Student Awards Form

WAIS Workshop 2022 Agenda (all times MDT)

YMCA of the Rockies
Estes Park, CO USA

Monday, September 26

4:00 pm – 8:00 pm	Check in: Pick up badges, room keys (check in Wednesday and Thursday will be available during breaks in the agenda)	Long's Peak Lodge
4:30 pm	WAIS Workshop Steering Group Meeting	Chasm Lake Room
5:30 pm	Icebreaker and pizza dinner	TBD

Tuesday, September 27 (all oral sessions are in the Chasm Lake Meeting Room)

Presenters upload slides by 7 am here

Breakfast: 7:00 am – 8:10 am

Session 0a	Welcome	Presenter
8:15 am	Welcome to WAIS Workshop 2021	WAIS Committee

Session 1	WAIS in the Community	Presenter
8:20 am	Polar Science & Early Career Community Office (PSECCO)	Mariama Dryak
8:30 am	Juneau Icefield Research Program (JIRP) and WAIS	Scott Braddock
8:40 am	Enlisting Historically Excluded Undergraduates in the Effort to Extend Knowledge of West Antarctica's Bedrock, Through Course-based Undergraduate Research Experiences (CUREs) and Art-Science Initiatives	Christine Siddoway
8:50 am	Discussion	All

Session 0b	Funders' Perspective	Presenter
9:10 am	View from NASA	NASA
9:30 am	View from NSF	NSF

9:50 am	One minute poster teaser pitches (upload **one** slide here by 7:00 am)	

Refreshment Break: 10:20 am – 10:40 am

Session 2	Community Health	Presenter
10:40 am	First we must consider Manoomin/Psiŋ: Intentional collaboration and knowledge co-production through tribal-university research on wild rice	Cara Santelli & Joe Graveen
11:40 am	Small-group break outs	All

Lunch: 12:00 pm – 12:55 pm

Session 3	Marine Ice Sheet Sensitivity 1	Presenter
1:00 pm	Reversible ice sheet thinning in the Amundsen Sea Embayment during the Holocene	Ryan Venturelli
1:10 pm	Prolonged Pliocene warm period in Amundsen Sea sector from drill records of IODP Expedition 379 and seismic data analysis	Karsten Gohl

1:20 pm	New GNSS Observations of Crustal Deformation due to Ice Mass Loss in the Amundsen Sea Region	Terry Wilson
1:30 pm	Coupled ice sheet-sea level modeling for improving projections of Antarctic Ice Sheet's contribution to sea-level change: simulation results following the new ISMIP6-2300 experimental protocol	Holly Kyeore Han
1:40 pm	Mapping of Traveling Velocity Waves over Thwaites Glacier with Sentinel-1	Justin Linick
1:50 pm	Evidence of Diminished WAIS and Open Interior Seaway, from Distinctive Dropstones in Amundsen Sea that Originated in the Ellsworth Mountains	Christine Siddoway/Stuart Thomson
2:00 pm	Discussion	All

Refreshment break: 2:20 pm – 2:40 pm

Session 4	**Improving Predictability**	**Presenter**
2:40 pm	The Stochastic Ice-Sheet and Sea-Level System Model v1.0 (StISSM v1.0)	Vincent Verjans
2:50 pm	Refined time series of Antarctic active subglacial lakes: New multimission volume flux estimates using evolving shorelines	Wilson Sauthoff
3:00 pm	Accounting for ice-shelf damage in rheology and calving laws reproduces observed changes and amplifies projected 21st century mass loss	Trevor Hillebrand
3:10 pm	Statistical Generation of Antarctic Ice Shelf Basal Melt Realizations with Realistic Spatiotemporal Variability	Shivaprakash Muruganandham
3:20 pm	Potentially Significant Water Exfiltration from Subglacial Till Driven by Contemporary Ice Sheet Thinning	Alexander Robel
3:30 pm	Estimating the dominant creep mechanisms and viscous stress exponent (n) in fast-flowing glaciers	Meghana Ranganathan
3:40 pm	Discussion	All

Poster Session: 4:00 pm – 5:30 pm (in Diamond East and West)
Dinner: 5:30 pm – 6:45 pm
Building supportive communities breakouts: 7:00 pm – 8:00 pm

Wednesday, September 28
Presenters upload slides by 7 am here

Breakfast: 7:00 am – 8:35 am

Session 5	**Marine Ice Sheet Sensitivity 2**	**Presenter**
8:40 am	Did WAIS existing during the Eemian? Evidence from ice core records	Eric Steig
8:50 am	On the Path Dependence of Ice-sheet Contribution to Sea-level Change	Surendra Adhikari
9:00 am	Rapid uplift bedrock uplift may slow retreat of Thwaites Glacier by decades over the coming centuries	Matthew Hoffman

9:10 am	Can sedimentation pause grounding-line retreat over retrograde slopes? A case study on the Pine Island paleo ice stream	John Erich Christian
9:20 am	Impacts of Cyclic Effective Stress Loading on Basal Slip	Natasha Morgan-Witts
9:30 am	Discussion	All

Refreshment Break: 10:00 am – 10:20 am

Session 6	**Atmosphere & Ocean Drivers**	**Presenter**
10:20 am	Antarctic Atmospheric Rivers in the Past and Future Climate	Michelle Maclennan
10:30 am	Antarctic subglacial precipitates record ice sheet response to millennial-scale Southern Ocean warming	Jessica Gagliardi
10:40 am	Climate Variability as a Major Forcing of Recent Antarctic Ice-Mass Change	Matt King
10:50 am	Pairing eyes in the sky with instruments in the deep: mapping the Antarctic Coastal Current in the eastern Amundsen Sea	Tasha Snow
11:00 am	Inferring ocean variability in ice-shelf cavities from basal melt rate time series	Irena Vankova
11:10 am	Climatic and Structurally-Controlled Drivers of Melt on the George VI Ice Shelf, Antarctic Peninsula	Emily Glazer
11:20 am	Potential triggers for the Larsen B fast ice break-up event and the initial glacier response	Naomi Ochwat
11:30 am	Discussion	All

Lunch: 12:00 pm – 12:55 pm

Session 7	**Antarctic Open Science 1**	**Presenter**
1:00 pm	The US Antarctic Program Data Center (USAP-DC) – Data Archive and Project Catalogue for Antarctic Sciences	Kirsty Tinto
1:10 pm	Towards Geologic Realism in the Subglacial Environment through Geostatistical Simulation with Open-Source Software	Mickey Mackie
1:20 pm	An updated 3-D model of ice shelf surface hydrology	Sammie Buzzard
1:30 pm	Redesigning Scientific Conferences: Insights from the International Firn Workshop	Megan Thompson-Munson
1:40 pm	Discussion	All

Refreshment Break: 2:00 pm – 2:20 pm

Session 8	**Antarctic Open Science 2**	**Presenter**
2:20 pm	How old, how accurate? A cautionary tale about inaccurate dates at the detection limit for radiocarbon	Brad Rosenheim
2:30 pm	Carbon oxidation in subglacial waters beneath the Antarctic ice sheet	Gavin Piccione
2:40 pm	Basal properties of the WAIS from inverse modeling including effective pressure	Lea-Sophie Höyns

2:50 pm	Under what conditions did WAIS collapse during the Last Interglacial?	Mira Berdahl
3:00 pm	Discussion	All

Activities at YMCA of the Rockies: 3:20 pm – 5:30 pm
Dinner: 5:30 pm – 7:00 pm

Thursday, September 29

Presenters upload slides by 7 am here

Breakfast: 7:00 am – 8:55 am

Session 9	Observational & Modeling Gaps	Presenter
9:00 am	Obtaining Maximal Sensitivity to Ice-Sheet Temperature with a Multi-frequency Radar-Radiometer System	Anna Broome
9:10 am	Evaluating the Hydrostatic Assumption for Antarctic Ice Shelves using Contemporaneous Laser and Radar Altimetry Measurements	Allison Chartrand
9:20 am	Advances in glacier dentistry: experimental constraints on transient slip with cavitation	Nathan Stevens
9:30 am	UAV-based ice-penetrating radar ice shelf monitoring: development and testing of a prototype system	Thomas Teisberg
9:40 am	Seismic signals from the Eastern Shear Margin of Thwaites Glacier	Marianne Karplus
9:50 am	Surface elevation change of Crane Glacier using 1960s trimetrogon aerial imagery and high-resolution satellite data	Sarah Child
10:00 am	Towards Automated Retrieval of Supraglacial Lake Depth Measurements from ICESat-2 Data Across Antarctica's Ice Shelves	Philipp Arndt
10:10 am	Discussion	All

Refreshment Break: 10:30 am – 11:00 am

Session 10	Actionable community discussions	Presenter
11:00 am	Future of U.S. ship-based Antarctic Science	
11:15 am	U.S. Antarctic Program's Sexual Assault and Harassment Needs Assessment	
11:30 am	Discussion	All

Lunch: 12:00 pm to 1:00 pm
Community College Curriculum Development Session: 1:00 pm – 3:00 pm

Posters

Title	Presenter
Automated Detection of West Antarctic Persistent Polynas with Multiband Remote Sensing Imagery	Ellianna Abrahams
Estimating the contribution of Atmospheric River precipitation to height changes over the Antarctic Ice Sheet 2019-2022	Susheel Adusumilli
The Integrated Ice Sheet Response to Stochastic Iceberg Calving	Aminat Ambelorun
Improved understanding of decadal surface mass balance, recent climate variability, and future ice core sites along coastal West Antarctica	Julia Andreasen
A paleo-perspective on West Antarctic Ice Sheet retreat	Philip Bart
Utilization of High-Resolution Ice Mass Balance Datasets for Predicting and Observing Global Patterns of Sea Level Change and Crustal Deformation	Sophie Coulson
In the Quest of a Parametric Relation Between Ice Sheet Model Inferred Weertman Sliding-Law Parameter $\beta 2$ and Airborne Radar-Derived Basal Reflectivity Underneath Thwaites Glacier, Antarctica	Indrani Das
The Sources of Moisture and the Impact of Southern Ocean Conditions on Snowfall Over Antarctica	Rajashree Datta
Surface melt on the Larsen C Ice Shelf: An AMSR-2 dynamic thresholding technique informed by microwave radiative transfer modeling	Marissa Dattler
Deciphering Basal Thermal Conditions with Ice-penetrating Radar and Ice Sheet Modeling	Eliza Dawson
New coastal Antarctic geochemical constraints from ice core subsamples at Mt. Murphy, West Antarctica	Kniya Duncan & Garrett Guillard
A Bayesian Modeling Approach to Quantify the Role of Suspended Sediment-Rich Meltwater in Antarctic Glacimarine Sediment Formation	Nicole Greco
The Polar Rock Repository: Samples and Data for Paleoclimate Research	Anne Grunow
Radar attenuation demonstrates advective cooling in the Siple Coast ice streams	Benjamin Hills
Understanding the Rheological Properties of Firn through Laboratory Compaction Experiments	Kris Houdyshell
Modeling the Processes that Determine the Propagation Paths of Ice-Shelf Rifts	Alex Huth
Decadal-scale oscillations in ocean-temperature reconstructed from geochemical ratios of pre-modern corals on the Ross Sea continental shelf	Colby Knight
Using benthic microfaunal communities to constrain oceanographic influence on the stability of Thwaites Glacier, Antarctica	Asmara A. Lehrmann
Subglacial processes inferred from grain-shape alteration of till and meltwater plume deposits from Antarctica and Greenland	Allison Lepp
Bathymetry and Geology model of the Venable Ice Shelf from Operation IceBridge (OIB) Airborne Gravity and Magnetometer Data	Caitlin Locke
An idealized model of ice flow with subglacial water coupling	George Lu
Behavior of Ice During Pulsed NIR Laser Cutting	Merlin Mah

Title	Presenter
Estimation of Englacial Attenuation and Basal Reflectivity Using Off-Nadir Radio Echo Sounding	Daniel May
Microseismic Events on the Ross Ice Shelf and Identifying Ocean Swell Controlling Mechanisms	Elisa McGhee
Influence of Topographic Highs on Ice Flow as Determined by Streamlined Bedform Morphology	Marion McKenzie
Enhanced Glacial Thinning and Retreat at an Ice-Cliff Terminus?	Sierra Melton
Time-dependent Strain-rate Fields Forecast Rift Propagation: Case Study on the Brunt Ice Shelf, Antarctica	Joanna Millstein
Characterizing Bed Roughness on a Deglaciated Continental Margin and its Impact on Past Streaming Ice Flow	Santiago Munevar Garcia
Triangular Perspective on the alteration of Sea ice	Hayat Nasirova
Grounded icebergs in East Antarctica: Estimating water depth using ICESat-2 laser altimetry	Laurence Padman
Calibrating extraterrestrial ^{3}He in ice-proximal marine sediments as a quantitative proxy for past West Antarctic Ice Sheet melt rates	Frank Pavia
Subglacial Precipitates Record Antarctic Ice Sheet Response to Late Pleistocene Millennial Climate Cycles	Gavin Piccione
Investigating temperature and origin of fluids that circulated within a brittle fault array in the West Antarctic Rift System	Emory Pollatsek
Subglacial meltwater as an enabler of CDW-driven retreat in Marguerite Bay, Antarctica	Lindsay Prothro
Changes in Dotson-Crosson Ice Shelf Flow Linked to Thinning and Tidal Interaction with Ice Rises and Rumples	Ted Scambos
Controlled-source seismic imaging of McMurdo Ice Shelf near Williams Airfield	Yeshey Seldon
Promoting Inclusivity, Diversity, Equity, and Accessibility within the International Thwaites Glacier Collaboration and beyond	Betsy Sheffield
"Big Bergs No More" – A Landsat Study of the Thwaites Ice Tongue and Glacier Front	Christopher A. Shuman
The surface expression of ocean influence upstream of Antarctic grounding lines	Ella Stewart
Evidence for Temperate Ice in Shear Margins of Antarctic Ice Streams from Airborne Radar Surveys	Paul Summers
Examining Micropaleontology to Gain Insights Into Long - Term Processes in the Western Amundsen Sea, Antarctica	Magkena Szemak
Revealing sub-ice shelf sediment basins with airborne magnetics: implications for solid-earth-ice interactions	Matt Tankersley
Archival airborne radio-echo sounding data geographical repositioning and calibration progress at Ross Ice Shelf, Antarctica	Angelo Tarzona
Autogenic, Not Orbital, Forcing of Snowball Glaciomarine Sedimentation	Adrian Tasistro-Hart
Topographic evolution of WAIS subglacial bedrock: Insights from low-temperature thermochronology and thermo-kinematic modeling in Marie Byrd Land, West Antarctica	Jennifer Taylor

Title	Presenter
ROSETTA-Ice Observations on Basal Melting of Ross Ice Shelf using Airborne Radio-echo Sounding Radar	Kiera Tran
Multidecadal surface elevation anomalies of the Crary Ice Rise region from combined ICESat, CryoSat-2, and ICESat-2 altimetry	Hannah Verboncoeur
The Role of Glacial Isostatic Adjustment on Cordilleran Ice Stream Stability Over the Last Glacial Cycle	Casey Vigilia
Decadal-Scale Onset and Termination of Antarctic Ice-Mass Loss Tipping Points During the last Deglaciation	Mike Weber
Breaking the Ice: Understanding Large-Scale Fracture Initiation Processes of Glacier Ice through Observations of Strain Rate and Estimates of Stress in Antarctic Ice Shelves	Sarah Wells-Moran
Recent thinning and speed-up may make the upper Pine Island Glacier more prone to diffusive thinning	Whyjay Zheng

Automated Detection of West Antarctic Persistent Polynas with Multiband Remote Sensing Imagery

Ellianna Abrahams[1], Dr. Tasha Snow[2], Eojin Lee[3], Michael Field[2], Elena Savidge[2], Prof. Jonathan Taylor[4], Prof. Matthew Siegfried[2], Prof. Fernando Pérez[1]
[1]UC Berkeley, [2]Colorado School of Mines, [3]Columbia University, [4]Stanford University

Sensible-heat polynyas, i.e. persistent polynyas produced thermodynamically, can form across multiple years where relatively warm water flows out from the sub-ice-shelf cavity toward ice shelf fronts, typically directed by channels carved into the ice-shelf base. Polynyas represent an important component of the interactions between ice shelves, channel water outflows, and ambient ocean properties and circulation. However, time-resolved investigations of persistent polynyas are sparse across Antarctica, due to a dearth of field observations and the complexity of identifying their extent and evolution in remotely sensed images. The challenge, particularly along the coastal margin of the West Antarctic Ice Sheet is not one of a paucity of data, but one of a plethora of pixels lacking classification; typically, an expert is required to label pixels belonging to ice shelf, iceberg, sea ice, open ocean, polynya, or a mixture. Here, we engineer a physics-featurized convolutional neural network with an approach that allows us to predict pixel classifications even in the case where expertly labeled data are sparse. We demonstrate the potential of physics-featurized neural networks to robustly automate complex classification tasks, such as pixel-based labeling of remote sensing imagery, that are often a necessary stepping stone to answering more specific scientific questions across the cryosphere.

On the Path Dependence of Ice-sheet Contribution to Sea-level Change

Dr. Surendra Adhikari[1]
[1]*Jet Propulsion Laboratory, Caltech*

The melting of ice sheets directly contributes to ocean mass and volume change. One key metric being used to keep track of ice-ocean mass exchange is the "ice-sheet contribution to sea-level change" (IS2SL), which is presumed to be a conservative metric that does not depend on what path an ice sheet takes to reach from its initial to final geometry. What appears to be a trivial book-keeping task unfolds a layer of complexities while quantifying IS2SL in real-world scenarios where ice sheets, solid Earth, and ocean geometries evolve continuously. Two research groups have independently proposed supposedly general formalism to quantify IS2SL [1,2]. The two methods do not seem to agree, especially where an ice sheet transits from the grounded to the floating state, or the reverse, much more of what happens in marine sectors of Antarctica. In particular, one method appears to predict a path-dependent solution for IS2SL [1], challenging the utility of one of the most fundamental glaciological metrics. Here, with a simple kinematic analysis, I argue why IS2SL is inherently a path-dependent metric and caution the paleo- and modern-glaciology communities regarding its utility for data and model inter-comparisons.

[1] https://doi.org/10.5194/tc-14-2819-2020
[2] https://doi.org/10.5194/tc-14-833-2020

Estimating the contribution of Atmospheric River precipitation to height changes over the Antarctic Ice Sheet 2019-2022

Dr Susheel Adusumilli[1], Dr Helen Fricker[1]
[1]Scripps Institution of Oceanography, UC San Diego

Estimating the relative contributions of the atmospheric, dynamic, and oceanic components of ice sheet mass balance is important for understanding the processes that drive ice sheet change. Existing estimates of changes in Antarctic Ice Sheet height, which can be used to infer mass changes, are only accurate at multi-year time scales due to issues with temporal sampling or radar penetration into the snowpack. However, NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) laser altimetry mission now allows us to measure seasonal changes in ice sheet height. Here, we use ICESat-2 data to measure height changes over Antarctica between April 2019 and June 2022. These estimates show widespread, previously unreported, changes in surface height at seasonal to annual timescales. We use firn model outputs and reanalysis data to isolate the contribution of the atmosphere to these height changes. We show that a substantial fraction of the atmospheric contribution was from precipitation and snowmelt due to landfalling Atmospheric Rivers, which are long, narrow bands of anomalously large poleward moisture transport. We examine whether changes in mass and firn air content due to Atmospheric Rivers is well-represented in firn models, and describe the impact of such surface processes on estimates of ice sheet mass balance.

The Integrated Ice Sheet Response to Stochastic Iceberg Calving

Ms Aminat Ambelorun[1], Dr Alexander Robel[1]
[1]*School of Earth and Atmospheric Sciences, Georgia Institute of Technology*

Title: The integrated ice sheet response to stochastic iceberg calving

Authors: Aminat Ambelorun & Alexander Robel

Iceberg calving is one of the dominant sources of mass loss from the Antarctic and Greenland Ice sheets. However, iceberg calving is still one of the most poorly understood aspects of ice sheet dynamics due to its complexity at a wide range of spatial and temporal scales. Despite this complexity, all large-scale ice sheet models currently assume that calving can be represented as a deterministic flux. In this study, we introduce stochastic calving within a one-dimensional tidewater glacier model to determine how changes in the calving style and size distribution of calving events cause changes in glacier state. We also quantify the time scale on which individual calving events need to be resolved within a stochastic calving model to accurately simulate the probabilistic distribution of glacier state. We find that incorporating stochastic calving within a glacier model changes the simulated mean glacier state due to nonlinearities in glacier terminus dynamics. Additionally, changes in calving frequency, without changes in total calving flux, lead to substantial changes in the distribution of glacier state. This new model provides a framework for building stochastic calving capabilities into large-scale ice sheet models that can be used to make well-constrained predictions of future ice sheet change.

