise contributions of the ice sheet, which typically make theoretical assumptions regarding basal friction at entire system-level scales.

Women's representation in the glaciological literature and the challenge of participation

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Equity remains elusive in the sciences, where minoritised groups experience segregation, stratification and the intrinsic harms that often accompany outsider status (Settles et al., 2013; Willness et al., 2007). Nevertheless, we persist. While women's participation in the professional sciences has grown over time, women continue to be underrepresented in the physical sciences and in some cases, progress made in the late 20th century has stalled (see Holman et al., 2018, for an international data set). Applying strong objectivity and standpoint epistemology (Harding, 1992), this presentation reprises Hulbe, Wang and Ommanney's (2010) investigation into the participation of women in glaciology and extends their data analysis it to the present. Classifying the authorship of articles published in the Journal of Glaciology, both the rate of change and apparent diverging trends in women's participation overall and their status as first authors are considered. Female authorship in the Journal is similar to female representation in other sources, for example, in the large ensembles that make up intercomparison projects. Patterns observed in the data are used as the basis to consider both the challenges to and opportunities for supporting diversity in glaciology more widely.

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Modeling ocean circulation in the Bellingshausen Sea

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The ice shelves in the Bellingshausen Sea (BS) are rapidly melting, retreating, accelerating, and thinning due to the modified Circumpolar Deep Water (mCDW) intrusions towards ice shelf cavities. Here, we conduct a regional ocean simulation from 1992-2018 and investigate mCDW and glacial meltwater circulations. We evaluate the ocean model by comparing it with existing observations including recent ship-based and seal CTDs. For mCDW located off-shelf, it takes 6±1.4 months and 9±1.4 months to travel through the Belgica Trough (BT) and the Marguerite Trough(MT) into George VI ice shelf cavity, respectively, following the 500–600m bathymetric contours. The mCDW intrusions toward the George VI ice shelf show little variability, while the mCDW intrusions toward Venable and Abbot ice shelves show seasonal variability with higher velocities in summer, likely caused by wind-driven coastally trapped waves. We also conduct particle experiments tracking glacial meltwater, showing that it travels westward by Antarctica Coastal current (ACoC) consistent with previous studies. After 2 years of model integration, 21% of particles are located in the AS implying the linkage between BS ice shelf meltwater and Amundsen Sea upper ocean hydrography.

Damage control: forming stable ice shelves in simulations with damage mechanics

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How do we represent sporadic iceberg calving and the small-scale fracture processes that precede it in large-scale ice dynamics simulations? A popular approach is to represent the readiness of ice to fracture and ultimately calve as a continuum damage field. However, most fracture- or failure-resolving models of ice shelves usually either disintegrate or evolve to a state with no fracture. Here we review a process-level description of damage that is computationally tractable, based on a linear stability analysis of crevasses evolving in a power-law rheology. This model explicitly links damage evolution to climate forcing and the large-scale stresses within an ice shelf, and produces simulated terminus positions and thicknesses for ice tongues similar to observations. However, as soon as we allow the damage to affect the ice's dynamics (e.g., by decreasing the viscosity with damage or removing ice by calving) in the presence of side friction, the immediate detachment of the of the ice shelf from its wall can result: all ice shelves become unbuttressed ice tongues. We examine the reason for this behavior and show that it is true for a host of models and discuss some possible reasons for this behavior along with some solutions and the implications for simulating ice sheet collapse.

Grain-size evolution controls the accumulation dependence of modeled isothermal firn thickness

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Surface accumulation b is predicted to increase over large areas of the Antarctica and Greenland ice sheets as the climate warms. Models disagree on how this will affect the thickness of the firn layer. This is important because changes in firn thickness influence altimetry-based estimates of ice-sheet mass change and paleo-climate reconstructions from ice cores.
Here we examine how b influences firn thickness in a simplified isothermal model based on Arthern and others (2010), which accounts for mass conservation, dry firn compaction, grain growth, and the rheological impact of grain size on compaction (larger grains compact faster). In contrast to previous work, treating b as a boundary condition and employing an Eulerian reference frame helps to untangle the factors controlling the b-dependence of firn thickness.
In the model, higher b leads to thicker firn, but advection of porosity and advection of grain size partly compensate for each other, reducing the influence of b on firn thickness. This is controlled by the surface grain size. We quantify the circumstances under which these two processes balance exactly, which counterintuitively renders steady-state firn thickness independent of b. We also simulate the response of firn thickness to step changes in b, showing that a transient in the grain size leads to a non-monotonic transient in firn thickness. These findings are qualitatively independent of the stress-dependence of firn compaction, but depend on the grain-size dependence of firn rheology.
Firn models usually ignore grain-size evolution, but this work highlights the complex effect it can have on firn thickness when it is described in models in a simplified way, particularly given that surface grain size varies in space and time on ice sheets. In order to capture these complexities accurately, the grain-size dependence of firn rheology must be better constrained. We highlight initial results from a NSF-funded project, which aims to provide these constraints using radar-derived compaction rates, ice-core grain size measurements, and laboratory compaction experiments.

West Antarctic archipelago covered by cool-temperate forests during early Oligocene glaciation

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The Eocene–Oligocene Transition (~34.4–33.7 Ma) marks a major step in the long-term evolution from the greenhouse climate of the Early Palaeogene to the icehouse regime of the Late Neogene and Quaternary. However, it remains uncertain which landmasses were covered by ice sheets during the Early Oligocene Glacial Maximum (~33.7–33.2 Ma), an interval of peak glaciation inferred from deep-sea benthic foraminifera oxygen isotope records that immediately follows the Eocene-Oligocene Transition. The scarcity of Late Eocene and Early Oligocene continental and shallow-marine records in both Arctic and Antarctic regions has prevented the reconstruction of environmental conditions and ice-sheet extent during the Early Oligocene, which is critical for assessing ice–ocean–atmosphere interactions during early stages of the Cenozoic icehouse. Here, we present the first Early Oligocene shallow-marine record from the Pacific margin of West Antarctica, recovered from the central Amundsen Sea Embayment shelf on RV Polarstern expedition PS104 at Site 21. Marine mudstones recovered at this site document the presence of a vegetated archipelago at a palaeo-latitude of 73.5°S. Pollen assemblages and organic biomarker proxies indicate a cool-temperate Nothofagus-dominated forest situated within a productive marine archipelago. No evidence for marine terminating ice was detected in the cores from Site 21, thus indicating that the West Antarctic Ice Sheet was small or entirely absent during the Early Oligocene.

Quantitative analysis of the maximum rate and minimum duration for a 200-km step-wise retreat of the Bindschadler Ice Stream at ~11.5 cal. kyr BP

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Reconstructing past grounding-line oscillations are a critical part of understanding how ice sheet dynamics contribute to global sea-level change. In this study, we analyzed a large-area survey of multibeam and chirp data to reconstruct key aspects of the post-LGM retreat of the Bindschadler Ice Stream in the Whales Deep Basin of eastern Ross Sea. The geophysical data were acquired aboard the RVIB Nathaniel B. Palmer in 2015 and reveal a 2000 km^2 field of small-scale recessional moraines. The regional stratigraphic framework indicates that the moraines record part of a 200-km stepwise grounding-line retreat following a grounding-line stillstand that ended at ~11.5 cal. kyr BP. In the area surveyed, more than 50 small-scale moraines extend across the foredeepened topset of the large-volume grounding zone wedge (GZW) deposited during the preceding stillstand. The recessional moraines have a general SW to NE trend along the eastern flank of the Whales Deep Basin and define one edge of a rapidly expanding grounding-line embayment. In cross-sections, the moraines resemble landforms created at retreating tidewater glaciers. We analyzed cross-sections across the moraine field to map the upper and lower surfaces of these small-scale grounding-zone landforms. The mathematical difference between the top and basal surfaces measured along a cross-section is the sediment volume deposited through time as the grounding line receded across that distance. We used published upper-end paleo-sediment flux for Bindschadler Ice Stream to deduce a minimum cumulative duration of grounding-line deposition. Dividing the cross-section distance by the minimum duration of grounding-line deposition provides the maximum estimate of the rate of grounding-line retreat at a specific cross-section. Our analysis suggests that the maximum grounding-line retreat along a 50 km cross-section in ~140 years would have averaged ~350 ma^{-1}. This maximum averaged paleo-grounding zone retreat rate of the Bindschadler Ice Stream provides important constraints on large-magnitude grounding line shifts against which modern observations can be compared. A comparison with modern grounding-line oscillations validates concern that the Pine Island, Thwaites, Haynes, Smith and Kohler glaciers are indeed experiencing unusually rapid rates of grounding line retreat.

An Observationally Based Investigation of Co-variability in the West Antarctic Atmosphere, Sea Ice, and Ice Sheet Surface Mass Balance

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The Antarctic ice sheet has experienced increased mass loss over the past 40 years which has been widely attributed to increased ice discharge. However, recent research suggests that surface processes may have more of an impact on the overall mass balance in coming decades due to changes in snowfall and surface melt. Given the uncertainty and growing concern on the future of the Antarctic ice sheet, a better understanding of the variability of surface mass balance and the processes in the ice-ocean-atmosphere system impacting it is crucial for predicting future ice sheet behavior and sea level rise. Here we investigate the co-variability of ice-ocean-atmosphere connections in the Antarctic using satellite remote sensing, reanalysis, and modeled climate datasets. We pay particular attention to the potential effects of the variability of sea ice, which has shown strong regional and interannual variability in recent decades. Given this, we evaluate the impacts of decreased sea ice in the Amundsen Sea region on the overlying atmosphere, and how this may then influence surface energy and mass balance processes of the adjacent ice sheet. Our initial analyses using correlation and composite methods show strong correlative relationships between sea ice, snowfall, and surface melt during anomalous high and low years for these climate variables. Based on these results, we employ causal effect networks (CEN) to better understand the relationship between the ocean, atmosphere, and ice sheet surface in West Antarctica. This research will help assess the coupled ice-ocean-atmosphere impacts of projected 21st century Southern Ocean sea ice decline on the mass balance of the adjacent Antarctic ice sheet.

Tracking Circumpolar Deep Water: Foraminifera as a proxy for oceanic conditions offshore Thwaites Glacier, Antarctica

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The glaciers that flow into the Amundsen Sea Embayment (ASE) of West Antarctica have accelerated in their retreat since at least the early 1990s (Rignot et al., 2019). Estimates of global mean sea-level rise due to a collapse of the West Antarctic Ice sheet are as high as 4.3 m (e.g. Fretwell et al., 2013). To better constrain models for the Amundsen Sea drainage sector's contribution to sea-level, we need to investigate the controls on glacial stability of Thwaites Glacier and Pine Island Glacier today, as well as over the last 10,000 years.

Relatively warm Circumpolar Deep Water (CDW) travels along glacial troughs of the ASE causing basal melting of Pine Island and Thwaites ice shelves (e.g. Jenkins et al., 2010; Hogan et al., 2020; Wahlin et al., 2021). CDW not only impacts the glaciers, but also influences local ecology, including the benthic foraminifera assemblages. Foraminifera are single celled zooplankton that are calcareous (made of calcite) or agglutinated (made of sand or other particles cemented together). These assemblages of foraminifera that live on the seafloor or in the uppermost centimeters of seabed sediment, are sensitive to habitat conditions, such as water depth, temperature, salinity, nutrients, and sediment type. This information can be obtained from modern assemblages of living (stained) benthic foraminifera, where CDW is present today, and then be used to interpret paleo-assemblages of foraminifera from older layers of seafloor sediment, i.e. that lived in the ASE environments in the past.

