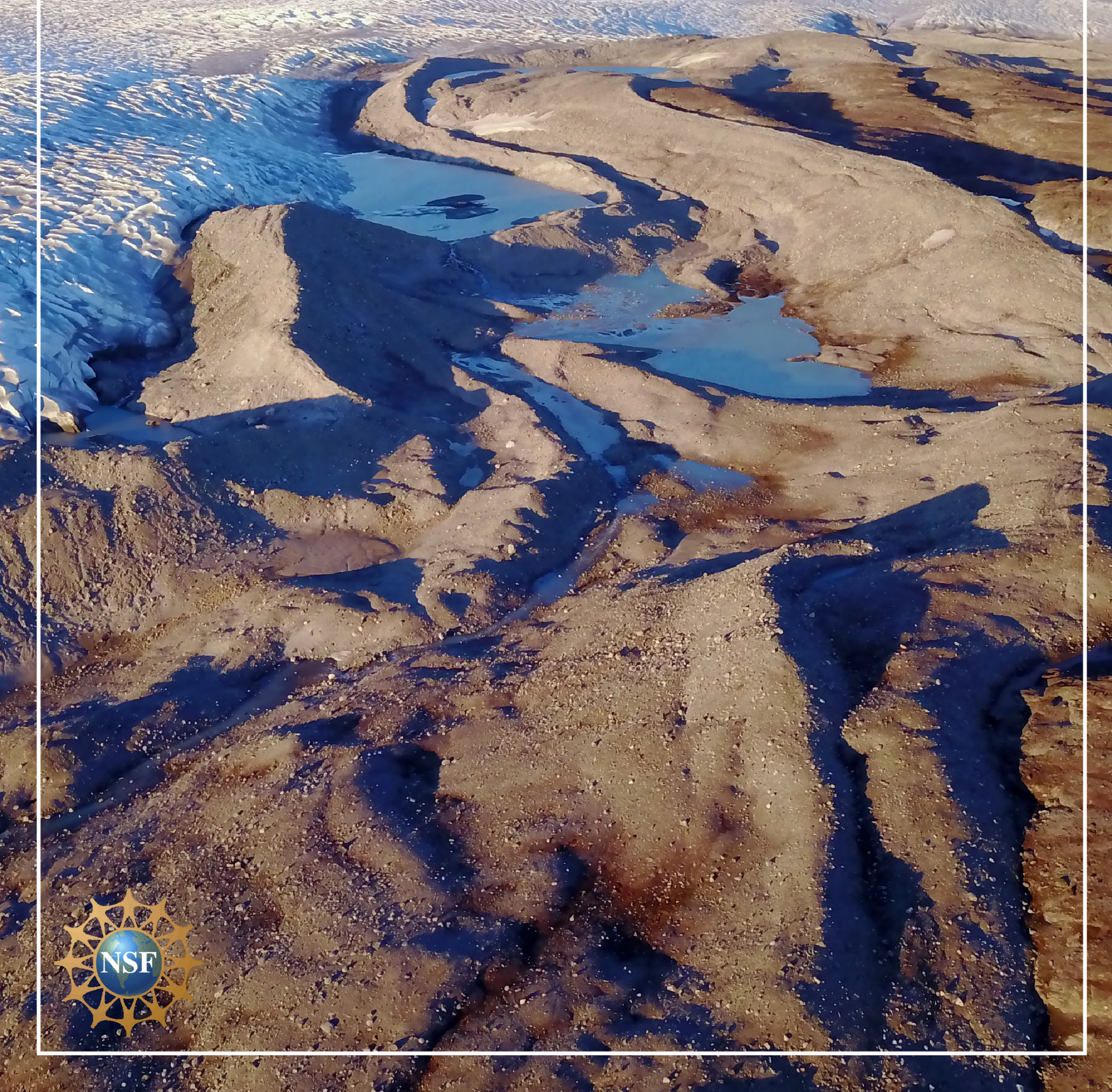
How stable is the Greenland Ice Sheet?

A white paper produced by the participants of an NSF-supported workshop
Buffalo, NY September 10-12, 2017



FRONT MATTER

White paper authored by: Briner, J.P., Alley, R.B., Bender, M.L., Csatho, B., Poinar, K. and Schaefer, J.M., with input by Axford, Y., Born, A., Hatfield, R., Jennings, A.J., Keisling, B., Kelly, M., Langebroek, P., Miller, G.H., Morlighem, M., Osterberg, E.C., Otto-Bliesner, B., Robel, A. and Young, N.E.

Photo credits: Jason Briner, Ian Joughin

This report nucleated from presentations and discussions held at a NSF-sponsored workshop on Greenland Ice Sheet stability in Buffalo, NY that took place September 10-12, 2017.

This work was supported by National Science Foundation grant "The Stability of the Greenland Ice Sheet," award No. OPP-1741833.

Table of Contents

Executive Summary

In the wake of devastating flooding related to recent hurricane strikes on heavily inhabited areas, the potential impact of sea level rise has never been clearer. Peak storm surges from Superstorm Sandy and Hurricane Harvey averaged 2 m, and peaked at about 4 m. Greenland's ice, if fully melted, would raise global sea levels more than 7 m. Thus, scientists are focused on the future behavior of the Greenland Ice Sheet. Warming will cause ice loss and sea-level rise, but the rate and amount of rise remain notably uncertain. Models matching reconstructed ice sheet changes over recent decades and millennia generally project significant future melting of Greenland in response to warming expected over the coming decades.

The latest data available to the scientific community – on emerging dynamic processes of ice sheets in general, and on new knowledge of Greenland Ice Sheet history specifically – paint a worrisome picture for the future stability of the Greenland Ice Sheet. For example, some recent pilot results suggest that modest warming in geologically recent times caused much greater ice loss and sea-level rise than projected by most ice sheet models. One possible interpretation is that existing models are substantially underestimating future sea-level rise, raising greater concerns about the impacts of future warming on coastal populations, global economies, and national security.

At present, we do not have data or models that allow for a definitive consensus view of Greenland Ice Sheet vulnerability to climate change. Furthermore, the apparent conflict within existing datasets raises fundamental questions that can guide future research on a variety of climate and glacier research topics, improving overall projections of sea-level rise. For these reasons, there is urgency in defining priorities for significantly improving knowledge of Greenland Ice Sheet vulnerability to climate change. In particular, the scientific community has the overarching task of delivering improved constraints for assessing the likely contribution of the Greenland Ice Sheet to sea level over the next decades and beyond. The time is ripe for a coordinated, interdisciplinary initiative including new direct information about Greenland Ice Sheet stability, ice sheet processes and new ice sheet simulations framed by new data assimilation.

A community of experts gathered in September 2017 in Buffalo, NY for an NSF-sponsored workshop on the stability, past and future, of the Greenland Ice Sheet. The group consisted of scientists primarily from three backgrounds: (1) geologists who study ice sheet and climate history, (2) glaciologists who examine (or isolate) physical glacier processes and (3) numerical modelers who simulate ice sheet response to climate change. Over the two-day workshop, the community pulled together the current state of knowledge of Greenland Ice Sheet stability and identified new opportunities for how

best to improve it. The group established a realistic set of research priorities for closing knowledge gaps that limit our ability to project Greenland Ice Sheet collapse. Appendix items contain the workshop program, abstracts and list of participants.

Future research prioritized by the community:

1. *New geologic data from key locations*. Recent investigations have focused on the bed of the ice sheet, including studies of basal ice and subglacial rock. This work would include studies of cosmogenic isotopes in rock under the ice sheet and in presently unglaciated areas, and require new drilling technology designed for fast and relatively inexpensive drilling to and into the bed. An important objective is to characterize ice sheet size during the Holocene and previous interglaciations (how small was it?). Ice margin reconstructions from the Holocene are particularly important because they provide the best opportunity to constrain *rates* of ice sheet change, a critical constraint for ice sheet modeling and improving knowledge of ice sheet sensitivity.

Additional key data should be captured over targeted intervals in the Quaternary, such as from the early and middle Pleistocene, the last interglaciation, and the last deglaciation and Holocene. Critical datasets include sampling of marine sediments for fluxes of ice sheet-derived sediments and regolith depletion, records of paleoclimate, particularly to more accurately reconstruct early and middle Pleistocene climate forcing, and glacial geologic and paleoclimatic data from the Holocene.

2. *Highly focused numerical ice sheet modeling in several key directions*. These include targeted experiments addressing existing ice sheet presence/absence and ice thickness datasets, coupled modeling including erosion and cosmogenic isotopes, paleoclimatic data assimilation, sensitivity experiments on effects of resolution and inclusion of “fast” physics on paleo-simulations, and improved ensemble exploration of parameter space and uncertainties. These exercises could provide model-based support for selecting optimal sites to obtain additional sub-ice data.

3. *Improved knowledge of ice sheet dynamics*. This is required on several fronts for the next generation of ice sheet models, including glacier hydrology and calving terminus dynamics. Improving understanding of positive feedbacks that increase vulnerability to collapse (e.g., albedo, elevation) is also critical. This progress must rely on increased efforts to extend and couple contemporary observations, process-scale modeling, and climate and ice sheet-scale modeling sensitivity experiments.

4. *Geophysical exploration of key ice sheet boundary conditions*. These quantities include constraining tectonic or geothermal forcings on the ice sheet through time; studying present-day locations of high geothermal flux; and searching for evidence of Quaternary volcanism at the bed.

5. *Improving cross-disciplinary collaboration*. It was very clear throughout the workshop, and specifically voiced during the breakout groups, that many of the above targets for research would advance most efficiently as *multi-disciplinary efforts*. Future research efforts need data-process-model-technology integration and coordination.

1. Introduction

The Greenland Ice Sheet (Figure 1) comprises 7.4 meters of sea level equivalent. Thus, even subtle changes in its mass balance can influence sea level change in populous regions and affect global economies. Because of this, significant resources have been invested in monitoring present-day Greenland Ice Sheet change. Resources also have been deployed to understand the history of Greenland, both in terms of paleoclimatic ice core records and fluctuations of the ice sheet's overall size as a key factor in the planet's oscillating climate (Alley et al., 2010).

The Antarctic, where major outlet glaciers that flow along reverse bed slopes threaten to collapse the West Antarctic Ice Sheet, has drawn considerable recent attention (e.g., Alley et al., 2005; DeConto and Pollard, 2016). However, mounting evidence suggests that the Greenland Ice Sheet may also be a source of rapid and significant sea-level change. New cosmogenic isotope data from a rock core collected below the ice sheet at Summit, central Greenland, reveal that the ice sheet may not be as stable as previously thought. There, measurements of cosmogenic isotopes demand the absence of ice at the GISP2 summit drill site for significant intervals of the Pleistocene (Schaefer et al., 2016). Additional independent studies also indicate that Greenland was periodically ice-free (or "nearly ice free") during interglacials of the last ~ 1 Myr. Perhaps Greenland was never completely deglaciated, given mountainous terrain that likely remains glaciated even during absence of continental-scale ice (e.g., Willerslev et al., 2007; Reyes et al., 2014). On the other hand, data from ice cores in central Greenland (e.g., Bierman et al., 2014; Yau et al., 2016) and from offshore sediment records (e.g., Bierman et al., 2016) that have been interpreted to suggest the long-term persistence of the ice sheet (albeit highly dynamic), and provide evidence that at least some ice has persisted for at least ~1 million years (Yau et al., 2016). A hybrid view comes from Yau et al., (2013). They concluded that the GIS lost enough ice during the Eemian to contribute ~ 5 m of global sea level rise, but Summit remained glaciated. These studies point to a dynamic but generally resilient ice sheet.

Given the information presently available, the vulnerability of the Greenland Ice Sheet

GLOSSARY

Last Interglaciation. 130-115 ka; also known as marine isotope stage (MIS) 5e or the Eemian; the interglacial period prior to the Holocene.
MIS 11. Marine isotope stage 11; ~420-400 ka. An unusually long interglacial period (most are ~10 kyr).
Pliocene. 5.3-2.6 Ma; a time of relative warmth and high CO_2 prior to decreasing CO_2 and cooling of the Quaternary.
Quaternary. 2.6 Ma to present; the present Ice Age period on Earth, characterized by dozens of glaciations and interglaciations.
Pleistocene. 2.6 Ma to 11.7 ka. All of the Quaternary except the present interglaciation.
Holocene. 11.7 ka to present; the present interglaciation; the rise of civilizations.
Mid-Pleistocene transition. A time around one million years ago when oscillations in global ice volume switched from ~40-kyr periodicity before the transition to ~100-kyr periodicity more recently.

to global warming remains uncertain. Our ability to project what the future may hold for Greenland can be no better than our understanding of how the ice sheet responded to climate change in the past. For this reason, the history of the Greenland Ice Sheet is a critical target for further study. In turn, this history provides an opportunity to understand ice sheet response to climate change using numerical modeling. These ice sheet models require a thorough treatment of dynamical glacier processes. This white paper makes the case that the community is now in a position to tackle this task with a novel and direct interdisciplinary scientific approach. We begin by first providing an overview of what is known about the history of the Greenland Ice Sheet. Next, we discuss how this history serves as a target for a fuller understanding of ice sheet response to climate change.