Improved understanding of decadal surface mass balance, recent climate variability, and future ice core sites along coastal West Antarctica

Ms. Julia Andreasen, Dr. Peter Neff
[1]*University of Minnesota*

The coastal margin of the West Antarctic Ice Sheet (WAIS) is a dynamic and critical region where ice, ocean, and atmosphere converge. Despite its importance, ice core records are largely unavailable along the WAIS coast, restricting observational surface mass balance (SMB) constraints to the continent's inland regions. To address this gap, we utilize NASA Operation IceBridge (OIB) airborne snow radar data to place new observational constraints on coastal WAIS SMB.

At eleven coastal WAIS ice rises, we investigate observed layering in OIB radargrams to automatically detect bright subsurface reflectors likely representing annual snow layers. We then apply depth-density corrections to calculate layer thicknesses and thus annual accumulation rates. This radar-derived snow accumulation time series is then compared to regional reanalysis precipitation and other variables from 1979 to the 2016 OIB overflight. Analysis at three ice rises located on the western, central, and eastern regions of the WAIS coast demonstrates the range of climate forcings affecting interannual snowfall variability along this dynamic coastline.

Radar-derived multi-decadal records of interannual snow accumulation variability at these locations are integral to improving the accuracy of ice sheet SMB calculations in the vicinity of ice shelves, validating climate reanalysis products, and exploring fundamental climate variability and extremes. Extracting information about this region through OIB and reanalysis data is the first step in better understanding the WAIS coast and its recent climate history. Future ice cores at several of these ice rises would expand spatial and temporal climate perspectives beyond what can be gained from snow accumulation alone.

Towards Automated Retrieval of Supraglacial Lake Depth Measurements from ICESat-2 Data Across Antarctica's Ice Shelves

Philipp Sebastian Arndt[1], Dr Helen Amanda Fricker[1]
[1]*Scripps Polar Center, University of California San Diego*

Summer melting on the surface of Antarctica's ice shelves forms complex supraglacial hydrological systems that can evolve rapidly in response to regional atmospheric forcing. Ponding of surface meltwater can trigger ice shelf collapse by hydrofracture, reducing the "buttressing" force those ice shelves provide for the grounded ice and leading to sea level rise. In a warming climate, meltwater production is projected to increase. To better understand the implications of this trend meltwater on the ice shelves needs to be closely monitored, which requires accurate estimates of meltwater depths and volumes. Interannual ice-sheet wide estimates of meltwater depths rely on passive optical satellite imagery, based on models of light attenuation in water. The parameters in such models remain poorly constrained and difficult to validate due to the lack of ground truth data. NASA's Ice, Cloud and land Elevation Satellite-2 (ICESat-2) has provided a new way to obtain accurate estimates of supraglacial lake depths requiring few, simple assumptions. Its laser altimeter system uses green light that penetrates clear water and its sensor allows for single-photon-sensitive detection. Over shallow melt lakes, ICESat-2 obtains two reflections: one from the water surface and a second from the underlying lake bed. We present an algorithm that automatically detects supraglacial lakes in the ICESat-2 photon cloud data product (ATL03) based on the flatness of the upper reflective surface (water) and the presence of a lower reflection. For each detected lake, the surface is delineated by fitting a straight line and the lake bed is found by applying a density-weighted robust LOESS fit to the remaining photons. The elevation difference is corrected for the refractive index of water to obtain a depth estimate. We demonstrate algorithm performance over George VI Ice Shelf, where we also highlight some of the limitations and challenges of using ICESat-2 for supraglacial lake bathymetry. Since the ATL03 data catalog is so large and the fraction of melt lake coverage is relatively small, we require an algorithm that can both detect lakes and extract water depths in a fully automated and scalable manner, allowing for large-scale computational implementation that is efficient, cost-effective, and reproducible. Our method represents significant progress towards these goals: it can be applied to any single raw or subsetted ATL03 data granule, so generating meltwater depth data sets across large regions or long time scales is highly parallelizable. To aggregate depth estimates across large amounts of granules, we use the Open Science Grid's Open Science Pool for distributed High-Throughput Computing, using idle resources across universities and other organizations on heterogeneous hardware. A comprehensive data set of such depth measurements across both ice sheets could further be used to tune and validate imagery-based algorithms, moving us closer towards accurately quantifying supraglacial meltwater volumes across the both ice sheets.

A paleo-perspective on West Antarctic Ice Sheet retreat

Dr Philip Bart[1], Mr Matt Kratochvil
[1]LSU Department of Geology and Geophysics, [2]Fugro Marine

Geological records of ice sheet collapse can provide perspective on the current dynamics. A major collapse that occurred during the early deglaciation is well recorded on the eastern Ross Sea continental shelf. There, following an ice shelf breakup at 12.3 ±0.6 cal. (calibrated) kyr BP, accelerated discharge of the Bindschadler Ice Stream (BIS) led to a significant negative mass balance that re-organized West Antarctic Ice Sheet (WAIS) flow across central and eastern Ross Sea. By ~11.5 ±0.3 cal kyr BP, dynamic thinning of grounded ice triggered a retreat that opened a ~200-km grounding-line embayment on the Whales Deep Basin (WDB) middle continental shelf. Here, we reconstruct the pattern, duration and rate of retreat from a backstepping succession of small-scale grounding-zone ridges that formed on the embayment's eastern flank. We used two end-member paleo-sediment fluxes to convert the cumulative sediment volumes of the ridge field to elapsed time for measured distances of grounding-line retreat. The end-members fluxes correspond to deposition rates for buttressed and unbuttressed ice stream flow. Both scenarios require sustained rapid retreat that exceeded several centuries. Grounding-line retreat is estimated to have averaged between ~100 ±32 ma-1 and ~700 ±79 ma-1. The evidence favors the latter scenario because iceberg furrows that cross cut the ridges in deep water require weakly buttressed flow as the embayment opened. In comparison with the modern grounding-zone dynamics, this paleo-perspective provides confidence in model predictions that a large-scale sustained contraction of grounded ice is underway in several Pacific-Ocean sectors of the WAIS.

Under what conditions did WAIS collapse during the Last Interglacial?

Mira Berdahl[1], Gunter Leguy[2], Eric J. Steig[1], William H. Lipscomb[2], Bette L. Otto-Bliesner[2], Esther C. Brady[2], Nathan M. Urban[3], Ian Miller[4], Harriet Morgan[5]
[1]University Of Washington, [2]National Center for Atmospheric Research, [3]Brookhaven National Lab, [4]Washington SeaGrant, [5]Washington Department of Fish and Wildlife

It is virtually certain that the West Antarctic Ice Sheet (WAIS) collapsed at some time in the last million years, and very likely that it did during the Last Interglacial (LIG, 129 to 116 kyr ago). The sensitivity of the WAIS to changing climate and its influence on local ocean conditions are challenges for models, largely due to inadequate model resolution and difficulty in process representation. Here, we present results from a set of transient modeling experiments that simulate the LIG using state-of-the-art models: the Community Ice Sheet Model (CISM) and the Community Earth System Model (CESM2). The experiments simulate the large meltwater event in the North Atlantic known as the Heinrich 11 (H11) event. The CESM2 results show that, as expected, the H11 forcing generally cools the NH and warms the SH, consistent with previous experiments and paleoclimate proxy records. However, closer to the Antarctic Ice Sheet, a sustained cooling is observed in ocean waters below 100 m – the depths most relevant for ice shelf melt. We explore the physical processes that lead to this new result.

Obtaining Maximal Sensitivity to Ice-Sheet Temperature with a Multi-frequency Radar-Radiometer System

Anna Broome[1], Dr. Dustin Schroeder[1], Dr. Joel Johnson[2]
[1]Stanford University, [2]The Ohio State University

Current observations of ice-sheet thermal structure are limited to temporally and spatially sparse boreholes, extrapolations using model-based retrievals with microwave radiometer data, and depth-averaged observations from ice-penetrating radars. To make accurate and reliable observations of ice-sheet thermal structure on the local to drainage scale, we seek a method that adapts easily to large spatial scales and that does not rely on strong a priori assumptions of the form of the thermal profile. To address this, we are developing a multi-frequency joint radar-radiometer, which combines active (radar) and passive (radiometer) microwave measurements of the ice sheet to obtain accurate measurements of thermal profiles. Active microwave measurements collected with an ice-penetrating radar sounder provide observations of two-way attenuation, which is highly sensitive to temperature, and in particular warm temperatures that typically occur deeper in the ice column. On the other hand, passive microwave measurements collected with a radiometer provide observations of microwave brightness temperature, a measure of the thermal emission of the ice sheet and bed. Microwave brightness temperature measurements are typically more sensitive to temperature in shallow portions of the ice column, due to the attenuation deeper thermal emissions must overcome to be visible at the surface. We exploit the complementary depth sensitivities to temperature of radars and radiometers, by combining them into a single integrated system. Here we present results from simulations demonstrating the performance of a combined radar-radiometer under a variety of plausible ice-sheet thermal structures.

An updated 3-D model of ice shelf surface hydrology

Dr Sammie Buzzard[1,2], Dr Alex Robel[2]
[1]Cardiff University, [2]Georgia Institute of Technology

The formation of surface meltwater has been linked with the disintegration of many ice shelves in the Antarctic Peninsula over the last several decades. Despite the importance of surface meltwater production and transport to ice shelf stability, knowledge of these processes is still lacking. Understanding the surface hydrology of ice shelves is an essential first step to reliably project future sea level rise from ice sheet melt.
In order to better understand the processes driving meltwater distribution on ice shelves, we present results from using a 3-D model of surface hydrology for Antarctic ice shelves, MONARCHS. It is the first comprehensive model of surface hydrology to be developed for Antarctic ice shelves, enabling us to incorporate key processes such as the lateral transport of surface meltwater.
This community-driven, open-access model has been developed with input from observations, and allows us to provide new insights into surface meltwater distribution on Antarctica’s ice shelves. This enables us to answer key questions about their past and future evolution under changing atmospheric conditions and vulnerability to meltwater driven hydrofracture and collapse.
Here we present recent updates to the model, including the results of case studies of ice shelves thought to be vulnerable to meltwater induced collapse, and recently developed validation methods.

Evaluating the Hydrostatic Assumption for Antarctic Ice Shelves using Contemporaneous Laser and Radar Altimetry Measurements

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

Estimates of ice shelf mass loss are strongly dependent on the assumption of hydrostatic equilibrium, especially when ice and firn thickness measurements are unavailable. This assumption that the ice shelf is freely floating allows an estimation of ice thickness from surface height measurements alone. Recent investigations have challenged the assumption that ice shelves are freely floating, particularly in proximity to structures such as basal channels and shear margins. However, the spatial scales of this imbalance and their impacts on ice shelf thickness and mass balance estimates are unknown. No studies to date have directly compared contemporaneous airborne ice penetrating radar (IPR) thickness measurements and laser altimetry surface height measurements at ice-shelf scale. Here, we used IceBridge MCoRDS and HiCARS IPR measurements and ATM and Riegl laser altimetry from the NASA and NSF Operation IceBridge and ICECAP projects to compare observed thickness and assumed hydrostatic thickness, and elucidate the implications of the hydrostatic assumption. We find that on average, for the ice shelves surveyed, the hydrostatic assumption overestimates ice shelf thickness by ~13 m +/- 35 m. The discrepancy between hydrostatic and observed thickness varies widely from ice shelf to ice shelf, and spatially within a single ice shelf. In general, the observed thicknesses of more confined ice shelves are closer to hydrostatic equilibrium, and the hydrostatic assumption tends to underestimate ice thickness of relatively thinner ice and overestimate the thickness of relatively thicker ice over 10s of km. However, on length scales <5 km, the hydrostatic assumption tends to overestimate ice thickness of relatively thinner ice and underestimate the thickness of relatively thinner ice, indicating that the surface topography is muted compared to changes in the thickness profile. Several factors may contribute to erroneous thicknesses estimated using the hydrostatic assumption in a given location, including unknown or uncertain firn thickness, firn density, ice density, presence of marine ice, and ocean density, as well as stress and strain rates. We tested for several conditions that would bring the hydrostatic thickness and observed thickness to equality, finding that small changes in assumed/estimated firn thickness can account for the imbalance in most locations. We also found that the over- or underestimation of ice shelf thickness under the hydrostatic assumption did not, on average, significantly change the estimated basal melt rate at a given point (<2% difference). However, it is difficult to extrapolate basal mass changes at along-track coordinates to an entire ice shelf, so work remains to be done quantifying the implications of using the hydrostatic assumption to estimate basal melt rates. Overall, the finding that the hydrostatic assumption overestimates ice thickness, and the spatial variability in hydrostatic imbalance indicate that more localized approaches are needed to estimate ice shelf thickness and rates of change at local scales.

Surface elevation change of Crane Glacier using 1960s trimetrogon aerial imagery and high-resolution satellite data

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Ice shelves are an integral component to maintaining the mass balance of the Antarctic Ice Sheet. Significant changes to ice shelves affect the flow dynamics of their incoming glaciers which subsequently contribute to sea level rise. At the Antarctic Peninsula, the Larsen A Ice Shelf collapsed in 1995 and the Larsen B Ice Shelf followed suit in 2002; one outcome from the breakup events is the dramatic increases their outlet glaciers underwent in ice discharge rates resulting from the removal of ice shelves' buttressing forces. Past research shows that surface temperatures began increasing in the region as early as the 1930s and the enhanced surface melt from higher temperatures was a contributing factor to ice shelf disintegration. In the decades leading up to the collapses, little is known about the dynamics of the two ice shelves and their feeding outlet glaciers due to large temporal gaps in observational data collection in this part of Antarctica. This study increases the temporal resolution of observations by using historical data to assess ice shelf and glacier hypsometry. We focus on elevation change over Crane Glacier (once terminated at the Larsen B Ice Shelf) using surface elevations derived from 1960s trimetrogon aerial (TMA) imagery. The surface elevations are generated using vertical TMA imagery with structure-from-motion photogrammetry software. The ground control applied in the bulk bundle application is exposed bedrock features extracted from elevations derived via high resolution (0.5 m) satellite imagery. Ice thicknesses are estimated from surface elevations with radar-derived bed topography, which we use to model the driving stresses for the historical and various ice shelf collapse timestamps. Surface velocities are currently unavailable from the 1960s; variations in Crane Glacier's driving stress over grounded ice—where we assume flow is due to creep—allow informed assessments in ice flow changes to be made. Future work will include processing oblique imagery of the remaining Larsen A and B outlet glaciers. This work is in support of a larger study examining the pre- and post-observations of the Larsen A and B marine terminating glaciers' dynamics surrounding potential ice cliff failure events.

Can sedimentation pause grounding-line retreat over retrograde slopes? A case study on the Pine Island paleo ice stream.

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Subglacial bedforms on Antarctica's continental shelf preserve information about ice-sheet retreat following the last glacial maximum (LGM). Grounding Zone Wedges (GZWs) are sedimentary features, typically 10s of m in amplitude, thought to indicate standstills of decades to millennia. In the Amundsen Sea's Pine Island Trough (PIT), several GZWs from post-LGM deglaciation exist on a portion of the shelf that deepens inland and lacks major lateral constrictions. The implied standstills at these locations are puzzling from an ice-dynamics perspective, as theory predicts that the inland-sloping bed would favor sustained retreat as ice flux at the grounding line increases with water depth. Under the same physical arguments, existing GZWs should tend to stabilize grounding lines by reducing effective water depth. However, it is unclear how the sedimentation that forms GZWs affects stability when retreat is already underway, and before a GZW is formed.

We investigate controls on grounding-line retreat using a 1-D ice-flow model with sediment transport and fine (~ 100 m) horizontal resolution near the grounding line. This model allows us to simulate the formation of sediment structures at the grounding line on the scale of GZWs, and to analyze their effects on ice flow. We run model experiments on a transect of PIT as well as on idealized topographies, to assess sedimentation alongside other controls on retreat rates. These include pre-existing bed peaks, ocean variability, and increased accumulation associated with postglacial warming.

Our experiments show that sedimentation can provide a strong stabilizing effect, consistent with previous work, but we find that during deglaciation, the effect can only take hold for sufficiently low retreat rates. However, when combined with other effects (climate or geometry), which on their own can only slow retreat, sedimentation can drive a distinct switch from slowdown to standstill or readvance. While parameters for subglacial sediment transport and deposition remain uncertain, this provides a plausible mechanism for significant standstills during otherwise progressive retreat. Finally, we discuss the implications for calibrating continent-scale models against chronologies provided by submarine landforms.

Utilization of High-Resolution Ice Mass Balance Datasets for Predicting and Observing Global Patterns of Sea Level Change and Crustal Deformation

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Rapid melting of ice sheets and glaciers drives a unique geometry, or fingerprint, of sea-level change. As an ice sheet loses mass, its gravitational attraction on the nearby ocean is reduced, causing ocean water to migrate away from the ice sheet. Additionally, the solid Earth rebounds in response to the reduction in surface loading. This combination of geophysical processes leads to a sea-level fall within ~2000 km of the melting ice sheet and a progressive sea-level rise outside of this region. We utilize high resolution satellite-based observational datasets supplemented with ensemble-based model reconstructions for ice mass loss to predict global patterns of crustal deformation and sea surface height change generated by mass loss from the polar ice caps and mountain glaciers over the last 3 decades. Variations in geometry and net magnitude of mass loss from the East and West Antarctic Ice Sheets generate patterns of sea level change that are highly variable through time. Using a wide set of model simulations, we explore how sea level changes due to mass loss from both polar ice sheets and mountain glaciers can be detected in ocean altimetry and GNSS datasets, and their implications on the use of these observational datasets for other geoscience applications. Additionally, we explore the use of mass loss predictions from multi-model ensembles for the evolution of the Greenland and Antarctic Ice Sheets for predictions of regionally variable sea level change through the 21st century.

In the Quest of a Parametric Relation Between Ice Sheet Model Inferred Weertman Sliding-Law Parameter β2 and Airborne Radar-Derived Basal Reflectivity Underneath Thwaites Glacier, Antarctica

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Numerical ice sheet models use sliding laws to connect basal shear stress and ice velocity to simulate ice flow. A sliding-law parameter β2 is used to control the Weertman's sliding law in numerical ice sheet models. Ice-penetrating radar-derived basal reflectivity also provides information about freeze or thaw conditions underneath glaciers. In order to assess whether basal reflectivity can be used to constrain β2, we carry out statistical experiments between two recently published datasets - β2 inferred from three numerical ice sheet models (ISSM, Úa and STREAMICE) and basal reflectivity from the AGASEA-BBAS mission. Our results show no robust correlation between the β2-reflectivity pair. Pearson correlation coefficient, a test for linearity of the pair, ranges from -0.26 to -0.38. Spearman correlation coefficient, generally used for non-linear relations, is also modest (<-0.4). We conclude that the Weertman sliding-law parameter β2 and basal reflectivity underneath Thwaites Glacier likely do not infer similar bed conditions.

The Sources of Moisture and the Impact of Southern Ocean Conditions on Snowfall Over Antarctica

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Snowfall over Antarctica is a major source of uncertainty in future sea level rise estimates, especially as it is projected to increase with global temperature. Snowfall can be strongly impacted by the surrounding ocean conditions, including sea surface temperatures at lower latitudes and sea ice concentration near the continent. Here, using a global climate model (GCM), we present experiments designed to quantify the impact of sea ice / sea surface temperatures on snowfall over Antarctica. By implementing moisture-tagging capabilities (connecting snowfall to a moisture source on the globe) and by producing high-temporal resolution outputs (enabling detection of Atmospheric Rivers), we will be able quantify how changes over the ocean impact both the global sources of moisture and the portion of total precipitation that reaches the surface during extreme events (atmospheric rivers).
Global climate models (GCMs) can provide valuable information for understanding snowfall dynamics. The CESM2 GCM has been used extensively over polar regions. A variable-resolution grid using CESM2 (VR-CESM) over Antarctica is used here, balancing the extensibility of a GCM with the high computational costs of a high-resolution climate model. Here, we nest a higher resolution grid (0.25°) over the larger Antarctic domain within a coarser-resolution global grid (1°). The setup uses forced sea surface temperature and sea ice concentration (as with the Atmospheric Model Intercomparison Project, AMIP).
Following a historical run (1979-2015), a baseline scenario was run from 2015-2021, including SSP3.7 atmospheric forcing and moisture-tagging. This period includes the 2017-2018 anomalous Antarctic sea ice minimum. Based on these results, we conduct focused experiments compare the baseline scenario to cases where sea ice concentration and sea surface temperatures are altered to test the sensitivity of snowfall and atmospheric rivers to these drivers.

