Joint Science-Technology Planning for Greenland by the U.S. Community: Elements of the U.S. Ice Drilling Program Long Range Science Plan

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Scientific discoveries from evidence within and beneath the polar ice sheets require drilling and coring through ice and occasionally the underlying rock, a specialized and challenging endeavor that requires extensive planning, technology, and logistics. The U.S. Long Range Science Plan was established by the NSF-funded Drilling Program Office (IDPO), working with its Science Advisory Board, associated working groups, and the broader research community to articulate the direction for U.S. ice coring and drilling science for the next decade, and it drives IDPO-IDDO planning for upgrade, maintenance, and use of ice drills owned by NSF and maintained at IDDO. The full plan can be downloaded from http://www.icedrill.org/scientists/scientists.shtml#scienceplan. This brief presentation will identify science projects and associated drills in planning for Greenland that may offer opportunities for sharing logistics or drilling efforts with science articulated at this meeting. A brief overview of relevant drills will be identified, along with the path forward for requesting IDPO-IDDO drilling support for new ideas from this meeting.

Ice-sheet/lithosphere interactions and Greenland ice-sheet stability—ways forward

Richard B. Alley
with contributions from B.R. Parizek, S. Anandakrishnan, D. Pollard, N.T. Stevens and M. Pourpoint

Past stability of the Greenland Ice Sheet (GIS) may in part have been controlled by lithosphere- ice sheet interactions. GIS Holocene shrinkage was minor, yet Schaefer et al. (2016, Nature) showed major Pleistocene GIS shrinkage, despite similar-amplitude warming in the Holocene and earlier interglacials. Many explanations are possible, including importance of interglacial duration as well as peak warmth. Here, we hypothesize a role for geological interactions.

Stevens et al. (2016, JGR) showed that GIS fluctuations create peak lithospheric flexural stresses similar to dike-opening stresses in plutonic systems. The Iceland hotspot passed beneath GIS, so onset of ice-age cycling may have shifted leftover melt upward to or near the ice-sheet base.

This would have increased geothermal flux to the ice sheet followed by an ongoing decrease. Based on physical understanding and simple modeling, this would have increased and then decreased GIS sensitivity to deglaciation, helping explain earlier deglaciation yet Holocene near- stability under similar forcing. The high geothermal flux beneath parts of GIS including near the head of the Northeast Greenland Ice Stream (NEGIS) may result from this history. A search for evidence of Pleistocene subglacial volcanism, and dating of any such evidence, would help test this hypothesis. Investigations might include targeted geophysical and geological studies, and careful analysis of NEGIS offshore sediments or subglacial sediments of the EastGRIP core, perhaps followed by coring into the region near the head of NEGIS.

NEGIS: Tectonic setting, basal hydrology and surface features

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The Northeast Greenland Ice Stream (NEGIS) is unique among Greenland ice-streams in extending over 700 km inland, nearly to the ice-sheet summit. NEGIS drains ~15% of the Greenland Ice Sheet (GIS), and its large catchment, deep marine calving outlets, and onset far inland motivate special consideration in projections of future sea-level rise. NEGIS' three marine outlets suggest that it may be especially prone to ocean forcing, which could be rapidly transmitted farther into the ice-sheet interior than for other ice streams. NEGIS starts at a relatively small region of especially high geothermal flux (GHF) near the ice-sheet summit, which likely causes its unique lack of a well-developed tributary system. Here we summarize the tectonic setting (crust and upper mantle seismic velocities, which can provide constraints on temperature and heat flow), the basal hydrologic system (which likely controls the location and properties of the ice stream and margins), and surface elevation and density patterns (again, likely controls on ice stream location and margin location).

Past climates along the Greenland Ice Sheet margin: Essential inputs for assessing ice sheet stability

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Summer temperatures along the Greenland Ice Sheet margin drive a large component of ice sheet mass balance, but are poorly constrained for periods of past climate change. This seriously limits our ability to quantify the drivers of reconstructed ice sheet variations, and thus our ability to assess ice sheet sensitivity to warming and other climate change.

New proxies in paleolimnology and expanded attention to this problem have potential to yield a network of temporally continuous, quantitative paleoclimate reconstructions from lakes around the ice sheet margin. Such records can provide abundant information about both colder and warmer climates than today (e.g., during the Little Ice Age, the early Holocene Thermal Maximum, and to a much more limited extent the Eemian interglacial). In addition to quantifying the temperatures that drove past ice sheet surface melt, such work can constrain rates of past temperature change and thus elucidate timescales of ice sheet response; improve our understanding of past isotopes of precipitation and thus interpretations of iconic ice core records; and yield new insights about past changes in precipitation, accumulation and humidity over Greenland.

Holocene climate reconstruction from Greenland ice cores: A data assimilation approach to forcing paleo ice-sheet models

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Using data assimilation to investigate past climate, we integrate information from both climate models and proxy measurements. This approach does not rely on geological and geophysical measurements of past ice-sheet behavior to constrain ice-sheet surface mass balance forcing and, instead, allows investigators to use these physical measurements to directly validate ice- sheet models. We use a novel data-assimilation framework developed under the Last Millennium Reanalysis Project (Hakim et al., 2016) to reconstruct past climate over ice sheets with the intent of creating an independent surface mass balance record for paleo ice-sheet modeling. Paleoclimate data assimilation combines the physics of climate models and the time series evidence of proxy records in an offline, ensemble-based approach. This framework allows for the assimilation of numerous proxy records and archive types while maintaining spatial consistency with known climate dynamics and physics captured by the models. In our reconstruction, we use the Community Climate System Model version 4, CMIP5 last millennium simulation (Taylor et al., 2012; Landrum et al., 2013) and a nearly complete database of ice core oxygen isotope records to reconstruct Holocene surface temperature and precipitation over the Greenland Ice Sheet on a decadal timescale. By applying a seasonality to this reconstruction (from the TraCE-21ka simulation; Liu et al., 2009), our reanalysis can be used in seasonally- based surface mass balance models. Here we discuss the methods behind our reanalysis, the resulting reconstruction, and performance through prediction of unassimilated proxy records and comparison to paleoclimate reconstructions and reanalysis products.

Sampling Basal Ice Units in Greenland

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Meltwater beneath the large ice sheets can influence ice flow by lubricating the base and by softening the ice sheet when refreezing produces new warm ice. Refreezing has produced large basal ice units in East Antarctica and bubble-free ice outcropping at the edge of the Greenland Ice Sheet. Refreezing of meltwater to the bottom of the ice sheet produces distinct ice units up to 1100m thick throughout northern Greenland. These basal units consist of a core of refrozen water commonly surrounded by heavily deformed meteoric ice. Basal units are seen along the ice sheet margin where surface meltwater is the prime source of water and in the interior where basal melt is the only water source. Sampling the features along the margin is important to determine if in the future increased surface meltwater will freeze on to the ice sheet base. Sampling these feature in the interior is key to determining the influence of basal water on ice sheet structure and rheology.