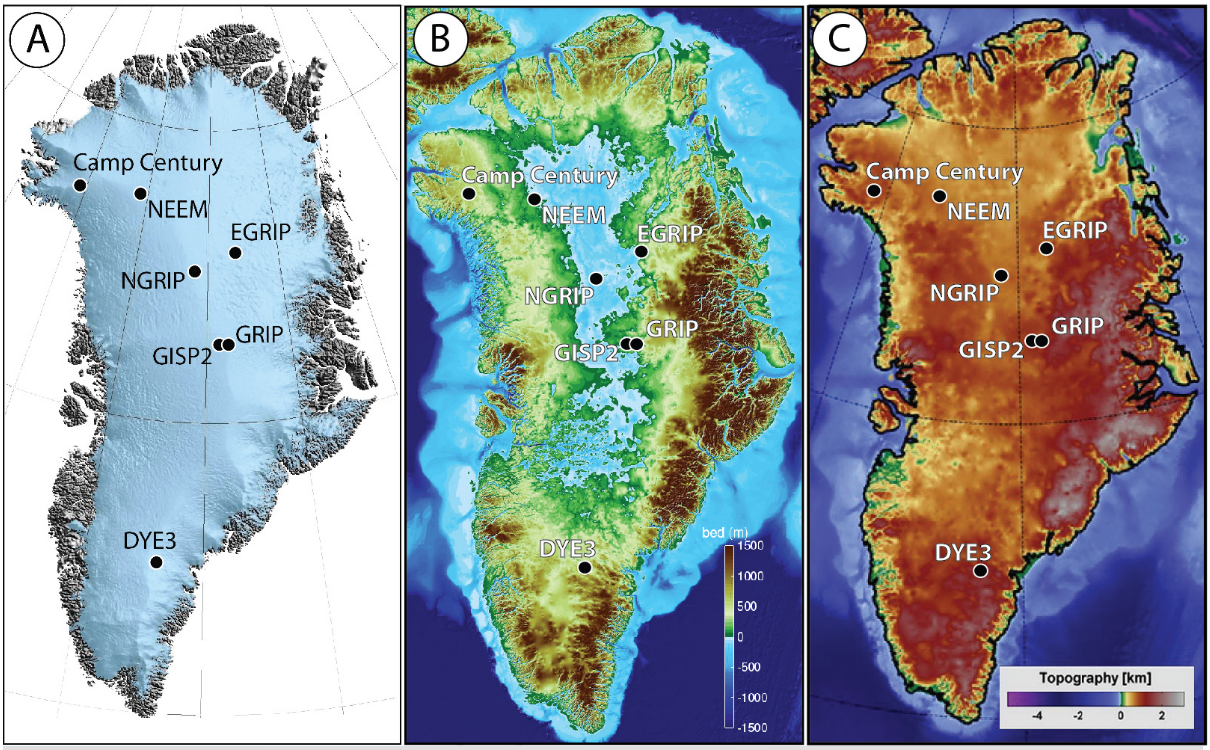


Figure 1. A) Present extent of the Greenland Ice Sheet, showing major ice core sites. B) Isostatically depressed topography of Greenland and surrounding seas from BedMachine v3 (Morlighem et al., 2017). C) Isostatically rebounded topography of Greenland bedrock (Medvedev et al., 2013).

2. The history of the Greenland Ice Sheet

Continental-scale ice sheets initiated in the Northern Hemisphere (Cordilleran, Laurentide and Greenland ice sheets in North America, Fennoscandian ice sheet in Europe and Asia) ~2.6 to 2.4 Ma (Ruddiman and Raymo, 1988). The Laurentide Ice Sheet, for example, extended south to 39°N in the Midwest US at ~2.4 Ma (Balco et al., 2005). Evidence for the onset of ice growth on Greenland comes largely from the surrounding oceans via records of ice-rafted debris. These data suggest that ocean-

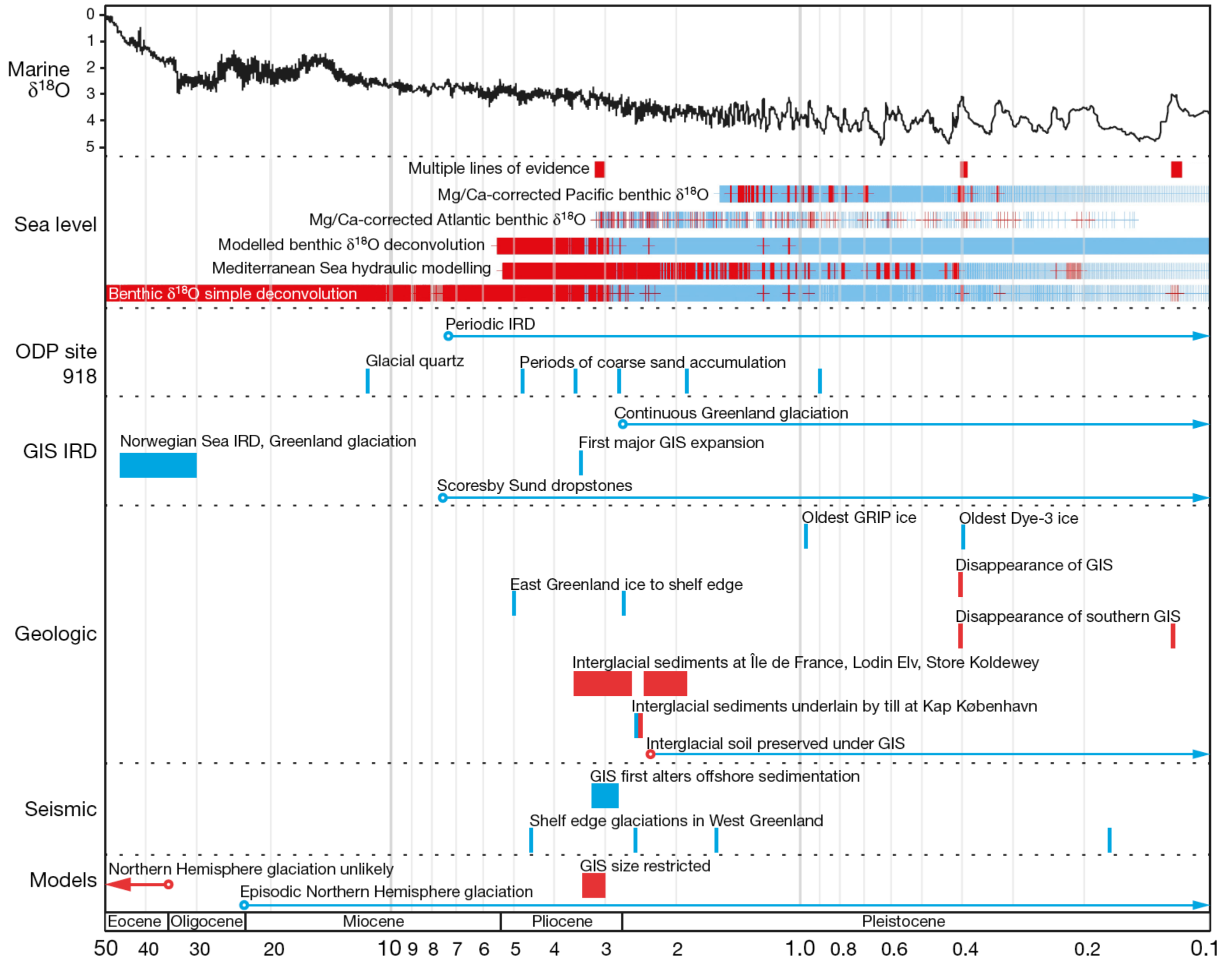


Figure 2. Compilation of some key records that constrain the history of the Greenland Ice Sheet (from Bierman et al., 2016; see original reference for data sources). Red = smaller ice; blue = larger ice.

terminating glaciers existed on Greenland as early as the Eocene (see Figure 2; Thiede et al., 1998; 2011; Eldrett et al., 2007). However, direct records of when Greenland ice grew to the continental scale are scarce. Two such records are ice-contact deposits on the continental margin off East Greenland that date to ~2.5 Ma (Larsen et al., 1994; Solheim et al., 1998), and intensifications of ice-rafted debris deposition in the North Atlantic at 3.3–2.4 Ma (Kleiven et al., 2002). Thus, it appears that continental ice advanced far onto the continental shelf, at least in East Greenland, by ~2.5 Ma.

The marine oxygen isotope stratigraphy of the oceans (Lisiecki and Raymo, 2005; Figure 3) has long been the standard template for Quaternary glaciation. This record reveals steadily growing (albeit oscillating) global ice volume since the Plio-Pleistocene transition. This has led some to suggest that sizeable ice sheets were relatively persistent since their inception at ~2.5 Ma (e.g., Bierman et al., 2014). However, sediment formations on North and East Greenland dating to 1.8 to 2.2 Ma (with notable age uncertainties) contain fossil assemblages (e.g., larch forests), indicating sufficiently high temperature to demand a more or less ice-free Greenland at this time (Funder et al., 1985; Bennike et al., 2010). Apparent inconsistencies such as these led Thiede et al. (2011), in a relatively recent review of Greenland Ice Sheet history, to comment on glaciation after ~2.5 Ma: "the timing of glaciation on Greenland and whether it has been glaciated continuously since are wide open questions of its long term history."

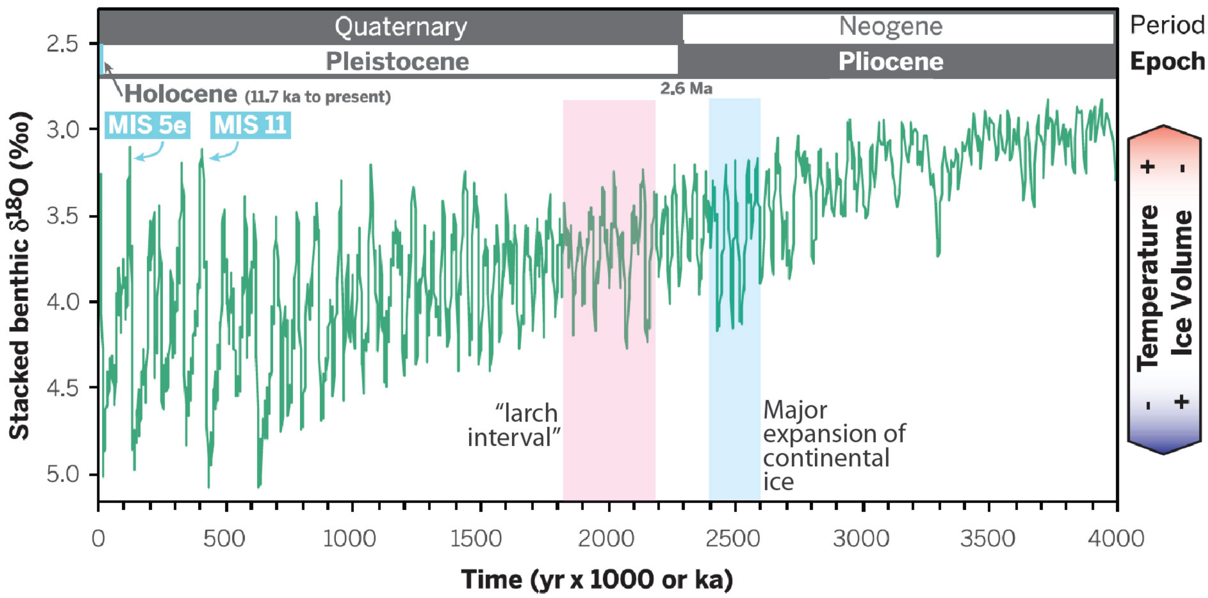


Figure 3. Marine oxygen isotope ($\delta^{18}O$) record of global ice volume spanning the last 4 Myr (Lisiecke and Raymo, 2005). Of note are the oscillations in global ice volume that likely were in part driven by Greenland Ice Sheet's history. Is it the exception that Greenland is free of continental ice during interglacial excursions, or the rule? Marine isotope stages (MIS) discussed in text are noted. Modified from Dutton et al. (2015).

Data from basal sections of ice cores have made an important contribution to our understanding of the history and stability of the ice sheet. The longest Greenland ice core records discontinuously extend at least to the penultimate glacial (MIS 6) and some stratigraphically disturbed ice core samples almost certainly extend to Marine Isotope Stage (MIS) 7 (~240 ka) (Suwa et al., 2006). Recent trapped-air studies support the antiquity of basal ice, suggesting that basal ice at the GRIP site (central Greenland) dates to ~1 Ma, and to ~430 ka at the DYE-3 site (south Greenland), with large uncertainties (Yau et al., 2016). These ages agree with coarser estimates obtained through a variety of methods (Willerslev et al., 2007). Collectively, these data suggest that basal ice at the DYE-3 site dates from before the Last Interglaciation, and basal ice at the GRIP site dates from well before MIS 11.

Other lines of evidence seemingly conflict with apparent sustained glaciation on Greenland. For instance, the "larch interval" suggests widespread deglaciation between 1.8-2.2 Ma, and ocean sediment proxy records are interpreted as recording a significant reduction in ice extent during MIS 11 (e.g., deVernal and Hillaire-Marcel, 2008; Reyes et al., 2014; Hatfield et al., 2016). During any such period of significantly reduced ice, however, mountainous terrain in eastern Greenland would likely harbor glaciers. Contrasting results could be reconciled if, following a nearly ice-free period during MIS 11, ancient ice in the eastern highlands flowed westward across the GRIP site. This would be akin to today's situation in western Greenland, where areas that were ice free in the Holocene were re-glaciated and are now covered by ice that predates the Holocene (Young and Briner, 2015).