Surface melt on the Larsen C Ice Shelf: An AMSR-2 dynamic thresholding technique informed by microwave radiative transfer modeling

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Surface melt on ice shelves has been linked to hydrofracture and subsequent ice shelf breakup. In this project, we focus on the Larsen C ice shelf, the largest ice shelf on the Antarctic Peninsula. Since the 1990s, scientists have been using microwave radiometers to track the appearance of melt on the surface of the Larsen C and other ice shelves and ice sheets. Since surface melt triggers a spike in microwave brightness temperature, thresholding algorithms have been used to determine when and where melt occurs on ice sheets and ice shelves. These algorithms detect melt when brightness temperature or a related parameter exceed a fixed value, which is often determined based on averaging brightness temperatures across the dry season. However, this technique is imperfect as microwave brightness temperature also fluctuates in response to changes in snow temperature, density, and microstructure. In our technique, we create a dynamic thresholding algorithm to account for these effects by modeling the radiative effects of changes in snow temperature, density, and microstructure. First, assuming no melt across our time series, we combine the Community Firn Model, Snow Microwave Radiative Transfer (SMRT) framework, and Advanced Microwave Scanning Radiometer 2 (AMSR-2) brightness temperatures (18 GHz v-pol) to back out correlation length, a component of snow microstructure. Second, we remove abnormally low correlation lengths that occur during austral summer, indicating they likely do not fit our requirement for no melt. Third, we place a median filter to generate a correlation length function across the full time series. Forth, we assume zero liquid water (dry) and use the Community Firn Model, our derived correlation lengths, and SMRT to model brightness temperature (18 GHz v-pol). We compare these modeled brightness temperatures to AMSR-2 to determine melt and non-melt days for these point locations. Finally, we compare the results of this dynamic thresholding technique with that of a fixed thresholding method.

Deciphering Basal Thermal Conditions with Ice-penetrating Radar and Ice Sheet Modeling

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Sea-level rise estimates rely on accurate model projections of ice mass loss from Antarctica. However, ice sheet models lack sufficient observational constraints in critical parts of the ice sheet, including the difficult-to-observe ice-bed interface. An important, but largely unconstrained condition is the thermal state at the ice-bed interface, which affects the onset of sliding and ice thermo-frictional feedback mechanisms. Here, we use a combination of numerical simulations and ice-penetrating radar analysis to investigate how basal thawing could influence the Antarctic ice sheet's evolution over 100 years. We show that some parts of Antarctica could start to contribute to mass loss – up to as much at 20 Gt/yr in Wilkes Basin and the George V Coast – if certain patches of frozen bed near the ice sheet margin were to thaw. This suggests that it is critical to know the basal temperature in these localized frozen bed patches near the ice sheet margin. We utilize the radar signal sensitivity to changes in basal thermal state and combine radar bed reflectivity and englacial attenuation to add constraints on where the bed is likely frozen, thawed, or thawable. We compare the radar derived basal thermal constraints to Ice-sheet and Sea-level System Model (ISSM) simulations to show what patches of the bed could be sensitive to thawing, and what regions could become new loci of mass loss as a result of basal thawing.

PSECCO: A New Community Office for Supporting Early Career Scientists and Advancing Equity and Inclusion in the Polar Sciences

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While the polar sciences offer unique opportunities for international, transdisciplinary research as well as connections with Indigenous knowledge systems, the US polar science community remains unrepresentative of the diversity of the country itself. While there are many reasons for the lack of diversity, including those familiar throughout STEM fields as well as the explicit historical exclusion of certain groups in polar science specifically, early career scientists in the polar community are driving efforts to broaden participation in polar research. The newly launched Polar Science Early Career Community Office (PSECCO) seeks to empower, elevate and give agency to the early career polar scientists who are leading the charge to make the polar sciences more welcoming, inclusive and diverse. The office will foster community among early career polar scientists, provide funding, training and travel opportunities, partner with other organizations to share opportunities, resources and support leadership development, while working together towards a more just, inclusive, diverse, equitable and accessible polar science environment. Launched early in 2022, we invite all current and future polar scientists to join PSECCO in building community together.

New coastal Antarctic geochemical constraints from ice core subsamples at Mt. Murphy, West Antarctica

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The Amundsen Sea coastline of the West Antarctic Ice Sheet (WAIS) is a dynamic region with significant implications for future sea level contributions and the focus of study of the International Thwaites Glacier Collaboration (ITGC). The Geological History Constraints (GHC) component of ITGC intends to collect information on past ice sheet behavior in the region using a range of geological and geochemical techniques. In the 2019-20 field season, a GHC team collected ice and rock samples from Kay Peak (75.2139ºS, 110.951ºW) near Mt. Murphy and Crosson Ice Shelf. Subsamples were opportunistically collected at 20 cm resolution from a 56 m ice core extracted while pursuing bedrock samples below; subsamples have now been analyzed for a range of geochemical species. Snow and ice core geochemistry is well known to reflect local-to-regional climate and environmental variability, and there is a paucity of such observations in this low-lying coastal region of WAIS. Although the Kay Peak location–proximal to a nunatak and sited for bedrock drilling–is not an optimal location for an ice core paleoclimate record, ice subsamples were collected and bottled at the site given the limited number of such observations available in the area.

In summer 2022, undergraduate researchers analyzed these subsamples for trace element chemistry (Na, Pb, Mg, Ca, Fe, K, Cu), water stable isotopes (δD and δ18O), and 10-Beryllium. Because of the complex snow and ice accumulation and deeper ice flow near nunataks, as well as the low sample resolution, establishing an age scale by counting annual layering and annual geochemical peaks is not expected. Variability of 10-Beryllium with time is known to be globally synchronized, hence this measure may establish an age scale for these unique ice samples from near Mt. Murphy. Trace element and water stable isotope data provide a range of well-developed climate and environmental proxies, and although our age control is likely to have limited resolution, these geochemical data can still be pooled and compared to other ice core geochemical data across West Antarctica. Mt. Murphy geochemical samples will be compared against similar data from ice cores including ITASE cores, Roosevelt Island, Bryan Coast, Ferrigno, and others, taking into account site elevation, climate, distance inland, and other parameters.

Even though these ice samples were collected opportunistically from a location suboptimal for ice core paleoclimate studies, they add to our spatial and temporal understanding of terrestrial Antarctic chemistry, climate and environmental conditions and particularly add valuable perspective from the Amundsen Sea region–one that is greatly undersampled with respect to surface snow chemistry and ice core records of past climate.

Antarctic subglacial precipitates record ice sheet response to millennial-scale Southern Ocean warming

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The response of the Antarctic ice sheet (AIS) to orbitally forced climate change on glacial-interglacial time scales is reasonably well characterized by offshore sediment records and model simulations. What remains poorly understood is how the AIS is affected by millennial-scale changes in Southern Ocean temperature. This study presents a compilation of U-Th age and isotopic compositional data (87Sr/86Sr, δ18O, δ13C) from both new and previously reported calcite and opal subglacial precipitates that formed beneath the periphery of the AIS. These U-Th dates from over 30 samples span 1 to ~500 ka and include locations across the continent. Carbonate precipitation from subglacial waters records the times when meltwater was present beneath the ice sheet margins. Isotopic data suggest that the meltwater originated beneath the polar plateau (δ18O <-50‰) while elevated 87Sr/86Sr and [234U/238U] water compositions indicate prolonged periods of rock-water interactions, possibly in subglacial lakes. Comparison between our U-Th dates and Antarctic climate records reveals a strong correlation between the timing of precipitate formation and Antarctic Isotopic Maxima (AIMs). We hypothesize that this correlation is due to Southern Ocean warming driving grounding line retreat, which induces ice acceleration that propagates upstream. The associated increase in shear heating dilates subglacial hydrologic systems, permitting infiltration of meltwater from the wet-based ice sheet interior towards AIS margins. This hypothesis implies that ocean forcing on millennial time scales strongly influences the Antarctic ice sheet, which will have implications for projections of future ice sheet behavior as ocean temperatures continue to rise.

Climatic and Structurally-Controlled Drivers of Melt on the George VI Ice Shelf, Antarctic Peninsula

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Across the Antarctic Peninsula, ice shelves have been experiencing both surface and basal melting that has contributed to their accelerated mass loss in recent decades. Rapid atmospheric warming since the mid-20th century has led to a proliferation of surface melt ponds on the ice shelves. The George VI Ice Shelf (GVIIS), in the Bellingshausen Sea sector, is an example of an ice shelf that experiences both surface and basal melting. GVIIS also experiences different climatic conditions on the northern and southern halves of the ice shelf. This is evidenced by the fact that the surface melt on GVIIS is concentrated mostly along the northern half of the ice shelf. The concentration of surface melting along the flow lines of the northern half indicates there could be a structural control to the surface melting as well. The ice flow structures that are so prominent on the northern side are largely subdued on the southern side.

In this work, we investigate the climate and structural controls on ice shelf surface melt on both sides of GVIIS. Using Landsat 7 and 8 imagery and the REMA DEM, we provide evidence that the flow lines provide structural control to channelize ice shelf surface melt. We use RACMO and ERA5 modeled parameters to identify the potential climate drivers of this concentrated surface melt on the northern half of the ice shelf, and analyze the reasons for the absence of surface melt on most of the southern half. We also use band analysis of Landsat 7 and 8 imagery to create lake masks across the area of interest and correlate lake coverage with modeled climate parameters. Identifying the relationship between climate and structural drivers of surface melt on the northern side of GVIIS will provide insights into how the surface melt area would expand with increased atmospheric warming. Future work will include investigation into linkages between surface and basal melt rates if the surface melt water reaches the base of the ice shelf via crevasses. This work is important because the surface melt water reaching the base of the ice shelf has the potential to influence basal melt rates.

Prolonged Pliocene warm period in Amundsen Sea sector from drill records of IODP Expedition 379 and seismic data analysis

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Major ice loss in the Amundsen Sea sector of the West Antarctic Ice Sheet (WAIS) is hypothesized to have triggered ice sheet collapses during past warm periods such as those in the Pliocene. International Ocean Discovery Program (IODP) Expedition 379 recovered continuous late Miocene to Holocene sediments from a sediment drift on the continental rise, allowing assessment of sedimentation processes in response to climate cycles and trends. Via seismic correlation to the shelf, we interpret massive prograding sequences that extended the outer shelf by 80 km during the Pliocene through frequent advances of grounded ice. Buried grounding zone wedges indicate prolonged periods of ice-sheet retreat, or even collapse, during an extended mid-Pliocene warm period from 4.2 to 3.2 Ma inferred from sediment cores and physical property records of IODP Expedition 379. These results indicate that the WAIS was highly dynamic during the Pliocene and major retreat events may have occurred along the Amundsen Sea margin. The extended warm period inferred from our study falls into a period of Pliocene sea-level highstands from 4.39 to 3.27 Ma, but occurred earlier than the so-called Mid-Pliocene/Piacenzian Warm Period. The enormous shelf growth in the Amundsen Sea Embayment, interrupted by long periods of glacial retreat, indicates that this drainage sector of the WAIS was highly dynamic in the Pliocene, likely acting as precursor to phases of partial or complete WAIS collapse since the establishment of a continent-wide ice sheet.

A Bayesian Modeling Approach to Quantify the Role of Suspended Sediment-Rich Meltwater in Antarctic Glacimarine Sediment Formation

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Meltwater plays a major role in the dynamics of grounded ice, yet quantification of its influence on paleo-ice is limited by accessibility to glacial environments. This limitation requires us to utilize alternative proxy methods of analysis and measurement to study the influence of meltwater. Glacial sediments provide insight into meltwater dynamics and past climatic conditions and can be used as a proxy for predictive models. Flocculation of fine sediment is pervasive in particle-rich nearshore fluvial margins, deltas, and meltwater-rich glacimarine environments. Floc abundance in the water column scales positively with the fluvial introduction of suspended sediment (SSC). Greater meltwater flux in temperate glaciers leads to downstream sorting of plume sediment with increased deposition of flocculated grains (flocs), whereas the lack of subglacial meltwater in polar glaciers results in decreased formation and deposition of flocs. This research uses sediment texture to determine how floc deposition can be recognized and quantified using grain size distributions and lithofacies. Curran et al. (2004) infer the flux of flocculated and single-grain sediment fractions to the seafloor with an inverse model developed by Kranck and Milligan (1985) applied to disaggregated grain size distributions (DIGS). Kranck's model proposes that abrasion of particles results in a Rosin-Rammler size distribution that can be described using a power-law formula. We quantify published grain size distributions from locations around Antarctica using a Bayesian approach by modeling the DIGS equation using Multichain Monte Carlo methods to determine the relative concentration of sediment deposited in flocs and as single grains (i.e., sortable silt, ice-rafted debris). Output of this model includes an estimate and uncertainty of the floc limit: the grain diameter for which the flux of mass to the seabed is equal for single-grain and floc deposition. Laboratory studies show coarser floc limits with higher suspended sediment concentrations, indicative of increased meltwater discharge. We hypothesize that more meltwater leads to increased floc formation (coarser floc limit), accumulation, and hydrodynamic sorting of single-grain silt sub-populations. This model is evaluated with published detailed lithofacies descriptions that can be used to control for terminus position on texture and develop predictive models.

The Polar Rock Repository: Samples and Data for Paleoclimate Research

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The Polar Rock Repository (PRR) is a National Science Foundation funded facility that provides online access to rock samples, unconsolidated glacial deposits, terrestrial cores, marine dredge samples, metadata and an image archive from Antarctica and surrounding areas. More than 59,000 physical samples are available as no-cost loans for research, including destructive techniques.

The collection contains Cenozoic samples from > 3200 sedimentary from the Sirius Group in the Transantarctic Mountains and the glacial tills around the Dry Valleys. The PRR has >5400 samples from the exposed Cenozoic volcanoes on the continent. In addition, a unique collection of sub-ice basal pebbles from the West Antarctic ice-streams is available. Dredge samples from the margin of the Ross Ice Shelf provide an opportunity to assess the frequency and characteristics of volcanic clasts derived from the Marie Byrd Land dome and the base of the WAIS.

The online database includes information useful to paleoclimate studies by noting locations with weathering salts/calcite skins, Fe-oxide staining, biological features, soil residues, inclusions etc., and include these as searchable criteria in the database. The dredge collection includes samples with corals and marine plants from known depths, collection dates and coordinates. The PRR has created an image/movie archive (with some images dating back more than 60 years) that provides logistical, geological, and glaciological information as well as recording surface features (ponds, icebergs, streams etc.) reflecting environmental changes.

Researchers may search for samples on the PRR website using multiple search criteria. Map layers (REMA, USGS, SCAR geology) are available to facilitate searches. The PRR uses the UMN Polar Geospatial Center Antarctic Viewer to locate samples. Search results can be viewed as a table or thumbnail, downloaded as a spreadsheet, plotted on an interactive map and/or placed into a ‘shopping cart’ for loan requests. Destructive techniques can be used on requested samples.

Coupled ice sheet-sea level modeling for improving projections of Antarctic Ice Sheet's contribution to sea-level change: simulation results following the new ISMIP6-2300 experimental protocol

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Sea-level changes following ice mass changes are geographically variable and feed back onto dynamics of the marine-based West Antarctic Ice Sheet (WAIS), which are sensitive to ocean depth. For example, sea level falls in response to ice mass loss because it causes the regional uplift of the solid Earth and drawdown of the gravitational equipotential surface on which sea surface height lies. This fall in sea level in turn has stabilizing effects on the WAIS (so-called "sea-level feedback"). However, none of the ice-sheet models that participated in the recent Ice-Sheet Model Intercomparison project for CMIP6 (ISMIP6) used by IPCC AR6 incorporated sea-level feedback in their projections.

In this presentation, we couple the US Department of Energy's MPAS-Albany Land Ice model (MALI) and a global 1D sea-level model that can capture the interactions between ice sheets, solid Earth and sea level. We then perform coupled ice sheet – sea level simulations of Antarctica using the centennial-scale climate forcings until 2300 CE provided by the recently released ISMIP6 protocol. We also introduce a new workflow that re-extrapolates ocean thermal forcing (temperature and salinity) into ice-shelf cavities in the ISMIP6 protocol based on regionally varying ocean bathymetry calculated by the sea-level model. This will allow us to investigate the impact of regional sea-level changes on ice-shelf basal melt rates. Our preliminary results indicate that regional sea-level fall associated with ice-sheet melting will lead to a non-negligible reduction in mass loss from the Antarctic Ice Sheet over the coming centuries, both directly due to the stabilizing effects on ice dynamics and indirectly due to a reduction in basal melt rates.

Accounting for ice-shelf damage in rheology and calving laws reproduces observed changes and amplifies projected 21st century mass loss

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The continued retreat of Thwaites Glacier, West Antarctica, is likely to substantially increase global sea level over the 21st century. Recent observations and modeling suggest that the Thwaites Eastern Ice Shelf could completely fragment within a decade, after which retreat of the glacier becomes highly uncertain due to uncertainty in calving processes. Here, we use the three-dimensional, higher-order, thermomechanically coupled MPAS-Albany Land Ice model to evaluate the ability of various calving parameterizations to reproduce the observed changes across the ice shelf from 2015 to 2020. We then simulate the evolution of the glacier through the 21st century using the validated calving parameterizations and SSP5-8.5 climate forcing. In all simulations, we calculate time-evolving ice shelf damage based on the plastic necking approximation that relates crevasse growth to ice dynamics and climate forcing, and we explore the effect of coupling damage to ice rheology in a subset of simulations.

We find that the commonly used eigencalving parameterization produces unphysical variability in calving rates across different parts of the ice shelf. A calving parameterization based on the tensile von Mises stress does a reasonable job of reproducing observations, but fails to remove heavily damaged ice in projection runs unless damage is coupled to ice rheology. If damage is not coupled to rheology, it is necessary to simultaneously employ the von Mises tensile stress calving parameterization and a damage threshold calving criterion.

In control simulations with fixed calving fronts, coupling damage to rheology increases the sea-level contribution by 46% by 2065 relative to the simulation without damage-rheology coupling. Adding the calibrated von Mises stress and damage calving parameterizations in the uncoupled case leads to 30% higher sea-level contribution by 2100 than the control run. Including calibrated calving leads to 25% more sea-level contribution by 2065 than the associated control run. The calving-enabled simulations agree that the ice shelf will unpin from the eastern pinning point within the next decade, but they also predict that Thwaites Glacier will retain a sizable ice shelf as the grounding line retreats. Thus, it is essential to incorporate time-evolving ice-shelf damage and calving in projections of Thwaites Glacier. However, a better understanding of both calving and damage is necessary to reduce uncertainty in sea-level rise from Thwaites Glacier this century.

Radar attenuation demonstrates advective cooling in the Siple Coast ice streams

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Ice-streams are warmed by shear strain, both vertical shear near the bed and lateral shear at the margins. Warm ice deforms more easily, establishing a positive feedback where fast flow leads to warm ice and then to even faster flow. Here, we use radar attenuation measurements to show that the Siple Coast ice streams are colder than previously thought which we hypothesize is due to along-flow advection of cold ice from upstream. We interpret the attenuation results within the context of previous ice-temperature measurements from nearby sites where hot-water boreholes were drilled. These in-situ temperatures are notably colder than model predictions, both in the ice streams and in an ice-stream shear margin. We then model ice temperature using a 1.5-dimensional numerical model which includes a parameterization for along-flow advection. Compared to analytical solutions, we find depth-averaged temperatures that are colder by 0.7°C in the Bindschadler Ice Stream, 2.7°C in the Kamb Ice Stream, and 6.2-8.2°C in the Dragon Shear Margin, closer to the borehole measurements at all locations. Modelled cooling corresponds to thermal strengthening by 3-3.5 times compared to the warm-ice case, suggesting some other weakening mechanism in ice-stream shear margins, such as material damage or ice-crystal fabric anisotropy.