History from the dirt

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Interglacial deposits in Greenland are referred to the Early, Middle and Late Pleistocene. The richest Early Pleistocene floras and faunas come from the Kap København Formation, which is a succession of clay, silt and sand in eastern North Greenland. The formation covers an area of ~ 300 km^2. It has been divided into member A and B. Member A is at least 50 m thick and is dominated by finely laminated clay and silt with rare stones. This member contains rare shells of bivalves and tests of foraminifers.

Member B is 40–50 m thick and dominated by two sandy units, which are separated by a more fine- grained unit. The sediments in member B were deposited in coastal, marine and fluvial environments. The marine fauna comprises the bivalve ocean quahog *Arctica islandica*, which is one of the most warmth demanding mollusc species found in the formation. The Kap København Formation contain a wealth of well- preserved remains of non-marine plants and animals, with many different groups represented. Vascular plants include a mixture of boreal and arctic species. Taxa such as larch, spruce, white cedar, yew, myrtle and red osier dogwood belong to the first group, whereas dryas and mountain sorrel belong to the second. All remains of wood come from small trees or shrubs and growth rings are narrow to extremely narrow, which indicate that the mean July temperature was about 6–7°C higher than today. The Greenland ice sheet could hardly have survived such warm summers and the Arctic Ocean was not covered by sea ice all year round.

The fossil flora shows that the area was dominated by forest-tundra, which grew in an oceanic type of subarctic climate. At least 210 species of beetles are present in the fauna, an impressive and surprising number when compared with the modern day beetle fauna of Greenland that comprises ~ 36 species. Ants are absent from modern Greenland, so it is remarkable that four species of ants are represented in the Kap København fauna. The insect fauna shows that humid terrestrial biotopes, forests and alpine biotopes dominated, but some species live in dry environments, including steppe and saline ponds.

The dating of the Kap København Formation is based on a number of different methods, of which the most important are biostratigraphy, palaeomagnetic studies and amino acid analyses. The biostratigraphically most important groups are mammals and foraminifers. The occurrence of the extinct rabbit *Hypolagus* sp. and the extant hare *Lepus* sp. in member B is particularly important. These genera co- occurred in North America during the time period from ~ 2.3 to 2.0 Ma. This is in good agreement with the latest age estimate based on benthic foraminifers, which indicate an age for member B of ~ 2 Ma, perhaps corresponding to one of the super interglacials that have been documented in Arctic Russia.

Other deposits that are referred to the Early Pleistocene are the Île de France Formation, the Store Koldewey Formation and the Lodin Elv Formation in East Greenland and the Pátorfik beds in West Greenland. The faunas and floras of these successions show marked similarities with the Kap København Formation.

Species-rich floras and faunas from the Last Interglacial Stage are mainly found in central East Greenland and north-west Greenland; the fossil assemblages comprise a number of warmth-demanding species, such as tree birch that do not live so far north at the present, as well as many beetle species that do not occur in Greenland today. The mean July temperature was probably ~ 5°C higher than at present. The deposits have mainly been dated using optically luminescence dating.

All interglacial deposits in Greenland are covered by till or show glaciotectonic features, but the glacial limit during the Last Glacial maximum in Greenland is poorly constrained. However, a growing body of data from the Greenland shelf indicates that most parts of the continental shelf were covered by the Greenland ice sheet during the LGM, and the ice margin may have extended to the shelf edge.

Deciphering the history and processes of Greenland's Ice Sheet(s) over thousands to millions of years using cosmogenic nuclides

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Over the past decade, we and others have made measurements of cosmogenic nuclides in Greenlandic samples of bedrock outcrops; glacial, fluvial and marine sediments; silt embedded in basal ice; and subglacial and englacial cobbles. These measurements reveal a Greenland Ice Sheet that is in places dynamic and erosive but in other places is so ineffective at eroding the bed that many hundreds of thousands of years of history are preserved in rock and sediment.

Analysis of in situ ^{10}Be and ^{26}Al in bedrock and boulder surfaces demonstrates that in some areas of Greenland, the pre- or early-icesheet landscape survives beneath the ice or at least as debris in the ice; cosmogenic nuclides in such areas integrate across many glacial/interglacial cycles and provide insight about erosional processes. In northern Greenland, ancient landscapes dominate the uplands outside today's ice margin while the lowlands have been more deeply eroded. In much of southern Greenland, erosion dominates and cosmogenic nuclide measurements can be used to inform better our understanding of when ice last melted away.

Meteoric ^{10}Be measured in silt extracted from "dirty ice" at the base of the GISP2 ice core (interpreted as 2.7 My of ice sheet stability) appears contradictory with results from sub-ice bedrock (interpreted as repeated deglaciation at the GISP2 coring site). The discrepancy can be resolved by assuming extended exposure of bedrock below the GISP2 coring site at >1.1 My and the preservation of silty basal sediment since then because of limited erosivity under ice that is otherwise frozen to the bed. Sediment rich in meteoric ^{10}Be is also found in ice sampled at the margin of the ice sheet but outwash sediment there is almost ^{10}Be free implying different sediment sources.

The offshore record, preserved in marine sediments, now analyzed at four different core sites, clearly reveals the build-up of the ice sheet during the Pliocene and its power to progressively strip pre-existing regolith. The marine record preserves the history of exposure and erosion and indicates the ice sheet has been dynamic over time, changing where, when, and how deeply it erodes the landscape. Comparison of Greenlandic marine core data with analogous data from the Laurentide and Antarctic Ice Sheets demonstrates the stability of Antarctic ice cover during the Plio-Pleistocene, a mostly absent Laurentide Ice Sheet, and a dynamic ice sheet covering and uncovering at least some parts of Greenland.

Data-model integration for ice sheets

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The full history of ice sheet stability and climate interactions is recorded in the vertical profiles of geochemical tracers in polar ice sheets. Numerical simulations of these archives promise great advances both in the interpretation of these reconstructions as well as for the validation of the models themselves. However, fundamental mathematical shortcomings of existing ice sheet models subject tracers to spurious diffusion, thwarting straightforward solutions.

I propose a new vertical discretization for ice-sheet models that resembles the layering of ice in the real world. This eliminates the issue of numerical diffusion entirely and therefore enables the synergistic integration of ice sheet simulations with ice core and radiostratigraphy data.