To summarize, existing datasets are mostly in agreement that ice in southern Greenland did not survive MIS 11 but did survive the Last Interglaciation. There remains much to be learned about the history of ice in central Greenland; trapped air records are compatible with some ice surviving even during MIS 11, whereas other records point to deglaciation in central Greenland at that time. Knowledge of ice sheet size during other interglacial periods is even more limited (cf. Hatfield et al., 2016), particularly between MIS 11 and the 1.8-2.2 Ma "larch interval."

3. A pair of papers in *Nature*

A major recent addition to the collective dataset on the stability of the Greenland Ice Sheet was unveiled in a pair of papers published in *Nature* in December 2016. We draw special attention to them here because their recent publication (along with the news pieces that accompanied them) provides an opportunity to assess our collective understanding of Greenland Ice Sheet stability across multiple lines of evidence.

In one *Nature* paper, Bierman et al. (2016) presented cosmogenic isotope data from sand grains in an ocean-sediment core off southeastern Greenland (Figure 4). They used ^{10}Be eroded from Greenland bedrock and delivered to the seafloor to infer the long-term build-up of the Greenland Ice Sheet through the Quaternary. The data were interpreted to suggest episodic yet overall expanding glaciation in the

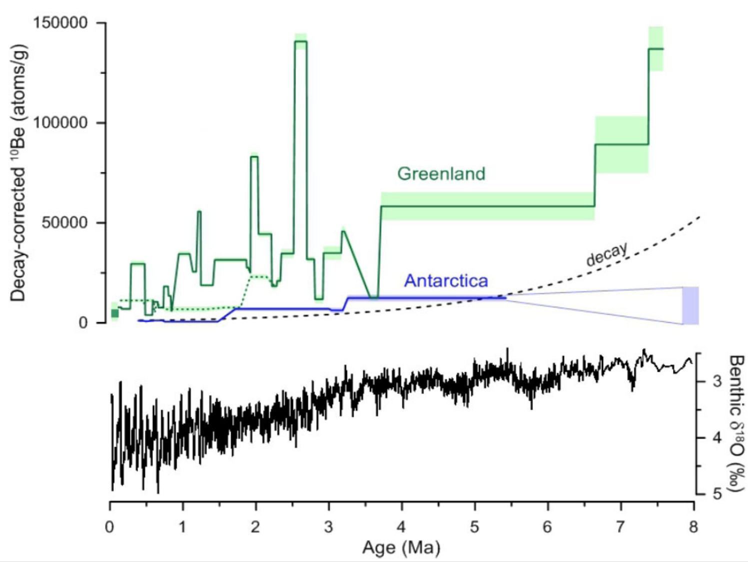


Figure 4. ^{10}Be data from ocean sediments offshore east Greenland (green curve; Bierman et al., 2016), alongside similar data from Antarctica and global ocean δ^{18}O data (Shakun, unpublished). The Greenland data suggest that although the Greenland Ice Sheet increased in size through time, it exhibited volatile behavior.

mountainous areas of eastern Greenland since 7.5 Ma, a conclusion that "challenges the possibility of complete and extended deglaciation over the past several million years" (Bierman et al., 2016).

In the other *Nature* paper, Schaefer et al. (2016) reported a surprisingly high concentration of cosmogenic nuclides (^{10}Be and ^{26}Al) in rock below the GISP2 site, which requires ice-free conditions for considerably longer than a few interglaciations in central Greenland (Figure 5). Models indicate that when ice over GISP2 bedrock is deglaciated, more than 90% of the ice sheet has melted. The nuclide measurements also put an upper bound of 1.1 Myr on the time that ice has continuously occupied the GISP2 site. These data support a scenario of periodic exposure during many of the interglacial periods in the Quaternary.

At first glance, these studies appear to reach opposite conclusions, yet they are not strictly inconsistent with one another. Bierman et al.'s (2016) findings provide information on the generalized ice extent along eastern Greenland, where one might expect localized glaciers to persist even during warm and long interglacials. Furthermore, there is ample room within the temporal resolution of their dataset for extensive deglaciation during interglacial periods. Schaefer et al. (2016), on the other hand, reconstructed ice cover in central Greenland directly, and thus mainly constrained the behavior of continental ice.

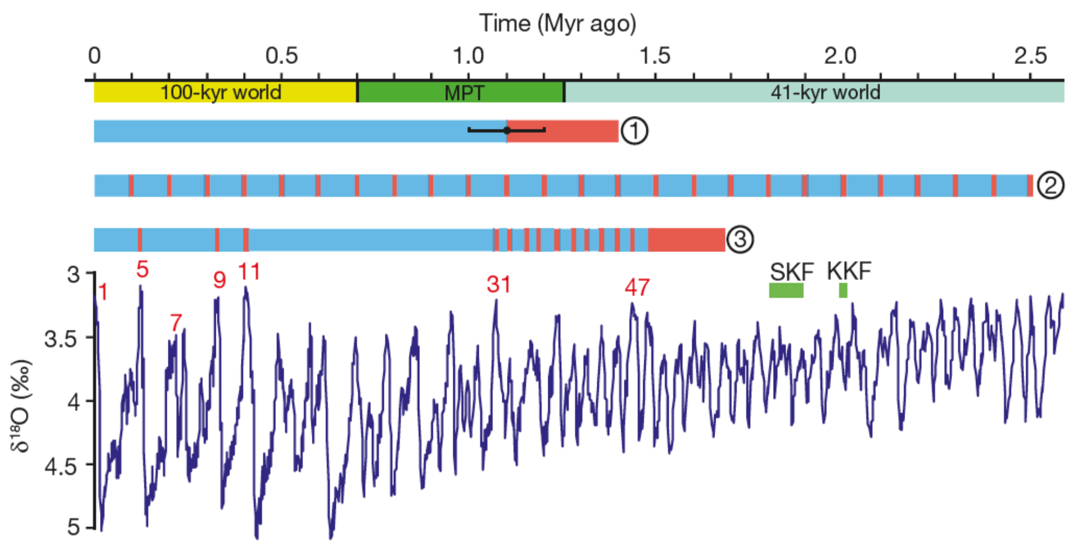


Figure 5. Blue and red bars are scenarios for ice sheet histories consistent with cosmogenic ^{10}Be and ^{26}Al data from the Greenland bed at the GISP2 core site (from Schaefer et al., 2016). Blue indicates Greenland Ice Sheet presence; red is absence. Scenario 1 is the limiting case for recent stability, with 300 kyr of exposure followed by 1.1 Myr of ice sheet occupation; the data do not allow the ice sheet to have continuously existed over GISP2 for longer than 1.1 Myr. Scenarios #2 and #3 are more realistic histories based on what we know about the climate history of Earth; they include many times during the Quaternary when the ice sheet was absent at the GISP2 core site (see Fig. 1). MTP=Mid-Pleistocene Transition; SKF/KKF are sediment formations interpreted to require ice free Greenland.

4. Did the Greenland Ice Sheet ever melt completely in the Quaternary?

The pair of *Nature* papers highlight this question, whose answer is still debated. Judging by trapped gas records in basal ice, the answer is no: these records suggest that ice persisted in central Greenland for at least the past ~1 Ma, and therefore possibly through the Quaternary. If, on the other hand, one trusts the chronologies and interpretations of sediment formations on Greenland, then the answer is yes: continental ice on Greenland was largely or completely removed sometime after it first grew. For example, the "larch interval" (dating to ~1.8-2.0 Ma) post-dates periods of major expansion of Greenland ice onto its continental shelves (2.5 Ma and/or earlier). If one trusts current reconstructions and attribution of global sea level data (Raymo and Mitrovica, 2012), then MIS 11 is another time when a significant retreat of the Greenland Ice Sheet occurred, which is also supported by indirect proxy records from ocean sediments (e.g., Reyes et al., 2014). And finally, the Schaefer et al. (2016) data suggest that central Greenland became ice free not just during these specific intervals, but during many interglacials.

A more targeted question regarding ice sheet stability is whether it is the norm or the exception for Greenland to be ice free during periodic Quaternary interglacials – and furthermore whether the periodicity of major ice sheet retreat changed in the Quaternary. It is possible that our view is skewed toward the stability of continental ice on Greenland because the Greenland Ice Sheet is present today, whereas neighboring nucleation areas of the largest continental ice sheets (e.g., northern Canada and Scandinavia) are largely ice free at present. What if the present pattern is not the norm? There are some data to support this. Preliminary cosmogenic isotope data from bedrock at the margin of the Barnes Ice Cap, which lies at a nucleation point of the Laurentide Ice Sheet, suggest that the Laurentide Ice Sheet almost never fully deglaciated during Quaternary interglaciations (very rare exposure, very long burial; Gilbert et al., 2017), but a more directed sampling and analytical effort is required to confirm that interpretation. The Laurentide results suggest less exposure and more burial during the Quaternary than do the cosmogenic data from central Greenland (Schaefer et al., 2016). Hatfield et al. (2016) also found, from 430,000 years of ocean sediments, that "the extent and stability of

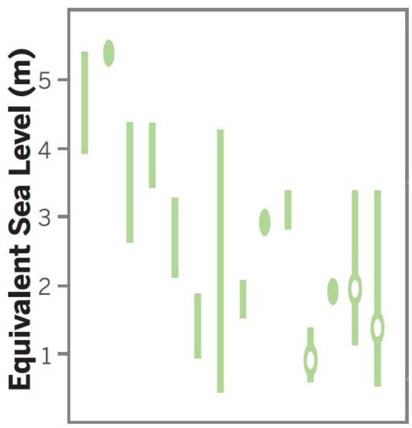


Figure 6. Estimates of sea level equivalent derived from the Greenland Ice Sheet (GrIS) during the Last Interglaciation (ice sheet total is 7.4 m). Compiled by Dutton et al. (2015); see original reference for data sources.

the southern Greenland Ice Sheet in the Holocene is anomalous in the context of late-Quaternary interglaciations."

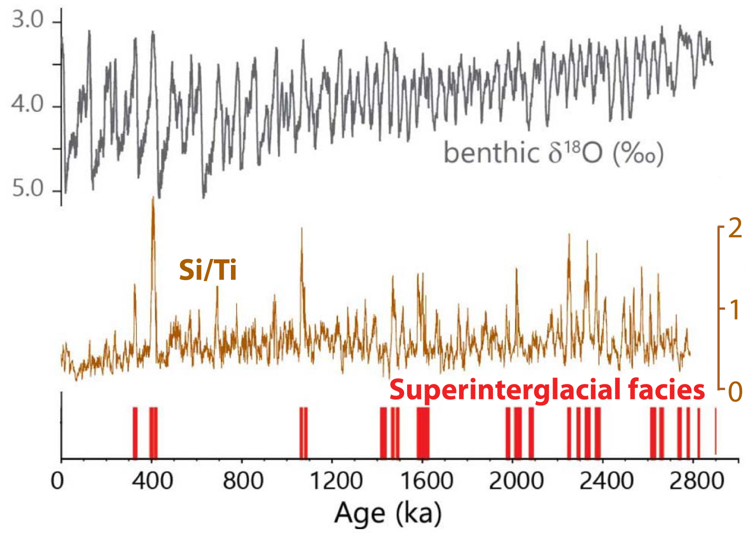


Figure 7. Arctic Superinterglacials from the sediment record (the Si/Ti ratio and facies data are shown here) at Lake El'gygytgyn (from Melles et al., 2012).

There are simply not enough data to know for sure, but if Greenland became ice free more regularly prior to a million years ago than since, it could be due to either (or both) climate change or non-climatic factors. In terms of a climatic cause, a recent characterization of Arctic terrestrial climate through the Quaternary described 15 "superinterglacials" that were exceptional in warmth compared to other interglacials (Melles et al., 2012). These include MIS 11, but not MIS 5e, and so are perhaps consistent with data, described above, that suggest an ice-free Greenland at MIS 11, but ice cover at MIS 5e (Figure 6). In any case, the Melles et al. (2012) record may be able to supply a framework for the best candidates of potential ice-free periods in Greenland's history (Figure 7). On the other hand, there are additional possibilities to explain why, given similar climatic scenarios, Greenland may be less likely to deglaciate now than in the past. The role of regolith and basal lubrication, which has been discussed in terms of the evolution of the Laurentide Ice Sheet (Clark and Pollard, 1998), could modulate ice sheet response to climate through the Quaternary. In addition, the geothermal heat flux of Greenland's crust, which is relatively poorly constrained and time-transgressive, could equally give rise to an evolving geothermal field that influences ice sheet behavior (Rogozhina et al., 2016; Stevens et al., 2016).

5. Ice sheet models and glacier processes

The opportunity to obtain information about the vulnerability of the Greenland Ice Sheet to past climate change requires tight integration of the paleo record with numerical ice sheet models. Ice sheet modeling is a broad and important topic that is partnered closely with process-scale glaciology and modern ice sheet observations. Models are run under present climatic and ice sheet conditions, constrained by observations, to invert for the many poorly understood parameters (e.g., conditions at the ice sheet bed, internal ice sheet physics). Models may also be run under boundary conditions different than those operating at present, such as during the geologic past when a different set of boundary conditions existed. Looking forward, ice sheet models are our primary tool for quantifying predictions of sea level rise in a future world with boundary conditions that are not operating today, but may have been operating in the geologic past. The past as an analog for the future is imperfect, but the past does allow us to address ice sheet change under conditions that differ from today.