Rapid uplift bedrock uplift may slow retreat of Thwaites Glacier by decades over the coming centuries

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Viscoelastic rebound of the solid Earth due to the removal of ice loads has the potential to delay marine
ice sheet retreat through a reduction in local sea level that translates the grounding line downglacier. Anomalously low mantle viscosity in West Antarctica may lead to substantial viscoelastic uplift on the order of decades or years rather than centuries, but the impact of this on marine glacier evolution is poorly understood. In this study, we assess the impact of solid-earth rheological structure on model projections of the retreat of Thwaites Glacier, West Antarctica, and the associated sea-level rise contribution by coupling the dynamic ice-sheet model MALI to the regional glacial isostatic adjustment (GIA) model giapy. We test the sensitivity of 500-year model projections of ice-sheet retreat to four solid-earth rheologies, forced by a standard ISMIP6 ocean and atmospheric dataset for the RCP8.5 climate scenario. For the mantle viscosity best supported by observations, the negative GIA feedback slows grounding line retreat after 500 years by 137 years and reduces mass loss to the ocean by 19% relative to control simulations without GIA. For the weakest plausible but unlikely solid-earth rheology, the delay in glacier retreat after 500 years is 263 years and mass loss reduction reaches 72%. At the same time, we estimate that water expulsion from the rebounding solid Earth beneath the ocean near Thwaites Glacier may increase the Thwaites Glacier sea-level rise contribution by up to 20% after 500 years, partially counteracting the negative GIA feedback to glacier evolution. Although limited constraints on solid-earth rheology lead to large uncertainty in future sea-level rise contribution from Thwaites Glacier, under all plausible parameters for this region the GIA effects are large enough to be important to include for future projections of Thwaites Glacier of more than a century.

Understanding the Rheological Properties of Firn through Laboratory Compaction Experiments

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There is currently little experimental knowledge of firn densification and its rheological properties. Understanding and modeling how rapidly firn compacts into ice is fundamental to our ability to measure present-day changes in ice sheets and past climate conditions. Compaction at densities between 550 and 830 kg/m3 occurs via grain sintering and the final stage, beginning at 830 kg/m3, occurs after bubble close-off. However, density transitions due to pressure sintering of firn are not well understood; with transitions occurring in four stages. We can express the uni-axial strain rate of compacting firn as ε'_z=G(ϕ) σ_z^n F(T,r); where σ_z^n is vertical axial stress, G(ϕ) is some function that depends on porosity, and F(T,r) is a function that depends on temperature and grain size. To obtain data and constraints on the mechanics of the compaction process (namely, G(ϕ)), we have conducted a suite of temperature controlled, uni-axial compaction experiments on dry firn samples. Our samples are syntheic firn, that we create by sieving pure ice grains to 210 – 500 µm. Experiments were conducted at constant temperature, in the range -20°C to -2°C, and constant axial stress in the range 0.3 MPa – 3.4 MPa. We also performed microstructural analysis of compacted samples by obtaining images under an optical microscope. Microscopic images reveal numerous features related to strain (slip planes, sub-grain boundaries, and pore closure). We also observed distinct, ringed deformation features that surround pores and triple junctions, either in smooth concentric or rough wave-like patterns. We have investigated the possibility that these deformation rings are caused by pressurization of pores after close-off. As pores close off and decrease in volume during densification, increases in pore air pressure will lag behind bulk pressure and can be represented as a difference between the applied axial stress and the pore pressure. Further microstructural analysis and pore closure studies are needed to constrain the source of these and other deformation features and better understand the material properties of compacting firn at variable stress, so that natural cores can be examined and interpreted for deposition, burial, and recrystallization.

Basal properties of the WAIS from inverse modeling including effective pressure

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The distribution of basal drag underneath the ice sheets is difficult to observe directly. However, it has a strong influence on ice flow speeds and is important for making realistic projections of future ice sheet behavior. To obtain this needed information for our models, one possible way is to use inverse methods. They are based on optimal control approaches with adjoint equations and can be used to estimate the basal friction parameter by fitting model output to observations of surface velocity.

Here, we conduct the inversion approach within the ice-sheet and sea-level system model ISSM in order to determine the basal friction parameter for the West Antarctic Ice Sheet region. We employ a non-linear sliding law acting beneath the ice sheet. To achieve more realistic results, we include into this sliding law the effective pressure simulated using a subglacial hydrological model, the confined-unconfined aquifer system model CUAS. We present the resulting friction parameter distribution and analyse its spatial variability. This will be the basis for further ice sheet model simulations in the West Antarctic region focusing on the elevation change. We hope to increase the exchange between field observation and modeling on the basis of this study, as we cannot perform realistic simulations without the observed data.

Modeling the Processes that Determine the Propagation Paths of Ice-Shelf Rifts

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Rifts are full-thickness fractures in ice shelves. The lateral propagation of rifts can cause ice-shelf weakening and lead to calving of tabular icebergs. In this study, we investigate how the path of rift propagation is influenced by the pressure on rift flank walls from seawater, ice mélange, and contact between flanks. We develop a scheme that incorporates these boundary conditions at runtime within a shallow-shelf, anisotropic damage model that captures rifting. As a test case, we simulate the rift propagation that preceded the calving of iceberg A68 from the Larsen C Ice Shelf in 2017. We demonstrate how the simulated rift path changes in response to varying the thickness and rigidity of ice mélange within the rift, as well as the extent of contact between rift flanks near the rift tip. Simulations with realistic combinations of parameters yield rift paths that match observations closely.

Seismic signals from the Eastern Shear Margin of Thwaites Glacier

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Understanding the stability of Thwaites Glacier, part of the West Antarctic Ice Sheet (WAIS), is a critical science challenge of global relevance. The future evolution of ice flow in Thwaites Drainage Basin is likely influenced by dynamics at its shear margins. To investigate the processes influencing Thwaites' shear margins, the Thwaites Interdisciplinary Margin Evolution (TIME) project set up two geophysical ice observatories at the Thwaites' Eastern Shear Margin. The ice observatories are designed to produce new and comprehensive constraints on englacial properties, including ice deformation, ice fabric, ice viscosity, ice temperature, ice water content, and basal conditions. From January 2020 to January 2022, the two observatories included passive seismic recording on fourteen broadband seismic stations. The network includes two hexagonal arrays, each with 7 broadband seismometers spaced at ~5-km (6 stations in a hexagon plus one in the middle). In this presentation, we provide an overview of these new seismic data at Thwaites' Eastern Shear Margin, including a summary of various seismic analyses that are ongoing. We detect and locate icequakes with these networks, using classical short-term-average/ long-term-average techniques for local phase arrival detection as well as machine learning approaches. We further investigate possible causes of the observed seismicity, such as crevassing, calving, or basal stick-slip events. We also look at other seismic signals recorded by the network and the implications of those observations for understanding processes and evolution at Thwaites' shear margins. Finally, we discuss the role and contributions of the passive seismic data in planning for future controlled-source seismic surveys at Thwaites Eastern Shear Margin.

Climate Variability as a Major Forcing of Recent Antarctic Ice-Mass Change

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The link between recent ice mass change and large-scale modes of climate variability is not well understood. Shorter-period mass variability has been partly associated with El Niño Southern Oscillation (ENSO) both for the grounded ice sheet and its bounding ice shelves, but the connection with the dominant climate mode, the Southern Annular Mode (SAM), is not clear. We show that space gravimetric (GRACE) estimates of non-linear ice-mass change over 2002-2021 may be substantially explained by a simple linear relation with both SAM and ENSO. We decompose the detrended GRACE time series using empirical orthogonal functions and show that the principal components are dominated by decadal variability that correlate closely with detrended, time-integrated SAM and ENSO indices. Multiple linear regression reveals that SAM and/or ENSO explain much of the inter-decadal variability from the whole ice sheet down to individual drainage basins. We find about 40% of the net whole-of-ice-sheet change (2002-2021) can be ascribed to increasingly persistent positive SAM forcing. We also show that satellite altimetry (1992-2020) shows a very similar spatial pattern of ENSO and SAM in ice elevation but with great spatial resolution. We discuss the roles of atmospheric and ocean forcing in these observations. Given the prominent role of SAM we identify, understanding the forcings of SAM variability over the geodetic period, which is largely anthropogenic over multi-decadal timescales, may be a pathway to partially attributing ice-sheet change to human activity. Assuming the relationship to SAM and ENSO hold over other timescales, accurate projection of the future of the ice sheet will require climate forcing which accurately represents the evolution of SAM and, for very near-term projections, ENSO.

Decadal-scale oscillations in ocean-temperature reconstructed from geochemical ratios of pre-modern corals on the Ross Sea continental shelf

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Upwelling of Circumpolar Deep Water (CDW), a relatively old and warm water mass, is currently causing sub-ice melting which is driving thinning and a lessening of the ice-shelf buttressing effect. Other than direct observations, there is a paucity of evidence indicating the pre-modern history of upwelled CDW on the Antarctic margins. Here, we report from our ongoing analyses of three corals (Flabellum flexuousum and F. impensum species) recovered from the Ross Sea continental shelf which build on previous deep and cold-water coral studies (e.g., Stewart et al., 2010). We generated a preliminary temperature record from geochemical ratios on a LA-ICP-MS at LSU. Specimen RS15-D52-SC2 is ~3 cm long, and has been radiocarbon dated to ~2600 ka (uncorrected). Top and bottom dates indicated a lifespan of ~90 years. A total of 26o laser-ablation spots equates to temporal sampling of ~ 4 months. Li/Ca, Mg/Ca and U/Ca show cycles with an apparent periodicity of ~30 years. Specimen RS15-D23-04 has one radiocarbon age of ~1360 ka (uncorrected) whereas specimen USNM 47361 was alive when collected. On the basis of published Li/Mg temperature calibrations (Case et al. 2010; Montagna et al. 2014; Cuny-Guirriec et al. 2019; Stewart et al. 2020), our Li/Mg suggest Ross Sea continental shelf ocean temperatures oscillated between -3.5 to 6.5°C. Today, Amundsen Sea ocean temperatures range between -0.5 to 2°C, which suggests that our high-end temperature estimates are not reliable.

Using benthic microfaunal communities to constrain oceanographic influence on the stability of Thwaites Glacier, Antarctica

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To best predict the stability of Antarctic glaciers and their contribution to rising sea level, it is imperative that we reconstruct and compare with glacial retreat rates in the past and further study the drivers of retreat on different time scales. To study oceanographic influence as a driver of past retreat for Thwaites Glacier, we employ a paleo-ecological tool in sediment cores offshore the rapidly retreating ice front, and specifically study benthic populations of single-celled protists, called foraminifera, where relatively warm Circumpolar Deep Water (CDW) has been observed. Modern populations and their ecological affinities to water masses in the Amundsen Sea can be used as a tool to interpret foraminiferal assemblages within older intervals of seafloor sediment, providing a measure for oceanographic drivers of Thwaites Glacier retreat over the last 10,000 years.

While foraminiferal populations have been studied in different water masses along the Antarctic Peninsula (e.g., Ishman and Domack, 1994), they have not yet been studied in the Amundsen Sea within this oceanographic context. Here we present the relationships of living foraminifera with sediment conditions of the seafloor and with water properties (temperature, salinity, nutrients) measured by the International Thwaites Glacier Collaboration's (ITGC) Thwaites Offshore Research (THOR) team during the 2019 field season aboard the RV/IB *Nathaniel B. Palmer* (NBP19-02). Samples range in water depth from 467 to 1138 m and were collected in CDW, modified CDW, and cold shelf water where CDW was not present.

Results suggest that foraminiferal populations can "fingerprint" water masses in the Amundsen Sea. With principal component analysis, the foraminiferal assemblages vary with presence of CDW, mCDW, and cold shelf water. While the main explanation of variance in the dataset is test composition of the foraminifera, the second is water temperature. Temperature variance is specifically observed in populations from the mCDW near the Thwaites Eastern Ice Shelf, which differ from areas influenced by meltwater mixing with mCDW in between Pine Island and Thwaites Eastern ice shelves, as well as from near the outflow at the Thwaites Ice Tongue as described in Wåhlin et al. (2021). Ongoing research further explores the effects of sediment composition, sedimentary environment, and available nutrients on foraminiferal populations. The THOR team will apply foraminifera assemblages as a proxy in sediment cores to reconstruct past oceanographic conditions near Thwaites Glacier over the Holocene.

Subglacial processes inferred from grain-shape alteration of till and meltwater plume deposits from Antarctica and Greenland

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An increasing number of studies from polar regions has identified a unique grain-size distribution associated with meltwater plume deposits. These fine-silt and clay-rich deposits are relatively well-sorted, distinguishing them from other glaciogenic sediments, often with little to no evidence for sorting by oceanic processes (e.g. current winnowing). Consistencies in grain-size modes and geochemistry between meltwater plume deposits and tills indicate a shared subglacial source. Yet, it is unclear how meltwater deposits are produced from tills, and whether grain-scale characteristics of plume deposits can reveal insight about subglacial processes that cannot be captured by remote sensing and geophysical observation. We examine dimensionless metrics (e.g. circularity, solidity, aspect ratio) of grain shapes from Holocene-age meltwater plume deposits offshore Antarctic and Greenland glaciers and compare those metrics against tills from formerly glaciated continental margins from the same glacier catchments. We observe quantifiable differences between till and meltwater plume populations in all metrics considered, indicating variations in sediment transport histories. Till and diamicton, which shares sedimentological properties with till but includes ice-marginal deposits, from all regions exhibit a wider variability in grain shape relative to their meltwater counterparts, suggesting meltwater-related sediment transport acts to homogenize grain morphologies. Additionally, Greenland meltwater plume deposits demonstrate significantly greater alteration from their subglacial origins compared to those from the Antarctic, which show nearly identical shape distributions across all regions considered. Ongoing work to integrate scanning electron microscopy of select Greenland and Antarctic plume deposits will determine whether observed differences in grain form are also marked by distinct microtextural differences. These findings support the application of grain and sub-grain characteristics to help distinguish sediment origin and transport history in facies models, and infer that subglacial hydrologic transport results in measurable grain alterations for glacial systems with different lithologies, glacial histories, catchment sizes, and meltwater production rates.

Mapping of Traveling Velocity Waves over Thwaites Glacier with Sentinel-1

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Mass loss at a glacial calving front drives acceleration and subsequent thinning upstream, signals that can propagate as traveling velocity waves through the glacier. With the recent influx of temporally dense, high spatial resolution remote sensing data we now can observe on scales that capture the propagation of these velocity waves. We process Sentinel-1 observations over Thwaites Glacier, from 2015 through 2022, to get time-dependent surface velocity fields. We use these time-series to quantify the propagation speed (phase velocity) and decay length of velocity waves. Observable properties of these velocity waves are determined by the mechanics of the ice-bed interface and therefore act as a unique measure of the spatial variations in the dynamics of Thwaites glacier. Preliminary results indicate that by fitting a wave model we can constrain values for attenuation length scale, phase velocity, and frequency across sections of Thwaites. Using a reduced model of the dynamic response of the glacier to stress perturbations, we relate these observables to the parameters in Glen's Flow Law.

Bathymetry and Geology model of the Venable Ice Shelf from Operation IceBridge (OIB) Airborne Gravity and Magnetometer Data

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An understanding of continental shelf bathymetry, including sub-ice shelf bathymetry, is critical for determining the future stability of the Antarctic Ice Sheet and its influence on sea level rise. Beneath floating ice, bathymetry controls the circulation of ocean waters and ice-ocean interactions at the grounding line. In ice covered waters along the Antarctic coast, limited ship multibeam echo sounding and satellite mapping make bathymetry beneath ice shelves poorly known. In the Bellingshausen Sea Sector, the ice shelves are thinning considerably and experiencing grounding line retreat. The Venable Ice Shelf, while also experiencing significant thinning, is undergoing insignificant grounding line retreat. Between 2009 and 2017, NASA's Operation IceBridge collected an airborne gravity and magnetic dataset over the Venable Ice Shelf in an effort to map the bathymetry of the region and understand its behavior. Here we present a model of the bathymetry beneath the Venable Ice Shelf from an inversion of gravity anomaly data, in addition to a geology model of the region from combined gravity and magnetic data analysis. Our model reveals ~0.6 km to ~2 km deep troughs in front of the Williams and Wiesnet ice streams and east of Farewell Island, as well as ~1.5 km deep onshore basin beneath the ice sheet that stretches ~88 km from east to west south of the Fletcher Peninsula. In these deep pathways, our model shows that circumpolar deep water can potentially access to the grounding line unobstructed. At the grounding line, however, the bed slopes upward towards the continent or is mostly horizontal, which can stabilize its position and prevent retreat. In the Venable Ice Shelf region, three geological units distinguished by magnetic anomaly character were identified from gravity and magnetic data beneath the ice shelf, in addition to a sedimentary basin beneath the eastern portion of the Abbot Ice Shelf.

An idealized model of ice flow with subglacial water coupling

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Ice sheet models used to predict sea-level rise generally do not include detailed physics-based descriptions of subglacial hydrology. However, theory and observations suggest that ice flow and subglacial water flow are bidirectionally coupled: ice geometry affects hydraulic potential, subglacial water pressure modulates basal shear stress, and ice flow advects the subglacial drainage system. This coupling could impact rates of ice mass change, but remains poorly understood. For example, key open questions include: What are the relative time scales of ice and subglacial water flow? Which components of the coupling have the greatest impact on ice-sheet evolution? And, are active, time-evolving subglacial drainage systems likely to accelerate or decelerate ice loss? In this work, we take the initial steps towards tackling these questions by examining subglacial-water/ice-flow coupling using an idealized model. We combine a channelized subglacial hydrology model with a depth-integrated marine ice-sheet model, incorporating each component of the coupling discussed above. This yields a set of differential equations that we solve using a finite-difference, implicit time-stepping approach. We will describe the model and present the results of numerical experiments with one-way coupling between subglacial hydrology and ice flow, along with preliminary results from experiments using bidirectional coupling. We will discuss challenges associated with choosing appropriate boundary conditions and a sliding law, as well as present preliminary findings regarding the differing time scales of model components. This project aims to elucidate the role time-evolving subglacial drainage may have in ice-sheet change and help to improve how subglacial hydrology is represented in ice-sheet models.

Towards Geologic Realism in the Subglacial Environment through Geostatistical Simulation with Open-Source Software

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Geostatistical simulation is a powerful means for modeling geologic phenomena while reproducing geologic heterogeneity and quantifying subsurface uncertainty. This approach is widely used in oil and mineral exploration and could be similarly effective for modeling subsurface ice sheet conditions such as topography or geology. The creation of multiple realizations of subglacial topography could play a particularly important role in quantifying uncertainty in ice sheet models. However, existing geostatistical algorithms and software were developed for industry applications and were not designed to accommodate the size and complexity of glaciers and ice sheets. Furthermore, many existing software are not open-source or easily integrated with other analyses. To address these issues, we have developed GlacierStats, an open-source geostatistical Python package that is specifically designed for cryosphere applications. This package features geostatistical modeling functions and tutorials for accommodating large datasets, non-linear trends, variability in measurement density, and non-stationarity. In its current state, the tools and tutorials focus on the geostatistical simulation of subglacial topography. Nonetheless, these protocols could be used to model a variety of phenomena in glaciology.

#WAISworkshop

Antarctic Atmospheric Rivers in the Past and Future Climate

Ms Michelle Maclennan[1], Dr Jonathan Wille[2], Dr Jan Lenaerts[1], Ms Christine Shields[3], Dr Andrew Winters[1], Ms Rebecca Baiman[1], Mr Leonard Barthelemy[4], Dr Francis Codron[4], Dr Vincent Favier[2]

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Atmospheric rivers (ARs) are long, narrow bands of warm and moist air that travel poleward from the midlatitudes. While Antarctic atmospheric rivers (ARs) occur only ~3% of the time, they are a significant contributor to Antarctic surface mass balance: they contribute 10% on average, and more than 20% locally, of Antarctic precipitation each year. Here we use an Antarctic-specific AR-detection algorithm developed by Wille et al. (2021) to identify ARs in MERRA-2 and ERA5 reanalyses and the Community Earth System Model version 2 (CESM2). We use this algorithm to quantify the frequency, location, and precipitation attributed to Antarctic ARs for the period 1980-2014 and use these factors to identify CESM2 biases compared to MERRA-2 and ERA5. We then apply the AR-detection algorithm to CESM2 for the future period (2015-2100). Focusing on the West Antarctic Ice Sheet, we examine how the frequency and intensity of ARs, AR-attributed total precipitation, and year-to-year variability in AR precipitation changes in future climate scenarios. Our results quantify the past and future impacts of ARs on Antarctic annual precipitation, interannual variability, and trends, and ultimately provide an early assessment of future AR-driven changes in Antarctic surface mass balance.