Dynamic response of Northern Greenland outlets glaciers to ice tongue loss and calving front retreat

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Northern Greenland outlet glaciers drain approximately 40% of the ice sheet by area, but their contribution to dynamic losses from the Greenland Ice Sheet is presently limited. Many of these glaciers terminate in large floating ice tongues, which are absent elsewhere on the ice sheet. In recent years, several northern outlet glaciers have lost large sections of their floating tongues, and produced icebergs of up to 25 km across, and tidewater margins have retreated. However, the dynamic response of outlet glaciers to losses of sections of their floating tongues and /or calving front retreat have been highly variable across northern Greenland. Here we present our current progress with numerical modelling of two major northern Greenland outlets: Humboldt Glacier and Peterman Glacier. For these experiments, we use the numerical model Ua (e.g. Gudmundsson, 2013), which uses the finite element approach, and combines internal deformation and vertically-averaged horizontal stresses. We use a variety of remotely sensed data sources to initiate the model. Humboldt Glacier's tidewater terminus exhibits very spatially variable dynamic behaviour: ice velocities and retreat rates are much higher in its northern section than in the south. This difference has been attributed to the presence of a large basal trough behind the northern section (Carr et al., 2015). Here, we use Ua to assess Humboldt's future dynamic behaviour, with particular focus on the impact of the basal trough and the role of a potential basal pinning point beneath the northern section. The neighbouring Peterman Glacier lost two major sections of its floating ice tongue in 2010 and 2012, which appeared to have little impact on ice velocities (Nick et al., 2012). Here we use the numerical model to assess the impact of removing further sections of the ice tongue and preliminary results indicate substantial ice acceleration in response to further tongue removal.

Using Radar Sounding to Constrain Temporal Changes in Subglacial Hydrology across the Greenland Ice Sheet

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Surface meltwater has long been known to contribute to seasonal speed-ups of glaciers. Data from Greenland have shown that the seasonal drainage development is key to this process. The spatial pattern of speed-ups varies widely, however, from practically no change to over 300% with similar meltwater input. What controls this variability? Why do some Greenland glaciers have such a large response while others barely notice surface melt? Here, we use multiple years of NASA IceBridge radar sounding data to answer these questions and provide new insights into the local mechanisms that control the seasonal drainage evolution for two adjacent glaciers in southwest Greenland.

Specifically, we use the reflectivity and the angular distribution of radar bed echoes to characterize the extent and the hydrological state of subglacial drainage system beneath Russell Glacier and Isunnguata Sermia. By applying this approach to two seasons of IceBridge data, we identified the first evidence of basal water storage in the wintertime beneath the Greenland Ice Sheet. Our results reveal extensive water storage on basal ridges beneath Isunnguata Sermia, while this winter storage is absent in the nearby Russell Glacier. The presence of storage primarily on ridges as opposed to basal troughs suggests that additional to bed topography, the material properties of the bed also strongly influence the subglacial drainage development. This variation in the wintertime water storage distribution explains why Isunnguata Sermia often experiences less pronounced summer velocity speed-ups relative to Russell Glacier. Together, our results provide insights into the relationship between surface melt, basal drainage and bed properties over a wide range of environment. Local conditions often determine how drainage evolves and thereby play a significant role in controlling individual catchment response to surface meltwater.

Geology and Ice Sheet Dynamics in Greenland

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Abstract: Ice dynamics and ice sheet stability is strongly influenced by the conditions at the ice sheet base and thus by ongoing interactions between moving ice and the underlying geology. Critical geological controls include subglacial bed lithology and geothermal heat flux, determined by local geology and regional tectonic setting. Despite detailed knowledge of coastal and off-shore geology, the crustal lithology, structure, age and tectonic history under the Greenland Ice Sheet have remained poorly understood. The presentation will review key scientific issues related to the geologic control on ice-flow in Greenland with an emphasis on the impact on long-term ice sheet stability.

Studying the Greenland Ice Sheet: Implications for climate past and present.

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The Greenland Ice Sheet is reacting to the recent climate change and is losing more and more mass for every year. One of our challenges in the future is to adapt to rising sea level. Looking into the past gains us knowledge on how the ice sheets react to changing climate of the past and this knowledge can be used to improver predictions of sea level rise in the future. The deep ice cores from Greenland contain information on the past climate more than 130.000 years back in time.

All the ice cores drilled though the Greenland ice sheets show that all the ice cores contain ice from the previous warm Eemian climate period, 130.000 to 155000 years before present. Is it thus clear that the Greenland Ice Sheet did exist for 120.000 years ago in this warm climate period where it was 5 ^{o}C warmer over Greenland and the sea level has been estimate to have been 6-9 m[1] higher than the present sea level?

In addition, macro fossils and DNA-determined basal deposits from the ice core sites suggest boreal forest covered Greenland before it was ice covered. A discussion of the timing of this event will be included in the presentation.

Greenland's slippery slope: examining subglacial hydrology development driven by high-elevation melt input variability

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The basal hydrological system of the Greenland Ice Sheet has direct impacts on ice dynamics. Marginal regions of the ice sheet behave similarly to Alpine glacial systems, where efficient drainage develops during the melt season, temporally limiting impact of seasonal acceleration on ice displacement. However, it is not yet clear how the higher-elevation areas, with thicker ice and shallow surface slopes, will respond as a result of increased meltwater input in a warming climate.

Here we test the effects of multiple types of high-elevation meltwater input on the development of the basal hydrologic system underlying an idealized Greenland outlet glacier, using the two-dimensional subglacial hydrology model, GLaDS. We keep the total volume of meltwater constant and test 1) firn aquifer drainage with low volume input into the basal system over a multi-year period and 2) rapid supraglacial lake drainage with high volume input over a short time period. For both systems, we also include low-elevation moulin input to initiate a realistic pressure gradient.

I will present the initial results of these experiments and discuss the sensitivity of the subglacial drainage system to the rate and location of water input. Our results have implications for understanding of the large-scale flow regime of the ice sheet in past and future climates.

Ice Flow and Ice Sheet Stability in Greenland

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The last two decades have demonstrated that accelerating outlet glaciers can rapidly impact the configuration of the ice sheet. The measured changes in ice flow are now pervasive around Greenland; most outlets that flow into the ocean have either accelerated, retreated, or both. There is good reason to point to a warming ocean as part of the cause, but the feedbacks between acceleration and thinning have moved a number of glaciers past this initial forcing, and continued retreat is likely. Whole ice sheet models have just begun to capture outlet glacier flow in enough detail that tidewater glacier physics can influence ice sheet evolution at the basin scale. When forced with warming scenarios, these more detailed model runs indicate that large-scale deglaciation may be accomplished on a millennial timescale.