5.1 The value of paleoclimatic data: Background

Extrapolation of a model outside its calibration dataset tends to underestimate deformation or, equivalently, overestimate the stability of the initial system. This is a general rule of materials science and engineering that has clear application to ice sheet modeling. The danger of mis-extrapolation thus strongly motivates the use of paleoclimatic data to extend the range of parameter space over which ice sheet models are constrained.

Ice can deform by several mechanisms, including migration of point or line defects, generation of new defects, along planes (e.g., grain-boundary sliding) or otherwise, and subcritical and faster crack growth (e.g., Cuffey and Paterson, 2010). Glaciers involve an additional set of processes at their beds, including subfreezing sliding, sliding by regelation or enhanced creep, plowing of clasts through till, distributed or localized till deformation, and stick-slip sliding. Models typically parameterize the rates of each of these processes as the deviatoric stress raised to some power, which generally ranges from 1 to >10. Many of the processes are also thermally activated, with exponential dependence on a wide range of activation energies.

For any temperature and stress (and perhaps also history, concentration of impurities, or other factors), one process typically dominates deformation. If, for example, two processes with stress exponents 1 and 4 contribute equally to deformation at some chosen temperature and stress, halving or doubling the stress will increase or decrease the linear process twofold and 16-fold, respectively, giving almost an order of magnitude difference in rate. An extreme case is subcritical crack growth, which depends on approximately the 30th power of stress (Atkinson, 1984); any shift in crack-growth rate from a doubling or halving of stress thus exceeds the rate change for a linear process by more than eight orders of magnitude.

Thus, a model that includes the dominant physics and fits the relevant data for some range of controlling variables may be highly accurate within the tuning conditions, but may underestimate deformation and thus overestimate stability if extrapolated too far. Even if all relevant deformational processes (ranging from elastic through plastic to brittle fracture) are included in a model and the values of parameters are set based on rigorous laboratory or field work, such data for a given system (such as a particular bridge, building, or ice sheet) cannot constrain parameterizations of non-dominant processes for that system outside of the range of observed conditions. In our case, ice sheet models are tested against the wide range of temperatures, accumulation rates, bed types, etc. that exist in modern ice sheets, yet these likely do not span the full range of future conditions. Documented changes in forcing that can be used for model testing are quite small compared to possible future climatic changes under high-emissions scenarios. Analogy then suggests great caution in interpreting the results of such models in response to large future changes in forcing.

Past ice sheets have experienced a much wider range of conditions and forcings than sampled by the instrumental record, including Pliocene warmth, rapid warming and sea-level rise from the last ice age with jumps linked to abrupt climate changes, different bed conditions before erosional or tectonic changes, and more. Assimilating paleoclimatic data to models that are as physically complete as possible offers an opportunity to improve ice sheet models and ensure they are applicable over a wider range of conditions. Also critical is decreasing uncertainties in parameterizations and better understanding the sensitivity to changes in boundary conditions. *Because future forcing may move outside of the historical range, use of paleoclimatic data with climate-ice sheet models with two-way coupling applied to past time periods is also essential.* This may not solve all difficulties in model testing, because future forcing may still move outside of the observational range. But, to broaden model testing, use of paleoclimatic data is essential.

5.2 Ways forward

Ice sheet models have been used to assess the size of the Greenland Ice Sheet during past interglacial periods, but these have largely focused on the Holocene and Last Interglaciation. These relatively data-rich interglaciations provide good targets for modeling. Important data that directly constrain ice extent during the Last Interglaciation include deep ice cores (e.g., Dahl-Jensen et al., 2013) and information from radar profiles (MacGregor et al., 2016). Many model simulations of the Last Interglaciation suggest that the DYE-3 site would become ice free before Summit. However, some suggest a tendency for northern Greenland to remain ice-covered (e.g., Otto-Bliesner et al., 2006), while others depict significant retreat in both the northern and southern sectors (e.g., Cuffey and Marhsall, 2000). Born and Nisancioglu (2012) also found significant ice retreat in north and west Greenland during the Last Interglaciation, but ice cover persisted at DYE-3 and most other ice core sites. Their finding is consistent with many records supporting glaciation at most ice core sites, yet also allows for several meters of sea level equivalent from Greenland during the Last

Interglaciation (Dutton et al., 2015; Figure 6). Many simulations have been conducted at sufficiently coarse resolution that they do not capture the deep, narrow bedrock troughs of the major outlet glaciers that have guided and are guiding ice sheet retreat, with implications for fidelity of the details of the simulated retreat patterns.

For the Holocene, evidence of ice sheet size through time includes a host of sediments and landforms surrounding the ice sheet both on- and off-shore. Some numerical simulations have focused on the Holocene, using relative sea level data (e.g., Tarasov and Peltier, 2003; Simpson et al., 2009; Lecavalier et al., 2014, 2017) and ice core data (Born, 2016) as constraints. However, modeling studies have yet to incorporate the abundance of glacial-geologic data from the Holocene. The Holocene provides the best opportunity for integrating empirical data with ice sheet modeling, as the glacial geologic and terrestrial paleoclimate communities have the best chance of generating

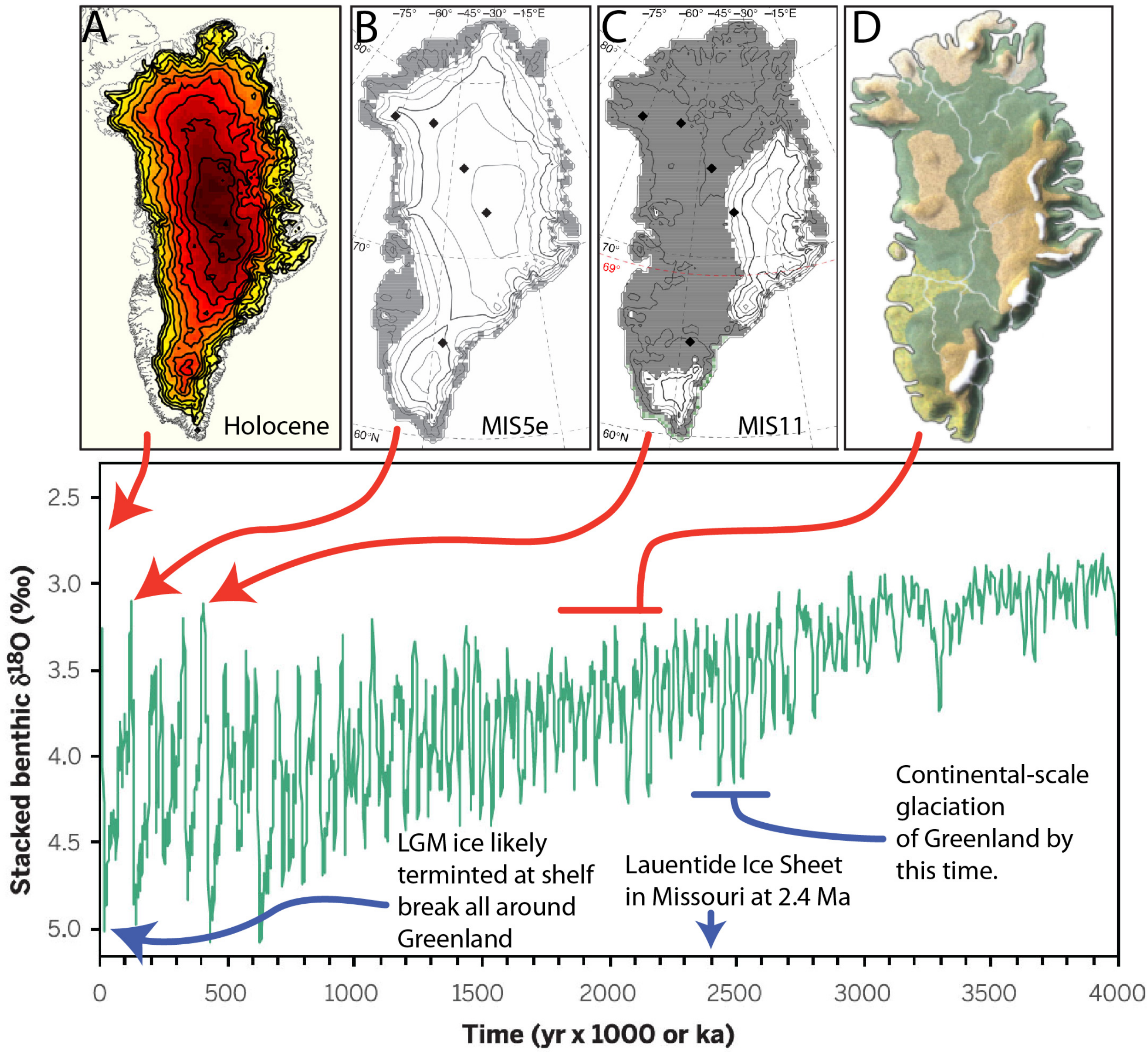


Figure 8. Greenland Ice Sheet extent for particular warm and cold times of the Quaternary. (A) from Lecavalier et al. (2014), (B),(C) from Robinson et al. (2017); (D) from Funder et al. (1985).

detailed records from around Greenland spanning this time period.

A grand challenge lies with improving the understanding of mechanisms (e.g., dynamic instabilities, feedbacks) that could cause great shrinkage or disappearance of the Greenland Ice Sheet for relatively well-known interglacial climate forcings. Based on available data, it seems apparent that there is no 1:1 relationship between the value of $\delta^{18}O$ in the global ocean stack and Greenland Ice Sheet size (Figure 8). Progress has been made in recent years in numerical methods, spatial resolution, and the incorporation of new physics into large-scale ice sheet models. However, there remains a gap in the complexity of ice sheet models used for paleo studies versus models used for modern or future projections.

Process studies relying on comprehensive contemporary remote sensing records have led to an improved understanding of critical processes controlling ice sheet dynamics, such as the role of hydrology in ice sheet processes (e.g., Zwally et al., 2002; Harper et al., 2012; Poinar et al., 2015), calving dynamics and the marine environment (e.g., Joughin et al., 2004; Howatt et al., 2007; Amundson et al., 2010) and temporal and spatial patterns in mass balance change (Andersen et al., 2010; Csatho et al., 2014; Khan et al., 2015). However, the inclusion of these processes into time-evolving numerical ice sheet models is still a challenge, because they involve problematic extrapolations as described above. Nonetheless, model intercomparisons, sensitivity studies, coupled climate and ice sheet modeling, as well as modeling experiments using an ensemble of climate forcings are essential for addressing the stability of the Greenland Ice Sheet (e.g., SeaRISE, Nowicki et al., 2013; PlioMIP, Dolan et al., 2015; ISMIP6, Nowicki et al., 2016).

Another area of concern is the insufficient knowledge of subglacial conditions and their evolution in time. For example, high geothermal heat flux (Fahnestock et al., 2001) and subglacial sediments (Christianson et al., 2014) have been detected under the Northeast Greenland ice stream (NEGIS), pointing to the possibility of rapid deglaciation over an area with a soft bed, perhaps extending to the ice divide (Clark et al., 1999). Long-term variations of Iceland mantle plume activity were detected at time scales of 5-10 Myr in the past 70 Myr (Clift et al., 1998; O'Connor et al., 2000; Spice et al., 2016). Pulsation of the Iceland plume could have a significant impact on the behavior and stability of the Greenland Ice Sheet. Pulses of hot material delivered to the base of the Greenland Ice Sheet could have caused periods of rapid crustal uplift, initiating and modulating glaciation in Greenland (Steinberger et al., 2014, Bonow et al., 2014). Mantle temperature beneath Iceland is currently increasing (Spice at al., 2016) and seismic tomography indicates that hot mantle material is flowing from Iceland, including in a NW direction, and is uplifting or has recently uplifted the central and NE sectors of the Greenland Ice Sheet. Steinberger et al. (2014) suggested that continuing uplift of eastern

Greenland, the northward-component of plate tectonic motion and a true polar wander contribution played a central role in the onset of Greenland glaciation. Recent investigations also revealed substantial differences in mantle viscosity at present, indicating temperature variations in the upper mantle. In addition to the region of hot mantle under a thin lithosphere at the onset of NEGIS (Rogozhina et al., 2016), low mantle viscosity was detected under the Kangerlussuaq Glacier catchment in Southeast Greenland (Khan et al., 2016). Overall, however, reconstructions of the critical geological controls and their past history are still lacking.

Many questions remain unanswered: With what amplitude of climate forcing and over what response time is the Greenland Ice Sheet susceptible to collapse? How resilient will the Greenland Ice Sheet be to climate change expected in upcoming decades and centuries? Given that its bed is mostly above sea level (Figure 1), the Greenland Ice Sheet will not likely collapse due to irreversible tidewater glacier retreat. On the other hand, substantial drawdown of the ice sheet surface may occur in regions prone to inland calving (e.g., Northeast Greenland Ice Stream, Jakobshavn), which could then advance the melt-elevation feedback at the ice sheet scale. Additional feedbacks that have yet to appear in large-scale ice sheet models, such as those related to basal lubrication via new drainage of inland water from supraglacial lakes or firn aquifers (e.g., Ignéczi et al., 2016; Poinar et al., 2017) or enhanced meltwater runoff due to the blocking of pore space in firn (Machguth et al., 2016), will allow for better predictions of ice sheet change, including the possibility of faster ice sheet demise than is currently modeled.