Wille, J. D., Favier, V., Gorodetskaya, I. V., Agosta, C., Kittel, C., Beeman, J. C., Jourdain, N. C., Lenaerts, J. T. M., and Codron, F. (2021). Antarctic atmospheric river climatology and precipitation impacts. Journal of Geophysical Research: Atmospheres, doi: 10.1029/2020JD033788

Behavior of Ice During Pulsed NIR Laser Cutting

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Scientific questions from continuous ice core records often require additional ice samples from targeted depths: large-volume sampling of microbial communities identified by fluorescence spectrometry probes, trapped gases or insoluble atmospheric compounds of a specific age, or simply to patch breaks in a larger core record. Near-infrared laser light, efficiently carried down an existing borehole by optical fiber, offers a uniquely compact and zero-force tool for excising samples from a sidewall. This promises an unprecedented ability to retrieve new samples of ice in a lightweight, maneuverable, and fast-deploying remote field system.

To optimize laser pulse parameters--a technique long used in industrial laser machining to remove material without excess heating--and better understand how ice behaves under machining, an effective method is required of monitoring ice-laser interactions in situ. Observations of cavity formation over time have been made using ~5 cm, visually clear tap-water ice samples combined with a dark field lighting method. Static-position drilling tests with a 500 W 1070 nm fiber laser, semi-collimated to a 1 mm spot and modulated at a fixed frequency, show a conical hole front which advances at least 0.35 mm per 3 ms pulse, and farther with increasing pulse durations; however, small samples show an increased risk of thermal cracking when pulses exceed 10 ms. Slot cutting tests indicate that cut depth can be adjusted with pulse duration, frequency, and scan speed. Ongoing investigations, as well as potential next steps, will be discussed.

Estimation of Englacial Attenuation and Basal Reflectivity Using Off-Nadir Radio Echo Sounding

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Knowledge of the bed conditions below glaciers is critical to development of ice sheet models and, thus, to improved projections of sea level rise. As high-density direct observations of basal conditions are not practical, airborne radio echo sounding (RES) is a useful tool for investigating the properties of the ice-bed interface at large spatial scales. The return power of basal echoes can be used to infer thermal conditions at the bed, with brighter and weaker echoes indicating wetter and drier conditions, respectively, as well as englacial attenuation and basal roughness. However, using only the nadir returns gives rise to ambiguity in the estimation of these parameters, as all have an impact on the returned power. Previous studies have used 2D spatial correlation of basal echo power and ice thickness to estimate englacial attenuation, while others have employed layer tracking methods. However, the former uses basal echoes from a large spatial footprint to estimate attenuation, and the latter assumes a spatially invariant reflectivity of a tracked layer. Here, a method for the estimation of englacial attenuation and basal reflectivity from unfocused radargrams is proposed which utilizes the drop in power from peak to tail of the hyperbolic event associated with a scatterer at the bed. Thus, these off-nadir returns can be used to estimate the relative englacial attenuation by comparing the observed return power and the path length in the ice. Further, analyzing the echo characteristics, such as echo width, of the bed returns can be used to constrain the scattering function of the bed. Combining the results of the echo characteristic and path length dependent power drop-off analyses allows for the estimation of basal reflectivity, scattering function, and englacial attenuation. We apply this technique to data collected with the British Antarctic Survey's Polarimetric-radar Airborne Science Instrument (PASIN) over the eastern shear margin of Thwaites Glacier. This location was selected as constraining the hydrological conditions at the bed, as well as identifying expected englacial thermal anomalies, is of particular interest to understanding the history and projecting the future of Thwaites Glacier.

Microseismic Events on the Ross Ice Shelf and Identifying Ocean Swell Controlling Mechanisms

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Cryoseismic events observed across the Ross Ice Shelf (RIS) are attributed to many dynamic fracturing and strain processes coupled to the environment that span from the grounding line to the shelf terminus. To monitor these sources and better understand their elasto-gravity wave propagation, a broadband seismic deployment of 34 seismic stations across the RIS continuously collected data at a high-sampling rate (100 and 200 s/s) between 2015-2017 (e.g., Bromirski et al., 2015). Interpretations of these seismic data paired with satellite imagery and other constraints have identified multiple seismogenic phenomena related to rifting, fracture, calving and flexure of the ice shelf induced by oceanic forcing, including tidal, infragravity, and ocean swell. Trapped extensional Lamb waves from multiple sources are commonly observed in these data, generally originating near the shelf front and propagating landward through the thin elastic ice shelf in the form of flexural-gravity waves and Lamb waves (e.g., Chen et al., 2018). In addition, seaward-propagating long-period Lamb waves excited by tidally triggered slow seismic events at the Whillans Ice Stream induce far-field cm-scale permanent translations in the ice shelf. Seismicity on shelf rift zones has been associated with tidally driven gravitational stress as the rising and falling tide alters ice shelf elevation and bending moment (Olinger et al., 2019). During summer periods of low sea ice extent, ocean swell (with periods of 8 to 30 s) generates micro-icequakes associated with wave impacts and fractures near the ice front. In spectral analyses, these stochastically swell-synchronized events create fundamental harmonics. Seismicity attributed to swell will be correlated with ocean state parameters to further investigate the hypothesized (Aster et al., 2021) controlling mechanism(s) of these signals, which arise from repeated and progressive swell-induced crevasse fracturing that occurs within a few kilometers of the ice front. Ocean state parameters, such as swell arrival azimuth, dispersion, period, intensity, strain, and duration, will be quantified for prominent storms (e.g., Hell et al., 2019, 2020) and interpreted in the context of the complete RIS/DRIS seismic event dataset.

Influence of Topographic Highs on Ice Flow as Determined by Streamlined Bedform Morphology

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Topographic highs ("bumps") across glaciated landscapes have the potential to temporarily slow or stabilize glacial ice flow or, conversely, increase ice flow through strain heating and subglacial meltwater production. Bumps of variable size across the deglaciated landscape of the Cordilleran Ice Sheet (CIS) in the Puget Lowland of Washington state present an opportunity to assess the influence of topographic highs on streamlined subglacial bedform morphology and, in turn, provide information on ice-bed interactions and ice flow around bumps in the subglacial environment. By assessing a single glacial system using high-resolution digital elevation models, results are not influenced by confounding variables that affect comparisons of different glacial systems such as local climate. This work utilizes two semi-automatic mapping techniques to identify and characterize streamlined subglacial bedform morphometrics including density, amplitude, elongation, and orientation. Subglacial streamlined bedforms are identified upstream, on top of, and downstream of nine bumps, indicating various ways in which bumps enhance, decrease, or maintain ice flow velocity and different organization at the ice-bed interface. Organization of sedimentary processes – fundamental to the genesis of streamlined subglacial bedforms – is variable downstream of the bump due to changes in sediment production and mobilization likely as a result of changes in sediment availability and subglacial meltwater production. Results from the deglaciated landscape in coastal Washington are being extrapolated to the subglacial topography across analogous parts of the contemporary Greenland Ice Sheet to infer the sensitivity of ice flow velocity to isolated topographic highs that are resolved through higher-resolution, machine-learned subglacial topography.

Enhanced Glacial Thinning and Retreat at an Ice-Cliff Terminus?

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Ice stored in the Greenland and Antarctic Ice Sheets largely flows to the ocean through fast-flowing outlet glaciers and ice streams. Most Antarctic ice flowing across the grounding line forms ice shelves, which provide buttressing that slows ice flow. Ice shelves are susceptible to melting and collapse, which has been observed to speed flow of non-floating ice and to expose grounded ice cliffs that retreat rapidly by iceberg calving, raising sea level. Most ice-sheet models informing the IPCC do not simulate coupled ice-shelf loss and calving-cliff retreat, in part because of difficulty in modeling the governing processes and/or parameterizing the physics involved in these transition regions. Some models use a "float-kill" approximation in which all ice crossing the grounding line is removed numerically, but this omits additional, potentially important stresses.

Many of the outlet glaciers in Greenland – including Helheim Glacier – have already lost their persistent floating ice shelves and now terminate in lightly grounded ice cliffs, where lack of support from an ice shelf causes a stress imbalance that reaches a maximum at the water line and increases with cliff height. Stresses within the ice compensate for the ice-front imbalance, so these internal stresses must also increase with cliff height. Ice deforms more rapidly under higher stress, with strain rate dependent on deviatoric stresses in all directions. To explore the impact of the additional stresses at an ice cliff on viscous thinning and retreat rates, we will compare rates for a Helheim-like ice cliff with results from the simplified float-kill approximation using the NASA-JPL Ice Sheet and Sea-level System Model (ISSM). Greater deviatoric stresses at an ice cliff should enhance rates of thinning to flotation and retreat, compared to the float-kill model. These results will ultimately help represent ice-cliff retreat more accurately in continuum ice sheet models to improve sea-level rise projections.

Time-dependent Strain-rate Fields Forecast Rift Propagation: Case Study on the Brunt Ice Shelf, Antarctica

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Full thickness fractures in ice shelves, known as rifts, propagate when there is sufficient energy to generate new surfaces. The energy available for rift propagation is a function of the stress state within the ice shelf, which is related to the observable strain rates through a constitutive relation, typically implemented as Glen's Flow Law. On the Brunt Ice Shelf, the recent propagation of multiple active rifts provides an excellent setting to improve intuition on the processes, drivers, and effects of rifts through the framework of the surface stresses. Here, we use remote sensing observations to estimate spatiotemporal variations in the strain rate and velocity fields, providing observational constraints on the rate of rift propagation and the intensification of stresses near the rift tip. Using the observational record of Sentinel-1A/B synthetic aperture radar, we are able to identify critical moments of rift development through derived strain rates prior to any optical indicators from imagery. This approach is a promising method to interpret the controls on rift propagation in a mechanistic framework, highlighting the benefit of strain rates as reliable inferences for changes on ice shelf surfaces. Deriving strain rates with high spatiotemporal resolution allows us to reliably forecast the location of rift propagation. This work provides a useful indicator for future dramatic changes on Antarctic ice shelves and emphasizes the utility of strain rate observations.

Impacts of Cyclic Effective Stress Loading on Basal Slip

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Cyclic time variant changes in effective stress at the ice-bed interface are common in glaciers and ice streams, through diurnal meltwater flux to the bed and tidal loading of grounding zones. For glaciers with deformable beds cyclic loading is hypothesized to change the thickness of the deforming till zone leading to alterations in till transport, increase of the grounding zone stability through progressive till consolidation, effects on basal drag, as well as altering a variety of other aspects that are integral to glacier slip. These hypotheses have significant ramifications for the long-term stability and dynamics of ice streams but lack an empirical basis as accessibility to glacier beds for direct measurements is limited. Prior experimental efforts have not examined cyclic loading on basal shear for deformable beds, instead focusing only on steady-state conditions. Using a large diameter cryogenic ring shear device, we slip temperate ice over a till bed under cyclic effective stress and monitor sediment transport and basal drag continuously. Drainage ports are located throughout the chamber walls and base, and pore pressure sensors are located above, below, and at the ice-bed interface to measure variable changes within the sample chamber. The outer walls of the cryogenic ring shear are made from clear acrylic, allowing for real time tracking of the shear band evolution through digital image correlation analysis. We conducted a series of sinusoidal cyclic loading experiments on tidal timescales under continuous velocity controlled basal slip. Temperate ice was sheared over saturated basal till at a rate of 100m/yr, and with effective stress amplitudes ranging from ~10kPa to ~40kPa on a diurnal period. Preliminary results show evidence for hysteresis between basal drag and effective stress. Here we report the response of variables such as sediment flux, basal drag, effective stress, and pore pressure in response to the cyclic loading.

Characterizing Bed Roughness on a Deglaciated Continental Margin and its Impact on Past Streaming Ice Flow

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The continental shelf of Antarctica reveals detailed glacial geomorphology that records late Pleistocene and Holocene ice-sheet behavior and its sensitivity to subglacial bed characteristics. Bed roughness (i.e., spatial changes in bed topography) can be used to infer basal processes yet it is often overlooked due to the poor resolution of subglacial bed topography. We utilize high-resolution bathymetry from the paleo-subglacial bed of the Pine Island-Thwaites ice stream to explore spatial variability of bed roughness in locations where streamlined subglacial bedforms allow for the determination of ice-flow direction.
The study sites are located in the inner- and middle-shelf of the eastern Amundsen Sea and contain diverse sets of glacial landforms and lithology, making them useful locations to assess and compare roughness. We quantify bed roughness parallel and orthogonal to dominant paleo-ice flow directions using Standard Deviation (SD) and Fast Fourier Transform (FFT) methods. Each method is employed at a local (1.6 km) and regional (7-40 km) scale, using different elevation detrending methods, to determine roughness expressions across scales and to explore patterns of roughness anisotropy relative to past ice-flow direction.
We find that topographic relief and transect orientation are the biggest controls on roughness, where the relief amplitude of streamlined bedforms correlates with roughness. Median roughness is higher for orthogonal transects across all sites, suggesting that roughness is modulated by glacial sedimentary processes (erosion and/or deposition) in the along-flow direction. The method and scale employed greatly impact resultant roughness, where values calculated at the regional scale are greater than values in the local scale and FFT results are more sensitive to abrupt changes in slope, resulting in distinct roughness peaks in areas of steep slopes. The SD method was also applied using bed topography from the BedMachine dataset; key differences include higher roughness values at the local scale in sites with rugged topography and higher median values for parallel transects.
Roughness anisotropy allows for identification of bedforms, such as glacial lineations, independently of the method and scale employed, highlighting its usefulness in isolation for determining patterns of streaming ice flow. This work supports the basal drag parameterization that allows for spatial variability in bed roughness in both the along- and across-flow orientations.

Statistical Generation of Antarctic Ice Shelf Basal Melt Realizations with Realistic Spatiotemporal Variability

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Basal melting of floating ice shelves fringing the Antarctic Ice Sheet (AIS) has been identified as a significant driver of uncertainty in sea level rise (SLR) projections. Part of this uncertainty derives from unpredictable internal variability in oceanic and atmospheric temperatures around ice shelves, in addition to poorly understood glaciological processes. However, quantifying this uncertainty with ensembles of climate and ice model simulations is prohibitively computationally expensive. Here, we develop and demonstrate a statistical technique that generates random realisations of basal melt rate projections which emulate a single long simulation from the Energy Exascale Earth System Model (E3SM) in a computationally efficient manner. This generation technique ensures spatially and temporally consistent variability, while also facilitating the sampling of a wide range of melt trajectories. Empirical Orthogonal Function (EOF) decomposition is used to emulate spatial variability fields, given that EOFs retain spatial correlation properties across the domain. The projection coefficients from the EOF analysis are then phase randomised to emulate temporal variability fields and generate reconstructed ensemble realisations of the basal melt trajectories. Each such ensemble member can be characterised as an independent realisation of the ice sheet model simulation output with variable thermal forcing. Once a statistical validation framework is set up, the goal is to integrate the generator within a large-scale ice sheet model for large ensemble simulations of the AIS under historical and future forcing scenarios to better quantify SLR uncertainty arising from the AIS.

Triangular Perspective on the alteration of Sea ice

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The Arctic regions are losing sea ice and their oceans are changing rapidly. The consequences of this transition extend to the whole planet. These regions will be profoundly different in the future compared to today, and the degree and nature of that difference will depend strongly on the rate and magnitude of global climate change. On this matter, sea ice has a significant addition and different characteristics compared to its freshwater counterparts such as glaciers. This presentation will cover the several interaction zones of sea ice that exist in polar regions. While Arctic sea ice reveals an overall declining trend in its extent, thickness, and age during the last decades, the sea-ice cover of the southern hemisphere has expanded on average. Moreover, the Antarctic-wide slight positive trend is composed of regionally opposing sea-ice changes, especially between East and West Antarctica. Although several studies suggest changes in the large-scale atmospheric and oceanic circulation patterns as the main drivers for the increase in Antarctic sea-ice extent and the strong regional sea-ice variability, the seasonal and inter-annual variability of snow and surface properties and thickness of Antarctic sea ice is rarely studied in this context. More than 80% of the ocean remains unexplored worldwide and it is difficult to protect what we don't know, only about 7% of the world's oceans are designated as marine protected areas. This presentation focuses on the model agreement with observations using various simple metrics that account for sea ice values and the regional distribution of sea ice. In addition, discussing biases in Antarctic sea ice that are common across multiple models as well as some recorded and research data basis drawbacks allow us to see the gap and form future field campaigns and research routes. An improved understanding of the seasonal cycle of dominant sea-ice in the Arctic and Antarctic is crucial for future investigations retrieving sea-ice variables from recent microwave satellite observations.

Potential triggers for the Larsen B fast ice break-up event and the initial glacier response

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In late March 2011, landfast sea ice formed in the Larsen B embayment that persisted until January 2022. In the eleven years of continuous landfast ice presence, the Larsen B tributary glaciers developed extensive mélange areas and formed ice tongues that extended up to 10 km from the 2011 ice fronts. Breakout of the landfast ice began January 19, 2022, immediately followed by retreat and break-up of the glacier mélange and ice tongue areas. The tributary glaciers have responded dynamically to changes in their stress regime in the past, such as in the disintegration of the Larsen B Ice Shelf in 2002. We investigate potential triggers for the loss of landfast ice in January 2022 and the upstream glacier response to the event.

We use ERA-5 climate reanalysis and passive microwave data to assess climate and melt anomalies on the landfast ice that occurred during the 2021/2022 season, and compare them to preceding summers with landfast ice present. The passive microwave data, AMSRE/2, indicate that 2021/2022 was not an exceptional melt season, suggesting the break-up event may have been due in part to the sustained long melt seasons in 2019-2020. AMSRE/2 sea ice concentration data reveals that January 2022 had the lowest sea ice concentration and the most open water in the northwestern Weddell Sea since 2010. Incorporating ocean wave data (wave height and frequency from WaveWatch III), we find that a significant wave event occurred on 18 January 2022, immediately prior to the break-out. Foehn winds initiated by an atmospheric river event were also present as the wave train arrived at the landfast ice front.

Examining the effect of the fast ice loss, we use ICESat-2, Worldview, Sentinel-1, and Landsat 8 and 9 data to estimate elevation and velocity changes of the glaciers in the months following the event. Initial assessment of the upstream glacier response indicates a speed-up of the tributary glaciers after the break-up event followed by lower speeds two weeks later. Our research indicates that the landfast ice, though relatively thin compared to the pre-2002 Larsen B Ice Shelf, provided sufficient backstress to limit glacier calving while still allowing termini to advance when present, and after its break-up, induced speedups and thinning of upstream glaciers.

Grounded icebergs in East Antarctica: Estimating water depth using ICESat-2 laser altimetry

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Icebergs that run aground on shallow banks on the Antarctic continental shelf can act as anchor points for development of landfast sea ice, which then affects ocean heat, freshwater and momentum exchanges with the ocean and may also provide additional buttressing to grounded ice flow. Spatial variability of iceberg groundings also provides information on bathymetry. A large database of icebergs, detected with a wide range of satellite sensors, exists; however, NASA's current ICESat-2 laser altimeter mission provides the highest along-track resolution combined with precise height determination. We identified Antarctic icebergs with ICESat-2 during October 2018 to March 2022, based on all ICESat-2 strong-beam data. For the George V Coast region of East Antarctica (roughly Cook to Mertz glaciers) we use repeated SAR imagery to identify which icebergs are grounded, then use their freeboard measured with ICESat-2 to estimate local water depths. These estimates have large uncertainties, primarily from uncertainties in firn air content, but provide valuable insights into the locations of banks and troughs that steer water masses across the continental shelf.

Calibrating extraterrestrial ^3He in ice-proximal marine sediments as a quantitative proxy for past West Antarctic Ice Sheet melt rates

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Satellite records of the extent of the West Antarctic Ice Sheet (WAIS) reveal continuous retreat of the Thwaites and Pine Island outlet glaciers and their floating ice shelves. This ice-shelf and grounding-zone melt results from the incursion of warm waters from below, and can be exacerbated by the outflow of buoyant subglacial meltwater discharge. The response of WAIS meltwater release to past warming events, as well as the spatial pattern of meltwater release, is in its nascent stages of understanding, due in part to a lack of quantitative sedimentary and geochemical proxies.

We present here the theory and initial results for extraterrestrial ^3He fluxes as a quantitative meltwater flux proxy from marine sediments just offshore the Thwaites Glacier Tongue. Polar ice accumulates extraterrestrial ^3He from the spatiotemporally constant rain of interplanetary dust particles to the Earth surface. Past measurements of Antarctic ice reveal concentrations of extraterrestrial ^3He that vary predictably with ice accumulation rate. We show unequivocal geochemical evidence for the presence of extraterrestrial ^3He in rapidly-accumulating (1-4 mm/yr) marine sediments. We find ^3He fluxes in these sediments that exceed the direct extraterrestrial ^3He input rate by a factor of 80-200, which can only be attributed to the release of ^3He-bearing particles from meltwater inputs. We conclude by discussing remaining steps necessary to quantify meltwater input rates from sedimentary ^3He fluxes, as well as prospects for paleo-records of meltwater release.