Greenland firn aquifers: Remote sensing, field measurements, and modeling

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Firn aquifers contribute to the Greenland ice sheet hydrology by storing substantial amounts of liquid water year-round in regions of the percolation zone where high-accumulation and high- melt conditions are found. We conducted five field seasons in Southeast Greenland (upslope of Helheim Glacier) from 2013-2016, deploying a set of non-invasive geophysical tools (radar, magnetic resonance, seismic refraction) complemented with borehole-based hydrologic studies (firn/ice core extractions, stratigraphy, aquifer and dilution tests, water sampling) and weather stations to monitor changes throughout the year. We complement these observations with remotely-sensed data (airborne radar and high-resolution DEMs) to extend observations in space and time. For the firn column, we observe that the water-table responds to surface meltwater input while the aquifer base remains relatively stable (28 m). The water volume stored ranges between 210 and 1940 kg/m^2 integrated over the saturated firn column.

Laterally, we found that water in firn aquifers flows downhill in a conductive firn (K = 2.7 x 10^{-4} m/s), controlled by surface slope, likely discharging into nearby crevasses potentially hydrofracturing to the bed. Indirect evidence indicates aquifers have existed at least since 1993 (dataset start) and direct observations show they have recently expanded toward the interior.

We combine these with measurements of the aquifer geometry, hydraulic properties, and flow observations to develop a conceptual model of the aquifer persistence. We then integrate this conceptual model into a numerical groundwater flow model, SUTRA-ICE, in 1D and 2D. SUTRA- ICE simulates fluid flow (both vertical and lateral) through the unsaturated and saturated zones, and accounts for freezing and thawing processes. We show that the basic conceptual model can be simulated numerically, indicating that the major controls on the aquifer are adequately constrained. We also show how increasing or decreasing recharge rates can cause the aquifer to grow or shrink in response to climate change.

Translating Climate Forcing to Ice Sheet Response

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The signal of external climate forcings (such as orbital changes or anthropogenic carbon emissions) are only delivered to the Greenland Ice Sheet (GrIS) after heavy modification by a complex chain of Earth System dynamical, thermodynamical, and geochemical processes. To make matters worse, the ice-sheet/Earth system is characterized by a poorly-quantified set of feedback loops which contribute additional complexity to climate-forced ice sheet change. Here, I hope to frame the issue of GrIS stability in the context of the feedback-mediated ice sheet response to external climate forcing. In particular, I will summarize the main set of GrIS-relevant Earth system processes and ice-sheet/Earth system feedbacks. I will compare causal chains by which past and future external climate forcings reach the GrIS, and compare external forcing timescales with timescales of ice sheet response. I will share progress in implementing ice sheets in global Earth System Models, which is a very promising but remarkably challenging approach for understanding ice-sheet/Earth system interactions. Finally, I will speculate on the potential for 'missing processes' that may increase the uncertainty of model- based GrIS stability assessments in both the past and future.

Discontinuous pre-glacial regolith preserved in at least three Greenland Ice Sheet locations

Joseph A. Graly, Lee B. Corbett, Paul R. Bierman, Tom A. Neumann

An unstable Greenland Ice Sheet would frequently move its ablation zone location over time. Because ablation zones of temperate ice bodies are highly erosive, tracers of long-lived glacial presence could be stripped by mobile and erosive ice sheet boundaries. Meteoric ^{10}Be is a tracer found in high concentrations in pre-glacial regolith, and quickly accumulates during interglacial exposure, but can only accumulate under very low erosion subglacial conditions. The presence of meteoric ^{10}Be in subglacial sediments indicates an environment insufficiently erosive to remove pre-glacial or interglacial sediment.

We measured meteoric ^{10}Be concentrations at 5 marginal Greenland Ice Sheet locations: Narsarsuaq (61.2º N), Tasiilaq (65.6º N), Kangerlussuaq (67.1º N), Ilulissat (69.4º N), and Upernavik (72.6º N). We analyzed samples of ice-bound sediment at the three northernmost locations (n=34), samples of glacial-fluvial sediment at the three southernmost sites (n=10), and samples of subglacial sediment accessed through hot-water drilling in marginal areas near Ilulissat and Kangerlussuaq (n=4). Sediment-bound meteoric ^{10}Be in the basal-most layers of the GISP2 core was previously measured and is suggestive of preserved pre-glacial soil there.

All of the sampled glaciofluvial material has meteoric ^{10}Be concentrations that can be explained by subglacial processes or brief interglacial exposure. However, some of the ice bound sediment, especially at the two northern locations (Ilulissat and Upernavik), has meteoric ^{10}Be concentrations comparable to that found in the GISP2 core. This suggests that one or more sources of eroding pre-glacial regolith are supplying the ice-bond sediment delivered to the margin in northern Greenland. Alternatively, the sediment may have been supplied ^{10}Be by basal melt for order of 10^6 years in a minimally erosive setting. Either interpretation requires a stable and minimally erosive ice sheet in northern Greenland. We found no evidence for long preservation of subglacial sediment in southern Greenland, suggesting less ice sheet stability there.

Acceleration of Greenland Ice Sheet's Sliding Motion in Response to Surface Meltwater Input

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Fifteen years have passed since Zwally et al., (2002) brought to the world's attention that the Greenland ice sheet's surface speed can be highly reactive to surface meteorological conditions. Direct linkages between the generation of surface melt water, subglacial hydrological conditions, and sliding speed, were well known for mountain glaciers, but not thought to be relevant to the cold and thick ice of Greenland. Evidence that similar relationships exist in Greenland has raised questions regarding how the ice sheet will respond to future increases of surface melt: faster flow speed tends to transfer more ice from center of the ice sheet to the periphery where it undergoes melting and calving. Thus, the meltwater/sliding mechanism potentially serves to amplify mass loss in a warming climate.

However, also known from mountain glaciers is that the subglacial hydrologic system has the ability of modulate melt water inputs and sliding speed through the evolution of efficient subglacial drainage systems. Over the last decade intensive research has addressed these topics as they pertain to Greenland using observational and modeling methods. Discussions in the literature have ranged from how sensitive the ice sheet speed is to increases in melt water input, to what physics are or are-not transferable from mountain glaciers to ice sheets. This overview intended for a general audience will discuss the knowledge gained and the outstanding issues related to meltwater and sliding of the Greenland ice sheet.

Reconstructing the response of the south Greenland Icesheet (sGIS) to climate using marine sediments.