SUMMARY

Recent measurements of cosmogenic isotopes demand the absence of ice at the GISP2 summit drill site for significant portions of the Pleistocene. On the other hand, new and published data from other ice cores in central Greenland and from offshore sediment records have been interpreted to suggest persistence of the ice sheet through the Plio-Pleistocene. It is clear that much ice persisted on Greenland during the last interglaciation, and at least some ice has existed on Greenland since ~1 Ma, although the ice sheet was likely much reduced during MIS 11. Results of ice sheet models can simulate the collapse of continental ice in Greenland, but with slightly different configurations or forcings, continental ice remains stable. In short, it is unclear how much time is needed or what external forcings are required to largely remove an ice sheet from Greenland, and how many times this may have occurred during the Pleistocene.

Collectively, the latest data available to the scientific community – both on ice sheet history and on emerging dynamic processes – paint a potentially worrisome picture for the future stability of the Greenland Ice Sheet. We have surpassed greenhouse gas forcing that resulted in ice sheet disappearance in the past. Thus, there is some urgency in defining priorities for tackling the Greenland Ice Sheet stability problem.

6. A consensus for future work

To confront the most pressing uncertainties about the vulnerability of the Greenland Ice Sheet in the face of a warming Arctic, a community of 51 junior and senior scientific leaders representing the wider community gathered in Buffalo, NY on September 10-12, 2017. The goals of the workshop were two-fold: (1) Bring different datasets and approaches together toward reconciling the current state of knowledge of Greenland Ice Sheet history and sensitivity to climate forcing, and (2) Develop key research priorities that will help guide future efforts to gain significant traction on the problem of Greenland Ice Sheet stability. See appendices for workshop program, participant list and abstracts. The workshop website is here:
http://www.glyfac.buffalo.edu/Faculty/briner/greenlandworkshop/

6.1 Key research areas

Tackling the issue of Greenland Ice Sheet stability requires input from a range of disciplines. These include ice and bedrock coring, climate and ice sheet modeling, glaciology, geophysics, geodesy, glacial geology, paleoceanography, geochronology, geochemistry, sea level studies, and others. These disciplines were each well represented at the workshop. Given the literature synthesized above, these disciplines have focused on three major (and integrated) approaches that collectively hold the most promise going forward: (1) geologic data used to constrain ice sheet response to past climate change, (2) ice sheet modeling studies, and (3) research on glacier processes. The workshop program featured three keynote talks and 36 additional shorter presentations focused on these three avenues of research.

1. Geologic Data. The most direct approach for constraining ice sheet history older than the Holocene involves measuring a variety of constituents in basal ice and subglacial rock. These methods include stable isotope stratigraphy, trapped-air geochronology, cosmogenic nuclide geochronology, ancient DNA, etc. Obtaining these materials involves the technical challenge of obtaining basal ice, and sub-ice sheet bedrock below the ice, relatively quickly and cheaply.

Stratigraphic records of sediments on and adjacent to Greenland, and morphostratigraphic records from landforms around Greenland, have provided much of the knowledge that we draw from to generate the history of the Greenland Ice Sheet. Constraining ice sheet size during brief interglacials is key, and further constraints on this are likely to come from sediments on and offshore. The offshore record has the potential to extend our indirect observations of ice sheet size back through the larch interval and into the Pliocene. This would require ocean drilling to access high resolution, well-dated records of change. Additionally, the available record of Holocene landforms and sediments fringing the ice sheet can be used to derive the pattern by which Greenland deglaciates, which will be useful for both ice sheet modeling and for understanding ice sheet processes.

2. *Ice sheet modeling*. Our ability to project ice sheet change into the future relies on numerical simulations of the ice sheet informed from the geologic record of ice sheet history (above), process-scale understanding of ice sheet dynamics, and projected climate scenarios. Assessing critical thresholds for ice sheet stability, isolating impacts of dynamic processes, and forecasting patterns and rates of ice sheet retreat can be achieved with ice sheet models.

3. *Glacier processes*. On the fundamental scale of ice sheet stability, attention needs to be paid to processes that can potentially lead to ice sheet collapse during interglacial climate forcing, and these should be integrated into modeling. For this reason, process-scale glaciologists who work on emerging topics such as glacier hydrology and glacier calving are key for informing mechanisms, those currently well described and otherwise, relating to ice sheet sensitivity to climate forcing. Contemporary ice sheet changes derived from remote sensing products are critical for constraining the physics of these processes.

In addition to talks on the above subjects, substantive discussions were held between presentation sessions, during coffee breaks and social time at the close of each day. In the afternoon on day 2, workshop participants were randomly assembled into six break-out groups that each prepared a list of priorities for future research that most quickly and robustly increase knowledge on the vulnerability of the Greenland Ice Sheet.

6.2 Main themes of discussion

The multi-disciplinary representation at the workshop led to much positive discussion focused on ways to surmount key obstacles for moving forward and culminated in a list of research priorities. Next, we describe some of the main themes of discussion; this is followed by a list of research priorities in section 7.

<u>Data availability.</u> New data that directly constrain ice sheet size through time are needed not only to compare with independent records of climate change but also as targets for numerical ice sheet simulations. The Schaefer et al. (2016) result is compelling, but remains a single rock core; replication and expansion of these data is critical. Few paleoclimatic records exist from the early/middle Pleistocene, and it may be that these earlier times were warmer than we generally believe, allowing deglaciation of Greenland to take place under weaker climate forcing than today. There is a great need for data from basal ice and subglacial rocks that constrain the footprint of the Greenland Ice Sheet during the last 1 Myr and beyond. When informed by the age

structure of the broader ice sheet inferred from radar stratigraphy (MacGregor et al., 2016), rapid ice coring to obtain basal ice can efficiently add to our knowledge.

Discussion also focused on the relative abundance of data from the Holocene, with fewer data available from the Last Interglaciation (the deep ice core sites), suggesting that these two interglacials should be a strong focus of ice sheet modeling. In particular, with the goal of understanding rates of ice sheet recession when forced by elevated temperature, the Holocene is the only interglacial with much to offer. In addition, earlier warm intervals (e.g., MIS 11, Pliocene) with their different and strong forcing offer inviting targets for modeling as well. Finally, important information from past ice sheet extent has been derived from ocean sediment records fringing the ice sheet, and from shelf and trough-mouth-fan stratigraphies via 3D seismic studies. There is great potential to use shelf archives for direct evidence of ice sheet initiation and subsequent maximum phases. Offshore sediments provide a more indirect measure on former ice sheet size, and can focus on questions regarding interglacial ice sheet conditions. Identification of new drilling targets and reoccupation of existing sites could provide an offshore view of ice sheet history onward from the Pliocene.

Numerical ice sheet modeling. The computing side of numerical ice sheet models is evolving rapidly, and models are increasingly capable of being run on realistic bed topographies and with increasingly complex ice physics. On the other hand, there remains ample room for improvement. Yet, there was widespread agreement that existing models are sufficient for addressing many targeted questions leveled at the appropriate model capability. It is also clear from intercomparison efforts that there are fundamental disagreements from model to model that motivate further research.

Existing models may not accurately capture aspects of the forcing and response (e.g., Milankovitch cycles do not repeat exactly), and may be missing aspects of ice sheet behavior. This is potentially why there is an apparent mismatch between modeled and actual ice sheet history. However, extensive focused studies have not been conducted to address the questions raised by new results, such as the Schaefer et al. (2016) findings of nearly ice-free Greenland during previous interglacials. Thus, a new generation of model simulations might lead to higher consistency between models and data.

Within the glaciology community, much attention has been given to improving the representation of physical processes such as calving, basal hydrology, and the fate of meltwater in modern ice sheet models. Inclusion of these processes into paleo-ice sheet models will only improve model capability. Attempts to match paleo-ice sheet extents with sophisticated ice sheet models have sometimes required severe parameter adjustments (e.g., Goelzer et al., 2016). Most paleo-ice sheet models fail to resolve the detailed topography that is becoming increasingly well constrained, including the deep troughs beneath Greenland (Figure 1b).

Finally, ice sheet model intercomparison efforts (for both paleo and modern periods) suggest that ice sheet model responses are more sensitive to the climatic forcing than to differences in ice sheet model configuration or internal physical quantities (Koenig et al., 2015; Dolan et al., 2015; Nowicki et al., 2013). Therefore, while we must improve model physics, processes, and data assimilation, we must also prioritize the development and incorporation of accurate climatic forcings that drive ice sheet evolution.

Non-climatic factors. The issue of a time-variation factor in the ease of deglaciation may be critical for understanding ice sheet sensitivity to climate change, especially when leaning on the paleo-record of past ice sheet change. For example, perhaps it was more difficult to significantly deglaciate Greenland during Holocene and MIS 5e as opposed to earlier in Pleistocene. Perhaps removal of regolith from glacial erosion has decreased basal lubrication and increased ice sheet stability as Pleistocene glaciation progressed (Clark and Pollard, 1998). In addition, the erosion of deep troughs may have increased ice sheet sensitivity over time by increasing the ability of warm ocean waters to interact with, and potentially destabilize, the ice sheet. This may affect ice sheet stability in ways that have not been extensively explored in models.

Ice sheet evolution also reflects a complex interplay of oceanic and atmospheric processes with the solid earth. For example, increasing mantle temperature produces uplift, leading to a more resilient ice sheet. However, higher mantle temperatures cause higher geothermal heat flux and basal temperatures, potentially contributing to rapid deglaciation. Therefore, to investigate the stability of the Greenland Ice Sheet, reconstructions of GrIS changes should take the spatiotemporal variations of mantle temperature and rheology into account (Khan et al., 2016). The passage of Greenland over the Icelandic hotspot tens of millions of years ago, and the potential for "ice-age cycling" to move mantle melt closer to the crust, further complicate the charting of geothermal flux through the Plio-Pleistocene period of interest. It is possible that tectonic or linked tectonic-glacial processes have led to a decrease in geothermal heat flux and thus basal lubrication with time (Stevens et al., 2016). Improvement is only possible by a better reconstruction of the tectonic evolution of the ice-covered regions of Greenland (Dawes et al., 2009) and by better understanding how the Icelandic hotspot interacted with the Greenlandic lithosphere (Medvedev et al., 2013).

Timescales of instability. It is possible that multiple interglacials have exceeded the temperature for survival of most ice on Greenland, but for too short a time to execute full removal of that ice. Some interglacials (e.g., MIS 11) were likely sufficiently long in duration to remove a significant portion of the ice sheet. Note, however, that there were not many interglacials of long duration in the Quaternary, especially prior to the Mid-Pleistocene transition, yet there remains evidence that the ice sheet was nearly gone nonetheless.

7. Research priorities

By the conclusion of the workshop, consensus was reached on several topics for further research on Greenland Ice Sheet stability. Workshop participants were enthusiastic about these topics, and felt the time was ripe to make progress on these chosen themes:

1. *Geologic data.*
→ New rock and basal ice cores from interior Greenland to replicate and improve the reconstructed history of ice sheet extent from the limited but powerful data at present (note the GRIP borehole remains open and is a potential low-cost access point).
→ New drilling technology designed for fast and relatively inexpensive drilling to and into the bed.
→ Bedrock from below the ice sheet perimeter, and beyond-ice-margin bedrock, landform and sediment sampling for ice margin history especially focused on the Holocene (e.g., Holocene thermal maximum, Little Ice Age, rates of change) and Last Interglaciation.
→ Additional sediment analysis from the marine environment (via piston coring, ocean drilling and/or geophysics) for sediment fluxes and regolith depletion, and variability in ice sheet size.

→ Paleoclimate records, from deeper time (through and prior to the Mid-Pleistocene transition), and recent (MIS 11, last interglacial) and current (Holocene) interglacials to elucidate ice sheet forcing.
→ Additional attention to, and better dating of, the deeper-time record from onshore sedimentary formations was also discussed.

2. *Ice sheet modeling.*
→ Progress in ice sheet modeling must proceed across three simultaneous fronts: physical processes and numerics, assimilation of paleodata, and feedbacks with climate forcings. In all cases, for modeling experiments in both the paleo and future domains, improvements in ensemble exploration of parameter space and forcing uncertainties will be fundamental in understanding the key drivers of ice sheet stability.

*******Physical processes and numerics within ice sheet models*. (a) Continued efforts to incorporate ice sheet processes into models, from contemporary observations and ice-sheet-scale modeling sensitivity experiments. (b) Additional studies of the timescales on which these processes occur and influence ice sheet mass balance: e.g., glacier calving occurs quickly but can control ice sheet geometry on millennial timescales; however, inclusion of calving requires higher-order model physics, which is computationally expensive. (c) Cost-benefit analyses of the inclusion of higher-order physics and its effect on the results of paleo-simulations.

***Targeted model experiments that use paleo-data*. (a) Model-based experiments that attempt to match existing glacial-geologic datasets of ice sheet extent. (b) Coupling of ice sheet models to erosion rates in order to compare to cosmogenic isotope datasets. (c) Data assimilation approaches to paleoclimate reconstruction.

***Feedbacks and climate forcings and ice sheet models*. (a) Climatic forcing appears to have strong influence on modeled ice sheet extent (both paleo and modern); further sensitivity testing of this effect should be performed. (b) Paleoclimatic data assimilation, including coupling of ice sheet models with climate models.
→ Ice sheet models constrained with paleo-data are poised to be used for selecting optimal sites for additional sub-ice data.