Carbon oxidation in subglacial waters beneath the Antarctic ice sheet

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The subglacial environment beneath the Antarctic ice sheet contains potentially significant reserves of carbon. Yet restricted access to the base of the ice sheet significantly limits our understanding of the processes that cycle this carbon, and the residence time of carbon in the basal environment. Here we present stable oxygen and carbon isotope data measured in a large suite of subglacial precipitates found throughout Antarctica. These samples originate from drainage paths within several major AIS catchments and in marginal sectors throughout the ice sheet, permitting a continent-wide survey of subglacial carbon cycling. Calcite forming waters from beneath the Transantarctic Mountains exhibit consistently 13C-depleted δ13Ccarb compositions as low as -23.5 ‰, pointing to widespread oxidation of existing stores of subglacial organic matter through microbial respiration. Conversely, calcite from marginal sectors of the AIS exhibit higher δ13Ccarb values suggesting carbon sourced not only from organic matter, but also from carbonate weathering and atmospheric carbon trapped in the overlying ice. Collectively, these data suggest that subglacial microbial respiration of fossil organic carbon is a potential carbon source to the global carbon budget, and that the subglacial carbon reserves beneath the AIS vary regionally.

Subglacial Precipitates Record Antarctic Ice Sheet Response to Late Pleistocene Millennial Climate Cycles

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Ice cores and offshore sedimentary records demonstrate enhanced ice loss along Antarctic coastal margins during millennial-scale warm intervals within the last glacial termination. However, the distal location and short temporal coverage of these records leads to uncertainty in both the spatial footprint of ice loss, and whether millennial-scale ice response occurs outside of glacial terminations. Here we present a >100kyr archive of periodic transitions in subglacial precipitate mineralogy that are synchronous with Late Pleistocene millennial-scale climate cycles. Geochemical and geochronologic data provide evidence for opal formation during cold periods via cryoconcentration of subglacial brine, and calcite formation during warm periods through the addition of subglacial meltwater originating from the ice sheet interior. These freeze-flush cycles represent cyclic changes in subglacial hydrologic-connectivity driven by ice sheet velocity fluctuations. Our findings imply that oscillating Southern Ocean temperatures drive a dynamic response in the Antarctic ice sheet on millennial timescales, regardless of the background climate state.

Investigating temperature and origin of fluids that circulated within a brittle fault array in the West Antarctic Rift System

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Outcrops of brittle faults are rare in Marie Byrd Land, West Antarctica, because fault damage zones commonly undergo enhanced erosion and form bedrock troughs occupied by glacier ice. Where exposures do exist, faults yield information about regional strain in the West Antarctic Rift System (WARS) and may host minerals that contain a record of the temperature and chemistry of fluids during regional-scale faulting. In MBL's southern Ford Ranges, bordering Ross Sea, a distinctive fault array was sampled that hosts tourmaline and quartz, a mineral-pair that can provide temperature and composition of fault-associated fluids, using δ18O. Host rocks are tourmaline-free. At three separate sites, fault surfaces display strongly aligned tourmaline, suggesting that mineralization occurred during tectonism. One site features highly polished, or mirrored, surfaces, a characteristic that may indicate tourmaline precipitation during seismic slip. The orientation and kinematics of the high angle faults are NNW-striking: normal-slip, and WNW-ESE striking: right-lateral strike-slip. The timing of mineralization is yet to be determined, but viable possibilities are that the faults formed during broad intracontinental extension during formation of Ross Embayment in the Cretaceous, or during development of deep, narrow basins beneath the RIS grounding zone, in the Neogene (newly detected, see Tankersley et al., this meeting).

Once formed, tourmaline is resistant to chemical and isotopic re-equilibration, and therefore can retain a record of its conditions during formation. We used oxygen isotope compositions of tourmaline and quartz pairs to investigate temperatures, fluid-rock ratios, and fluid sources, with bearing on fault-localized flux of fluids and geothermal heat. Analyzed tourmaline and quartz were separated from the upper ~2mm of the fault surfaces, as well as quartz separated from host rock in the same hand samples.

Tourmaline δ18O ratios (n=4) fall within a range of +9.2 to +10.4 ± 0.1 ‰ VSMOW (average 9.7‰, StDev = 0.7). Paired quartz yield δ18O values of +11.1 to +10.3 ± 0.1 ‰. Relative isotopic homogeneity between sites suggests similar fluid conditions were present across the region and supports field evidence for that the structures form a regional fault array. ∆Qtz-Trm values fall between 1.3 and 2.0, and δ18O of quartz in faults closely resembles δ18O of host rock quartz. We tentatively determine the water oxygen isotope ratio as greater than ~7.7 ‰. Plutonic-metamorphic associations in the immediate region, and comparisons with similar faults elsewhere (e.g. Elba island, in Italy), suggest temperatures as high as 500°C for the fluids that circulated into the faults.

The data are interpreted to show that brittle faults provided pathways for hot fluids derived from mid-crustal processes to make their way to shallow crustal depths. δ18O values indicate magmatic and/or metamorphic fluid sources, with minor to no introduction of meteoric fluids. Tourmaline-quartz pairs did not attain equilibrium, likely due to tourmaline's rapid crystallization. On-going investigation includes analysis of H and B isotopes in tourmaline, which will better characterize the relationship between fault-hosted and mid-crustal fluids.

Subglacial meltwater as an enabler of CDW-driven retreat in Marguerite Bay, Antarctica

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Ice sheet margins are vulnerable to the relatively warm Circumpolar Deep Water (CDW) that floods the continental shelf along much of the West Antarctic coastline. With the community focus on understanding the past, present, and future of the ongoing retreat in the Amundsen Sea sector, we thought it prudent to examine a physiologically similar embayment that has already experienced near-complete deglaciation. Marguerite Bay's continental shelf is similar to that offshore of Amundsen's Thwaites/Pine Island Glacier system, with a subglacial meltwater-scoured bedrock interior that transitions to sedimentary substrate on the outer continental shelf. Like the modern Amundsen Sea, Marguerite Bay was likely perturbed by incursions of warm CDW during the early Holocene, as revealed by the micropaleontological work of previous researchers.

Recently, we sought to improve the retreat chronology and better understand the forcings of retreat in Marguerite Bay. We reanalyzed archived sediment cores from Marguerite Bay by measuring grain size, collecting new radiocarbon ages and evaluating previously published ages, and reconstructing grounded and floating ice configuration from 14 cal ka to present. We have previously presented some of these results, but we have now improved on these by recalibrating old and new ages according to the latest calibration curve (Marine20). Additionally, because all relevant publications in Marguerite Bay have used various naming schemes for sedimentary facies, we have carefully reassigned these naming schemes to a unified facies model to add clarity and give paleoenvironmental relevance to previously published radiocarbon ages.

During our reanalysis of archived sediment cores from Marguerite Bay, we identified a prominent sedimentological marker of subglacial meltwater activity coinciding with significant retreat. We have previously suggested meltwater may have played a major role in facilitating that retreat. We suggested further that modern meltwater activity at Thwaites/Pine Island Glacier could become similarly influential. However, we failed to identify a specific glaciofluvial cause of instability. Now, rather than solely considering subglacial processes, we consider oceanographic mechanisms that link meltwater activity with ice sheet retreat. We suggest that meltwater-induced freshening of shelf waters caused favorable density conditions for dense CDW to impinge in Marguerite Bay, thereby honoring both previous and new interpretations. The water masses offshore of Thwaites and Pine Island Glaciers, with their active modern meltwater system, may also be partly modified by these processes.

Estimating the dominant creep mechanisms and viscous stress exponent (n) in fast-flowing glaciers

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Ice flow is generally modeled through a constitutive relation, which relates the rate of deformation to applied stress. While it is common the use a single power-law form known as Glen's Law, the constitutive relation can be more generally represented as a sum of power laws, each representing a different mechanism of ice deformation that is dependent upon the parameters of each mechanism, such as its activation energy and stress exponent. These parameters have significant implications for how we model the relative contributions of different deformation mechanisms, which in turn affects the effective rheology of ice and outputs of ice-flow models. Here, we apply a composite flow law, a steady-state grain size model, and a thermomechanical model to illuminate the dominant deformation mechanism in different regions of the Antarctic Ice Sheet. We propose a framework for estimating the value of the stress exponent n from this suite of models and show that dislocation creep (n=4) is likely dominant in all fast-flowing regions of Antarctica. Further, we demonstrate that the balance of deformation mechanisms is highly sensitive to the values of activation energy for creep. Our results help to explain the range of values of the stress exponent (n) previously inferred in laboratory and field studies and our method provides a straightforward way of parameterizing the effect of varying flow conditions on the constitutive relation for ice flow.

Potentially Significant Water Exfiltration from Subglacial Till Driven by Contemporary Ice Sheet Thinning

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Recent observations indicates potentially large portions of the West Antarctic Ice Sheet are underlain by deep sedimentary basins saturated with water. Complex hydromechanical models have been used to predict how the rate of ice sheet thinning drives exfiltration of water out of the aquifer into subglacial hydrological systems or infiltration of water from subglacial hydrology into the aquifer. However, small differences in boundary conditions or model parameters produce large differences in the predictions of these models. Here we present a closed-form theory for the rate of exfiltration under thinning ice sheets and its close correspondence to results from more complex and computationally expensive numerical models. For high till permeabilities within the range suggested by laboratory measurements of sheared Antarctic tills, rates of exfiltration due to recent West Antarctic thinning can be potentially dominant contributors to the basal meltwater budget. Additionally, in areas with seasonal melt input to the ice sheet bed, exfiltration following the end of the melt season can potentially sustain subglacial drainage for months. We conclude by discussing the importance of improving constraints on till properties and the prospect for incorporating interactions with aquifers in models of subglacial hydrology.

How old, how accurate? A cautionary tale about inaccurate dates at the detection limit for radiocarbon

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Accurate interpretation of time is essential to answering the questions of “How much, how fast?” Interpreting the amount of radiocarbon (^{14}C) as an “absolute” age has been particularly useful in Antarctic paleo-glaciological and paleoceanographic studies because the timescales of radiocarbon decay and the last deglaciation are similar. However, environmental challenges in interpretation of radiocarbon dates from Antarctic marine and subglacial sediments necessitate the use of less precise methods (Ramped PyrOx and Compound Specific) to constrain the amount of radiocarbon in a sample. We show evidence that sacrificing precision in radiocarbon age interpretations does not always yield improvements in accuracy, specifically in Ross Sea glaciomarine sediments. Diachronicity between marine diatom microfossils and old radiocarbon age interpretations from organic matter in the same sediments necessitate a critical re-assessment of radiocarbon ages that are at or near the detection limits of ^{14}C analysis. We will discuss the potential mechanisms that can introduce younger carbon to older sediments as well as the types of environments that may be susceptible such mechanisms.
A specific example stems from a biosiliceous interval, likely reflecting a cool-interglacial event, identified in the lower interval of Core ANTA099-CD3B, which is dated via diatom biostratigraphy as older than 140,000 years. However, this core interval yields a date of 25,000 - 26,000 yr BP (AIOM) and 31,700 ^{14}C y BP for the youngest portion of the organic carbon and ranged to >38,400 ^{14}C BP for the oldest portion (Ramped PyrOx). The diatom-based age is indicated by the abundant presence in a well-preserved diatom assemblage of Rouxia leventerae the last appearance of which is a MIS 6/5 boundary marker, ~0.14 Ma). The absence of older diatoms that are common on the Antarctic shelf supports this age, and indicates that Rouxia leventerae is not reworked into younger sediments and the age of its last occurrence reliably dates this core interval.
This example presents a cautionary tale in the interpretation of ^{14}C ages near the detection limits of dating, and we discuss when caution (different lithologies, different radiocarbon dating methods) must be taken in dating sediments.

Refined time series of Antarctic active subglacial lakes: New multimission volume flux estimates using evolving shorelines

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Subglacial water systems and deeper groundwater networks beneath the Antarctic ice sheet connect glacial and oceanic systems, modulate ice dynamics, and remain a major physical uncertainty of future ice sheet predictions. Subglacial water collects in subglacial lakes, some of which are "active" lakes that episodically fill and drain inferred from ice-surface uplift and subsidence respectively. Active lake drain-fill cycles generate time-varying evolution of subglacial water distribution, transport mechanisms, and freshwater flux into sub-ice-shelf cavities and the Southern Ocean. When these lakes were initially discovered in the 2000s, the coarse spatial resolution and short temporal duration of available ICESat observations limited comprehensive knowledge about how lake geometry changed through fill-drain cycles. This limited view resulted in uncertain and stationary lake boundaries representative of a brief observational window when lakes were initially discovered. Now almost two decades later, the time series surface observations demonstrate shoreline position is another dynamic aspect of active subglacial lakes. Here, we combine multi-mission radar and laser altimetry records from the CryoSat-2 and ICESat-2 missions, into a 12-year time series of ice-surface deformation over active subglacial lakes in Antarctica to apply a robust, reproducible shoreline delineation method. This method generates time-varying lake outlines to quantify lakeshore migration and time-variable water fluxes. We find general agreement of temporal trends observed using this method compared to using static outlines; however, the amplitude of volume flux estimates is doubled or tripled in some cases using our refined approach due to lake activity adjoining the static outlines. These improved estimates of interconnected subglacial lake activity using variable shorelines will inform transient subglacial water models with more precise inferences of water flux through the subglacial system, across the land-ocean interface at the grounding zone, and into sub-ice-shelf 'estuaries' and the greater Southern Ocean.

#WAISworkshop

Changes in Dotson-Crosson Ice Shelf Flow Linked to Thinning and Tidal Interaction with Ice Rises and Rumples

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The Dotson-Crosson Ice Shelf system has changed dramatically over the past several decades as extreme basal thinning and grounding line retreat have re-configured the shape of numerous ice rumples, and in some cases eliminated ice rumples. Using a combination of Landsat images (spanning 1973 – 2021), MEaSURES grounding line data, ICESat elevation profiles, and GoLIVE – ITS_LIVE ice velocity data, we track the grounding line retreat over the ice shelves, track flow speed changes, and assess the style of interaction with the several pinning points within the ice shelf system.

Using a series of 16-day repeat Landsat 8 images, we detected an oscillating flow pattern in a region of the Dotson Ice Shelf surrounding Wunneberger Rock (WR), a feature that combines the character of ice rumple and nunatak. WR has a fin-like shape that protrudes through the ice shelf with the fin aligned closely to the mean flow direction. An analysis of variations in flow direction with the CATS2008b tide model for a region surrounding WR (broadly, the outflow area of Kohler Glacier onto the Dotson Ice Shelf) shows that the flow direction variations are linked to tidal cycles. Landsat 16-day intervals including more low-tide periods show a more northerly flow direction (bearing 340-360°). Intervals including more high-tide periods show a shift in flow direction to more north-easterly (bearing 015-035°). A field visit to the area confirmed the link between tide height and flow direction in a 3-day record of 5-second GPS data from a site 8km southwest of WR. The GPS-derived path of the surface motion of the ice shelf is corkscrew-like with relatively abrupt changes in flow direction as different points in the tidal oscillation.

Curiously, the correlation between tide height and flow direction is degraded when an interpolated inverse barometer effect (IBE) is included. We interpret this as a consequence of the different rates of vertical motion induced by tides (sub-daily) and air pressure patterns (>daily). We infer that the ice shelf is interacting with sub-surface bedrock slopes, relatively steep, and that the interaction is moderated by the relative pace of horizontal flow and vertical uplift (or lowering). That pace is in turn dominated by tidal motion, since the rate of IBE changes is in general slower and smaller in scale.

Controlled-source seismic imaging of McMurdo Ice Shelf near Williams Airfield

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Understanding the structure and thickness of the McMurdo Ice Shelf and the ocean environment below is important from an operational as well as a scientific perspective. The McMurdo Ice Shelf is part of the Ross Ice Shelf, and ice shelf mass loss has been observed due to warming ocean conditions in the Ross Sea. In December 2021, the Thwaites Interdisciplinary Margin Evolution (TIME) project team collected a controlled-source seismic survey along an 1150-meter-long line near William's Airfield on McMurdo Ice Shelf. We deployed twenty-four Magseis Fairfield, Z-Land Generation 2, 5-Hz, 3-component seismic nodes at 50-m spacing for 30 days. During one day, we used a 12-lb sledgehammer as a seismic source at 23 locations, with 3 hammer strikes at each location to stack and enhance the signal. The seismic nodes also recorded a variety of passive seismic sources, including icequakes and anthropogenic seismic sources like vehicle and airplane traffic. We process the controlled-source refraction data to develop a velocity model of the ice shelf and environment below. We use Python ObsPy tools to visualize the seismic data and make observations about the data quality and wave propagation. The survey was also a methods test for the use of seismic nodes for ice shelf (and glacier) imaging with controlled sources, and we discuss lessons learned for future deployments such as those planned by the TIME project for Thwaites glacier in 2022-23.

Promoting Inclusivity, Diversity, Equity, and Accessibility within the International Thwaites Glacier Collaboration and beyond

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The International Thwaites Glacier Collaboration (ITGC) is a large, multi-disciplinary program funded by the U.S. National Science Foundation and the U.K. Natural Environment Research Council to investigate Thwaites Glacier in West Antarctica. ITGC projects cross scientific disciplines to understand the glacier's flow dynamics and project its ice mass loss and potential contributions to sea level rise. The ITGC formed an Inclusivity, Diversity, Equity, and Accessibility (IDEA) Council of PIs, postdocs, students, contractors, and outreach specialists in 2020 in response to the heightened concerns about diversity, equity and inclusion (DEI) across the globe. The Council consists of representatives from the eight ITGC research projects and the Science Coordination Office (SCO), meeting together twice a month with a goal of becoming a more inclusive and welcoming community. Significant projects included creating "Community Norms and Values" and "Field and Ship Best Practices" guides; hiring a diversity consultant to lead inclusivity workshops, guide discussion, and share expertise; organizing screenings and introspective discussions of "Picture a Scientist;" offering pre-field season conversations about social dynamics; conducting post-field season surveys for field participants; and incorporating IDEA activities into conferences.

Having had both successes and challenges, we are learning from what has worked and what hasn't worked and creating new initiatives. One of our next important steps is to connect with polar researchers outside of ITGC who are doing DEI work and to hear about the successes and challenges of other groups. What can we learn from each other and how can we work together to address our shared goals? This poster is an opportunity to exchange ideas with WAIS colleagues about DEI, to support each other, and to discuss next steps for the future.

"Big Bergs No More" - A Landsat Study of the Thwaites Ice Tongue and Glacier Front

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Published research has documented early changes to the Thwaites Glacier front (Ferrigno et al., 1993; USGS I-2600F, 2003) and the US National Ice Center has officially documented other major and minor icebergs that have been calved from there in the past ~six decades all observed with remote sensing data. A great deal of additional research has been focused on Thwaites Glacier over the years but especially so as it rapidly thinned and retreated in recent decades.

In order to put long-term changes into a clearer context at this location, we chose to access clear Landsat scenes through the full archive and to better position some of the earliest scenes so they can be properly compared to the most recent images available. Using specific landscape features, generally offshore islands, a Landsat 4 scene pair from 1988 and multiple Landsat 1 scenes from 1972 can now be directly compared to the more numerous Landsat 8 and 9 scenes now being acquired.

One of the results that resulted from this long-term analysis is stated in the abstract title. Whereas the 1988 to 2002 imagery reveals the advance of the Thwaites Glacier tongue and the eventual release of very large Iceberg B-22 (5212 km²). Although decreasing in size, its main piece is still largely aground within the Amundsen Sea Embayment in 2022. In contrast, the more precisely geolocated 1972 imagery reveals the full extent of Iceberg B-10 as 7380 km² along with two smaller bergs that may have been released at about the same time as 1166 km² and 255 km². If they were originally all together, that would easily make B-10 the second biggest iceberg in the satellite record at about 8800 km². Even if they were not, the B-10 visible in late 1972 would still be slightly bigger than the current second largest iceberg on record, A-20 at 7280 km² although still well below of the estimated area of B-15 of 11000 km².