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The terrestrial geological record provides the most direct evidence for paleo ice-sheet extent and behavior, but such records are largely limited to the last deglaciation. In contrast, marine sediments can provide well-dated evidence of ice-sheet retreat through multiple glacial–interglacial cycles. The Eirik Ridge is an extensive marine sediment drift, south of Greenland, that accumulates sediments advected along the path of the deep western boundary current (DWBC). Magnetic, geochemical, mineralogical, and radiogenic properties of Eirik Ridge sediments show that crystalline basement rocks from Greenland and volcanics surrounding Iceland are the two principal sources of drift sediments. Physical property variations in Eirik Ridge sediment cores over glacial-interglacial timeframes suggests they are sensitive to the responses of the southern Greenland Ice-Sheet (sGIS) and the DWBC to variations in climate. To isolate and characterize sGIS variability we developed silt-size magnetic and radiogenic end-member fingerprints capable of discriminating sediments sourced from Iceland (DWBC transported) from those originating in southern Greenland (sGIS erosional products). Integration of end-member unmixing of core MD99-2227 sediments with the sedimentological record revealed a recurring interglacial signature of Greenlandic sourced sediments that can be related to deglaciation of the sGIS. The proportion and flux of Greenlandic derived sediment varies over the last five glacial-interglacial cycles, suggesting considerable retreat of the sGIS during marine isotope stages (MIS) 5e, 9, and 11 that contrast more modest retreat in the Holocene and MIS 7. The longer records from IODP Sites U1305, U1306, and U1307 provide a deeper time perspective, extending back to the late Pliocene warm period in U1307, and suggest near-complete deglaciation of southern Greenland prior to M2. Future drilling is now being proposed to facilitate a regional rather than a site specific understanding of the history of sGIS, the DWBC, and other paleoceanographic conditions.

Comparison of Transient Simulations of the Interglacial Climate Evolution over the Greenland in a Coupled Global Climate Model‐the Holocene vs. the Eemian

Feng He

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A synchronously coupled transient global climate simulation has just been completed with Community Climate System Model Version III (CCSM3) before, during and after the last interglaciation‐the Eemian. This transient simulation spans the periods between 140,000 years ago and 114,000 years ago, including the penultimate deglaciation (Termination II), the Eemian and the last glacial inception. In this short presentation, a comparison of simulated surface temperature evolution over the Greenland is provided between the current interglaciation (the Holocene) and the last interglaciation to investigate 1) the performance of coupled global climate models in simulating interglacial Greenland temperatures, 2) the mechanism of interglacial climate evolutions over the Greenland and 3) the mechanism for the differences of the climate evolutions between the two interglaciations. In general, CCSM3 reproduces major features of interglacial climate evolution over the Greenland, which can be attributed as the response to the major climatic forcing of the greenhouse gases, Earth's orbital variation and the Atlantic Meridional Overturning Circulation (AMOC).

Greenland Ice Sheet History from NW Greenland Margin Trough Mouth Fans

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A high-resolution sediment sequence of Neogene climate and Greenland ice sheet (GIS) development preserved on the NW Greenland margin in the Melville Bugt and Upernavik trough mouth fans (Knutz et al., 2017) provides information on the past stability of the GIS. Using seismic data mapping, Knutz et al. (2015; 2017) identified 11 progradational units on the shelf that comprise glacial-interglacial cycles. The progradational units mark 11 previous positions of the shelf break as it migrated seaward with sediment supplied by successive advances of the Greenland Ice Sheet.

Each progradational unit can be traced to contourite drift deposits on the slope allowing paleoceanographic conditions during each sequence to be reconstructed. Remarkably, topset strata that represent interglacial conditions were preserved beneath subsequent ice advances allowing paleoceanographic reconstructions of interglacial shelf environments. The shelf tills themselves may provide evidence of previous ice-free periods on Greenland in the form of terrestrial and marine fossils excavated from the fjords and via the cosmogenic isotope signatures of the sediments. An IODP proposal (Knutz and 6 co-PIs) to drill 7 sites in this sequence is in preparation with the goals of advancing knowledge on GIS glacial inception, glacial history, ice-sheet ocean interactions, and to test the hypothesis that the marine onlap sediments capping each progradational sequence represent superinterglacials (Knutz et al., 2017). A wide range of analyses is proposed to develop the chronology, paleoceanography, sedimentology and biostratigraphy of the sequence.

Knutz, P. et al., 2017. A seismic perspective on the evolution of the NW Greenland Ice Sheet. Programs and Abstracts of the 47th Annual International Arctic Workshop, 23-25 March, 2017, Buffalo, New York, p.99.

Knutz, P.C., et al., 2015, A contourite drift system on the Baffin Bay-West Greenland margin linking Pliocene Arctic warming to poleward ocean circulation: Geology 43, 907- 910.

Greenland Ice Mapping Project: Measuring rapid ice flow

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Numerous recent studies have revealed rapid change in ice discharge from Greenland, as many of the ice sheet's outlet glaciers have accelerated dramatically over the last decade. These observations are significant in that they show Greenland's mass balance can fluctuate rapidly and unpredictably. Despite the large magnitudes of these changes, we do not yet understand the underlying processes controlling fast flow well enough to determine their long-term impact on sea level. As a consequence, outlet glacier dynamics were a "wild card" in the sea-level projections included in the recent Intergovernmental Panel on Climate Change (IPCC) assessments. Improving such predictions and gaining a firm understanding of the dynamics that drive mass balance requires annual to sub-annual observations of outlet glacier variability (velocity and ice front position) to avoid aliasing of this rapidly varying signal. Since 2009 TerraSAR-X and later TanDEM-X have regularly imaged many of Greenland's fast moving glaciers in an effort to measures change in flow speed and geometry. The technology for measuring velocity in Greenland is mature and, under the ongoing Greenland Ice Mapping Project (GIMP), we have processed these X-band data to produce 8-year record of change. This record is now in the process of being extended using C-band Sentinel 1 (6-day repeat) and Landsat 8 data. Here we summarize some of the large changes that have occurred on Greenland's outlet glaciers over this period.

Climatic controls on the initiation and persistence of ice in Greenland during the Pleistocene

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Recent work has made clear that the volume of ice on Greenland during the Pleistocene has varied more than previously appreciated, with periods of stability punctuated by substantial ice-sheet collapse. Existing measurements cannot exactly constrain the history of the ice sheet, but they highlight potential scenarios that have different implications for ice-sheet stability.

Here we use a three-dimensional hybrid ice-sheet/ice-shelf model coupled to a regional climate model to investigate the controls on glaciation in Greenland during the Pleistocene. We apply multiple synthetic temperature and precipitation forcings based on Pleistocene benthic $d^{18}O$ to investigate the behavior of the ice sheet as it initiates on a pre-glacial Greenland. We find that the ice sheet shows three distinct phases: first, oscillations between little ice and a modern-size ice-sheet; second, oscillations between a modern-size ice-sheet and an LGM-size ice-sheet; and third, persistence in an LGM-like size through multiple glacial-interglacial cycles. The duration of these phases, and the timing of transitions between them, affect the exposure histories of deep ice-core sites. We directly compare these results with ^{10}Be measurements from beneath ice- core sites and around the periphery of the ice-sheet. We discuss the importance of the atmospheric lapse rate chosen to couple climate forcing to the growing ice-sheet, and suggest that externally-forced changes to the atmospheric lapse rate also be investigated as a control on the stability of the ice-sheet, especially during warm "super-interglacial" periods. We find that ice is most persistent in southeast Greenland and, surprisingly, over the DYE-3 ice core site in Southern Greenland. These results may aid efforts to locate pre-Eemian ice in Greenland, and can be tested by further investigation of the exposure history of basal material at additional sites beneath the ice sheet.