3. Glacier processes.
→ Improvements are needed in glacier hydrology and calving terminus dynamics. Both topics relate to positive feedbacks that may increase ice sheet vulnerability to rapid collapse.
→ Increased efforts are required to extend and couple contemporary observations, process-scale modeling, and climate and ice-sheet-scale sensitivity experiments.

4. Tectonics.
→ Additional effort on the geophysical exploration for tectonic forcing, especially focused on the “hot” region near head of NEGIS and surrounding areas.

→ Search for evidence of recent volcanism (EGRIP till cores?) perhaps related to heat flow changes.

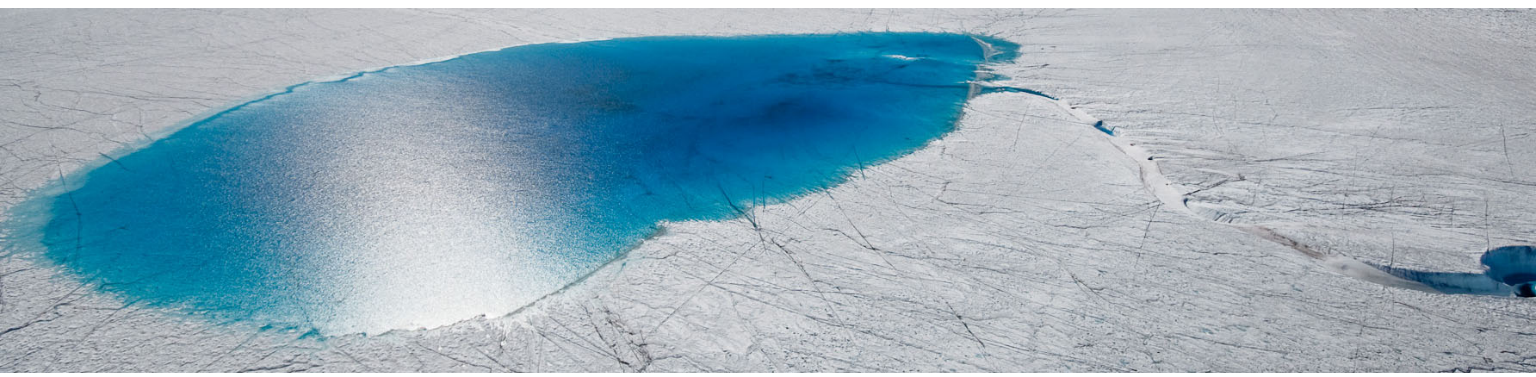
5. Integration. It was very clear throughout the workshop, and it was specifically voiced during the breakout group presentations, that many of the above targets for research would advance most efficiently as multi-disciplinary efforts. Data-process-model-technology are components that future research efforts need, and staying coordinated is of utmost importance.

8. Final Remarks

The community is poised to fill the gap in knowledge about the Greenland Ice Sheet's potential vulnerability to climate change. Our current understanding of Greenland is not sufficient to allow confident projections of its contribution to future sea level rise. While the uncertainty on the low end of future sea level rise is reasonably narrow (we are nearly certain that Greenland will contribute at least a small amount to sea level rise in a warming world), the uncertainty is quite large on the upper bound, because we cannot rule out a very large sea-level rise contribution from Greenland in the near future.

It is possible that the Greenland Ice Sheet has been more resilient to climate change in the latter portion of the Quaternary ice age than it was during the early and middle Quaternary. Perhaps the record of Arctic "superinterglacials" from Lake El'gygytgyn provides the template for past Greenland Ice Sheet disappearance (Figure 7), and Greenland became largely deglaciated more routinely in the early and middle Quaternary than in the past million years. Or perhaps early deglaciation was not due to a change in climate, but due to non-glacial factors, such as tectonics, subglacial heat flux, or the stripping of pre-Quaternary regolith, that allowed the ice sheet to disappear more easily early in the Quaternary.

Alternatively, with more data we may learn that the Greenland Ice Sheet has become nearly ice free several times in the past million years. We may learn that there are thresholds we have yet to understand, that when crossed cause irreversible ice sheet collapse. We may learn that the Arctic system as a whole, of which Greenland is only part, is critical to understand for running ice sheet models into the future. With new joint data and modeling efforts, we may constrain the combination of factors that lead to ice sheet survival, or demise, during interglacial periods. Investments in this new knowledge will be paid off in terms of better defining Greenland's contribution to sea level rise in the coming years, decades and centuries. With accurate forecasts in hand, global leaders and communities can begin to plan for likely sea-level futures.



9. References

Alley, R.B., Andrews, J.T., Brigham-Grette, J., Clarke, G.K.C., Cuffey, K.M., Fitzpatrick, J.J., Funder, S., Marshall, S.J., Miller, G.H., Mitrovica, J.X., Muhs, D.R., Otto-Bliesner, B.L., Polyak, L., White, J.W.C., 2010. History of the Greenland Ice Sheet: paleoclimatic insights. Quaternary Science Reviews, Special Theme: Arctic Palaeoclimate Synthesis (PP. 1674-1790) 29, 1728–1756. doi:10.1016/j.quascirev.2010.02.007

Alley, R.B., Clark, P.U., Huybrechts, P., Joughin, I., 2005. Ice-Sheet and Sea-Level Changes. Science 310, 456–460. doi:10.1126/science.1114613

Amundson, J.M., Fahnestock, M., Truffer, M., Brown, J., Lüthi, M.P., Motyka, R.J., 2010. Ice mélange dynamics and implications for terminus stability, Jakobshavn Isbræ, Greenland. J. Geophys. Res. 115, F01005. doi:10.1029/2009JF001405

Andersen, M.L., Larsen, T.B., Nettles, M., Elosegui, P., van As, D., Hamilton, G.S., Stearns, L.A., Davis, J.L., Ahlstrøm, A.P., de Juan, J., Ekström, G., Stenseng, L., Khan, S.A., Forsberg, R., Dahl-Jensen, D., 2010. Spatial and temporal melt variability at Helheim Glacier, East Greenland, and its effect on ice dynamics. J. Geophys. Res. 115, F04041. doi:10.1029/2010JF001760

Ashby, M.F., 1972, A first report on deformation-mechanism maps, Acta Metallurgica 20, 887-897.

Atkinson, B.K., 1984. Subcritical crack growth in geological materials, Journal of Geophysical Research 89, 4077-4114.

Balco, G., Rovey, C.W., Stone, J.O.H., 2005. The First Glacial Maximum in North America. Science 307, 222–222. doi:10.1126/science.1103406

Bender, M.L., Burgess, E., Alley, R.B., Barnett, B., Clow, G.D., 2010. On the nature of the dirty ice at the bottom of the GISP2 ice core. Earth and Planetary Science Letters 299, 466–473. doi:10.1016/j.epsl.2010.09.033

Bennike, O., Knudsen, K.L., Abrahamsen, N., Böcher, J., Cremer, H., Wagner, B., 2010. Early Pleistocene sediments on Store Koldewey, northeast Greenland. Boreas 39, 603–619.

Bierman, P.R., Corbett, L.B., Graly, J.A., Neumann, T.A., Lini, A., Crosby, B.T., Rood, D.H., 2014. Preservation of a Preglacial Landscape Under the Center of the Greenland Ice Sheet. Science 344, 402–405. doi:10.1126/science.1249047

Bierman, P.R., Shakun, J.D., Corbett, L.B., Zimmerman, S.R., Rood, D.H., 2016. A persistent and dynamic East Greenland Ice Sheet over the past 7.5 million years. Nature 540, 256–260. doi:10.1038/nature20147

Bonow, J. M., Japsen, P., & Nielsen, T. F. D., 2014. High-level landscapes along the margin of southern East Greenland—A record of tectonic uplift and incision after breakup in the NE Atlantic. Global and Planetary Change 116, 10–29. http://doi.org/10.1016/j.gloplacha.2014.01.010

Born, A., 2016. Tracer transport in an isochronal ice-sheet model. Journal of Glaciology

63, 22-38.
Born, A., Nisancioglu, K.H., 2012. Melting of Northern Greenland during the last interglaciation. The Cryosphere 6, 1239–1250. doi:10.5194/tc-6-1239-2012
Christianson, K., Peters, L.E., Alley, R.B., Anandakrishnan, S., Jacobel, R.W., Riverman, K.L., Muto, A., Keisling, B.A., 2014. Dilatant till facilitates ice-stream flow in northeast Greenland. Earth and Planetary Science Letters 401, 57–69. doi:10.1016/j.epsl.2014.05.060
Clark, P.U., and Pollard, D., 1998, Origin of the mid-Pleistocene transition by ice-sheet erosion of regolith. Paleoceanography 13, 1-9.
Clark, P.U., Alley, R.B., Pollard, D., 1999. Northern Hemisphere Ice-Sheet Influences on Global Climate Change. Science 286, 1104–1111. doi:10.1126/science.286.5442.1104
Clift, P. D., Carter, A., & Hurford, A. J., 1998. The erosional and uplift history of NE Atlantic passive margins: constraints on a passing plume. Journal of the Geological Society 155(5), 787–800.
Csatho, B.M., Schenk, A.F., Veen, C.J. van der, Babonis, G., Duncan, K., Rezvanbehbahani, S., Broeke, M.R. van den, Simonsen, S.B., Nagarajan, S., Angelen, J.H. van, 2014. Laser altimetry reveals complex pattern of Greenland Ice Sheet dynamics. PNAS 111, 18478–18483. doi:10.1073/pnas.1411680112
Cuffey, K.M., Marshall, S.J., 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. Nature 404, 591–594. doi:10.1038/35007053
Cuffey, K.M. and W.S.B. Paterson, 2010, The Physics of Glaciers, 4th Edition, Elsevier
Dahl-Jensen, D., Albert, M.R., Aldahan, A., Azuma, N., Balslev-Clausen, D., Baumgartner, M., Berggren, A.-M., Bigler, M., Binder, T., Blunier, T., Bourgeois, J.C., Brook, E.J., Buchardt, S.L., Buizert, C., Capron, E., Chappellaz, J., Chung, J., Clausen, H.B., Cvijanovic, I., Davies, S.M., Ditlevsen, P., Eicher, O., Fischer, H., Fisher, D.A., Fleet, L.G., Gfeller, G., Gkinis, V., Gogineni, S., Goto-Azuma, K., Grinsted, A., Gudlaugsdottir, H., Guillevic, M., Hansen, S.B., Hansson, M., Hirabayashi, M., Hong, S., Hur, S.D., Huybrechts, P., Hvidberg, C.S., Iizuka, Y., Jenk, T., Johnsen, S.J., Jones, T.R., Jouzel, J., Karlsson, N.B., Kawamura, K., Keegan, K., Kettner, E., Kipfstuhl, S., Kjær, H.A., Koutnik, M., Kuramoto, T., Köhler, P., Laepple, T., Landais, A., Langen, P.L., Larsen, L.B., Leuenberger, D., Leuenberger, M., Leuschen, C., Li, J., Lipenkov, V., Martinerie, P., Maselli, O.J., Masson-Delmotte, V., McConnell, J.R., Miller, H., Mini, O., Miyamoto, A., Montagnat-Rentier, M., Mulvaney, R., Muscheler, R., Orsi, A.J., Paden, J., Panton, C., Pattyn, F., Petit, J.-R., Pol, K., Popp, T., Possnert, G., Prié, F., Prokopiou, M., Quiquet, A., Rasmussen, S.O., Raynaud, D., Ren, J., Reutenauer, C., Ritz, C., Röckmann, T., Rosen, J.L., Rubino, M., Rybak, O., Samyn, D., Sapart, C.J., Schilt, A., Schmidt, A.M.Z., Schwander, J., Schüpbach, S., Seierstad, I., Severinghaus, J.P., Sheldon, S., Simonsen, S.B., Sjolte, J., Solgaard, A.M.,

Sowers, T., Sperlich, P., Steen-Larsen, H.C., Steffen, K., Steffensen, J.P., Steinhage, D., Stocker, T.F., Stowasser, C., Sturevik, A.S., Sturges, W.T., Sveinbjörnsdottir, A., Svensson, A., Tison, J.-L., Uetake, J., Vallelonga, P., van de Wal, R.S.W., van der Wel, G., Vaughn, B.H., Vinther, B., Waddington, E., Wegner, A., Weikusat, I., White, J.W.C., Wilhelms, F., Winstrup, M., Witrant, E., Wolff, E.W., Xiao, C., Zheng, J., 2013. Eemian interglacial reconstructed from a Greenland folded ice core. Nature 493, 489–494. doi:10.1038/nature11789

Dawes, P. R. 2009. The bedrock geology under the Inland Ice: the next major challenge for Greenland mapping. Geological Survey of Denmark and Greenland Bulletin 17, 57–60.

de Vernal, A., Hillaire-Marcel, C., 2008. Natural Variability of Greenland Climate, Vegetation, and Ice Volume During the Past Million Years. Science 320, 1622–1625. doi:10.1126/science.1153929

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597.