And, in contrast to the current extent of the Thwaites Glacier's ice extent, after its floating ice effectively disintegrated in the mid-2010s when the last named iceberg was released, the original ice tongue, as visualized in 1972, represents at least 100 years of ice advance using the minimum flow speed near the grounding zone from by Ferrigno et al. (1993) derived from 1972 to 1984 imagery. The takeaway message from the review of available Landsat images is that Thwaites Glacier can no longer generate notable icebergs due to visible degradation of the ice as it reaches the Amundsen Sea.

Enlisting Historically Excluded Undergraduates in the Effort to Extend Knowledge of West Antarctica's Bedrock, Through Course-based Undergraduate Research Experiences (CUREs) and Art-Science Initiatives

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An enormous reserve of information about the subglacial bedrock, tectonic and topographic evolution of Marie Byrd Land (MBL) exists within glaciomarine sediments of the Amundsen Sea shelf, slope and deep sea, and MBL marine shelf. Investigators of the NSF ICI-Hot and NSF Linchpin projects partnered with Arizona Laserchron Center to provide course-based undergraduate research experiences (CUREs) for members of groups who do not ordinarily find access points to Antarctic science. Our courses enlist BIPOC and gender-expansive undergraduates in studies of ice-rafted debris (IRD) and bedrock samples, in order to impart skills, train in the use of research instrumentation, help students to develop confidence in their scientific abilities, and collaboratively address WAIS research questions at an early academic stage. CUREs afford benefits to graduate researchers and postdoctoral scientists, also, who join in as instructional faculty: CUREs allow GRs and PDs to engage in teaching that closely aligns with their active research, while providing practical experience to strengthen the academic portfolio (Cascella & Jez, 2018). Members of our project also create and lead art-science initiatives that engage students and community members who may not ordinarily engage with science, forging connections that make science relatable. Re-casting science topics through art centers personal connections and humanizes science, to promote understanding that goes beyond the purely analytical.

Academic research shows that diverse undergraduates gain markedly from the convergence of art and science, and from involvement in collaborative research conducted within a CURE cohort, rather than as an individualized experience (e.g. Shanahan et al. 2022). The CUREs are offered as regular courses for credit, making access equitable via course enrollment. The course designation carries a legitimacy that is sought by students who balance academics with part-time employment. Course information is disseminated via STEM Bridge programs and/or an academic advising hub that reaches students from groups that are insufficiently represented within STEM and cryosphere science.

CURE investigation of Amundsen Sea and WAIS problems is worthy objective because: 1) A variety of sample preparation, geochemical methods, and scientific best-practices can be imparted, while educating students about Antarctica's geological configuration and role in the Earth climate system. 2) Individual projects that are narrowly defined can readily scaffold into collaborative science at the time of data synthesis and interpretation. 3) There is a high likelihood of scientific discovery that contributes to research award objectives. 4) Enrolled students will experience ambiguity and instrumentation setbacks alongside their faculty and instructors, and will likely have an opportunity to withstand/overcome challenges in a manner that trains students in complex problem solving and imparts resilience (St John et al., 2019). Based on our experiences, we consider CUREs as a means to create more inclusive and equitable spaces for learning to do research, and a basis for a broadening the future WAIS community. Our groups have yet to assess student learning gains and STEM entry in a robust way, but we can report that two presenters at WAIS 2022 came from our 2021 CURE, and four polar science graduate researchers gained teaching experience through CURE.

Evidence of Diminished WAIS and Open Interior Seaway, from Distinctive Dropstones in Amundsen Sea that Originated in the Ellsworth Mountains

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IODP Expedition 379 to the Amundsen Sea continental rise recovered latest Miocene-Holocene sediments from two sites on a drift in water depths >3900m. Sediments that are dominated by clay and silty clay host pebbles and cobbles of ice-rafted detritus (IRD) (Gohl et al. 2021, doi: 10.14379/iodp.proc.379.2021). Cobble-sized dropstones also appear as fall-in, in the top of cores recovered from sediments >5.3 Ma. The principle means to deposit abundant IRD and sparse dropstones in deep sea sediment is through melting of icebergs released by Antarctic ice-sheet calving events. We use petrological and age characteristics of clasts from the Exp379 sites to fingerprint their bedrock provenance to extend knowledge of subglacial bedrock, and with the intention to illuminate changes in icesheet extent between 7 – 3 Ma that lend credence to forecasts of extensive future change.

Mapped onshore geology shows pronounced distinctions in bedrock age between tectonic provinces of West or East Antarctica (e.g. Jordan et al. 2020). Therefore we use geochronology and thermochronology of clasts and minerals for tracing their provenance, and ascertain whether IRD deposited at 379 drillsites originated from proximal or distal Antarctic sources. We here report zircon and apatite U-Pb dates from several sand samples and dropstones taken from latest Miocene, early Pliocene, and Plio-Pleistocene-boundary sediments. Additional Hf isotope data, and apatite fission track and 40Ar/39Ar Kfeldspar ages for some of the same samples help to strengthen provenance interpretations.

The study revealed three distinct zircon age populations at ca. 100, 175, and 250 Ma. Using Kolmogorov-Smirnov (K-S) statistical tests to compare our new igneous and detrital zircon (DZ) U-Pb results with previously published data, we found strong similarities to West Antarctic bedrock, but low correspondence to prospective sources in East Antarctica, implying a role for icebergs calved from the West Antarctic Ice Sheet (WAIS). The ~100 Ma age resembles plutonic ages from Marie Byrd Land and islands in Pine Island Bay. The ~250 and 175 Ma populations match published mineral dates from shelf sediments in the eastern Amundsen Sea Embayment as well as granite ages from the Antarctic Peninsula and the Ellsworth-Whitmore Mountains (EWM). The different derivation of coarse sediment sources requires changes in iceberg origin, likely the result of changes in WAIS extent during deglaciation.

One unique Exp379 dropstone is green quartzite containing mostly 500-625 Ma detrital zircons. In appearance and dominant U-Pb age population, it resembles a sandstone dropstone recovered from Exp382 U1536 in the Scotia Sea (Hemming et al. 2020, GSA abstract). K-S tests yield high values ($P \geq 0.6$), suggesting a common provenance for both dropstones recovered from late Miocene to Pliocene sediments, despite the 3270 km distance separating the sites. Comparisons to published data, in progress, narrow the group of potential on-land sources to exposures in the EWM or isolated ranges at far south latitudes in the Antarctic interior. If both dropstones originated from the same source area, they signify that dramatic shifts in the WAIS grounding line position do occur, along with periodic opening of a seaway connecting Amundsen and Weddell Seas.

Pairing eyes in the sky with instruments in the deep: mapping the Antarctic Coastal Current in the eastern Amundsen Sea

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The Antarctic Coastal Current (AACC) flows along much of the Amundsen Sea coastline in West Antarctica and plays an important role in governing heat and mass exchange at the ice-ocean interface. It is also a major transport pathway for meltwater discharged from ice shelves in the region, modulating downstream water mass formation and ice-ocean interaction. Thus, understanding AACC variability is crucial for constraining future ice loss in the Amundsen Sea sector. As part of the Thwaites-Amundsen Regional Survey and Network Integrating Atmosphere-Ice-Ocean Processes (TARSAN) project of the International Thwaites Glacier Collaboration (ITGC), hydrologic surveys were conducted with the goal of constraining water mass properties and circulation variability throughout the Amundsen Sea. Although much work has been aimed at understanding deep water variability here, the surface currents, especially the relatively fresh AACC, remain less examined.

Here, we investigate the seasonal and interannual variability in the AACC within the eastern Amundsen Sea from hydrographic and satellite-derived oceanographic observations. We use hydrographic measurements taken by shipboard conductivity-temperature-depth and acoustic doppler current profiling, autonomous underwater gliders, and instrumented seals in 2014, 2019, and 2020 to characterize the AACC. We found that the AACC is composed of relatively fresh waters, predominantly flows along the front of ice shelves, and is likely confined to the top 100 m of the water column, similar to the current in other Antarctic regions. We also constructed and analyzed Landsat 8 sea surface temperatures to better constrain the AACC spatial and temporal variability at the surface. We suggest that shifts in the coastline structure or AACC location as ice shelves retreat may change the distance at which the AACC flows from the ice front, thereby modifying the amount of heat delivered to the ice and having potential impacts on glacier stability.

Did WAIS existing during the Eemian? Evidence from ice core records.

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We do not know whether the West Antarctic Ice Sheet collapsed during the last (Eemian) interglacial period. Definitive evidence, from sediment cores beneath a West Antarctic ice stream (Scherer et al., 1998), shows only that that there was open water in the Ross sector of the ice sheet some time in the last million years. Moreover, new results suggest that the Eemian sea level high stand may have been as little as 1.2 m, and not greater than 5.3 m (Dyer et al., 2021), much lower than previous estimates of 6 to 9 m (Dutton et al., 2015). These revised sea level estimates do not require contributions from WAIS (even if that remains likely).

Ice core records can provide independent constraints. Large changes in topography affect atmospheric circulation over the ice sheet, causing measurable changes to ice-core properties such as water-isotope ratios. Recently, Dütsch et al. (in review) completed simulations using WRF, the Weather Research and Forecasting model at sufficiently high resolution (15 km) to assesses the impact of WAIS topography at the local scale, for direct comparison with ice core records, including water isotopes.

Topographic changes are reflected in relative differences – e.g., the size of the Eemian anomaly in $\delta^{18}O$ compared to the Holocene -- among the different ice core records. This assumes that in the absence of ice-sheet topography changes all ice core locations would have been equally warmer during the Eemian than during the Holocene (and therefore equally enriched in $\delta^{18}O$). This is a good approximation, provided that the topographic changes are large.

Data at key locations are consistent with WAIS collapse. At SkyTrain Ice Rise, just inland of the Ronne Ice Shelf, $\delta^{18}O$ is 2.5‰ higher during the Eemian (at 126 ka) than the Holocene (Eric Wolff, Mackenzie Grieman, pers. comm., May 2022). This is an anomaly 1.5‰ greater than at Dome C, and 2.5‰ than at Dome F. In the WRF simulations, SkyTrain Ice Rise is about ~1‰ enriched compared with Dome C, and 3‰ more than at Dome F. The strong anomaly at SkyTrain Ice Rise is a very robust feature of the simulations, reflecting anomalous southward transport of warm air across the Ronne Ice Shelf, as a consequence of greater cyclonic flow from the lower WAIS topography. At Talos Dome (Stenni et al., 2011), East Antarctica, the $\delta^{18}O$ anomaly at 126 ka is about the same as during the Holocene: hence it is anomalously low compared with Dome C or Dome F. This also compares well with the WRF simulations.

Together, these results suggest that WAIS was much lower, and probably collapsed, during the Eemian. Additional simulations using a greater variety of topographic and climate boundary conditions, and additional ice core data, would be helpful. The WRF simulations also predict significant anomalies in $\delta^{18}O$, as well as significant anomalies in deuterium excess, temperature, and snowfall, at Hercules Dome, which is to be drilled in the next five years.

Advances in glacier dentistry: experimental constraints on transient slip with cavitation

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Glacier slip facilitates fast glacier flow and produces cavities when slipping over hard beds. The presence of cavities can profoundly affect the force balance at the ice-bed interface, which in turn regulates slip speeds. Cavities grow and contract in response to changing slip speeds and local effective pressures, resulting in feedback loops between cavity geometries and the basal force balance. The implementation of slip rules in ice flow models assumes gradual transitions between steady-state configurations when estimating basal force balances, but sparse field observations and process-focused modeling indicate significant deviations can occur from this core assumption. We present results from a novel glacier sliding experiment where a large diameter cryogenic ring shear device was used to slip temperate ice over a hard, sinusoidal bed. Measurements from the experiment constrain the geometric response of cavities and the force balance evolution under prescribed periodic effective pressures. Cavity geometries systematically lag effective pressure oscillations, and system-averaged shear stresses evolve as a nonlinear combination of both factors, giving rise to notable hysteresis not included in most slip rules that tend to enhance shear stresses compared to steady-state conditions. Furthermore, these relationships systematically vary with the effective pressure oscillation period. Despite the simplified conditions of this experiment, our observations provide mechanistic insights on transient glacier slip that corroborate behaviors predicted by emerging transient slip rules.

The surface expression of ocean influence upstream of Antarctic grounding lines

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Seawater intrusion upstream of the grounding line could drive basal melt and accelerate retreat, yet this is not well understood and difficult to observe. Previous theory, experiments, and observations have found that a layer of dense seawater over an impermeable bed can penetrate tens of kilometers inland from the terminus over a flat or reverse sloped bed. Simulations with large-scale ice sheet models have found that merely a few hundred meters of seawater intrusion increases ice loss projections by 10-50% (Robel et al., 2022). The objective of this study is to investigate whether a regime of reduced basal friction upstream of the grounding line, which can be induced by seawater intrusion melt, can be detected observationally by surface features over the grounding zones of Antarctic marine-terminating glaciers.

Simple models typically assume that basal friction changes in a stepwise fashion seaward of the grounding line from a strong basal frictional resistance under grounded ice to zero as ice goes afloat. When seawater intrudes inland of the grounding line, this can cause both melting and reduced basal friction, lubricating the ice-bed interface over a distance of hundreds of meters to many kilometers. We tackle this problem with a 1D numerical flowline model of a marine-terminating glacier with an unconfined ice shelf. Reduced basal friction is applied inland of the grounding line to investigate characteristic surface slope profiles. We find that a regime of decreasing friction seaward of the grounding line is accompanied by a surface slope break that is not co-located with the grounding line as defined by the floatation thickness.

We also deduce locations in Antarctica where basal friction is ocean-influenced inland of the grounding line by analyzing ICESAT-2 tracks. The onset of reduced basal friction inland of the grounding line is accompanied by a substantial surface slope break that can be detected without boots ever touching the ground. Li et al. (2022) uses ICESAT-2 observations to identify slope breaks and inland limits of ice flexure along Antarctic grounding zones. We infer that a region of reduced basal friction exists where a slope break is detected upstream of the inland limit of ice flexure, and discuss where these regions exist in Antarctica. Further investigation could illuminate whether these regions experience seawater intrusion.

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

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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, termed shear zones. The intense shearing in these regions can drive significant englacial heating, which in extreme cases is thought to warm pockets of ice near to 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.

Examining Micropaleontology to Gain Insights Into Long - Term Processes in the Western Amundsen Sea, Antarctica

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The West Antarctic Ice Sheet (WAIS) is highly vulnerable to changes in Southern Ocean hydrography, specifically that of heat transport. The outlet glaciers draining into the Amundsen Sea Embayment (ASE) have exhibited the highest rates of change, primarily due to the influx of relatively warm (>1°C), and extremely dense Circumpolar Deep Water (CDW). Around Antarctica, coastal polynyas contribute to dense shelf water (DSW) formation. DSW formation by the Amundsen Sea polynya today is complicated by mixing with glacial meltwater and impinging CDW, but little is known about these complexities during the entirety of retreat since the Last Glacial Maximum. We use micropaleontological records of diatoms and foraminifera to interpret the relationships between water masses and the polynya to better understand the natural long-term history of CDW movement and its relationship to ice retreat. This is critical for better understanding the oceanographic controls on the stability of this sector of Antarctica, especially with fear this sector could trigger future WAIS collapse.

To investigate the long-term glacial and ocean conditions and processes in the Amundsen Sea, we sampled three archived sediment cores collected from the Dotson-Getz Trough in central ASE. These cores represent the top 31-90 cm of sediment and are reflective of recent environmental conditions. We intend to use these results as a baseline for the analysis of additional, longer cores. Quantitative diatom counts and species identification were completed to identify spatiotemporal environmental trends in productivity and sea ice. In general, concentrations of diatom valves, including Chaetoceros resting spores (CRS), decline significantly from the inner continental shelf to the outer continental shelf, reflecting decreasing productivity with distance from the Amundsen Sea Polynya. The most abundant non-CRS species includes the common Antarctic diatom Fragilariopsis curta, which is typically found in ice-edge waters or surface water associated with melting sea ice and is thereby used as a proxy for sea ice. We note a general increase in percentage Fragilariopsis curta with time in the mid-shelf core, suggesting a gradual transition from cold, open water masses to increased sea ice conditions. We also see an interval of increased productivity, indicated by high CRS and an increase in overall abundance, following a possible period of ice shelf breakup, indicated by a high percentage of Fragilariopsis vanhuerkii. These preliminary results will soon be supplemented by foraminifera analysis, grain size, and radiocarbon dating to provide a more comprehensive interpretation.

Revealing sub-ice shelf sediment basins with airborne magnetics: implications for solid-earth-ice interactions

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The bedrock geology beneath Antarctica's southern Ross Embayment is concealed by 100–1000s of meters of sedimentary deposits, seawater, and the floating Ross Ice Shelf (RIS). Our research strips away those layers to discover the shape of the consolidated bedrock below, which we refer to as the basement. To do this, we use the contrast between non-magnetic sediments and magnetic basement rocks to map out the depth of the basement surface under the RIS. Our primary data source is ROSETTA-Ice airborne measurements of the variation in Earth's magnetic field across the ice shelf, from flight lines spaced 10-km apart. We use the resulting basement topography to highlight sites of possible influence upon the Antarctic Ice Sheet and to further understand the tectonic history of the region. The basement features we image are characteristic of extensional tectonics, consistent with the setting in the West Antarctic Rift System. These features show continuity with Ross Sea basement features, suggesting a common tectonic development. In the center of the ice shelf, we delineate a broad, segmented, N-S basement high with thin (0–500m) sedimentary cover. We discover contrasting basement characteristics on either side of the RIS. The West Antarctic side displays evidence of active faults, which may localize geothermal heat, accommodate movements of the solid earth caused by changes in the size of the Antarctic Ice Sheet, and control the flow of groundwater between the ice base and aquifers. The East Antarctic side contains a wide and deep basin, with sediments over 3 km thick. This work contributes critical information about Ross Embayment basement topography and subglacial boundary conditions that arise from an interplay of geology, tectonics, and glaciation.

Archival airborne radio-echo sounding data geographical repositioning and calibration progress at Ross Ice Shelf, Antarctica

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Understanding the conditions beneath Ross Ice Shelf (RIS) is important for improving estimates of ice-shelf stability. However, existing Antarctic satellite altimetry and radar-echo sounding observations only extend back to the early 2000s. Here we present historical observations of RIS collected by Scott Polar Research Institute, National Science Foundation, and The Technical University of Denmark (SPRI-NSF-TUD) airborne radar sounding in 1974-75. These data provide critical information on past ice-shelf basal conditions of RIS, including marine ice formation and basal crevasses development, as well as subglacial hydrology of nearby ice streams draining from West and East Antarctica. We develop methods to improve the positioning accuracy of the pre-satellite positioning era by carefully identifying stable control points (e.g,. An ice rise) throughout the radargrams. We also develop algorithms to calibrate the vertical scale of historical radargrams with comparable two-way travel times to those provided on modern radargrams. We will showcase several geographically positioned and vertically calibrated results at several selected sites in West Antarctica, including Crary Ice Rise and Roosevelt Island. We will also present changes in observed ice thickness and basal conditions by comparing historical and modern NASA Operation IceBridge data. Our improved methods can be used to calibrate all SPRI-NSF-TUD collected across Antarctica, and would be adaptable to other historical radar film data, such as the 1970s DTU Greenland Ice Sheet observations.

Autogenic, Not Orbital, Forcing of Snowball Glaciomarine Sedimentation

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The Sturtian and Marinoan snowball Earth glaciations of the Cryogenian are instances of the runaway ice-albedo feedback in Earth's climate system, providing examples of dramatic climate variability in our planetary history. The drivers of sedimentary variability in records of these events remain contested, with hypotheses including tectonic, climatic, and autogenic forcings. We turn to the modern analogue of Antarctic glaciomarine sedimentation to test the climatic, specifically, orbital, hypothesis. Using a novel Bayesian age modeling approach, we probabilistically constrain the compensation time and length scales of glaciomarine sedimentation recorded by the ANDRILL AND-2A Antarctic sediment core. We argue that the compensation length scale is set by the amplitude, 30–36 m, of orbitally forced Neogene glacioeustasy, providing a reference value from the best modern analogue for sub-ice shelf glaciomarine sedimentation. Using hundreds of bed traces on high resolution drone imagery of the well-exposed snowball glaciomarine stratigraphy of the Marinoan Ghaub Formation along Fransfontein Ridge in Namibia, we independently estimate a compensation length scale of roughly 6 m. This smaller value is inconsistent with Cenozoic-style glacioeustatic variability, and, given a constant tectonic environment during deposition, suggests instead the role of autogenic variability in driving glaciomarine sedimentary variability.