A case for understanding Greenland Ice Sheet stability

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In order to understand the current retreat and potential future instability of the Greenland Ice Sheet, we believe a critical question to answer is "under what conditions was the ice sheet most recently stable?" The last time that the ice sheet achieved equilibrium and deposited moraines was approximately 500-1000 years ago (likely during what is commonly referred to as the Little Ice Age). Since its maximum Little Ice Age extent, the ice sheet has receded in most locations indicating a negative mass balance. With an understanding of the recent ice-sheet stability, we will be able to assess the various factors that are influencing the current retreat and transition to instability. For example, determining the climate conditions that caused the ice sheet to reach its Little Ice Age extent, and defining the ice-sheet extent during this time provides two important baselines against which we can assess: 1) the magnitude of the climate forcings (e.g., temperature and precipitation changes) between the Little Ice Age and present, and 2) the magnitude of ice-sheet loss during this time. This information is critical for accurately modeling the response of the ice sheet to future climate conditions.

Carrying out this work requires a community effort. It involves defining past climate conditions including temperature and precipitation near the ice-sheet margins, remote and field mapping of maximum ice-sheet extents during the last ~1000 years, and dating of these ice-sheet extents. Ice sheet modeling is then needed to reconstruct the steady state (i.e., "stable") ice- sheet extents, and to assess the various climate forcings that influenced ice-sheet recession from the Little Ice Age to the present.

IDDO Subglacial Sampling Drill Systems: Capabilities and Results from Initial Field Seasons

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The Ice Drilling Design and Operations group at the University of Wisconsin-Madison has recently designed and fielded two drill systems for accessing subglacial environments to recover basal material. The Agile Sub-Ice Geological (ASIG) Drill System is designed to operate to a depth of 700 meters with 39mm core diameter. Future upgrades to ASIG could increase the operating depth to approx. 1000 meters. The Winkie Drill System can currently operate to 120 meters depth with 33mm core diameter. Drill system weights are highly project-dependent but range from 20-31 klbs for ASIG and 4-9 klbs for Winkie, including fuel and drilling fluid. Both systems can be deployed by light fixed- wing aircraft or helicopter and assembled without heavy-equipment support in the field. The ASIG and Winkie drill systems were used successfully in Antarctica during the 2016- 17 field season to drill through overlying ice and recover high-quality bedrock core samples.

Ice on Greenland during the Eocene-Oligocene transition

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The Eocene-Oligocene transition (~34 Ma) is one of the major climate transitions of the Cenozoic era. Atmospheric CO_2 decreased from the high levels of the Greenhouse world (>1000 ppm) to values of about 600-700 ppm in the early Oligocene. High latitude temperatures dropped by several degrees, causing a large- scale expansion of the Antarctic ice sheet.

Concurrently, in the Northern Hemisphere, the inception of ice caps on Greenland is suggested by indirect evidence from ice-rafted debris and changes in erosional regime. However, ice sheet models have not been able to simulate extensive ice on Greenland under the warm climate of the Eocene-Oligocene transition. We show that elevated bedrock topography is key in solving this inconsistency. During the late Eocene / early Oligocene, Greenland bedrock elevations were likely higher than today due to tectonic and deep-Earth processes related to the break-up of the North Atlantic and the position of the Icelandic plume. When allowing for higher initial bedrock topography, we do simulate a large ice cap on Greenland under the still relatively warm climate of the early Oligocene. Ice inception takes place at high elevations in the colder regions of north and northeast Greenland; with the size of the ice sheet being strongly dependent on the climate forcing and the bedrock topography applied.

Radiostratigraphy of the Greenland Ice Sheet and its potential constraints on millennial-scale ice-sheet stability

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In collaboration with many colleagues, I led the development of the first dated radiostratigraphy for the whole of the Greenland Ice Sheet from two decades of NASA airborne radar-sounding surveys. This radiostratigraphy reveals a wealth of new information regarding this ice sheet's three-dimensional structure and history. For example, south of Jakobshavn Isbræ, most of the ice sheet is Holocene-aged, whereas Eemian ice is mostly confined to central northern Greenland. Elsewhere, disrupted radiostratigraphy is often located near the onset of the largest outlet glaciers, suggesting a strong connection to the onset of basal sliding. This spatially extensive radiostratigraphy directly constrains the ice sheet's evolution since the beginning of the Eemian, but it is non-unique, complex and limited by the physical assumptions applied to date individual radiostratigraphic layers. A reliable assessment of the evolution of the Greenland Ice Sheet since the Eemian from this radiostratigraphy will likely require further development of testable hypotheses and advances in ice-sheet models.

Does the Laurentide Ice Sheet ever disappear? CRN data constrain the stability of the Barnes Ice Cap

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The dimensions of the Laurentide Ice Sheet (LIS) during Quaternary interglaciations remain highly uncertain. The pattern of retreat is only known with certainty for the most recent deglaciation. Although most of the LIS volume was lost by the early Holocene, the LIS continued to recede into the late Holocene, until finally stabilizing as the 6000 km^2 Barnes Ice Cap (BIC) prior to 2 ka. The BIC is sensitive to summer temperature. Unlike Greenland, the BIC rests on a high plateau, and will expand rapidly in response to modest ELA lowering. However, with the ELA now above its summit, the BIC will disappear in a few centuries, even with no additional warming (Gilbert et al., 2016 JGR; 2017 GRL). Did the LIS follow the same spatial recession pattern during previous interglacials? How frequently did the LIS fully disappear in earlier interglacials? Gilbert et al. (2017) report in situ ^{14}C, ^{10}Be, and ^{26}Al concentrations in bedrock and erratics at the margin of, and from summits near the BIC. These data confirm that previous LIS deglaciations occurred with a spatial pattern similar to the last deglaciation. CRN inventories are most consistent with a long pre-Quaternary exposure and nearly continuous burial beneath thick ice throughout the Quaternary. Furthermore, their data suggest that LIS deglaciation resulted in a residual ice cap similar to or smaller than the current BIC only during a few brief previous interglacials. We speculate that the only pre-Holocene intervals where the residual LIS was similar to or smaller than the current BIC were brief exposure during MIS 5e and MIS 11. A more focused sampling campaign along the northern BIC margin will provide better constraints on the stability of the BIC through the Quaternary and whether its projected disappearance within a few centuries is unprecedented.

Constraining and understanding the deglacial history of the Greenland ice sheet

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The large response of the Greenland ice sheet (GrIS) to climate change following the last glacial maximum provides an ideal testing ground for ice models that simulate changes of the GrIS on century to multi-millennial time scales. Furthermore, accurate model reconstructions of GrIS changes for this period are necessary to ensure that model simulations of future changes have the correct initial conditions. I will briefly review recent efforts in developing a deglacial model of the GrIS and highlight observational and modelling advances required to improve upon this model reconstruction and thus our understanding of GrIS evolution during this key period.