Dolan, A.M., Hunter, S.J., Hill, D.J., Haywood, A.M., Koenig, S.J., Otto-Bliesner, B.L., Abe-Ouchi, A., Bragg, F., Chan, W.-L., Chandler, M.A., Contoux, C., Jost, A., Kamae, Y., Lohmann, G., Lunt, D.J., Ramstein, G., Rosenbloom, N.A., Sohl, L., Stepanek, C., Ueda, H., Yan, Q., Zhang, Z., 2015. Using results from the PlioMIP ensemble to investigate the Greenland Ice Sheet during the mid-Pliocene Warm Period. Climate of the Past 11, 403–424. doi:Dolan, A. M. , Hunter, S. J. , Hill, D. J. , Haywood, A. M. , Koenig, S. J. , Otto-Bliesner, B. L. , Abe-Ouchi, A. , Bragg, F. , Chan, W. L. , Chandler, M. A. , Contoux, C. , Jost, A. , Kamae, Y. , Lohmann, G. , Lunt, D. J. , Ramstein, G. , Rosenbloom, N. A. , Sohl, L. , Stepanek, C. , Ueda, H. , Yan, Q. and Zhang, Z. (2015) Using results from the PlioMIP ensemble to investigate the Greenland Ice Sheet during the mid-Pliocene Warm Period, Climate of the Past 11, pp. 403-424. doi:10.5194/cp-11-403-2015

Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P., Rahmstorf, S., Raymo, M.E., 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349. doi:10.1126/science.aaa4019

Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., Roberts, A.P., 2007. Continental ice in Greenland during the Eocene and Oligocene. Nature 446, 176–179. doi:10.1038/nature05591

Fahnestock, M., Abdalati, W., Joughin, I., Brozena, J., Gogineni, P., 2001. High Geothermal Heat Flow, Basal Melt, and the Origin of Rapid Ice Flow in Central Greenland. Science 294, 2338–2342. doi:10.1126/science.1065370

Khan, S.A., Sasgen, I., Bevis, M., van Dam, T., Bamber, J.L., Wahr, J., et al., 2016. Geodetic measurements reveal similarities between post-Last Glacial Maximum and present-day mass loss from the Greenland ice sheet. Science Advances 2(9), e1600931–e1600931. http://doi.org/10.1126/sciadv.1600931

Kleiven, H.F., Jansen, E., Fronval, T., Smith, T.M., 2002. Intensification of Northern

Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma) – ice-rafted detritus evidence. Palaeogeography, Palaeoclimatology, Palaeoecology 184, 213–223. doi:10.1016/S0031-0182(01)00407-2

Funder, S., Abrahamsen, N., Bennike, O., Feyling-Hanssen, R.W., 1985. Forested Arctic: Evidence from North Greenland. Geology 13, 542–546. doi:10.1130/0091-7613(1985)13<542:FAEFNG>2.0.CO;2

Gilbert, A., Flowers, G.E., Miller, G.H., Refsnider, K., Young, N.E., Radić, V., submitted. The projected demise of Barnes Ice Cap: evidence of an unusually warm 21st century Arctic. Geophysical Research Letters 44, 2810-2816.

Goelzer, H., Huybrechts, P., Loutre, M.-F., Fichefet, T., 2016. Impact of ice sheet meltwater fluxes on the climate evolution at the onset of the Last Interglacial. Clim. Past 12, 1721–1737. doi:10.5194/cp-12-1721-2016

Harper, J., Humphrey, N., Pfeffer, W.T., Brown, J., Fettweis, X., 2012. Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn. Nature 491, 240–244.

Hatfield, R.G., Reyes, A.V., Stoner, J.S., Carlson, A.E., Beard, B.L., Winsor, K., Welke, B., 2016. Interglacial responses of the southern Greenland ice sheet over the last 430,000 years determined using particle-size specific magnetic and isotopic tracers. Earth and Planetary Science Letters 454, 225–236. doi:10.1016/j.epsl.2016.09.014

Howat, I.M., Joughin, I., Scambos, T.A., 2007. Rapid Changes in Ice Discharge from Greenland Outlet Glaciers. Science 315, 1559–1561. doi:10.1126/science.1138478

Ignéczi, Á., Sole, A.J., Livingstone, S.J., Leeson, A.A., Fettweis, X., Selmes, N., Gourmelen, N., Briggs, K., 2016. Northeast sector of the Greenland Ice Sheet to undergo the greatest inland expansion of supraglacial lakes during the 21st century. Geophysical Research Letters 43, 9729–9738.

Joughin, I., Abdalati, W., Fahnestock, M., 2004. Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. Nature 432, 608–610. doi:10.1038/nature03130

Khan, S.A., Aschwanden, A., Bjørk, A.A., Wahr, J., Kjeldsen, K.K., Kjær, K.H., 2015. Greenland ice sheet mass balance: a review. Rep. Prog. Phys. 78, 46801. doi:10.1088/0034-4885/78/4/046801

Koenig, S.J., Dolan, A.M., de Boer, B., Stone, E.J., Hill, D.J., DeConto, R.M., Abe-Ouchi, A., Lunt, D.J., Pollard, D., Quiquet, A., Saito, F., Savage, J., van de Wal, R., 2015. Ice sheet model dependency of the simulated Greenland Ice Sheet in the mid-Pliocene. Clim. Past 11, 369–381. doi:10.5194/cp-11-369-2015

Larsen, H.C., Saunders, A.D., Clift, P.D., Beget, J., Wei, W., Spezzaferri, S., Ali, J., Cambray, H., Demant, A., Fitton, G., Fram, M.S., Fukuma, K., Gieskes, J., Holmes, M.A., Hunt, J., Lacasse, C., Larsen, L.M., Lykke-Andersen, H., Meltser, A., Morrison, M.L., Nemoto, N., Okay, N., Saito, S., Sinton, C., Stax, R., Vallier, T.L., Vandamme, D., Werner, R., 1994. Seven Million Years of Glaciation in

Greenland. Papers in the Earth and Atmospheric Sciences.
Lecavalier, B.S., Milne, G.A., Simpson, M.J.R., Wake, L., Huybrechts, P., Tarasov, L., Kjeldsen, K.K., Funder, S., Long, A.J., Woodroffe, S., Dyke, A.S., Larsen, N.K., 2014. A model of Greenland ice sheet deglaciation constrained by observations of relative sea level and ice extent. Quaternary Science Reviews 102, 54–84. doi:10.1016/j.quascirev.2014.07.018
Lecavalier, B.S., Fisher, D.A., Milne, G.A., Vinther, B.M., Tarasov, L., Huybrechts, P., Lacelle, D., Main, B., Zheng, J., Bourgeois, J., Dyke, A.S., 2017. High Arctic Holocene temperature record from the Agassiz ice cap and Greenland ice sheet evolution. PNAS 114, 5952–5957. doi:10.1073/pnas.1616287114
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography 20, PA1003. doi:10.1029/2004PA001071
MacGregor, J.A., Fahnestock, M.A., Catania, G.A., Aschwanden, A., Clow, G.D., Colgan, W.T., Gogineni, S.P., Morlighem, M., Nowicki, S.M.J., Paden, J.D., Price, S.F., Seroussi, H., 2016. A synthesis of the basal thermal state of the Greenland Ice Sheet. J. Geophys. Res. Earth Surf. 121, 2015JF003803. doi:10.1002/2015JF003803
Machguth, H., MacFerrin, M., As, D. van, Box, J.E., Charalampidis, C., Colgan, W., Fausto, R.S., Meijer, H.A.J., Mosley-Thompson, E., Wal, R.S.W. van de, 2016. Greenland meltwater storage in firn limited by near-surface ice formation. Nature Climate Change 6, 390–393. doi:10.1038/nclimate2899
Medvedev, S., Souche, A., and Hartz, E.H., 2013. Influence of ice sheet and glacial erosion on passive margins of Greenland. Geomorphology 193(C), 36–46. http://doi.org/10.1016/j.geomorph.2013.03.029
Melles, M., Brigham-Grette, J., Minyuk, P.S., Nowaczyk, N.R., Wennrich, V., DeConto, R.M., Anderson, P.M., Andreev, A.A., Coletti, A., Cook, T.L., Haltia-Hovi, E., Kukkonen, M., Lozhkin, A.V., Rosén, P., Tarasov, P., Vogel, H., Wagner, B., 2012. 2.8 Million Years of Arctic Climate Change from Lake El'gygytgyn, NE Russia. Science 337, 315–320. doi:10.1126/science.1222135
Morlighem, M., Williams, C.N., Rignot, E., An, L., Arndt, J.E., Bamber, J.L., Catania, G., Chauché, N., Dowdeswell, J.A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T.M., Kjeldsen, K.K., Millan, R., Mayer, L., Mouginot, J., Noël, B.P.Y., Cofaigh, C.Ó., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M.J., Slabon, P., Straneo, F., van den Broeke, M.R., Weinrebe, W., Wood, M., Zinglersen, K.B., n.d. BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multi-beam echo sounding combined with mass conservation. Geophys. Res. Lett. 2017GL074954. doi:10.1002/2017GL074954
Nowicki, S., Bindschadler, R.A., Abe-Ouchi, A., Aschwanden, A., Bueler, E., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C.,

Johnson, J., Khroulev, C., Larour, E., Levermann, A., Lipscomb, W.H., Martin, M.A., Morlighem, M., Parizek, B.R., Pollard, D., Price, S.F., Ren, D., Rignot, E., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., Wang, W.L., 2013. Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project I: Antarctica. J. Geophys. Res. Earth Surf. 118, 1002–1024. doi:10.1002/jgrf.20081

Nowicki, S.M.J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., Shepherd, A., 2016. Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. Geosci. Model Dev. 9, 4521–4545. doi:10.5194/gmd-9-4521-2016

O'Connor, J. M., Stoffers, P., Wijbrans, J. R., Shannon, P. M., & Morrissey, T., 2000. Evidence from episodic seamount volcanism for pulsing of the Iceland plume in the past 70 Myr. Nature 408(6815), 954–958. http://doi.org/10.1038/35050066

Otto-Bliesner, B.L., Marshall, S.J., Overpeck, J.T., Miller, G.H., Hu, A., Members, C.L.I.P., 2006. Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation. Science 311, 1751–1753. doi:10.1126/science.1120808

Poinar, K., Joughin, I., Das, S.B., Behn, M.D., Lenaerts, J.T.M., van den Broeke, M.R., 2015. Limits to future expansion of surface-melt-enhanced ice flow into the interior of western Greenland. Geophys. Res. Lett. 42, 2015GL063192. doi:10.1002/2015GL063192

Poinar, K., Joughin, I., Lilien, D., Brucker, L., Kehrl, L., Nowicki, S., 2017. Drainage of Southeast Greenland Firn Aquifer Water through Crevasses to the Bed. Frontiers in Earth Science 5. doi:10.3389/feart.2017.00005

Raymo, M.E., Mitrovica, J.X., 2012. Collapse of polar ice sheets during the stage 11 interglacial. Nature 483, 453–456. doi:10.1038/nature10891

Reyes, A.V., Carlson, A.E., Beard, B.L., Hatfield, R.G., Stoner, J.S., Winsor, K., Welke, B., Ullman, D.J., 2014. South Greenland ice-sheet collapse during Marine Isotope Stage 11. Nature 510, 525–528. doi:10.1038/nature13456

Robinson, A., Alvarez-Solas, J., Calov, R., Ganopolski, A., Montoya, M., 2017. MIS-11 duration key to disappearance of the Greenland ice sheet. Nat Commun 8. doi:10.1038/ncomms16008

Rogozhina, I., Petrunin, A.G., Vaughan, A.P.M., Steinberger, B., Johnson, J.V., Kaban, M.K., Calov, R., Rickers, F., Thomas, M., Koulakov, I., 2016. Melting at the base of the Greenland ice sheet explained by Iceland hotspot history. Nature Geosci 9, 366–369. doi:10.1038/ngeo2689

Ruddiman, W.F., Raymo, M.E., Lamb, H.H., Andrews, J.T., 1988. Northern Hemisphere Climate Regimes During the Past 3 Ma: Possible Tectonic Connections [and Discussion]. Philosophical Transactions of the Royal Society of London B: Biological Sciences 318, 411–430. doi:10.1098/rstb.1988.0017