Topographic evolution of WAIS subglacial bedrock: Insights from low-temperature thermochronology and thermo-kinematic modeling in Marie Byrd Land, West Antarctica

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Bedrock topography is a key boundary condition for ice sheet modeling, and determining changes in subglacial topography through time can provide insight into the timing of ice sheet development, the magnitude of glacial erosion, and the co-development of glaciers and glacial topography.

West Antarctica hosts an unusually high geothermal gradient supported by hot, low-viscosity mantle which likely enhanced the lithospheric response to West Antarctic Ice Sheet (WAIS) cycles of growth and increased the sensitivity of thermochronometers to landscape evolution on million-year timescales. Thus, a valuable record of glacial landscape change might be recovered from apatite fission track [AFT 80-130°C range] and (U-Th)/He [AHe; 50-90°C] dating, provided that landscape evolution can be distinguished from tectonic signals, including the effects of faults. This study utilizes AFT-AHe thermochronology and thermo-kinematic Pecube modeling to investigate interactions between the hot geotherm, glacial erosion, and inferred crustal structures in the Ford Ranges and the DeVicq Glacier trough in western and central Marie Byrd Land (MBL), respectively.

The Ford Ranges host glacial troughs (up to 3km relief) dissecting a low-relief erosional surface. Previous work suggests a majority of bedrock exhumation and cooling occurred at/by 80 Ma. However, new data hint at renewed exhumation linked to glacial incision since WAIS formation at 34 or 20 Ma. Prior (U-Th)/He zircon dates from exposures of crystalline bedrock span 90 – 67 Ma. New AHe bedrock dates are 41 to 26 Ma, while two glacial erratics (presumed to be eroded from walls or floor of glacial troughs) yielded AHe dates of 37 Ma and 16 Ma. Initial modeling results suggest a tectonic boundary between the Ford Ranges and Edward VII Peninsula separating regions with distinct exhumation histories. The boundary may cause differential WAIS incision at 34 or 20 Ma, a possibility being investigated with new models.

The DeVicq Glacier trough (>3.5km relief) coincides with a prominent crustal lineament but lacks temperature-time information compared to other regions. The crustal structure may have accommodated motion between elevated central MBL and the subdued crust of the Ford Ranges. Here, owing to the lack of onshore non-volcanic bedrock exposure, we have employed AHe and AFT dating of glacial sediment marine core samples offshore of the DeVicq Glacier to investigate the timing and rates of exhumation of the bedrock carved by the DeVicq trough, with initial results revealing detrital AHe ages as young as 24 Ma.

Our new Pecube models test a series of thermal, tectonic, and landscape evolution scenarios against a suite of thermochronologic data, allowing us to assess the timing of glacial incision and WAIS initiation in the Ford Ranges, and to seek evidence of an inferred tectonic boundary at DeVicq Trough. Modeling efforts will be aided by new AHe and AFT analyses from ongoing work. These models combine topographic, tectonic, thermal, and key thermochronologic datasets to produce new insight into the unique cryosphere-lithosphere interactions affecting landscape change in West Antarctica.

UAV-based ice-penetrating radar ice shelf monitoring: development and testing of a prototype system

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Ice-penetrating radar is the primary tool for measuring the internal geometry and properties of ice sheets and ice shelves at high spatial resolution. These surveys, which rely on crewed aircraft logistics, are prohibitively expensive in many cases, limiting the spatial extent of data collection and ruling out repeat measurements for time-series data in all but a few cases. Ice-penetrating radar measurements are often treated as static, but, especially in rapidly evolving areas, temporal measurements can provide a new window into the physical processes governing these changes. We present preliminary development and results from three test campaigns of our fixed-wing UAV-borne ice-penetrating radar system. We have completed three test campaigns, two in Iceland and one in Svalbard, demonstrating the functionality of the system. We will present radargrams from these tests and discuss future Antarctic-focused plans for the system.

Preliminary analysis suggests a sufficient link budget to see through most fast-flowing areas of the West Antarctic Ice Sheet. One particularly compelling application is temporal monitoring of ice shelves. Ice shelves play a critical role in buttressing the flow of fast-moving ice streams. In recent years, there have been multiple demonstrations of how rapidly ice shelves can change, with significant consequences for upstream grounded ice. The cost and complexity of crewed aircraft logistics has limited our ability to get temporal data to better understand ice mechanics within ice shelves, especially those small enough that significant portions are not in hydrostatic equilibrium. We focus specifically on these small to medium size ice shelves and explore the applications of a UAV-borne temporal monitoring system in these locations.

Redesigning Scientific Conferences: Insights from the International Firn Workshop

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Scientific communities rely on conferences, meetings, and workshops for exchanging scientific advancements and creating networking opportunities. However, financial and social barriers prevent these opportunities from being available to everyone. Access to these opportunities is essential for achieving open science and serving a broader community of scientists. To work toward an inclusive open-science framework, a group of researchers at the University of Colorado Boulder developed a free, online workshop for the global firn community. The inaugural International Firn Workshop took place during May and June 2022. To enhance collaboration and create several opportunities for participation, the workshop comprised three key phases with both synchronous and asynchronous formats. In Phase 1, participants had access to professional presentation coaching that they used for recording and sharing 5-minute research videos. Phase 2 included synchronous online topical discussions led by early career scientists. Finally, Phase 3 brought all participants together online to (1) summarize the discussions throughout the workshop, and (2) identify directions of future research and collaboration. All videos and recorded sessions from the three phases are publicly available. The International Firn Workshop is an example of a new type of conference that takes advantage of the recent global shift to online interactions. Redesigning conferences within an open-science framework is made easy with the vast array of web conferencing platforms and online workspaces. The International Firn Workshop increased accessibility by blending synchronous and asynchronous formats, creating completely free registration, highlighting early career scientists, providing presentation mentorship, and facilitating structured discussions with clear goals. Moreover, costs for organizing the workshop were kept very low since no physical meeting place, food, housing, or travel was required. This also reduced the environmental impact of the workshop, thus making it a more sustainable event compared to in-person conferences that require long-distance travel for participants. Lessons from the International Firn Workshop can be applied to meetings of other scientific communities aiming for accessible and open science.

The US Antarctic Program Data Center (USAP-DC) – Data Archive and Project Catalogue for Antarctic Sciences

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Availability and findability of existing data is key for reuse of the data for open, reproducible science, and for enabling data comparison, compilations and analysis of historical developments. The US Antarctic Program Data Center (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.

ROSETTA-Ice Observations on Basal Melting of Ross Ice Shelf using Airborne Radio-echo Sounding Radar

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Basal melting, marine ice formation, and calving of Ross Ice Shelf (RIS) – the largest ice shelf in Antarctica – are strongly influenced by ocean forcings, and RIS provides essential buttressing for the stability of both East and West Antarctica grounded ice. Nevertheless, basal melting and other ocean-related processes observations on RIS are limited and often display disagreements depending on the deployed methodology. Here, we provide new observations on basal melting of RIS by directly deriving basal melt rate from englacial attenuation using data collected by ROSETTA-Ice airborne radar sounding survey. In this study, we develop a model-integrated method which allows us to create relationships between ice shelf temperatures, englacial attenuation, and ice shelf basal melt rates. Although the basal melt rates produce higher ranges of values compared to a previous study using the same dataset, our updated map of RIS's basal melt rate covers from the ice shelf front to the grounding line regions where previous methods excluded. Overall, we observe higher melt rates along deep ocean troughs in the West Antarctica side, including the ice flow lines of Byrd Glacier, several Siple Coast ice streams. We also compare our basal melt rate patterns with historical marine ice distribution and modern oceanographic, climate, and sea-ice changes to further examine the linkage between ice shelf basal conditions and ocean warming in the Ross Sea.

Inferring ocean variability in ice-shelf cavities from basal melt rate time series

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In-situ observations of basal melting beneath ice shelves at high temporal resolution have recently become possible via an autonomous phase-sensitive radar technique. These measurements allow us to infer oceanographic processes and variability in ice-shelf cavities, which would be very difficult and costly to observe directly.
I will show results from Filchner-Ronne Ice Shelf (FRIS) and Totten Ice Shelf (TIS), two ice-shelf cavities representing very different melting and oceanographic regimes.

The more extensive, FRIS dataset is combined with historic oceanographic measurements from sub-ice-shelf moorings and yields an understanding of the propagation pathways of seasonal and inter-annual melt rate variability over the past three decades. The shorter, TIS dataset shows high east-west asymmetry in basal melting that coincides with asymmetry in water column thickness from newly derived bathymetry.

Inter-annual melt rate variability at FRIS is much too low to be captured in existing satellite-derived estimates; the range of temporal melt rate variability from the satellite estimates is exaggerated and any correspondence between the in-situ and remotely derived inter-annual variability is limited to a single site.
At TIS, the mean annual melt rate difference between the two observed years is comparable with typical year-to-year melt rate difference from the satellite estimates.

In addition to understanding sub-ice-shelf oceanography and validating satellite-derived melt rate estimates, our in-situ-derived basal melt rate time series will be useful for an assessment of how accurately numerical models, used for sea-level projections, represent melt rate variability in the present-day climate, a prerequisite for confidence in projections under future climate.

Reversible ice sheet thinning in the Amundsen Sea Embayment during the Holocene

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Cosmogenic-nuclide concentrations measured in subglacial bedrock cores at Kay Peak, a site between the Thwaites and Pope Glaciers in the Amundsen Sea sector of the West Antarctic Ice Sheet, show that the ice sheet at the core site was at least 35 meters thinner than present during the middle to late Holocene, and subsequently thickened to present conditions. At present, tens of meters of ice thinning in the vicinity of the core site in recent decades has been associated with tens of kilometers of retreat of the Pope Glacier grounding line. Thus, the past thinning-thickening episode was likely associated with a grounding line retreat-advance cycle. This is important because of concern that present thinning and grounding line retreat in the Amundsen Sea region may be irreversible, with potential catastrophic sea-level impacts. The past thinning episode, which took place in a similar although not identical climate was not irreversible. We propose that the past thinning-thickening episode was most likely due to a glacioisostatic rebound feedback, similar to that proposed as a possible stabilizing mechanism for current grounding line retreat, in which isostatic uplift caused by earlier Holocene thinning led to relative sea level fall favoring grounding line advance.

Multidecadal surface elevation anomalies of the Crary Ice Rise region from combined ICESat, CryoSat-2, and ICESat-2 altimetry

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Ross Ice Shelf is responsible for providing resistance to the seaward flow of large outlet glaciers and ice streams that drain an integrated ice mass equivalent to 11.6 m of global sea level rise from the East and West Antarctic ice sheets. The regions containing persistent, dome-shaped ice rises at which Ross Ice Shelf interacts with land on its sides or beneath are critical for providing frictional resistance to outflowing land ice, stabilizing the ice shelf. Ice rises and their contribution to ice shelf buttressing are sensitive to ongoing glaciological and oceanographic processes that cause the local region to evolve. Here we use satellite altimetry combined from the ICESat, CryoSat-2, and ICESat-2 missions to produce a multidecadal characterization of the structural changes occurring in the Crary Ice Rise region. We found a persistent trend of thickening and thinning ice upstream of Crary Ice Rise and at the grounding zone, possibly indicating the effects of Siple Coast ice stream rerouting on Crary Ice Rise's contribution to buttressing. The derived surface elevation anomalies combined with future efforts to characterize the bed in this region will provide insight into ice rise adaptations to highly dynamic ice systems and its effects on contributed buttressing for the greater Ross Ice Shelf. Our results demonstrate the potential for combining decades of remote sensing data to evaluate the interactions between century-scale ice-dynamic cycles and the local evolution of pinning points pertinent to the stress regime on Ross Ice Shelf, such as the Crary Ice Rise, and may be extended to other key regions where ice rises provide significant buttressing to grounded ice across Antarctica.

The Stochastic Ice-Sheet and Sea-Level System Model v1.0 (StISSM v1.0)

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The Stochastic Ice-sheet and Sea-level System Model (StISSM v1.0) is the first large-scale ice sheet model with stochastic capabilities. In StISSM v1.0, stochastic parameterizations simulate climatic fields with internal variability, as well as glaciological processes exhibiting variability that cannot be resolved at the typical spatiotemporal resolution of ice sheet models: calving and subglacial hydrology. Because both climate and unresolved glaciological processes include internal variability, stochastic parameterizations allow StISSM v1.0 to account for the impacts of their high-frequency variability on ice dynamics, and on the long-term evolution of modeled glaciers and ice sheets. StISSM v1.0 additionally includes stochastic time series models representing surface mass balance and oceanic forcing as autoregressive processes. When combined together, these novel features of StISSM v1.0 enable quantification of irreducible uncertainty in ice sheet model simulations, and of ice sheet sensitivity to noisy forcings.

We detail the implementation strategy of StISSM v1.0, and evaluate its capabilities in idealized model experiments. Results from our experiments demonstrate the complexity of ice sheet response to variability. Stochastic forcing not only causes variability in the final state, but also asymmetry in the response, noise-induced drift, and long timescales needed for ice sheet state convergence. The response of a particular system is sensitive to the type of forcing, to the system state, to the geometrical configuration, and to the intrinsic non-linearity of ice dynamics. Our results thus raise important questions about accounting for temporal variability in ice-sheet model forcing. Finally, we describe how our implementation strategy for StISSM v1.0 facilitates easy sampling of internal variability within the broader glaciological community.

The Role of Glacial Isostatic Adjustment on Cordilleran Ice Stream Stability Over the Last Glacial Cycle

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During the Last Glacial Maximum, the Cordilleran Ice Sheet comprised many marine-terminating ice streams that flowed into the Pacific Ocean. There is evidence based on ice-rafted debris records and freshwater proxies that these ice streams were dynamic over the last glacial cycle (Walczak et al., 2020). Nevertheless, the controls on these dynamics remain poorly understood. In this study, we quantify the impact of glacial isostatic adjustment on the stability of Cordilleran marine terminating ice streams. We focus on the Yakutat Sea Valley ice stream, based on previous documentation of corresponding trough mouth fan formations and ice rafted debris records. For the Yakutat Sea Valley ice stream, we force a simple marine-terminating ice stream model with topographic (and associated slope) changes due to glacial isostatic adjustment over the last ice age. In particular, we explored uncertainty on the size and extent of the Cordilleran Ice Sheet during Marine Isotope Stage 3 (MIS 3) in the period leading into the Last Glacial Maximum. We seek to discover how the different plausible glacial build-up histories for the Cordilleran Ice Sheet would impact grounding line stability of marine-terminating ice streams due to differing histories of glacial isostatic adjustment (and topographic or sea-level change). Ultimately, understanding the control of glacial isostatic adjustment on grounding line stability will improve our understanding of ice sheet sensitivity to climate changes, in addition to providing a potential constraint on Cordilleran Ice Sheet configurations (volume and extent) during the last glacial build up phase through comparison with ice-rafted debris records.

Decadal-Scale Onset and Termination of Antarctic Ice-Mass Loss Tipping Points During the last Deglaciation

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Emerging ice-sheet modeling suggests once initiated, retreat of the Antarctic Ice Sheet (AIS) can continue for centuries. Unfortunately, the short observational record cannot resolve the tipping points, rate of change, and timescale of responses. Iceberg-rafted debris data from Iceberg Alley identify eight retreat phases after the Last Glacial Maximum that each destabilized the AIS within a decade, contributing to global sea-level rise for centuries to a millennium, which subsequently re-stabilized equally rapidly. This dynamic response of the AIS is supported by empirical evidence from a West Antarctic blue ice record of ice-elevation drawdown >600 m during three such retreat events related to globally recognized deglacial meltwater pulses, and a step-wise retreat up to 400 km across the Ross Sea shelf. Independent ice-sheet modeling confirms that calving and grounding line retreat co-vary on decadal scales today and that the total deglacial AIS mass loss mimics the IBRD flux rate in Iceberg Alley, with discernable tipping points for AIS re-stabilization. Our findings are consistent with a growing body of evidence suggesting the recent acceleration of AIS mass loss may mark the beginning of a prolonged period of ice sheet retreat and substantial global sea level rise.

Breaking the Ice: Understanding Large-Scale Fracture Initiation Processes of Glacier Ice through Observations of Strain Rate and Estimates of Stress in Antarctic Ice Shelves

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The conditions under which ice fractures and calves off of Antarctic ice shelves are poorly understood due largely to a lack of observations on ice fracture processes. Previous studies have estimated the stresses at which ice fractures in the laboratory and through sparse remotely-sensed observations, helping to illuminate the failure envelope of ice under various conditions. However, there remains significant uncertainty in the applicability of these results to naturally deforming glacier ice. Here, we aim to better constrain the stresses under which ice fractures using remote sensing data, which gives us a unique opportunity to explore the strength of ice on a Pan-Antarctic scale. We manually identified fractures on the Amery, Larsen C and D, Ronne-Filchner, and Ross ice shelves using MODIS Mosaic of Antarctica (MOA) imagery. After identifying fractures from MOA imagery, we compute the stress state across Antarctica from RACMO surface temperature and strain rate fields calculated from surface velocity fields derived from Landsat 7 and 8 satellite imagery. We then evaluate effective and principal stress and strain rate values along each identified rift, as well as values leading up to the rift tip and in uncrevassed areas on each ice shelf. We fit three yield criteria around our principal stress data, and we find crevasses that exist in high stress states have minimal overlap with the stress states in uncrevassed areas. Further, we find significant (~ factor of 8) intensification of strain rates leading up to active rift tips in regions such as the Loose Tooth rift system on the Amery Ice Shelf. Ongoing work is focused in these regions of intensification. Using these observations, we constrain a failure envelope for Antarctic ice shelves, which can inform models for predicting ice fracture and calving events.

New GNSS Observations of Crustal Deformation due to Ice Mass Loss in the Amundsen Sea Region

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Twelve continuous GNSS systems are deployed on bedrock across the Amundsen Embayment region, spanning the Pine Island, Thwaites and Pope-Smith-Kohler (PSK) glacial drainage network. Continuous daily position time series for these sites range from nearly 3 to 11 years, sufficient for reliable crustal motion velocity solutions at these fast-moving bedrock sites. Remarkably, multiple stations record sustained uplift of 40-50 mm/yr. Maximum uplift defined by the current distribution of sites is centered on the Pope-Smith-Kohler glaciers, where rapid thinning and grounding line retreat is well documented. Horizontal bedrock displacements, which are particularly sensitive to the location of changing surface mass loads, show a clear radial pattern with motion outward away from upstream portions of the Pope/Smith glaciers. More broadly across the Amundsen region, a zone of rapid uplift is encompassed by a zone of subsidence, mapping a bullseye pattern that can be interpreted as a broad uplift dome and narrow subsiding forebulge. Decadal mass loss documented from satellite measurements drives elastic uplift at rates of up to 20 mm/yr in the Amundsen region. Several modeling studies indicate there is also a viscous deformation response to this decadal mass loss. The Amundsen Embayment region provides an example of how very low mantle viscosity shortens the response time of the solid earth, with displacements attributable to decadal time scale ice mass change. Rapid GIA response allows for cryosphere-solid earth interactions that can alter ice sheet behavior, with significant implications for the ongoing rate and pattern of grounding line retreat in the region.

Recent thinning and speed-up may make the upper Pine Island Glacier more prone to diffusive thinning

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Pine Island Glacier in West Antarctica experienced significant speed-up and associated dynamic thinning of grounded ice in the past three decades. Most of the acceleration is driven by the changing frontal conditions, including retreats of the grounding line, calving front, and thinning of the ice shelf. However, according to the modeling results, a changing basal slipperiness or a heterogeneous plastic bed should exist to accommodate the rest of the speed-up. Changes in ice thickness and flow speed due to these basal conditions will further change the glacier's tendency to respond to future perturbations, either from the front or the bed. Under favorable conditions, a frontal perturbation can propagate further inland and destabilize a larger area upstream. We characterize this tendency for Pine Island Glacier by calculating key parameters in the kinematic wave equations using open data sets, including Bedmap2, ITS_LIVE glacier speeds, and ICESat-2 derived elevation models. Our preliminary results indicate that between the early 2010s and 2019, Pine Island Glacier slightly shifted toward diffusion thinning, which encourages a perturbation to propagate inland. This shift is most prominent in areas with reverse slopes (i.e., roughly 0-150 km from the current grounding line) but is observed further inland until 200-250 km from the grounding line. In the scenario that the grounding line continues to retreat, areas closer to the ice divide may begin to thin and speed up. The resulting strong tendency of diffusive kinematic waves can affect the entire basin and even make the ice divide migrate outward. This positive feedback cycle may eventually expand the extent of Pine Island Glacier, elevating its contribution to sea level rise.