Here, we present preliminary results on the relationship of live foraminiferal assemblages with the oceanic conditions measured at the time of collection on the Thwaites Offshore Research (THOR) cruise NBP19-02 aboard the RVIB Nathaniel B. Palmer during the 2019/2020 field season in water depths ranging from 467-1138 m and located in water masses CDW, modified CDW, or lacking CDW. Ongoing analyses of modern benthic foraminifera assemblages will help us characterize the wide range of environments in the ASE (including new data from ITGC cruises NBP20-02 and upcoming NBP22-01), and we will apply this information to determine the oceanic conditions in the Holocene sediment record, such as the influence that CDW had on Thwaites Glacier stability through centennial to millennial time scales.

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Best practices in Glaciology: Building inclusivity through cryospherecollective.org

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The field of glaciology remains one of the least diverse sub-disciplines of the geosciences. This lack of diversity stems from the legacy of cultural and structural exclusion of marginalized scholars that is pervasive in STEM fields, and acute in glaciology. These barriers exist throughout career trajectories — from undergraduate and graduate programs extending through post-graduate careers inside and outside of academia. Here, we present examples of best practices, collated on our website, cryospherecollective.org, that are designed to build an inclusive glaciological community for all career stages. We focus on research-informed tools that will support individuals across career stages, as well as those aimed at strengthening our community through cultivating a more inclusive culture. In particular, we recommend strategies to build equitable and inclusive spaces within our research groups and for all workplace environments, including the lab, the field, and conferences. We also outline recommendations to reduce bias in the graduate admissions process and support students through graduation and beyond. Ultimately our goal is to open a dialogue about the changes needed to create an equitable and inclusive culture within glaciology and share resources amongst the community.

Geostatistical simulation reveals subglacial hydrologic and geologic boundary conditions in the Amundsen Sea Embayment

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The subglacial hydrologic and geologic conditions in the Amundsen Sea Embayment play an important role in governing ice sheet dynamics. However, the incomplete characterization of the geology and hydrology in this region make it difficult to determine the effect of subglacial conditions on ice flow. Recent developments in geostatistics have enabled the simulation of the subglacial topography and geology across the Amundsen Sea Embayment. We use the simulated topography to model subglacial hydrological flow paths and investigate the statistical relationships between basal conditions and ice velocity. Our findings have implications for the transition between a distributed drainage system and concentrated drainage system and the connectivity of active subglacial lakes. Our findings provide a catchment-scale geologic template for ice sheet modeling that can inform the modeling of sliding and retreat across a combination of outcropping bedrock and deformable sediments.

Climatology of West Antarctic Atmospheric Rivers and their Impacts on Thwaites Glacier Surface Mass Balance

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While Antarctic Ice Sheet (AIS) mass loss is dominated by accelerated ice discharge from the West Antarctic Ice Sheet (WAIS) due to ocean-induced basal melting, surface mass balance (SMB) processes return mass to the WAIS through snowfall. On Thwaites Glacier (TG) in West Antarctica, snowfall is the primary driver for SMB (125 ± 16 Gt snowfall per year), and extreme snowfall events contribute more than 60% of the total snowfall over TG ice shelf, and 30-50% of the total snowfall over grounded TG. Many of these extreme snowfall events are associated with the landfall of atmospheric rivers (ARs) over TG. ARs are long, narrow bands of warm and moist air that contribute intense precipitation and surface melting on the AIS, meaning they contribute both positively and negatively to the SMB. Here, we use an Antarctic-specific AR detection tool combined with MERRA-2 and ERA5 reanalyses to develop a regional climatology of AR events that made landfall over TG from 1980-2020, including their frequency and duration. We quantify the snowfall and surface melt attributed to AR events to determine their impacts on TG SMB. Using two case studies of AR events in December 1999 and February 2020, we illustrate the spatial patterns in snowfall and surface melt associated with AR landfall. We then compare the seasonal and spatial patterns in AR-attributed snowfall to the climatology of all snowfall over TG. Finally, we highlight the interannual and decadal variability of TG AR events and their relationships to large-scale modes of atmospheric variability. Our results enable us to quantify the past impacts of ARs on TG SMB and characterize their interannual variability and trends, enabling a better assessment of future AR-driven changes in TG SMB.

Laser Cutting to Collect Ice Samples in Boreholes

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Deep ice cores are typically retrieved using complex and expensive coring drills. Large-scale coring projects often require many field seasons and a huge logistical footprint to complete. Most scientific questions require a continuous paleoclimate record over more than one glacial cycle, which also requires additional ice samples from specific ages (depths) or an array of ice cores. A more economical and time-efficient approach would be to drill one or more boreholes using thermal or hot water drills and then extract ice samples from the desired depths using a modified borehole sonde. In certain studies, such a tool could eliminate the need for drilling entirely by extracting new ice from old boreholes at whatever depths were desired. We have begun a program entitled "RELIC", for Robotics-Enhanced Laser Ice Cutting, to do just this. In this presentation, we discuss our initial work in the program, particularly our findings on the optimal laser wavelength for glacier-ice laser sampling. We are also testing acoustic sensors to measure the fracturing of brittle ice, since laser cutting may cut ice with lower external stresses than mechanical saws.

In order to effectively cut ice at useful scales, light must have an absorption length of at most a few centimeters and a powerful laser source. Based on the cost-effectiveness of available laser technologies, we have successfully tested lasers at 1.07 and 10.6 micron wavelengths on ice. Both technologies demonstrated the ability to quickly sample thin, fragile pieces of ice without cracking or shattering, raising the potential that the lack of mechanical vibration may make it inherently better than mechanical saws for retrieving and processing brittle ice. For usage in the field, 1.07 micron lasers hold an overwhelming advantage over longer wavelengths because of the wide availability of robust, high-power, long-lifetime, portable sources and their compatibility with low-loss optical fiber.

Glacier ice from the brittle zone is extremely susceptible to cracking and breakage during even gentle handling. Laser cutting will expose ice to fewer mechanical stresses than a traditional saw, which brings the possibility that laser cutting may reduce fracture and better preserve the structure of brittle ice in field core processing. To test this concept we have examined the acoustics of ice fracture by embedding piezoelectric sensors into artificial ice stressed by extreme temperature gradients, such as that provided by liquid nitrogen cooling. The piezoelectric sensors easily pick up voltage spikes with broad high frequency acoustic spectra consistent with destructive cracking. Further work to identify the acoustic features of laser and saw cutting and isolate longitudinal and shear stress frequency content for crack location and orientation sensing is in progress. Use of this effect opens up possibilities for constant in situ monitoring of fracturing in freshly retrieved ice cores.

Streamlined bedform sensitivity to bed characteristics from deglaciated landscapes

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Erosional and depositional processes mold subglacial beds and sediments into bedforms streamlined in the direction of ice flow. Study of these landforms in deglaciated landscapes provides the opportunity to assess the sensitivity of ice flow to bed characteristics across broader spatiotemporal scales than possible for contemporary glacial systems. While many prior studies rely on manual mapping and qualitative assessment of these bedforms, we semi-automatically identify over 11,400 bedforms formed during and following the Last Glacial Maximum from nine deglaciated sites in the Northern Hemisphere. The diversity of topography and bed substrate at the sites allow us to test bed substrate and topographic controls on bedform morphology and ice-flow behavior. Using this large and geographically diverse dataset, we find a minimum length-width ratio threshold of bedforms across all sites, suggesting twice the amount of erosion or deposition in the direction of ice flow than orthogonal to ice flow must be achieved in order for streaming to be detected by the formation of these bedforms. More elongate bedforms are associated with lower bed elevation range across individual bedforms, qualitatively higher bedform density, and uniform bedform orientation, indicating greater qualitative velocity and spatial persistence of ice flow. Topographically constrained sites contain the most elongate bedform features, supporting the concept of topographic funneling increasing qualitative ice speed. Low elevation variability across bedforms in regions with unconstrained topography and sedimentary bed composition indicate ice-flow persistence and subglacial process organization under open and soft-bed conditions. Crystalline, volcanic, and mixed sedimentary-crystalline beds produce bedforms with a wide range of surface elevation, further suggesting non-sedimentary and transitional beds inhibit ice-flow persistence, uniformity in depositional and erosional processes, and hence predictable bedform morphology. Bedform elongation is not solely contingent on bed type, as the full range of elongation ratios for the dataset can occur on all bed types. Bedform morphologies controlled by topography and bed substrate provide key information on ice streaming behavior and can be used to inform sensitivities of contemporary glacial systems.

A thermomechanical model for subglacial frozen fringe

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Ice-infiltrated sediment, known as a frozen fringe, leads to phenomena such as frost heave, ice lenses, and meters of debris-rich ice under glaciers. Understanding the dynamics of frozen fringe development is important as frozen sediments at the base of glaciers can modulate glacier flow, influencing the rate of global sea level rise. Here we study the physics of interstitial freezing water in sediments and focus on the conditions relevant for subglacial environments. We describe the thermomechanics of liquid water flow through and freezing in ice-saturated frozen sediments. The force balance that governs the frozen fringe thickness depends on the weight of the overlying material, the thermomolecular force between ice and sediments across premelted films of liquid, and the water pressure within liquid films that is required by flow according to Darcy's law. We combine this mechanical model with an enthalpy method which conserves energy across phase change interfaces on a fixed computational grid. The force balance and enthalpy model together determine the evolution of the frozen fringe thickness and our simulations predict frost heave rates and ice lens spacing. Our model accounts for premelting at ice-sediment contacts, partial ice saturation of the pore space, water flow through the fringe, the thermodynamics of the ice-water-sediment interface, and vertical force balance. We explicitly account for the formation of ice lenses, regions of pure ice that cleave the fringe at the depth where the interparticle force vanishes. Our model results allow us to predict the thickness of a frozen fringe and the spacing of ice lenses at the base of glaciers.

The Antarctic Meteorological Research and Data Center

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The Antarctic Meteorological Research and Data Center (AMRDC) aims to bring Antarctic meteorological datasets, with an emphasis on observational datasets, to the broader community. Easy access to Antarctic meteorological datasets is of the utmost importance to encourage data exchange, extend scientific research, and increase engagement in earth system study. Housed within the center is a new repository that will host currently available datasets (e. g. Wisconsin Automatic Weather Station data, Antarctic satellite composites, field camp observations, etc.) as well as campaign meteorological datasets deposited by other Antarctic investigators. As a discipline-specific data center, the AMRDC aims to be an active host of real-time and archived data. Data servers and services will be a part of this effort including formal support for the Antarctic-Internet Data Distribution system. The AMRDC will engage students throughout the project not only in its data efforts, but also via case study work, climatological reporting (complimenting existing efforts), and development of white papers on associated topics. This effort will be advised by a peer advisory board. The AMRDC will be a recognized Antarctic meteorological data center, for and by the community. It has the potential to be a participant in the WMO's Antarctic Regional Climate Center network.

The primary focus of the AMRDC project is the establishment of a data repository. The AMRDC will use the Comprehensive Knowledge Archive Network (CKAN), an open-source platform, for the storage and distribution of archived data. The initial demonstrational release of the AMRDC repository can be found here: https://amrdcdata.ssec.wisc.edu/. All of the data holdings currently/historically held by the Antarctic Meteorological Research Center (AMRC) will be placed in this new repository. The repository is structured around construction of descriptive and comprehensive metadata, assigning Digital Object Identifiers (DOIs) for the data and supporting interoperability standards and FAIR data principles: Findable, Accessible, Interoperable, and Reusable. A companion effort is the recasting of the website that the AMRC has used to provide Antarctic real-time meteorological data and information to the community. The new site, under construction, will mirror the new emphasis on data.