Schaefer, J.M., Finkel, R.C., Balco, G., Alley, R.B., Caffee, M.W., Briner, J.P., Young, N.E., Gow, A.J., Schwartz, R., 2016. Greenland was nearly ice-free for extended

periods during the Pleistocene. Nature 540, 252–255. doi:10.1038/nature20146
Shoji, H. and A. Higashi, 1978, A deformation mechanism map of ice, Journal of Glaciology 21 (85), 419-427.
Simpson, M.J.R., Milne, G.A., Huybrechts, P., Long, A.J., 2009. Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. Quaternary Science Reviews, Quaternary Ice Sheet-Ocean Interactions and Landscape Responses 28, 1631–1657. doi:10.1016/j.quascirev.2009.03.004
Solheim, A., Faleide, J.I., Andersen, E.S., Elverhoi, A., Forsberg, C.F., Vanneste, K., Uenzelmann-Neben, G., Chanell, J.E.T., 1998. Late Cenozoic seismic stratigraphy and glacial geological development of the east Greenland and Svalbard-Barents Sea continental margins. Quaternary Science Reviews 17, 155–184. doi:10.1016/S0277-3791(97)00068-1
Souchez, R., Tison, J.-L., Lorrain, R., Lemmens, M., Janssens, L., Stievenard, M., Jouzel, J., Sveinbjörnsdottir, A., Johnsen, S.J., 1994. Stable isotopes in the basal silty ice preserved in the Greenland Ice Sheet at summit; environmental implications. Geophys. Res. Lett. 21, 693–696. doi:10.1029/94GL00641
Spice, H.E., Fitton, J.G., and Kirstein, L.A., 2016). Temperature fluctuation of the Iceland mantle plume through time. Geochemistry Geophysics Geosystems 17(2), 243–254.
Steinberger, B., Spakman, W., Japsen, P., and Torsvik, T. H., 2015. The key role of global solid-Earth processes in preconditioning Greenland's glaciation since the Pliocene. Terra Nova 27(1), 1–8. http://doi.org/10.1111/ter.12133
Stevens, N.T., B.R. Parizek and R.B. Alley. 2016. Enhancement of volcanism and geothermal heat flux by ice-age cycling: A stress modeling study of Greenland. Journal of Geophysical Research—Earth Surface, 121, doi:10.1002/2016JF003855.
Suwa, M., von Fischer, J.C., Bender, M.L., Landais, A., Brook, E.J., 2006. Chronology reconstruction for the disturbed bottom section of the GISP2 and the GRIP ice cores: Implications for Termination II in Greenland. Journal of Geophysical Research 111. doi:10.1029/2005JD006032
Tarasov, L., Richard Peltier, W., 2002. Greenland glacial history and local geodynamic consequences. Geophys J Int 150, 198–229. doi:10.1046/j.1365-246X.2002.01702.x
Thiede, J., Jessen, C., Knutz, P., Kuijpers, A., Mikkelsen, N., Nørgaard-Pedersen, N., Spielhagen, R.F., 2011. Million years of Greenland Ice Sheet history recorded in ocean sediments. Polarforschung 80, 141–149.
Thiede, J., Winkler, A., Wolf-Welling, T., Eldholm, O., Myhre, A.M., Baumann, K.-H., Henrich, R., Stein, R., 1998. Late Cenozoic history of the polar North Atlantic: Results from ocean drilling. Quaternary Science Reviews 17, 185–208. doi:10.1016/S0277-3791(97)00076-0

Willerslev, E., Cappellini, E., Boomsma, W., Nielsen, R., Hebsgaard, M.B., Brand, T.B., Hofreiter, M., Bunce, M., Poinar, H.N., Dahl-Jensen, D., Johnsen, S., Steffensen, J.P., Bennike, O., Schwenninger, J.-L., Nathan, R., Armitage, S., Hoog, C.-J. de, Alfimov, V., Christl, M., Beer, J., Muscheler, R., Barker, J., Sharp, M., Penkman, K.E.H., Haile, J., Taberlet, P., Gilbert, M.T.P., Casoli, A., Campani, E., Collins, M.J., 2007. Ancient Biomolecules from Deep Ice Cores Reveal a Forested Southern Greenland. Science 317, 111–114. doi:10.1126/science.1141758

Yau et al., 2013

Yau, A.M., Bender, M.L., Blunier, T., Jouzel, J., 2016. 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. doi:10.1016/j.epsl.2016.06.053

Young, N.E., Briner, J.P., 2015. Holocene evolution of the western Greenland Ice Sheet: Assessing geophysical ice-sheet models with geological reconstructions of ice-margin change. Quaternary Science Reviews 114, 1–17. doi:10.1016/j.quascirev.2015.01.018

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., Steffen, K., 2002. Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow. Science 297, 218–222. doi:10.1126/science.1072708

NSF Workshop

How Stable is the Greenland Ice Sheet?

PROGRAM AND ABSTRACTS

September 10-12, 2017
Buffalo, New York

Steering Committee:
Richard Alley
Michael Bender
Jason Briner
Beata Csatho
Kristin Poinar
Joerg Schaefer

Local Organizing Committee:
Jason Briner
Barbara Catalano
Allison Cluett
Alia Lesnek
Avriel Schweinsberg
Elizabeth Thomas

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

Mary Albert
Ice Drilling Program Office Thayer School of Engineering at Dartmouth Hanover, N.H. 03755

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

Sridhar Anandakrishnan
Penn State University

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

Y. Axford, M.R. Osburn, J. McFarlin, G.E. Lasher, L. Larocca and M.L. Chipman
Department of Earth and Planetary Sciences, Northwestern University

M.A. Kelly and E.C. Osterberg
Department of Earth Sciences, Dartmouth College

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

Jessica Badgeley[1], Eric Steig[1], Greg Hakim[2], Josh Anderson[1], Robert Tardif [2]
[1]Department of Earth and Space Sciences, University of Washington, Seattle, Washington (USA)
[2]Department of Atmospheric Sciences, University of Washington, Seattle, Washington (USA)

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

Robin Elizabeth Bell
Lamont-Doherty Earth Observatory of Columbia University

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

Ole Bennike
Geological Survey of Denmark and Greenland, obe@geus.dk

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

Paul Bierman and Lee Corbett
Geology Department, University of Vermont
Jeremy Shakun
Department of Earth and Environmental Sciences, Boston College

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

Andreas Born
Bjerknes Centre for Climate Research and Department of Earth Science, University of Bergen, Norway

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

Rachel Carr
Newcastle University

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

Winnie Chu
Stanford University

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

Bea Csatho
University at Buffalo

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.

Dorthe Dahl-Jensen

Niels Bohr Institute, University of Copenhagen
Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark, ddj@gfy.ku.dk

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

Christine Dow[1], Kristin Poinar[2], Lauren Andrews[2], Sophie Nowicki[2]

(1)University of Waterloo, Waterloo, ON, Canada
(2)NASA Goddard Space Flight Center, Greenbelt, MD, United States

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

Mark Fahnestock and Andy Aschwanden
University of Alaska Fairbanks Twila Moon, University of Colorado

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

Authors: Richard Forster[1], Clément Miège[1], Olivia Miller[1], Lora Koenig[2], Kip Solomon[1], Nick Schmerr[3], Lynn Montgomery[2], Anatoly Legtchenko[4] and Stefan Ligtenberg[5]

1: University of Utah (USA), 2: University of Colorado (USA), 3: University of Maryland (USA), .4: Université Joseph Fourier (FR), 5: Utrecht University (NL)

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 ($K = 2.7 \times 10^{-4}$ 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

Jeremy Fyke
Los Alamos National Laboratory

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

Joel Harper
University of Montana

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.

Hatfield[1], R.G., J.S. Stoner[1], A.V. Reyes[2], A.E. Carlson[1], M.H. Walczak[1], and B.L. Beard[3].

[1]College of Earth, Ocean, and Atmospheric Science, Oregon State University, Corvallis, OR 97331, USA [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, T6G 2E3, Canada [3]Department of Geoscience, University of Wisconsin-Madison, 1215 West Dayton Street, Madison, WI 53706, USA

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

Oregon State University

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

Anne Jennings[1] and Paul Knutz[2]
[1] INSTAAR, University of Colorado, Colorado USA
[2] Geological Survey of Denmark and Greenland, Copenhagen, Denmark

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

Ian Joughin (ian@apl.washington.edu), Laura Kehrl (kehrl@uw.edu) and Ben Smith (besmith@uw.edu)
Polar Science Center, Applied Physics Lab, University of Washington, 1013 NE 40th Street, Seattle, WA 98105-6698 USA

Twila Moon (twila.moon@nsidc.org) and Ted Scambos (teds@nsidc.org)
National Snow and Ice Data Center, CIRES, 449 UCB
University of Colorado, Boulder, CO 80309-0449 USA

Ian Howat (teds@nsidc.org)
The Ohio State University 108 Scott Hall, 1090 Carmack Rd, Columbus, OH, 43210 USA

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

Benjamin Keisling
University of Massachusetts - Amherst

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

Meredith A. Kelly[1], Thomas V. Lowell[2], Brenda L. Hall[3], Yarrow Axford[4], Laura B. Levy[5], Erich C. Osterberg[1]

[1]*Department of Earth Sciences, Dartmouth College*
[2]*Geology Department, University of Cincinnati*
[3]*School of Earth and Climate Sciences and Climate Change Institute, University of Maine*
[4]*Department of Earth and Planetary Sciences, Northwestern University*
[5]*Geology Department, Humboldt State University*

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

Tanner Kuhl
IDDO – University of Wisconsin-Madison

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

Petra M. Langebroek
Uni Research Climate, Bjerknes Centre for Climate Research, Bergen, Norway

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

Joseph A. MacGregor
Cryospheric Sciences Lab (615), NASA Goddard Space Flight Center

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

Gifford Miller, Kurt Refsnider, Nicolas Young, Adrien Gilbert, and Gwenn Flowers

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 <u>only</u> 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

Glenn Milne
University of Ottawa

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

Aurelien Mordret
MIT

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

Mathieu Morlighem
University of California Irvine

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

Meredith Nettles
Department of Earth and Environmental Sciences and Lamont-Doherty Earth Observatory

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.

Sophie Nowicki
NASA Goddard Space Flight Center

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

Erich Osterberg[1], Robert Hawley[1], Hans-Peter Marshall[2], Gabriel Lewis[1], Karina Graeter[1], Tate Meehan[2], Sean Birkel[3]

[1]Dartmouth College Department of Earth Sciences, Hanover, NH [2]Boise State University Department of Geosciences, Boise, ID [3]University of Maine Climate Change Institute, Orono, ME

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

Bette L. Otto-Bliesner[1], Marcus Lofverstrom[1], William Lipscomb[1], Jeremy Fyke[2], Shawn Marshall[3], and William Sacks[1]

[1]Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, Colorado, USA
[2]Los Alamos National Laboratory, Los Alamos, New Mexico, USA
[3]Department of Geography, University of Calgary, Calgary, Canada

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

Alexander A. Robel[1,2], Victor C. Tsai[1], Gerard Roe[3], Marianne Haseloff[4], Helene Seroussi[5]
1 California Institute of Technology, Division of Geological and Planetary Sciences
2 University of Chicago, Department of the Geophysical Sciences
3 University of Washington, Department of Earth and Space Sciences
4 4 Princeton University, Atmospheric and Oceanic Sciences
5 California Institute of Technology, Jet Propulsion Laboratory

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

J.M. Schaefer[1,2], M.L. Bender[3], R.C. Finkel[4], K. Fifield[5], G. Balco[6], M. Caffee[7], R.A. Alley[8], J. Briner[9], N. Young[1]

1: Lamont-Doherty Earth Observatory, Palisades, NY, USA
2: Columbia University, New York, USA
3: Princeton University, Princeton, USA
4: UC Berkeley, Berkeley, USA
5: ANU, Canberra, Australia
6: Berkeley Geochronology Center, Berkeley, USA
7: Purdue University, Purdue, USA
8: Pennsylvania State University, College Station, USA
9: University at Buffalo, Buffalo, USA

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

Nicolás E. Young[1], Joerg Schaefer[1], Jason Briner[2]
1 - Lamont-Doherty Earth Observatory
2- Department of Geology, University at Buffalo

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.

Workshop Participants

Mary Albert
Dartmouth

Richard Alley
Pen State University

Sridhar Anandakrishnan
Penn State University

Yarrow Axford
Northwestern University

Jessica Badgeley
University of Washington

Michael Bender
Princeton University

Robin Bell
Lamont-Doherty Earth Observatory

Ole Bennike
Geological Survey of Denmark and Greenland

Paul Bierman
University of Vermont

Andre Bjørk
University of California Irvine

Andreas Born
University of Bergen

Jason Briner
University at Buffalo

Rachel Carr
Newcastle University

Winnie Chu
Stanford University

Allison Cluett
University at Buffalo

Beata Csatho
University at Buffalo

Dorthe Dahl-Jensen
Niels Bohr Institute, University of Coppenhagen

Christine Dow
University of Waterloo

Mark Fahnestock
University of Alaska, Fairbanks

Rick Foster
University of Utah

Jeremy Fyke
Los Alamos National Laboratory

Chris Gibson
University of Wisconsin

Joseph Graly
Indiana University Purdue University

Joel Harper
University of Montana

Robert Hatfield
Oregon State University

Feng He
Oregon State University

Anne Jennings
INSTAAR, University of Colorado

Ian Joughhin
Polar Science Center, Applied Physics Lab, University of Washington

Benjamin Keisling
University of Massachusetts – Amherst

Meredith Kelly
Dartmouth College

Tanner Kuhl
IDDO – University of Wisconsin-Madison

Petra Langebroek
Uni Research, Bjerknes Centre for Climate Research

Alia Lesnek
University at Buffalo

Joe MacGregor
NASA Goddard Space Flight Center

Gifford Miller
University of Colorado Boulder

Glenn Milne
University of Ottawa

Aurelien Mordret
MIT

Mathieu Morlighem
University of California Irvine

Meredith Nettles
Columbia Univ/Lamont-Doherty Earth Obs.

Tom Neuman
NASA Goddard Space Flight Center

Sophie Nowicki
NASA Goddard Space Flight Center

Erich Osterberg
Dartmouth College

Bette Otto-Bliesner
National Center for Atmospheric Research

Kristin Poinar
NASA Goddard Space Flight Center
University at Buffalo

Alexander Robel
California Institute of Technology

Joerg Schaefer
Lamont-Doherty Earth Observatory

Marc Stieglitz
National Science Foundation

Joseph Stoner
Oregon State University

Elizabeth Thomas
University at Buffalo

Gisela Winckler
Lamont-Doherty Earth Observatory

Nicolás Young
Lamont-Doherty Earth Observatory