3D image of the Greenland lithosphere using ambient seismic noise

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I image the Greenland lithosphere down to 300 km depth with seismic noise tomography. The 3D shear-wave velocity model mostly highlights the Iceland hotspot track as a linear high-velocity anomaly in the middle crust associated with magmatic intrusions. In the upper mantle, low velocity anomalies are the signature of the past action of the Iceland hotspot when heating the Greenland lithosphere. Modelling suggests that these anomalies can be related to temperature and/or viscosity anomalies. By taking into account the 3D distribution of temperature and viscosity of the Greenland lithosphere, it will be possible to drive more accurate geodynamic reconstructions of tectonic plate motions and prediction of Greenland heat flow, which in turn will enable more precise estimations of the Greenland ice-sheet mass balance.

Modeling the response of Northwest Greenland to enhanced ocean thermal forcing and subglacial discharge

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Glacier-front dynamics is an important control on Greenland's ice mass balance. Warm and salty Atlantic water, which is typically found at a depth below 200-300 m, has the potential to triggerice-front retreats of marine-terminating glaciers, and the corresponding loss in resistive stressleads to glacier acceleration and thinning. It remains unclear, however, which glaciers are currently stable but may retreat in the future, and how far inland and how fast they will retreat.

Here, we quantify the sensitivity and vulnerability of marine-terminating glaciers along the Northwest coast of Greenland (from 72.5°N to 76°N) to ocean forcing using the Ice Sheet System Model (ISSM), and its new ice front migration capability. We rely on the ice melt parameterization from Rignot et al. 2016, and use ocean temperature and salinity from high-resolution ECCO2 simulations on the continental shelf to constrain the thermal forcing. The ice flow model includes a calving law based on a Von Mises criterion. We investigate the sensitivity of Northwest Greenland to enhanced ocean thermal forcing and subglacial discharge. We find that some glaciers, such as Dietrichson Gletscher or Alison Gletscher, are sensitive to small increases in ocean thermal forcing, while others, such as Illullip Sermia or Qeqertarsuup Sermia, are very difficult to destabilize, even with a quadrupling of the melt. Under the most intense melt experiment, we find that Hayes Gletscher retreats by more than 50 km inland into a deep trough and its velocity increases by a factor of 10 over only 15 years. The model confirms that ice-ocean interactions are the triggering mechanism of glacier retreat, but the bed controls its magnitude.

Seismic constraints on the crust and upper-mantle structure of Greenland

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The nature of three-dimensional variations in crust and mantle structure under Greenland is poorly known. Geological and geochemical constraints are largely confined to the island's ice-free margins, and little regional seismological imaging has been conducted, owing to the previous sparsity of available data. Global tomographic models typically resolve Earth structure on a lengthscale as large as, or larger than, Greenland itself. However, crust and mantle structure control the surface deformational response to loading and unloading due to changes in ice mass, and determine geothermal heat flux to the base of the ice sheet. Better estimates of laterally varying crust and mantle structure are thus important for improved modeling of deformation and ice flow. Better interpretation of seismic velocity models in terms of underlying controls from temperature and compositional variations is also needed. Modern studies of glacial isostatic adjustment (GIA) have begun to incorporate laterally varying strength parameters derived from tomographic models, but most assume that variations in mantle seismic velocity reflect only variations in temperature. This assumption is known to be violated in cratonic regions like Greenland, where compositional variations contribute significantly to seismic velocity variations in the mantle. I use seismic surface-wave data to obtain an initial set of constraints on velocity variations in Greenland, taking advantage of a dramatic increase in data availability due to the international, cooperative GLISN seismic network, and data from a two-year deployment of seismic stations designed to improve coverage. The modeling approach allows for higher resolution in regions of good data coverage while still accounting for propagation variations due to long-wavelength structure outside the region of interest. I will present initial results towards goals of improved characterization of the crust and mantle structure under Greenland and improved methods for predicting rheologically relevant parameters from tomographic models.

Stability of the Greenland ice sheet: insights from ice sheet model intercomparison projects.

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Model intercomparison projects (MIPs) of ice sheet provide a valuable tool when seeking to understand the potential evolution of ice mass in response to external drivers. The standard experimental framework and model output protocols of MIPs facilitate the assessment of the strengths and weaknesses of models, which in turn can focus the development of future models or experimental designs. MIPs can also reveal whether a given ice sheet evolution from a particular model is typical of other models, or in the case of model outliers, the framework may provide insight into the processes or assumptions that are causing the distinct response. Recent MIPs for the Greenland ice sheets have targeted very distinct time periods: the Pliocene Ice Sheet Model Intercomparison Project (PLISMIP) focused on the Pliocene warm period (between 3.264 and 3.025 Ma), while the Sea-level Response to Ice Sheet Evolution (SeaRISE) effort focused on centennial projections (between present day to 2100). This talk will present and contrast the PLISMIP and SeaRISE efforts. Due to the different timescales and climatic settings considered by PLISMIP and SeaRISE, the two efforts have very distinct participating models and experimental protocols, yet the efforts may provide insights into the stability of the Greenland ice sheet. Furthermore, the efforts do have similarities especially in the lessons learned from the inter-models and inter-scenarios considered. For example, the inter-model response may point to feedbacks or processes that are poorly or well captured by the current generation of ice sheet models. This knowledge from PLISMIP and SeaRISE may provide valuable for the design of an experimental framework for gaining insight into the Greenland ice sheet states during the Pleistocene, or during shorter interglacial timescales.

GreenTrACS *In Situ* Surface Mass Balance Measurements from the Western Greenland Percolation Zone

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Surface mass balance (SMB) now exceeds glacial discharge as the dominant term in total mass loss of the Greenland Ice Sheet (GrIS). Understanding current and future GrIS retreat and its contribution to sea level rise depends on SMB reconstructions and projections from state-of-the-art regional climate models (RCMs). However, the most commonly used RCMs show significant regional differences in their SMB reconstructions over recent decades under identical re-analysis forcing, and these differences are even larger for their SMB components (e.g. accumulation, melting and refreeze). Thus, *in situ* measurements of accumulation, melting and refreeze are critical for RCM validation, particularly in the rapidly evolving percolation zone.