Firn Aquifer-Induced Disintegration of Antarctic Ice Shelves

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Firn aquifers are subsurface reservoirs formed by a meters-thick water-saturated firn layer. Here, we present observations identifying firn aquifers on current and former ice shelves in the northwestern Antarctic Peninsula based on satellite microwave radiometry, synthetic aperture radar, and visible imagery as well as recent and earlier airborne radar campaigns and field expeditions. Additionally, we correlate firn aquifers with slow ice flow derived from satellite optical feature tracking. Our analyses indicate expansive firn aquifers on the Wilkins, the northern George VI, the Müller, the former Jones, and the former Wordie ice shelves. Catastrophic disintegration events on the Wilkins and the former Wordie ice shelves previously attributed to brine infiltration at the waterline are instead attributed, at least in part, to meltwater firn aquifers or meltwater-brine firn aquifer systems. Thus, as Antarctica's climate warms, firn aquifer formation may precondition other Antarctic ice shelves for hydrofracturing and thereby facilitate disintegration leading to ice sheet-wide instability. Previous studies have suggested that the key reservoir preconditioning Antarctic ice shelves for hydrofracturing is meltwater stored within ponds formed on impermeable layers at the surface during the summer. However, our results indicate that firn aquifers represent alternate subsurface reservoirs capable of storing significant volumes of meltwater year-round, hidden, decimeters beneath the surface within permeable, cohesionless, large-grained firn.

n=4

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The value of the stress exponent n in Glen's Flow Law is a 'known unknown' in glacier dynamics. For the past few decades, it has been common practice to assume n=3 everywhere and at all times when modeling ice flow, deformation, and fracture. But there are good reasons to step back and reassess whether this common practice is good practice. Indeed, a lot of evidence compiled in numerous independent studies supports the use of values of n that differ from the canonical n=3. Laboratory studies suggest variations in the partitioning of creep between different mechanisms, with a transition in the dominant creep mechanism (and thus change in the value of n) within the range of stresses and temperatures commonly found in terrestrial glaciers and ice sheets. Observations from Antarctica, Greenland, and other glaciers suggest values of n > 3 better fit the data than does n=3. Here, we add to this work using modern remote sensing observations of ice deformation and thickness in the Antarctic ice shelves. We study the floating ice shelves because the underlying ocean provides negligible drag at the base of the ice, meaning that the strain rate fields we calculate from observations of ice surface velocity should be good approximations for strain rates at all depths within the ice column. We further focus on areas of the ice shelves that are primarily undergoing extensional flow because in this regime, the extensional deviatoric stress approximates the effective deviatoric stress in Glen's law and is proportional to the local ice thickness. Thus, we calculate the effective strain rate and stress from independent observations, allowing us to fit the data to infer the prefactor and exponent in Glen's law. We find that n=4.1 +/- 0.4 (one standard deviation error) in the extensional and largely undamaged regions of the Antarctic ice shelves. This value for n closely approximates the value found in laboratory studies to represent dislocation-creep-dominated ice deformation, a regime that is expected to continue to dominate at higher stresses found in other dynamic regions of Antarctica. Therefore, we expect our results to apply to most dynamic regions in Antarctica, both grounded and floating, and we make two modest suggestions. First, we suggest that models of ice flow in Antarctica should use n=4 (or, more precisely, n=4.1 +/- 0.4), adjusting tabulated values for the prefactor according to a reference value of stress and strain rate. This higher value of n increases the sensitivity of ice viscosity to changes in stress, effects inferences of other properties (like the sliding law parameters), and should meaningfully influence model behavior and projections of sea-level rise. Second, we suggest more concerted efforts using available observations to refine the calibration of the flow-law parameters in many different areas to better capture the deformation of ice in models and quantify the uncertainties in these parameters.

Closing the frequency gap between remote sensing and in situ observations

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Remote sensing and in situ observations of ice flow, deformation, and fracture have revolutionized our understanding of WAIS and its connections to the broader climate system. But as useful as these instruments are, there remains a nagging gap in their capabilities. Radar and optical remote sensing provide broad spatial coverage (>10s of km2) with fine spatial resolution (sub-meter in some cases) but generally have temporal resolutions of days to weeks. Such long repeat times are too crude to capture detailed measurements of most calving events, responses of ice flow to ocean tides, and other higher-frequency variations. On the other hand, seismometers and geodetic (GNSS) observations generally provide temporal resolutions from fractions of seconds to days but at a single point per sensor. Here, we discuss recent efforts to close the frequency gap between remote sensing and in situ observations by developing drones capable of flying in the stratosphere for months at a time while collecting remote sensing observations. Two fundamentally different drone concepts are under development. One is a solar plane that can fly about 2500 km/day for 3-4 months during the summer. It features long (~20 m) wings covered with solar panels that provide all the lift and power for the aircraft and payload. It will be launched and recovered from airports and can transit to a desired location in a day or two. The other aircraft is a hybrid airship (a blimp with wings, known as a dynastat) that combines aerodynamic and buoyant lift. The dynastat will travel around 2000 km/day, can be launched like a balloon, and is intended to be relatively low-cost to prove a flexible platform that is accessible to the community, much like GPS and seismic instruments are now. Both aircraft are expected to collect their first data in the next 5 years and are designed to support many different remote sensing instruments, from optical to radar to lidar. We plan to fly a small, lightweight (~5 kg) synthetic aperture radar (SAR) instrument developed by GAMMA Remote Sensing. When mounted on one of these drones, it will allow us to collect SAR data with meter-scale resolution at sub-hourly repeat times over areas like Thwaites. The radar will allow for more sensing modes than are currently available, allowing us to collect multiple components of motion in a single path. These features will enable detailed observations of velocity and strain-rate fields associated with a host of phenomena, including calving, migration of grounding lines, high-frequency variations in ice flow velocity that are not currently observable. In essence, our plan is to augment satellite observations with high-temporal resolution observations of a few key areas, providing a new way forward in understanding the dynamics of WAIS and the rest of the crysophere. In this talk, we'll discuss current progress on these forthcoming observational systems and some methods we are developing to analyze the data and quantify phenomena such as wave propagation.

Response of the Antarctic continental shelf heat budget to WAIS meltwater

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Ocean circulation features at the Antarctic continental shelf margin play an important role in modulating the transport of oceanic heat from the open Southern Ocean to the grounding lines of ice shelves. Coastal freshening associated with accelerating WAIS melt may alter dynamics both at the coast and at the shelf break, with implications for the transport of warm open ocean Circumpolar Deep Waters and their intrinsic melt potential to ice shelf cavities. Due to the scarcity of observations near the Antarctic shelf break and difficulties associated with resolving important high-latitude processes in ocean models, such responses are poorly constrained and confer uncertainties to projections of future ice shelf melt and sea-level rise.

In this work, we present results from a set of high resolution (0.1°) global ocean—sea-ice numerical simulations conducted with a model that faithfully represents near-Antarctic water mass properties and shelf break dynamics. Motivated by increasing rates of melt from WAIS ice shelves, we conduct 2 experiments where the ocean model is forced with constant elevated glacial melt rates of 1.5 and 2.8 times the control rate. The perturbations are applied primarily in West Antarctica. Within 10 years of the onset of enhanced meltwater forcing, the generation of Antarctic Bottom Water from Dense Shelf Water ceases as shelf waters become increasingly buoyant. Increased ocean stratification triggers subsurface warming in Dense Shelf Water source regions, suggesting a localized positive feedback to melt. In a parallel response, meltwater forcing enhances the subsurface lateral density gradients of the Antarctic Slope Front that modulate the transport of warm Circumpolar Deep Water across the continental slope toward ice shelf grounding lines. Consequently, coastal freshening acts to isolate the Antarctic Ice Sheet from open ocean heat, suggesting a cooling response to melt that counteracts warming associated with stratification. These results suggest coastal freshening by meltwater may alter the thermal forcing of the Antarctic ice sheet in ways that both accelerate and inhibit ice shelf melt at different timescales and different locations along the Antarctic coastline. In this presentation we provide an overview of the simulated thermal response of Antarctic coastal seas to meltwater forcing and highlight the implications of these results for projecting the ocean forcing of the WAIS.

Mechanism for the Subglacial Formation of Cryogenic Brines

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Cryogenic brines have been found in deep boreholes in formerly glaciated terrains in the Northern Hemisphere as well as in Antarctica. These brines represent a potential expansive microbial habitat, may provide an important source of nutrients to the coastal ocean, and can provide information about past ice sheet climate sensitivity through mineral precipitation. Cryogenic brines appear to form through cryoconcentration of seawater, although the actual environment and mechanism of formation has been debated. The commonality between previous conceptual models of brine formation is that they require seawater to be periodically isolated from the ocean in a basin which experiences freezing. Previous conceptual models for the generation of cryogenic brines were developed to explain the presence of cryogenic brines in the Northern Hemisphere. However, they are unable to explain the presence of cryogenic brines found in the pore spaces of two deep cores drilled into the Ross Sea (AND-1B and AND-2A) due to the absence of geomorphic evidence of a past marine basin. We propose instead that the cryogenic brines in the AND-1B and AND-2A cores may have formed in the pore spaces of marine sediments which experienced repeated cycles of ice sheet advance and retreat. Periods of glacial retreat allow seawater to enter the sediment pore spaces, whereas periods of glacial advance subjects the uppermost sediments to either freezing or melting of the bed. Basal freezing concentrates the brines and induces downward flow driven by unstable density stratification. Simulating these repeated cycles of ice sheet advance and retreat with an advection-diffusion model of porewater chemistry, we successfully recreated the porewater chemistry of two deep Antarctic cores (AND-1B and AND-2A). This suggests that cryogenic brines can be formed through the repeated isolation and cryoconcentration of marine waters within clastic sediments.

Hunt Fjord Ice Shelf: Insight into a Northern Greenland Ice Shelf

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Ice shelves, particularly Arctic ice shelves, have declined in area precipitously over the past several decades, one of many indications of a rapidly changing Arctic resulting from intense regional warming. Here we use a special collection of off-nadir Landsat 8 images, a 1978 digital airphoto mosaic and derived DEM, satellite altimetry, and other data to track the evolution of an understudied Arctic ice shelf in northernmost Greenland, the Hunt Fjord Ice Shelf (HFIS). An airphoto mosaic from 1978 reveals that the shelf is comprised of several merged floating ice provenance regions, consisting of floating glacier tongues and multi-decadal fast ice that express a corrugated surface (like many Arctic ice shelves) with varying thicknesses (5-64m). Satellite images show little change in HFIS extent (total, ~75 km2) between 1978 and 2012. This has been followed by several mid-summer calving events (2012, 2016, and 2019) that reduced HFIS by 42.5 km2 (~57%). Comparing the 1978 DEM and Arctic DEM, as well as ICESat and ICESat-2 data interpolated with the Arctic DEM shows that HFIS lost elevation over the 37-year study period, except for two regions where thickening occurred. Recent calvings occurred during open-water periods at the ice shelf front; however, prior to 2012 there were no calvings during similar open water periods. The presence of dynamic sea ice has also contributed to the mechanical failure of HFIS in the period since major calvings began to occur (after 2012). Shelf area losses began as the regional number of melt days on the adjacent ice sheet more than doubled relative to the 1980s. Tributary glaciers in HFIS fjord have generally increased in speed since the 1980s, and grounding lines have retreated and thinned by 3 to 20 m near their grounding zones, likely due to contact with warm Atlantic Water. With increasing warming and surface melting, we anticipate further reductions in shelf area in the coming years to decades. This analysis shows that the collapse of Arctic ice shelves is not unlike the collapse of Antarctic ice shelves, despite different climate-ocean-ice dynamics and oceanographic conditions. Prior to break-up, both types of ice shelves undergo high surface melt, likely inducing hydrofracture. Sea ice appears to have both buttressing and wave-dampening effects that reduce the tendency for calving and retreat or limit the periods when it can occur. Differences lie in the age of the ice shelves and oceanographic characteristics. HFIS is a snapshot of an intermediate age ice shelf with distinct ice regions likely to be a few hundred years old, whereas the Antarctic ice shelves resemble mature ice shelves at least tens of thousands of years old. However, HFIS was unlikely to have ever become a mature ice shelf due to warmer Arctic Ocean temperatures and fjord geometry. Comparing HFIS to Antarctic ice shelves gives a generalized view of ice shelf evolution from their formation to their demise.

Inverting ice surface elevation and velocity for bed topography beneath Thwaites Glacier

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There is significant uncertainty over how ice sheets and glaciers are going to respond to rising global temperatures. Limited knowledge of the topography and rheology of the bed beneath the ice is a key cause of this uncertainty, as models show that small changes in the bed can have a big influence on predicted rates of ice loss. Most of our detailed knowledge of bed topography comes from airborne and ground-penetrating radar observations. However, these direct observations are not spaced closely enough to meet the requirements of ice sheet model, meaning interpolation and inversion methods are used to fill in the gaps. Here we present the results of a new inversion of surface elevation and velocity data for bed topography and slipperiness in the Thwaites Glacier region. This inversion method is based on a steady-state linear perturbation analysis of the shallow-ice-stream equations. The method works by identifying disturbances to surface flow which are caused by obstacles or sticky patches in the bed, and can therefore be applied wherever surface data are available, even where the ice thickness is not well known. Comparison with the radar data available for the Thwaites Glacier region allows an analysis of how this inversion method performs. Although it struggles where the bed slopes steeply, it is much more successful in the flatter central trunk of the glacier. This method could therefore be very useful as either an independent test of other interpolation methods such as mass conservation and kriging, or as a complementary technique in regions where those techniques struggle. Increasing confidence in bed topography products will lead to reduced uncertainty in predictions of future sea level rise.

Riftquakes: Recording and Modeling Seismic Signals of Rifting at Pine Island Glacier

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Nearly 50% of ice mass loss from the Antarctic ice sheet occurs through iceberg calving. The largest icebergs calve along through-cutting cracks in ice shelves called rifts, but the physics of rifting are poorly understood. What forces drive rifting? How fast does rift propagation occur? Does the timing of rift fracture coincide with episodes of rapid ice deformation? We investigate these questions using data from seismometers and GPS sensors deployed on Pine Island Glacier ice shelf (PIG) from January 2012 to December 2013 surrounding the calving of iceberg B31, which exceeded 700 km² in size and calved in November 2013 along a large rift. This geophysical array recorded what are to our knowledge the only direct observations of a large rift propagation event. Using TerraSAR-X imagery, we identify a 7km-long rift that opened between May 8 and May 11, 2012. We identify a large-amplitude seismic signal on May 9, 2012, which we attribute to the rifting event. The signal is broadband, containing energy at frequencies higher than 1 Hz and lower than 0.01 Hz, and exhibits pronounced dispersion characterized by high frequencies arriving before low frequencies. We use features of the May 9 2012 "riftquake" to detect thousands of similar events, which we classify using K-shape clustering. We find and locate two major classes of events, which originate at the rift tip and the southern shear margin. We hypothesize that the observed signals are flexural gravity waves generated by a bending moment applied to the ice shelf during fracture. To test this hypothesis, we model the ice shelf as a dynamic beam supported by an inviscid, incompressible ocean. We find that the model reproduces observed riftquake waveforms when forced with a bending moment. A Markov Chain Monte Carlo inversion reveals that source durations on the order of seconds have the highest likelihood of explaining observed riftquake waveforms, suggesting that rifting occurs over timescales on which ice behaves elastically. Finally, we note that more seismic events are detected from the rift tip during 2013 than in 2012, corresponding to increased visible extension and widening at the rift tip in imagery. In particular, rift-tip events occur most frequently following a rapid drop and subsequent increase in ice velocity during June 2013, suggesting that the stress concentrations driving rift opening are influenced by changes in ice dynamics. Consistent with the low fracture toughness of ice, our work supports the preliminary hypothesis that rift propagation is a fast and brittle process.

Sensitivity of the West Antarctic Ice Sheet to +2 °C (SWAIS 2C)

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The West Antarctic Ice Sheet (WAIS) presently holds enough ice to raise global sea level by 4.3 meters if completely melted. The unknown response of the WAIS to future warming remains a significant challenge for numerical models in quantifying predictions of future sea level rise. Along with international partners (New Zealand, Germany, South Korea, Japan, Italy, the United Kingdom, Spain, Australia, and the Netherlands) we developed the Sensitivity of the West Antarctic Ice Sheet to +2 °C (SWAIS 2C) Project, a four-year project (2022-2025), to drill two holes through the ice to recover and analyze sediment cores from locations along the Siple Coast, adjacent to the grounding zone at Kamb Ice Stream and Crary Ice Rise. A new drill developed for this project will allow the SWAIS 2C Project team to collect important sediment archives from drill sites in the Ross Sea sector of WAIS, at two key sites proximal to the sensitive ice margin grounding zone. The overall aim of the project is to integrate new paleoenvironmental data of past ice sheet response with numerical modeling experiments and modern process studies to investigate the influence of climate dynamics and solid Earth processes that drive ice sheet variability. The results will lead to improved modeling estimates in predicting WAIS's likely response to future climate change, and resultant sea level rise. SWAIS 2C Project results will contribute new information from the southern end (most proximal to the ice grounding zone) of a transect of recent drillholes in the Ross Embayment. In addition, the SWAIS 2C Project is complementary to the US-UK Thwaites Glacier Project on the other side of West Antarctica, allowing for broader understanding of WAIS history and more accurate predictions of future change.

Application of machine learning methods to identify glacial seismicity in a Distributed Acoustic Sensing dataset from Store Glacier, West Greenland

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Seismic surveys are widely used to study glacial systems, from the basal material and conditions beneath the ice, to ice temperature and crystal orientation fabric. The emerging technology of Distributed Acoustic Sensing (DAS) uses fibre optic cables as pseudo-seismic receivers, reconstructing seismic measurements at a higher spatial and temporal resolution than is often possible using traditional geophone deployments. However, DAS generates large volumes of data, especially when continuously recording, which can be costly in time and cumbersome to analyse. Machine learning techniques provide an effective means of automatically identifying events within these records, avoiding a bottleneck in the data analysis process. Here, we explore the use of machine learning for identifying active and passive seismic events detected on a borehole-deployed DAS system on Store Glacier, West Greenland.

Store Glacier is a fast-moving outlet of the Greenland Ice Sheet. The instrumented borehole is located 30 km upstream of the glacier terminus. Data were acquired in July 2019, using a Silixa iDAS interrogator and a BRUsens fibre optic cable installed in a 1043 m-deep borehole. The interrogator sampled at 4000 Hz, recording both controlled-source vertical seismic profiles (VSPs), made with hammer-and-plate source, and a three-day passive record of cryoseismicity. We use a convolutional neural network (CNN) to identify events within the passive seismic record. CNNs are a powerful classification tool that have been widely applied to the analysis of both images and time series data, and have been shown to work effectively on seismic datasets from a variety of environments.

Initial testing of the CNN was done by training the algorithm on manually-labelled windows of data containing either no visible arrivals or high signal-to-noise ratio seismic arrivals within the controlled-source VSPs. Once trained, the CNN achieved an accuracy metric of 90% in recognising whether previously unseen windows contained seismic arrivals. We are now applying this algorithm to the passive dataset in a similar manner, using the increased volume of available data within the full three-day record to retrain the algorithm, with an aim to automatically identify seismic events within the passive record for interpretation and event location. The identified seismic events will provide information on Store Glacier’s seismic velocity structure, ice temperature and ice crystal orientation fabric. Initial inspection of the data has shown seismic events occurring in the upper 300 m of the glacier, likely to be associated with crevassing. We also expect a range of other seismic sources, for example basal seismicity, related to basal sliding and diurnal variations in meltwater supply. Once developed further, the use of CNNs for analysing large volumes of seismic data can be applied widely in glacier settings, with the efficiency of the CNN allowing detailed insights to be made into the origins and style of glacier seismicity and facilitating further use of passive DAS instrumentation.

Flow Laws for Ice Sheet Modelling: Experiments tell us that n ~ 4 not 3?

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n = 3 does not describe the mechanics of ice undergoing steady state power-law creep and should not be used for ice flow models where ice achieves significant strain! Experiments (all of them - published and new) constrain n ~ 4 for steady state creep.

Field data highlight rapid changes occurring at the ice-ocean interface that potentially increase the driving force for sea-ward motion of ice sheets. Estimation of the timescales of ice sheet response, and resultant sea-level rise, depends critically on the use of realistic ice flow laws. Viscoplastic deformation is a significant component of ice movement, and laboratory experiments provide key data that can be extrapolated to natural strain rates.

In laboratory experiments, the viscosity of ice reaches a peak value at low strains (< 3%) before decaying to a steady-state value at intermediate to large strains (10–50%). This flow “enhancement” is accompanied by changes in the microstructure of the ice, primarily a reduction in grain size due to dynamic recrystallization and the development of a crystallographic fabric. At strains higher than 10–50%, a steady-state viscosity is obtained when the microstructure is in steady state.

As in all other minerals, the strain rate of ice (at a given stress and temperature) is the sum of the rates from to grain-size-sensitive (GSS) and grain-size-insensitive (GSI) creep mechanisms. Experiments on ice samples with different starting grain sizes reveal a grain-size sensitivity of the strain rate, and a power-law dependency of strain rate on stress, characterized by a stress exponent, n, with values between ~2 and ~4. Experiments at high stress and/or on samples with coarse grain size yield high n values (~4), whereas experiments at low stress and/or on fine-grained samples yield low values of n (~2). Intermediate values of n (3–3.5) are common, and a value of 3 is usually assigned, but such values have little relevance to the deformation of ice at high strains.

Experiments show that for large-enough strains to achieve a steady-state microstructure, the recrystallized grain size is inversely proportional to the differential stress. GSS mechanisms contribute significantly to deformation at these conditions, but, because the grain size is stress-dependent, the dependency of strain rate on grain size can be eliminated from a flow law and the apparent stress exponent at steady state will be equal to that of the GSI mechanism, n ~ 4. A simple flow law for high-strain natural scenarios, such as flow of basal and marginal glacier ice, and in ice stream margins, should use a stress exponent of n ~ 4.

Feedbacks between ice deformation and ice rheology

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Most of the mass loss from the Antarctic Ice Sheet occurs through glaciers and ice streams, where fast-flow is partially controlled by rapid ice deformation in the shear margins. Positive feedbacks driven by this rapid deformation influence how glaciers and ice sheets evolve and respond to changing climate. However, few models account completely for these feedbacks, in particular those between deformation, heating, and recrystallization. Here, we estimate the respective contributions from heating- and microstructure-based feedbacks and consider the integration of these rheological feedbacks into ice-flow models. We derive an idealized model for ice temperature and grain-size that partitions deformational work into dissipated heat and changes in strain and surface energy, all of which drive dynamic recrystallization. Under conditions common in glacier shear margins, we show that a large portion of deformational work is stored as elastic energy, with the remainder dissipated as heat. This result revises our current picture of the amount of heat generated in glacier shear margins and suggests that changes in internal strain through dynamic recrystallization of ice likely play an important role in facilitating fast-flowing glacial ice. Further, these estimates suggest that ice flow models may need to account for these processes, such as recrystallization, to effectively model changes that will occur to fast-flowing glaciers. We suggest a framework for which to do so.