Here we describe our two-year traverse of the western GrIS percolation zone to collect *in situ* SMB measurements spanning the past 50 years. Known as the Greenland Traverse for Accumulation and Climate Studies (GreenTrACS), we collected a total of 16 shallow (22-32 m) firn cores and 4800 km of ground- penetrating radar data using several systems including 400 and 900 MHz GSSI systems, a frequency modulated continuous wave system (FMCW; 6-18 GHz), and multi-offset radar systems (500 and 1000 MHz) enabling us to calculate continuous density profiles. Eight of our ice cores reoccupy sites where cores were collected during the PARCA program in 1997 and 1998, allowing us to directly assess changes in melt refreeze and firn density at these locations. Our year 1 results find significant increases in melt refreeze and density, but no significant trends in accumulation over recent decades. Our climate analyses highlight the importance of North Atlantic sea surface temperatures and blocking high pressure for the recent increase in summertime melt.

COUPLED LONG-TERM EVOLUTION OF CLIMATE AND THE GREENLAND ICE SHEET DURING THE LAST INTERGLACIAL

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The Greenland Ice Sheet (GrIS) is expected to contribute increasingly to global sea level rise by the end of this century, and potentially several meters in this millennium, but still with considerable uncertainty. The rate of Greenland melt will impact on regional sea levels. The Last Interglacial (LIG, ~129 ka to 116 ka) is recognized as an important period for testing our knowledge of climate-ice sheet interactions in warm climate states. Although the LIG was discussed in the First Assessment Report of the IPCC, it gained more prominence in the IPCC Fourth and Fifth Assessment (AR4 and AR5) with reconstructions highlighting that global mean sea level was at least 5 m higher (but probably no more than 10 m higher) than present for several thousand years during the LIG. Model results assessed for the AR5 suggest a sea level contribution of 1.4 to 4.3 m from the GrIS. These model simulations, though, did not include all the feedbacks of the climate system and the GrIS.

Here, we examine the response of the Arctic climate system and the GrIS in simulations with the Community Earth System Model (CESM) fully coupled to the Community Ice Sheet Model (CISM), using a surface energy balance scheme and without bias corrections. The analysis focuses on how the GrIS responds to the imposed high boreal summer insolation of the LIG and in addition, to the long-term feedbacks of high-latitude vegetation changes. Results highlight the evolution of the ice sheet and the surface mass balance (patterns of ablation and accumulation) as compared to data-based reconstructions for the LIG. We conclude with a discussion on how the LIG may be informative as a potential process analogue for the GrIS response for future centuries to come.

Beyond the Ice Sheet (In) Stability Binary

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The theories of ice sheet instability (both marine and terrestrial) have shown that climate change can force ice sheets into irreversible collapse. However, in recent years many studies have shown that the rate of this ice sheet collapse under dynamic instability can vary significantly depending on the physical ice sheet environment. This talk is a short overview of recent work to advance classical mathematical analyses of the marine and terrestrial ice sheet instabilities. We show that there are two forms of the marine ice sheet instability that occur at very different time scales on very different bed topographies. We also discuss a revised theory for terrestrial ice sheet multi-stability and collapse, which incorporates critical aspects of ice sheet geometry to explain deglacial accelerations in sea level rise. The speed of these marine ice sheet instabilities plays a critical role in amplifying ice sheet projection uncertainty associated with future climate forcing. Based on this uncertainty, we advocate for the use of stochastic ensemble approaches in simulating future ice sheet evolution.

Direct constraints about the Greenland Ice Sheet Stability from Cosmogenic Nuclide Analyses of the GISP2 bedrock core and $^{40}Ar/^{38}Ar$-dating of basal ice of the GRIP ice core

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The Greenland Ice Sheet (GIS) contains the equivalent of 7.4 meters of global sea- level rise. Its stability in our warming climate is therefore a pressing concern. However, the scarcity of direct constraints of both, the palaeo-stability of the GIS and the age of the oldest ice on Greenland[1] means that the history of the GIS fluctuations over the last million years remains controversial (for example [2] vs. [3]).

Here we compare recent and new cosmogenic nuclide analysis of a bedrock core underneath the GISP2 ice core with argon isotope dating of air trapped in basal ice underneath the GRIP and DYE-3 ice cores [4].

The published ^{10}Be and ^{26}Al results of the GISP2 bedrock core show that Greenland was nearly ice-free for extended periods during the Pleistocene (2.6 Myr -11.7 kyr ago) [5]: the longest period of stability of the present ice sheet that is consistent with the data is 1.1 Myr, assuming that this was preceded by more than 280 kyr of ice-free conditions, but more dynamic GIS scenarios are also possible. New ^{36}Cl (half-life ~ 0.3 Myr) data from feldspars separated from the same bedrock core further narrow the range of possible GIS scenarios. Argon isotope dating of air from the silty basal ice of the nearby GRIP core gives a minimum age 970 ± 140 ka, suggesting that the GIS survived the interglacial periods over the last million years [4]. We discuss the implications of these direct, complementary and apparently controversial constraints about ice-free periods at Greenland summit and the presence of antique Greenland ice for the past, present and future GIS stability.

References:

1 Members, N. C. Eemian interglacial reconstructed from a Greenland folded ice core. *Nature* **493**, 489-494 (2013).

2 de Vernal, A. & Hillaire-Marcel, C. Natural variability of Greenland climate, vegetation, and ice volume during the past million years. *Science* **320**, 1622-1625, doi:10.1126/science.1153929 (2008).

3 Bierman, P. R., Shakun, J. D., Corbett, L. B., Zimmerman, S. R. & Rood, D. H. A persistent and dynamic East Greenland Ice Sheet over the past 7.5 million years. *Nature* **540**, 256-+, doi:10.1038/nature20147 (2016).

4 Yau, A. M., Bender, M. L., Blunier, T. & Jouzel, J. Setting a chronology for the basal ice at Dye-3 and GRIP: Implications for the long-term stability of the Greenland Ice Sheet. *Earth and Planetary Science Letters* **451**, 1-9 (2016).

5 Schaefer, J. M. *et al.* Greenland was nearly ice-free for extended periods during the Pleistocene. *Nature* **540**, 252-255, doi:doi:10.1038/nature20146 (2016).

Using cosmogenic isotopes to reconstruct Greenland's minimum Holocene ice extent

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Cosmogenic isotopes are now routinely used to build chronologies of ice sheet and glacier change during intervals when ice was larger than today. However, reconstructing the dimensions of ice sheets or glaciers when these ice masses were smaller than today is more challenging due to the simple fact that any evidence on the landscape that once marked the position of a retracted glacier margin has since been overrun by ice re-expansion. One approach that can help address this problem is measuring the concentration of cosmogenic isotopes in 1) bedrock that still rests beneath the modern ice sheet footprint (see Schaefer, this meeting), and 2) bedrock fronting the modern ice margin that has just recently become exposed to the atmosphere. Here, we will briefly outline a new effort to constrain the magnitude of inland retreat of the southwestern Greenland ice sheet margin during the Holocene using a combination of coupled *in situ* ^{14}C-^{10}Be measurements from recently exposed bedrock surfaces paired with unique sediment packages in "threshold" proglacial lakes fronting the ice margin.