Calibrating flow law parameters and uncertainties over Antarctic ice shelves with physics-informed neural networks

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The flow and deformation of glacier ice in response to stress is often described using Glen's Flow Law, a power-law relation that compactly represents ice rheology with a prefactor, A, and stress exponent, n. For natural ice, these parameters (and the parameters subsumed within them) come with large uncertainties that have not been robustly quantified with observations. Modern remote sensing technologies that collect data with finer resolutions and broader coverage provide us with an opportunity to robustly calibrate these rheological parameters for certain environments. Here, we utilize publicly available observations of ice sheet surface velocity and elevation acquired with remote sensing platforms to calibrate the flow law parameters over select Antarctic ice shelves. We build upon recent work that used remote sensing observations to quantify the relationship between ice stress and strain rate in extensional flow to infer an exponent of n = 4.1 +/- 0.4 for Antarctica. Here, we model two-dimensional flow and perform parameter calibration by constructing and training physics-informed neural networks (PINNs) to learn spatially-varying A and uniform n for each ice shelf. We cast the parameter estimation problem as a neural network optimization problem through minimization of a cost function that includes both data reconstruction errors and momentum balance residuals derived from the 2D shallow-shelf approximation. Thus, our neural networks predict high-resolution velocity, ice thickness, and A fields that best match the surface observations while conserving linear momentum. Additionally, we formulate the networks to predict spatially-varying uncertainties for A by using variational inference techniques, which approximate Bayesian inference (traditionally a computationally-intensive procedure) as an additional optimization objective. Finally, we demonstrate the use of time-dependent surface velocities, which are becoming increasingly more available over the ice sheets, to independently constrain the stress exponent n, confirming the appropriateness of n = 4 derived from previous work. Overall, calibration of these parameters with robust uncertainties are critical for placing observational constraints on prognostic ice flow model parameters and to improve our understanding of flow and fracture processes on ice shelves in Antarctica.

Does grounding line sinuosity drive ice shelf rifting on tidal timescales? Evidence from eastern Thwaites

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Across the eastern Thwaites ice shelf, several grounding line embayments show large-scale ice shelf rifting that initiates just downstream of the embayment. However, satellite-derived strain rates do not have local highs in the vicinity of the rifts. As a result, previous work has hypothesized that these 'rifts' may be formed by high melt in preexisting crevasses (as opposed to ice necking from flow dynamics). Here, we use a two-month GPS record of flow across the grounding zone to show that rifting may result from tidally-forced flowspeed variations.

We find that grounded ice in the embayment experiences effectively zero tidal flowspeed variations, but freely floating ice undergoes ~2x flowspeed increases at the highest tides in the spring-neap cycle. This results in extremely high strain rates within the ice for several days per month. These flow accelerations are unlikely to be captured in satellite velocity products because of their short timescales, but may be responsible for rift formation. We hypothesize that buttressing of ice flow within the grounding line embayment decreases nonlinearly with tidal height and drives rift formation with particularly high tides.

A generalized theory for layered subglacial seawater intrusion under grounded ice and implications for marine ice sheet retreat

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The grounding line has traditionally been viewed as a hydraulic barrier that prevents seawater from intruding beneath grounded glacier ice. In this view, pressurization of seawater through tides or other effects is required for seawater to intrude upstream of the grounding line. Recent theoretical and experimental work has shown that the subglacial hydraulic gradient is not a barrier to seawater intrusion when seawater is vertically layered within subglacial channels. Here we provide a generalized theory for such layered seawater intrusion in different types of subglacial hydrology, including macroporous shallow water flow over hard beds and microporous Darcy flow through soft beds. This theory can be used to make analytic and numerical predictions for the horizontal distance over which seawater intrudes upstream of the grounding line, and how this distance depends on the properties of the subglacial hydrological system. We show that there are realistic conditions, relevant to Antarctica and Greenland, under which seawater intrusion may be expected to occur over hundreds of meters to tens of kilometers. We also demonstrate the relevance of seawater intrusion for projections of the retreat of idealized and real marine-terminating glaciers by adding an intrusion melt parameterization into ISSM. Even just a few hundred meters of intrusion melt upstream of marine ice sheet grounding line can cause projections of marine ice sheet volume loss to be 10-50% higher in benchmark model simulations of transient marine-terminating glacier retreat. We conclude by discussing where to look for seawater intrusion in observations, and paths forward on modeling the ice-ocean-bed triple junction.

Observing connected subglacial lake drainage at Slessor Glacier, East Antarctica, using ICESat-2 laser altimetry

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Slessor Glacier, East Antarctica, drains grounded ice and subglacial freshwater across nearly 100 km of reverse-slope bed into Filchner Ice Shelf and its sub-ice-shelf cavity. Seven subglacial active lakes were first identified using NASA's Ice, Cloud, and Elevation Satellite (ICESat) mission (2003–2009). ESA's CryoSat-2 SARIn-mode altimetry (2013 to present at Slessor) has observed the three most downstream Slessor Glacier subglacial lakes, including capturing the 2014 surface expression of the most rapid Antarctic subglacial flooding episode recorded. Ice-penetrating radar analysis from NASA's Operation IceBridge before and after this event was consistent with subglacial water movement: bed echos were dimmer post-drainage compared to pre-drainage, indicating a shift from an ice-freshwater to an ice-bedrock or ice-till interface. However, lake activity up-catchment remained ambiguous during the CryoSat-2 mission due to lack of SARin-mode coverage. ICESat-2 (2018 to present) provides complete coverage of the catchment to 88° S with higher spatial resolution and vertical precision. Here, we investigated catchment-wide Slessor Glacier subglacial lake activity and observed connected drainage pathways between lakes and to the grounding line. Subglacial lake surface expressions did not conform to previously published outlines, instead appearing offset or smaller. In addition to surface-height anomalies near known subglacial lake outlines, we found numerous surface height anomalies between subglacial lakes with circular and linear shapes. These off-lake features were temporally coincident and in-phase with the surface activity within the bounds of previously defined lakes suggesting a connected system of lakes, ephemeral smaller storage cavities, and channelized flow. From the most downstream lake (Slessor1) to the grounding zone (~80 km), we did not find any coherent surface anomalies, which may suggest a transition in subglacial water flow to distributed or porous flow through the thick sediments that have been identified beneath Slessor Glacier. Our ICESat-2 investigation of a subglacial lake system in an marine ice-sheet setting shows clear indications of connected drainage between Slessor subglacial lakes and a variety of inferred water storage features that drive freshwater across the grounding line and into the sub-ice-shelf cavity.

Investigating persistent polynya structure and variability at Pine Island Glacier, West Antarctica, using seal-borne measurements and thermal remote sensing

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Antarctica's ice shelves play a critical role in modulating ice loss to the ocean by buttressing grounded ice upstream. Persistent polynyas are open water areas that are maintained by winds and/or ocean heat, often occurring near ice-shelf fronts. Although persistent polynyas are key sites of consistent interaction between atmosphere, ocean, ice-shelves, and sub-ice-shelf ocean cavities, in situ observations are sparse due to the logistical constraints of collecting field measurements in Antarctica. Here we used temperature and salinity observations derived from seal-borne satellite-linked CTD tags deployed in 2014 and 2019 (January to October) in conjunction with MODerate resolution Imaging Spectroradiometer (MODIS) visible and thermal imagery to investigate the spatial, temporal, and structural variability of polynyas near Pine Island Glacier (PIG). We found anomalously warm (>1σ) monthly surface ocean (< 300 m) temperatures near the ice front in wintertime (May to September) in both 2014 and 2019, consistent with our remote sensing observations and coincident with known polynya locations. This warmer temperature signal extends more than 20 km west of the PIG front in both instrumental records, suggesting the widespread presence of open wintertime polynyas near the western shear margin of the glacier. This warm water, combined with strong circulation beneath the ice shelf may contribute to increased margin fracturing, mechanical weakening, and rift initiation up-glacier. Our results demonstrate the potential of using seal tag measurements to investigate persistent polynyas at PIG on sub-annual timescales, allowing for more frequent observations than available via ship-borne methods. Used in tandem with remote sensing observations, our findings provide insight into key polynya properties and frontal ice-ocean processes at PIG, which can be extended elsewhere on the Amundsen coast in regions with similar hydrographic conditions.

Thwaites Glacier Research at the mid-point of ITGC

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The international effort to understand the world’s most threatening single glacier, both within and outside of the International Thwaites Glacier Collaboration, has made several major advances in the first three years of ITGC. ITGC was designed from the beginning to be multi-disciplinary, with a goal of synthesizing insights from a range of studies, both field-oriented and model-focused. Among the first-order questions to be addressed were the potential impact of MICI and MISI processes, processes at the grounding line and sub-ice-shelf cavity, regional ocean circulation and its drivers, ice-bedrock interaction and hydrology, and processes at the shear margin. Modelling studies focused on calving, and on near-term forecasts of ice mass balance, were included alongside the observational efforts.

An overview of the results of ITGC and some from outside this research group are presented. Among the early results were refinements of the lower glacier bed topography and adjacent ocean bathymetry, and confirmations of water flow pathways and the conditions in the sub-ice-shelf cavity and at the ice-ocean interface. Investigations of the grounding line, both with remote sensing and with in-situ sensors and robots, show that grounding line retreat and sub-glacial ice erosion can happen at retreat rates of 1 km per year, and elevation change rates of tens of meters per year. Modelling results of ice cliff failure processes suggest that, while the process may be an important feature of rapid ice sheet retreat, sustaining a runaway ice cliff calving requires a narrow range of geometry and flow speed. Most recently, an additional related project looking at ice-ocean-life interactions (ARTEMIS) has the promise of assessing the ability of the ice-adjacent ocean to sequester carbon, and in general will look at biological impacts from the Thwaites-Amundsen evolution.

Community health has been a focus of the ITGC from the start, but accelerated as the urgency of the issue was underscored by events of early 2020. On issues of justice, we issued a statement jointly with NSF on support of Black Lives Matter; we revamped our Code of Conduct and expectations for collaboration and co-authorship with a view toward equity; and we have worked with professionals to improve awareness on issues of diversity and inclusivity.

Evaluating Antarctic precipitation-circulation relationships in CESM2 and what they mean for our understanding of historical and future snowfall trends

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Snowfall on the Antarctic Ice Sheet is expected to increase in a warming world, with the potential to partially offset the ice sheet's contribution to sea level rise. Yet, by how much and where Antarctic snowfall will increase is highly uncertain. Here, we use both models and observations to provide insight to this question. A recent snowfall reconstruction shows contrasting regional patterns, with strong increases across the Antarctic Peninsula and decreases in Marie Byrd Land and Ross Ice Shelf region over the past ~50 years. As such, the regionality of snowfall trends suggest a role for atmospheric circulation in driving them, and there is every reason to believe that atmospheric circulation trends will continue to shape snowfall patterns into the future. Therefore, our first objective in this work is to evaluate the relationship between Antarctic precipitation and major patterns of atmospheric circulation variability (including the Southern Annular Mode, the latitude and strength of the westerly jet, and the Amundsen Sea Low) in the CESM2, and assess how well such relationships are modeled. Our second objective is to compare these precipitation-circulation relationships to the response patterns associated with stratospheric ozone depletion and increased atmospheric concentrations of greenhouse gases. Finally, we will apply this new knowledge to re-interpreting the historical record of Antarctic snowfall, addressing both why Antarctic-wide snowfall apparently has not increased very much, and why models like CESM2 tend to overestimate this increase.

Glaciological Constraints on Link Budgets for Orbital Radar Sounding of Earth's Ice Sheets

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Orbital radar sounding of terrestrial ice sheets is an area of increasing research interest with mission concepts at 45 MHz, P-Band, and L-Band under development. However, large uncertainties remain in impact of glacial conditions and platform altitude on their link budgets. Here, we present a collection of empirically and glaciologically informed constraints on orbital sounder link budgets using airborne radar sounding data. We also analyze the effects of geometric spreading and englacial water. Finally, we discuss link-budget considerations for investigations beyond bed mapping including observing basal reflectivity, englacial hydrology, ice-shelf thickness, englacial layers, and estimating vertical ice velocity.

Stability of Marine Ice Sheets in the Presence of Feedbacks

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The existing stability analyses of marine ice sheets do not account for feedbacks between ice sheets and environmental conditions. However, ice-sheet interactions with atmosphere and ocean give rise to a number of feedbacks such as between the surface elevation and accumulation rate or between sub-marine melting and the ice thickness. Results of an analysis of ice sheets experiencing feedbacks show that there no general stability condition similar to one associated with the “marine ice-sheet instability” hypothesis, and stability of specific configurations can be determined on a case-by-case basis only. These results suggest that the observed mass-loss from the present-day ice sheets that experience a number of feedbacks, cannot be attributed to marine ice-sheet instability in its traditional form.

Community Building Efforts around Justice, Equity, Diversity, and Inclusion (JEDI) within the International Thwaites Glacier Collaboration (ITGC)

Betsy Sheffield[1], members of the ITGC JEDI Council
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ITGC is a research initiative tasked to investigate the past and present physical processes of Thwaites Glacier, one of the most vulnerable glaciers in the West Antarctic. Funded by the U.S. National Science Foundation (NSF) and the U.K. Natural Environment Research Council (NERC), with partners from a few other countries, the ITGC is a research collaboration with around 150 team members.

Although diversity and inclusion were not part of the initial project's scope, members of ITGC recognized the desire for establishing an inclusive culture that supports and welcomes people from diverse backgrounds with diverse experiences. We made fostering this culture a priority and formed a "JEDI Council" in fall 2020, consisting of PIs, post-docs, students, logistics personnel, and outreach specialists to tackle the challenges around JEDI within ITGC and the greater Antarctic sciences. By nature of our international collaboration, our team members come from a variety of disciplines, career stages, nationalities and backgrounds. Additionally, we benefit from the strong engagement of our Early Career Researchers, who drive positive change around JEDI issues and were key in establishing the JEDI Council. Lastly, NSF and NERC are supportive of our JEDI efforts, providing funding to hire a diversity consultant to offer training, tailor content, and lead discussions. Our focus thus far has included dialoguing exercises and professional development opportunities along with facilitated discussions on issues related to gender, race, ableism, and inclusive leadership; development of shared community norms; and ongoing work on best practices for inclusive, equitable and supportive groups in the field and the lab.

Despite positive progress, barriers exist that limit our success. These may be common to other efforts, and include the significant time commitment required and the fact that most JEDI work happens outside of the funded workload; a sense that our reach is limited to those already engaged in diversity, equity and inclusivity actions; and taking the time to honor a variety of perspectives, sometimes feeling as if we are talking in circles, while building a new program. The multi-disciplinary, multi-institutional, and multi-national nature of our community, while a strength overall, creates difficulty in developing policies and paths forward as each institution and country has their own reporting structure and guidelines. We are inspired by other similar groups to find strategies to address these barriers, and we believe that future projects could likewise build on our JEDI Council model to widen the reach of these efforts and provide opportunities for a broader segment of the community to work towards a more inclusive cryosphere community.

Eastern Thwaites basal channel outflow inferred from persistent polynya variability

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Enhanced localized basal melt rates can incise ice-shelf basal channels that structurally weaken ice shelves. Many of these channels convey water sourced from upstream locations or the grounding zone to the ice shelf edge. This outflow often includes residually warm ocean water with enough remaining heat to maintain locally sea ice free ocean conditions, seasonally or year-round, for small areas near the ice front, which we term 'persistent polynyas'. The evolution of persistent polynyas provides insight into processes driving ice-shelf thinning and stability. However, direct in situ outflow measurements are sparse, and few studies to date have explored the use of remote sensing for this task.

Here we use Landsat 8 optical and thermal infrared imagery from 2013 to 2021 to assess year-round characteristics and variability of the persistent polynya located along Thwaites Eastern Ice Shelf. Over the eight-year record, the polynya appeared every year, indicating active basal channel outflow. The polynya exhibited consistent seasonal variability, generally appearing in austral spring, expanding to its maximum extent in December or January, and disappearing in summer or fall. However, the timespan over which the polynya was open each year ranged from as little as 1 month to more than 4 months, and its maximum areal extent varied between ~0.05 km² (2018 and 2019) to > 1.8 km² (2014). This wide range of variability suggests there may be large seasonal and interannual fluctuations in outflow heat content, ocean surface stratification, and/or local sea ice thicknesses, which all moderate polynya formation. We suggest that years with greater polynya longevity and extent in the first half of the record may indicate enhanced ice-shelf basal melt rates and greater heat transport to the ocean surface. Our findings highlight that these small windows into the ice may provide rich and critical insight into ice-ocean interactions occurring within basal channel systems and impacting whole ice-shelf stability.

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Reconsidering multi-decadal ice-margin sliding deceleration associated with rising meltwater supply: Insights from alpine glacier analogues

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Basal sliding is one of the fundamental processes that govern ice-sheet flow, and it is highly sensitive to the presence, distribution, and magnitude of pressurized water along the ice-bed interface. Higher water pressures reduce drag from the bed and increase sliding velocities in most cases. The evolution of water pressure along the bed is the result of changing meltwater inputs and the geometry and dynamics of drainage elements that facilitate water flow. Whereas annual and sub-annual dynamics of meltwater inputs and drainage system (re)organization have significant observational and theoretical constraints, their multi-decadal dynamics are poorly constrained. Increases in meltwater supply are shown to increase sliding rates on sub-annual timescales, but on inter-annual timescales current physical understanding suggests that increased meltwater supply to the bed results in sliding deceleration at ice-sheet margins. This deceleration arises from more frequent/larger lake-drainage events and/or longer-lived channelized drainage networks that reduce basal water pressures by draining distributed and isolated water reservoirs across the bed. Large regions of the Antarctic Ice Sheet (AIS) do not have seasonal surface hydrologic systems that impose notable shifts in meltwater supply to the bed, but margins of the Greenland Ice Sheet (GrIS) and most alpine glaciers do. These analogs offer insight onto the future dynamics of the AIS. For the case of GrIS margins and several alpine glaciers, our understanding of process is supported by decades of observation, showing inter-annual increases in meltwater supply correlating with less sliding-facilitated flow. There are notable exceptions.

Here we present cases of two alpine glaciers that have undergone a multi-decade enhancement of their inter-annual sliding rates in the face of warming climate: Haut Glacier d'Arolla (HGdA) and Saskatchewan Glacier (SG). Their overall surface velocities have declined, but the deceleration is far smaller than that predicted by reduced internal deformation from thinning, meaning greater contributions from sliding are required to reconcile surface observations. Although initially attributed to more frequent/powerful spring speed-up events at HGdA, 45 years of proglacial discharge records indicate a multi-decadal rise in diurnal meltwater supply variability concentrated in the later half of successive melt seasons for this system. Process modeling supports both accelerating inter-annual trajectory for sliding and deceleration along the GrIS margin and in other alpine settings, depending on the variability of meltwater supply to the bed.

We propose that the growing prominence of these short-period hydrologic processes over several decades has facilitated enhanced sliding at HGdA and SG. Long-term records of flow dynamics for SG are sparsely populated, but trends in both multi-decadal flow and sub-diurnal flow records from the 1950's and 2019, as well as long-term regional meteorologic data, are consistent with this framework. These systems demonstrate behaviors in response to climate forcing that are not readily accounted for in many ice-sheet models and are likely to affect AIS and GrIS in strong warming scenarios. The potential for sliding velocity enhancement at ice-sheet margins could significantly contribute to ice-mass losses, even if limited to a few decades, and thus warrants numerical investigation.

Resolving solid earth properties through co-location of high-resolution ice load histories and GNSS measurements in West Antarctica

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Surface exposure dating using cosmogenic nuclides has revolutionised our understanding of past Antarctic Ice Sheet behaviour. Accumulation of these rare nuclides (e.g. ^{10}Be, ^{26}Al, ^{14}C) in bedrock and glacial deposits provides direct, quantitative constraints on the timing and magnitude of changes in ice thickness. This technique is particularly powerful for examining ice sheet processes that operate over 100s to 1000s of years, such as deglaciation of marine based sectors.

GNSS measurements of bedrock deformation record the integrated response to both modern and ancient ice mass change. The elastic component due to modern ice mass fluctuations can be modelled using satellite observations constraining ice mass balance. The viscous component recording a 'memory' of centuries to millennia-scale ice load history can be constrained by surface exposure dating of glacial deposits. Obtaining spatially coincident ice load reconstructions and geodetic/geophysical observations are a powerful tool to robustly model Glacial Isostatic Adjustment (GIA), a complex suite of ice sheet-bedrock-sea level feedbacks critical for projections of future global sea level.

Glacial erratic samples opportunistically collected by POLENET scientists from two difficult to access sites in West Antarctica provide a proof-of-concept for integrated studies. At Clark Mountain, exposure ages of glacial erratics provide a strong link with existing high-resolution constraints from a seminal study in Marie Byrd Land (Stone et al., 2003). At Lepley Nunatak, lying between the fast-changing Amundsen Sea sector and the Bellingshausen Sea sector where past ice thinning histories are poorly constrained, glacial erratics provide the first constraints on local glacial thinning. A new ice load reconstruction using a decadal mass change record together with centennial-millennial scale ice history from cosmogenic results will allow enhanced assessment of ice sheet sensitivity to ocean and atmosphere forcing using ice sheet modelling, a critical step given that detection and attribution of ice sheet changes to forcing is an emerging research focus. Using both the data-constrained ice histories and the deformation response recorded by GNSS at the sites, GIA models for West Antarctica can be refined. In particular, both the long- and short-term ice loading histories are essential to better estimate rheological properties of the Earth from GIA modelling, given the variation from weak to strong properties across West Antarctica.

This project has a future focus on continuing collaborative efforts to co-locate GNSS and passive seismology sites with collection of sample suites to obtain ice history records, filling large spatial data gaps in West Antarctica. This international collaboration will enable access to and sampling of difficult to reach areas of West Antarctica, providing logistical efficiency and leveraging critical interdisciplinary science.

Inward Migration of the Shear Margins at Thwaites Glacier in Response to Thinning

Mr. Paul Summers[1], Dr. Cooper Elseworth[2], Dr. Jenny Suckale[1]
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Projections of global sea level depend sensitively on the ongoing rapid ice loss at Thwaites Glacier. Prior studies have focused primarily on understanding the evolution of ice velocity and whether the reverse-sloping bed at Thwaites Glacier could drive irreversible retreat. However, the overall ice flux to the ocean and the possibility of irreversible retreat depends not only on the ice speed, but also on the width of the ice stream. Here, we complement prior work by focusing specifically on understanding whether the lateral boundaries of the ice stream, termed shear margins, might migrate over time. We hypothesize that the shear margins at Thwaites Glacier will migrate on a decadal time scale in response to the continued rapid thinning. We test this hypothesis by developing a depth-averaged, thermomechanical free-boundary model that captures the complex topography underneath the glacier and solves for both the surface velocities and for the position of the shear margins. We find that the shear margins are prone to inward migration in response to ice thinning. To evaluate the robustness of this finding, we construct three end-member cases of basal strength that represent a range of physical processes governing basal friction. These cases differ notably in both the pace of migration and whether migration initiates at the eastern or western margin, suggesting that margin migration depends sensitively on basal strength.

Evidence for Temperate Ice in Shear Margins of Antarctic Ice Streams from Airborne Radar Surveys

Mr. Paul Summers[1], Dr. Dustin Schroeder[1], Dr. Jenny Suckale[1]
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A majority of the ice flux contributing to sea level rise from Antarctica flows through narrow, fast flowing outlet glaciers and ice streams. These features are laterally bounded by and partially controlled by intense regions of lateral shear, terms shear zones. The intense shearing in these regions can drive significant englacial heating, which is thought to warm pockets of ice near to or at the melting temperature of ice. Such temperate zones are characterized by reduced effective viscosity, important for glacial dynamics, and increased electric conductivity, important for radar attenuation. We hypothesize that the increased electric conductivity of large pockets of temperate ice in shear margins leads to significantly increased englacial attenuation, resulting in a measurable decrease in bed echo power through the shear margin when controlling for other factors. To test this hypothesis, we implement existing process based models of englacial temperature to construct models of englacial attenuation, both with and without internal shear heating. We then apply these attenuation models to existing bed echo data from a number of shear margin crossings. We find that the inclusion of shear heating driven temperate pockets increasing englacial attenuation is consistent with the observed dimming and fading of bed echoes for a number of Antarctic shear margins.

Wave propagation on Pine Island Glacier, West Antarctica, quantified with remote sensing

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Over the past few years, several large calving events and the partial disintegration of an ice-shelf shear margin have allowed Pine Island Glacier (PIG), West Antarctica, to accelerate. Here, we are interested in understanding where and why these signals originate and quantifying how they propagate through the ice shelf and the grounded glacier. Time series of remote sensing observations combined with new analysis tools allow us to relate local changes in ice velocity to discrete calving events and to quantify the propagation of acceleration events as waves of varying frequency with discrete propagation speeds and attenuation characteristics. This quantification of wave propagation is a recent advance in remote sensing observations that provides unique information about the mechanics of slip along glacier beds and the rheology of ice.

We use synthetic aperture radar data collected by Sentinel-1 from 2017–2020 to show that the most significant acceleration recorded by the data occurs when a rift that originates near the southern shear margin of the ice shelf reaches the northern shear margin, which is shortened by the subsequent calving event. The acceleration caused by this calving event originates near the downstream end of the northern shear margin and propagates rapidly across the ice shelf and grounding line. While on the ice shelf, the wave shows little measurable change in propagation speed (phase velocity) and appears to maintain the same amplitude and frequency content. Once onto the grounded ice, the speed of wave propagation slows considerably, the amplitude attenuates more rapidly, and the frequency is modulated. The phase velocity and apparent path of wave propagation, attenuation rate, and frequency modulation all show strong sensitivity to the bed topography and are relatable to the mechanics of slip and ice rheology in simple physical models. In this presentation, we will explore these observable characteristics and show how they help us to constrain the form of the sliding law and the rheology of glacier ice in this portion of WAIS.

Simulation of flexural-gravity wave response of geometrically complex ice shelves to ocean waves and tides

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Floating ice shelves off the coast of Antarctica play an important role in buttressing the outflow of grounded ice. These ice shelves are subject to the continuous impact of ocean waves and tides which can induce its flexure, create bending stresses, and possibly facilitate rifting and calving. Ice shelves have complex geometries and spatially variable ice thickness and water depth. These features are challenging or impossible to capture with the commonly used semi-analytical methods that have been used to study wave reflection, transmission, and propagation. To address this challenge, we introduce a provably stable, higher-order-accurate finite difference method to solve the 2D (map view) problem of an incompressible ocean partially covered with an elastic plate. The method is based on the summation-by-parts–simultaneous approximation terms (SBP-SAT) framework, and uses curvilinear multiblock grids to handle complex geometries. The model solves the Euler-Bernoulli plate equation, with spatially variable properties, coupled with the 2D variable depth shallow water equations. We demonstrate the stability and accuracy of the numerical model using the method of manufactured solutions. We are currently applying the new method to study ocean wave forcing of the Thwaites Glacier Ice Tongue and Eastern Ice Shelf, with ice thickness and water depth from BedMachine (Morlighem et al., 2020). Furthermore, we plan to apply our model to Ross Ice Shelf, where seismic and geodetic data exists for validation. Our modeling will quantify the response of ice shelves to forcing from ocean waves and tides, providing additional constraints on ice thickness and bending stiffness through comparison with data, as well as identification of regions in which bending stresses are amplified by wave focusing.

Ice thickness interpolation with physics-informed neural networks

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Accurate maps of the bed topography beneath the Antarctic Ice Sheet at high spatial resolution are critical to accurate predictions of the future evolution of the ice sheet and its contributions to sea level rise. Unfortunately, direct measurements of ice thickness are logistically difficult to collect and, as a result, only sparsely available. A number of interpolation methods have been proposed for accurately filling in the gaps in the available data. Mass-conservation interpolation has proven to be a highly effective approach in fast-flowing areas of the ice sheet. We explore an alternative numerical approach based on a physics-informed neural network that leverages the same mass conservation constraint while offering the flexibility to incorporate geophysically realistic regularization terms.

We present an initial comparison of our physics-informed neural network based approach with existing bed maps in the Byrd Glacier catchment and explore introducing a new geophysically-realistic regularization term to avoid over-smoothing of the bed topography. This approach could enable better uncertainty quantification of bed topography and allow for easier simultaneous estimation of ice velocity, bed topography, and sliding parameters.

The three-dimensional overturning circulation of the West Antarctic shelf seas

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The importance of the oceanic circulation of the West Antarctic shelf seas has been framed around its role in delivering warm Circumpolar Deep Water from the continental shelf break towards ice-shelf cavities and ultimately to the grounding zone. Recent observational and modeling work has suggested that pathways of heat transport from shelf break to grounding zone may depend sensitively on boundary currents such as the Antarctic Slope Current, and its associated Undercurrent, as well as the Antarctic Coastal Current (AACC). These circulation features enable the exchange of water properties between different shelf seas with important implications for the future evolution of the West Antarctic Ice Sheet. In this presentation we will make use of two tools to highlight key dynamical processes over the continental shelf that modify the delivery of heat to the grounding zone, with a focus on how remote perturbations to the AACC can have a non-local impact on basal melt rates.

First, we present results from a suite of high-resolution (~3-km) numerical simulations of the ocean circulation in West Antarctica that includes dynamic sea-ice, ice-shelf cavities and forcing from ice shelf-ocean interactions. Motivated by persistent warming in the northern Antarctic Peninsula since the 1950's, freshwater perturbations are applied to the West Antarctic Peninsula. This leads to a strengthening of the AACC and a westward propagation of the freshwater signal. Critically, basal melt rates increase throughout the WAP, Bellingshausen and Amundsen Seas in response to this perturbation. The freshwater anomalies stratify the ocean surface near the coast, modifying the partitioning of vertical and lateral heat transport that produces enhanced ice-shelf melt rates. A suite of sensitivity studies show that changes in melt rates are linearly proportional to the magnitude of the freshwater anomaly, changing by as much as 30% for realistic perturbations, but are relatively insensitive to the anomaly's distribution across the WAP shelf. These results indicate that glacial run-off at the Antarctic Peninsula, one of the first signatures of a warming climate in Antarctica, could be a key trigger for increased melt rates in the Amundsen and Bellingshausen Seas.

Second, we briefly introduce an idealized model of the continental shelf overturning circulation that represents dynamical processes located close to the coast, including convection due to sea-ice formation, glacial melt, and fluctuations in the strength of the AACC. The model describes the evolution of the ocean's vertical stratification close to the face of floating ice shelves in response to changes in surface stress and buoyancy forcing. The overturning circulation is diagnosed based on simple relationships between the stratification and water mass transformation processes. These mechanisms can conspire to support multiple steady overturning states for a given heat and volume transport at the continental shelf break.

The US Antarctic Program Data Center (USAP-DC) – data archive and project catalogue for Antarctic Sciences

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USAP-DC provides data services to support data archive and discovery across all disciplines of NSF-funded Antarctic research. The USAP-DC project catalogue is a summary of current and past projects that have been registered with the data center, and provides search functions and ongoing updates to facilitate data discovery and collaboration.
Investigators are encouraged to register their projects at the USAP-DC as soon as they are funded, creating a project page that summarizes the research goals, planned fieldwork and anticipated data for each project. As projects continue, the project page can be updated by adding links to datasets and publications, providing a centralized location connecting diverse outputs of a single project. Records can also be created for past projects, and USAP-DC can provide a permanent archive for new and legacy datasets.
Datasets submitted to USAP-DC for archive are assigned DOIs and are available for download from dataset pages. These pages summarize metadata and connect associated publications. Links to datasets archived at USAP-DC and those in discipline-specific repositories are added to the project page. Dataset visibility is increased by sharing through the Antarctic Master Database and DataOne.

What lies beneath: Using sub-ice archives to assess the Holocene (in)stability of the West Antarctic Ice Sheet

Ryan Venturelli[1], Brent Goehring[1], Brad Rosenheim[2], the SALSA Science Team[3], the GHC Science Team[4]

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Reconstructions of ice-sheet evolution through the geologic past can help constrain models that predict future ice dynamics. Existing geological records of West Antarctic deglaciation are largely confined to ice-free marine and terrestrial archives. Such geographic limitations reflect the primary loci of ice dynamics from periods of more extensive ice cover and due to the relatively easy access provided by ice free regions. As a result, we have historically viewed grounding line retreat in West Antarctica as a monotonic process since the Last Glacial Maximum. Recent efforts to recover geologic archives (e.g., sediment and bedrock cores) beneath grounded ice in West Antarctica offer insight into the southernmost extent of grounding line retreat, yielding a more complete view of ice dynamics during the recent geologic past. Here, we will present results from recent subglacial access efforts to identify periods when the West Antarctic Ice Sheet may have been less extensive in the Holocene compared to today. New constraints on the timing and extent of West Antarctic grounding line retreat allow for a mechanistic understanding of drivers of marine ice-sheet evolution, a key component of quantifying change over the coming 100s to 1000s of years.

The Impact of Elevation-SMB Feedbacks on the Evolution of Thwaites Glacier, West Antarctica

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The Amundsen Region of the West Antarctic Ice Sheet is one of the major active contributors to global sea level rise. Thwaites Glacier is a large, fast-flowing glacier in this region that is experiencing mass loss, flow acceleration, and rapid grounding line retreat, indicative of the marine ice sheet instability. Although there are many factors that may influence the potential destabilization and collapse of Thwaites Glacier, surface mass balance is an important factor as the balance of precipitation and ablation change with changing glacier geometry. This study investigates a surface elevation-SMB relationship and its influence on projected future stability at Thwaites Glacier. Observational data and regional climate model outputs are used to identify a strong elevation-SMB relationship at Thwaites Glacier. The Ice-Sheet and Sea-Level System Model is then used to simulate Thwaites Glacier's evolution with an added elevation-SMB feedback. Incorporating an elevation-SMB feedback increases the model prediction for ice mass loss by 5%-10% over a 200-year transient simulation.

A synthesis of ice-ocean interface observations from the underwater vehicle Icefin

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The accumulated mass loss from the Earth's cryosphere currently represents the largest contribution to global sea level rise. A large portion of this mass loss is driven by physical processes occurring at the marine margin of the Antarctic and Greenland ice sheets, where the ice sheet interacts with the ocean. However, there are extremely limited direct observations of the ice-ocean interface where these two physical environments meet. Here, we synthesize three years of ice and ocean observations in Antarctica, from beneath the Ross and Thwaites ice shelves and McMurdo Sound, using hydrographic and sonar data, and video footage from the underwater vehicle Icefin. Near-ice ocean conditions vary between these environments from below freezing to greater than two degrees above freezing, with considerable variability in current velocities. Ice base morphology likewise varies within and between environments, with ablating ice forming scallops, runnels, and terraces with horizontal scales of tens of centimeters to tens of meters and vertical scales of centimeters to meters. Supercooled waters in turn form marine ice platelets, which accumulate in both unconsolidated and rigid bulbous masses observed at meter scales. These variations in ice basal roughness affect the turbulent transfer of heat and salt from the ocean to the ice, and represent one of the most poorly constrained parameters in the equations that describe ice-ocean interactions. Our results provide direct observations of the ice-ocean boundary in several environments, and therefore inform on these processes that are critical for the future behavior of the Antarctic and Greenland ice sheets, as well as other peripheral ice caps that contain marine-terminating outlet glaciers.

Evidence of Recent Ocean-Driven Grounding Zone Retreat at Kamb Ice Stream Grounding Zone

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Antarctica's Ross Ice Shelf (RIS) represents a third of all floating ice on Earth by area. 12 tributary ice streams from both East and West Antarctica sustain RIS with 200 gigatons of ice annually, but fluxes from the Siple Coast ice streams vary on decadal timescales. Notably, the downstream portion of Kamb Ice Stream (KIS) stagnated circa 1860, leading to accumulation of ice upstream in the KIS trunk, now one of the few positive mass balance regions in West Antarctica. To explore the sequence of events following KIS stagnation, in collaboration with Antarctica New Zealand we deployed a remotely operated underwater vehicle ~4 km downstream from the present KIS grounding zone (GZ) and flew a combined 5 km of survey tracks, up to one km from the hot water borehole. Below the 587 m thick ice, we observed a stratified, two-layer water column, currents up to 13 cm/s, basal crevasses, and a predominantly meteoric ice base with a remnant patch of sediment-laden basal ice. At the seafloor, banded impressions left by basal crevasses as the ice lifted off are interpreted as evidence of post-stagnation GZ retreat, and considering the present ice flow rate indicate the water column here began to form approximately 50 years ago. Within a basal crevasse, we also directly observed active ice pumping and marine ice formation.

Ice loss from asymmetric melting at Thwaites Glacier grounding zone

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Thwaites Glacier drains a significant portion of the West Antarctic Ice Sheet and is grounded below sea level, which makes it susceptible to runaway melting from a warming ocean, often referred to as the marine ice sheet instability. Recent acceleration in ice flow, reduced area of the floating ice tongue and shelf, and retreat of the grounding line argue that rapid ice loss is likely to continue. We report the first in situ observations extending 3 km from the grounding line of Thwaites Eastern Ice Shelf and from the ice-ocean interface to the seafloor that resolve ice shelf melting at fine-scale. These observations reveal a rough ice base and seafloor sloping upward towards the grounding line. We show that the warmest water exceeds 2°C above freezing and infiltrates the cavity near the grounding line. Under these conditions, the ice shelf base evolves from corrugated with irregular slopes inherited from the upstream bed to stair cased sequences of steep-sided terraces. Data closest to the ice base show that strong melting occurs along sloped surfaces, producing stratification that suppresses melt along flat interfaces. This effect is pronounced within crevasses, and implies that ice loss under ice shelves is strongly influenced by ice base topography of the grounding zone.

The Automatic Weather Station Network

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The University of Wisconsin has overseen the Antarctic Automatic Weather Station (AWS) network since 1980. The broader network consists of approximately 60 weather stations located throughout Antarctica with 11 of these stations located in West Antarctica. This includes a station located in close proximity to WAIS named Kominko-Slade. There are currently plans to install a 30m Tall Tower AWS at Byrd station.

A standard AWS consists of a 3 meter tower with standard measurements of air temperature at two levels, relative humidity, air pressure, snow accumulation, wind speed, and wind direction. Integration of surface temperature, radiation sensors, and snow temperature strings, as well as other sensors has been implemented and can expand the sensor suite. This data is transmitted out every 10 minutes via Argos, or iridium satellite transmission. The data gathered is provided real time, as well as in quality controlled format via the Antarctic Meteorological Research and Data Center (AMRDC) ftp site and in the future through the AMRDC repository.

Antarctic Atmospheric River Climatology and Impacts in West Antarctica

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The mass balance of Antarctica is sensitive to intrusions of extremely warm, moist airmasses from the mid-latitudes in the form of atmospheric rivers (ARs). These storms provide a sub-tropical link to the Antarctic continent and engender extreme atmospheric conditions that are largely consequential to surface melt, snowfall, and ice-shelf stability. Using primarily an AR detection algorithm and regional climate simulations from MAR, both designed for designed for polar regions, we characterize the AR life cycle and demonstrate their impacts on processes ranging from high precipitation events to surface-melt induced hydrofracturing.

Despite their rarity of occurrence over Antarctica (maximum frequency of ~3 days per year over a given point), ARs have a relatively large impact on the surface melt and snowfall processes in West Antarctica. AR landfalls and their associated radiative flux anomalies and foehn winds trigger surface melt in regions rarely exposed to such events. Overall, AR accounted for around 40% of the total summer surface melt on the Ross Ice Shelf (approaching 100% at higher elevations in Marie Byrd Land) and 40-80% of total winter surface melt on the ice shelves along the Antarctic Peninsula from 1979-2017.

During the summer season along the Antarctic Peninsula ice shelves, AR landfalls lead to conditions (i.e. extreme temperatures, rainfall, surface melt, sea-ice clearing, ocean swell enhancement), that act to destabilize the leeward ice shelves. This occurs through a combination widespread surface-melt induced hydrofracturing and sea-ice clearing allowing storm enhanced swells to apply strain along the ice shelf front. Intense AR landfalls coincided with 60% of calving events on the Larsen A and B ice shelves since 2000 along with the collapses of these ice shelves in 1995 and 2002 respectively.

Regarding West Antarctic precipitation from 1980-2018, ARs contribute modestly to the annual snowfall budget but are responsible for a majority of extreme precipitation events with ramifications for past climate reconstruction using ice cores. The warm moist air transport associated with ARs also leads to occasional rainfall along the West Antarctic coastline which will likely become more frequent under global warming scenarios.

Our results suggest that atmospheric rivers play a significant role in the Antarctic mass balance. Thus, any future changes in atmospheric blocking or tropical-polar teleconnections, which control AR behavior around Antarctica, along with further global warming, may have significant impacts on future mass balance projections and subsequent sea level changes.

Can international consortia support pan-Antarctic observational networks?

Dr Terry Wilson[1]
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U.S. and international Antarctic and Southern Ocean vision documents all point to international collaborative efforts as the way to achieve ambitious science goals. What frameworks can lead to implementation of this vision? The International Polar Year 2007-08 provides examples. POLENET (POLar Earth observing NETwork), a network of geophysical and geodetic instruments, was initially deployed in 2007-08 during the International Polar Year as a consortium of 28 nations collecting data across the Antarctic and Arctic regions. The network vision and collaborative relations were formed in the SCAR Antarctic Neotectonics (ANTEC) research program, requisite technology development was supported by the NSF MRI program, and IPY provided the funding boost in national Antarctic programs to implement network deployment. Since IPY, the Antarctic component of POLENET (ANET) has continued in some sectors, supported piecemeal, mainly by PI-led awards. A more sustainable model is required to support acquisition of the continuous time series of observations required to meet science objectives across a range of disciplines, and particularly for interdisciplinary research on the West Antarctic Ice Sheet. Can SCAR-US, the NAS Polar Research Board, international SCAR research programs, and collaborative initiatives between national Antarctic programs, work synergistically to re-establish the successes of the IPY framework? What actions can the science community take to push international, interdisciplinary science frameworks forward?

Sedimentary and Bathymetric Structure Near the Grounding Line of Totten Glacier, East Antarctica.

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The Totten Glacier drains a significant portion of the Aurora Subglacial Basin in East Antarctic Ice Sheet and has the largest flux of any East Antarctic glacier. Over decadal time-scales the region near the grounding line has been observed decreases in mass, however, superimposed on this long-term trend is strong interannual variability that appears the be driven by oceanographic variability. Improved insight into the controlling factors of the Totten Glacier are essential for improved understanding these ongoing changes and future projections. During the past decade several geophysical surveys as well as ground based geophysical campaigns have been conducted near the grounding zone of the Totten Glacier. We utilize active and passive seismic as well as gravity observations to constrain sedimentary structure and topography in the region.

Development of a fixed-wing UAV for ice-penetrating radar data collection

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The use of airborne ice-penetrating radar to study the internal structure of glaciers and ice sheets has conventionally required the use of crewed aircraft and the corresponding costs and logistical complexity of operating aircraft over remote ice sheets. Given the accelerating changes to Earth's ice sheets due to climate change, there is an increasing need to map and monitor ice sheets, but the vast scale of Antarctica and Greenland and the expense of using airborne ice-penetrating radar is a significant barrier. One potential alternative to conventional crewed aircraft for airborne radar sounding is a smaller-scale autonomous aircraft.

In this study, we explore small-scale, autonomous, uncrewed aircraft as platforms for ice-penetrating radar sounding. The radar systems employed on the autonomous aircraft must be altered to account for the limited space inside the aircraft. This necessitates the use of smaller antennas, which constrains the bandwidth of the radar instrument. In addition, the transmission power in each chirp will be limited, and signal processing methods must be altered accordingly. Additional design challenges include the greater exposure of the radar electronics to sub-freezing temperatures, which necessitates the development of a heating apparatus, and shorter flight times compared to conventional airborne radar systems. Overcoming these challenges would provide researchers with a convenient method of gathering ice-penetrating radar data, ultimately enabling a far greater volume of data collection and corresponding improvements in sea level rise predictions.

Stability of Surface/Basal Crevasses in Marine Ice Shelves

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Iceberg calving contributes to the mass balance of ice sheets and indirectly to sea-level rise; changes in calving rate can shorten the ice shelves, speed up the grounded ice and increase changes in ice sheets. Therefore, having a better understanding of this phenomenon by mathematical modeling seems essential. A systematic investigation of the critical parameter values and a precise representation of stability of crevasses has not been undertaken which may yield to nonphysical predictions.

Calving in our model defines as a crevasse that fully propagates across the ice thickness. This could be stable propagation: a crack that grows continuously across the thickness of the ice as a forcing parameter such as applied stress is increased, and eventually reaches the other side of the ice at some critical level of forcing. Alternatively, propagation could be unstable: a change in forcing renders a geometry with a crack that has partially propagated unstable, and the crack will dynamically propagate across the remaining finite thickness of ice between its original crack tip position and the other side of the ice. Having water inside the crack brings us into a contact problem, with two different hydraulic system assumptions: limited water supply or near-surface hydrological prescribing water levels. Here we use the boundary integral method to perform a parameter study by scaling the governing equations and finding the essential groups of parameters. We analyze the stability of the crack propagation by considering this process as a dynamical system.

Circulation-Melt Interactions within Glacial Fjords

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Glacial fjords are long, narrow, and deep inlets that connect glaciers to the open ocean. These glacial fjords exist around the margins of the West Antarctica Peninsula, Greenland, Patagonia, Alaska, and other regions, and are collectively a significant source of ice discharge into the ocean, which can lead to sea level rise. Over the past two decades, tidewater glaciers have accelerated in many of these regions and there is growing evidence that this acceleration is caused by deep warm water currents that flow into the fjords from the open ocean. These warm water currents have the potential to melt the submarine sides of the tidewater glaciers, causing them to retreat over time. However, this submarine melt process is presently poorly understood.

Fjord circulation modulates the connection between marine-terminating glaciers and the ocean currents offshore. These fjords exhibit both overturning and horizontal recirculations, which are driven by water mass transformation at the head of the fjord via subglacial discharge plumes and distributed meltwater plumes. However, little is known about the interaction between the 3D fjord circulation and glacial melt and how relevant fjord properties influence them.

To tackle this, we use high-resolution, process-oriented simulations to understand the currents within these fjords, how they vary with different fjord characteristics, and how they lead to different rates of submarine melting of the glacier face. We find that the submarine glacial melt can cause feedbacks by amplifying the strength of the ocean currents, which further increase glacial melt. Specifically, we demonstrate that recirculation strength controls melt, which feeds back on overturning and recirculation. The overturning circulation strength is well predicted by existed plume models for face-wide melt and subglacial discharge, while the relationship between the overturning, horizontal recirculation, and melt rate is well predicted by a vorticity balance. These theories allow improved predictions of fjord overturning, recirculation, and glacial melt by taking intrafjord dynamics into account. These results are an important step towards understanding a critical process, which may also influence melt-circulation feedbacks in ice-shelf cavities as well.