US CLIVAR
Climate Variability & Predictability

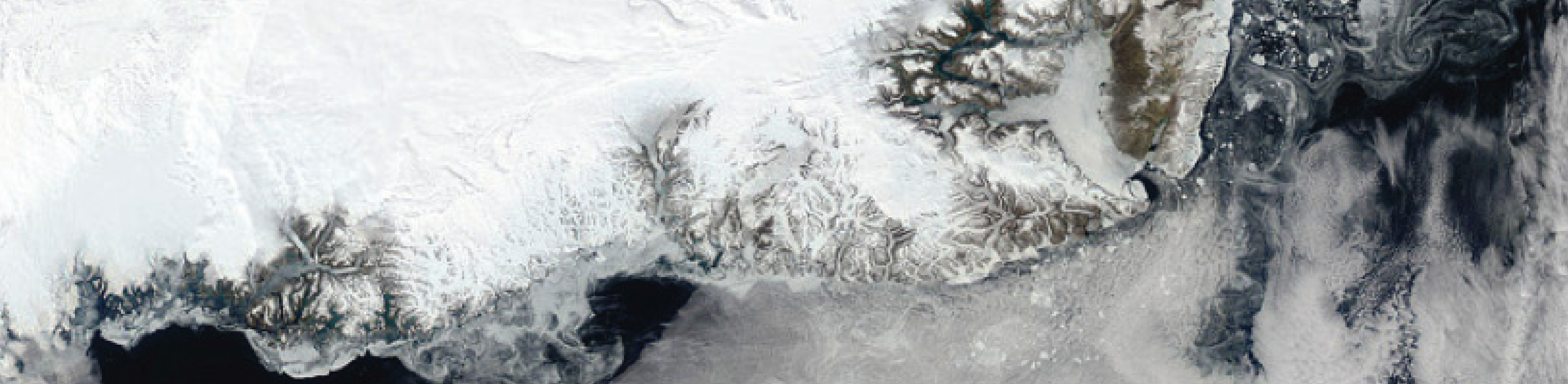
INTERNATIONAL WORKSHOP ON UNDERSTANDING THE RESPONSES OF GREENLAND'S MARINE-TERMINATING GLACIERS TO OCEANIC AND ATMOSPHERIC FORCING

Challenges to improving observations, process understanding and modeling

June 4-7, 2013

Wylie Inn & Conference Center

Beverly, Massachusetts



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COVER IMAGE:

View of Greenland from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on June 28, 2010, following an exceptionally early onset of melting and two months of anomalously high surface temperatures in the Arctic. Image credit: NASA Image by Jeff Schmalts, MODIS Rapid Response Team, Goddard Space Flight Center http://visibleearth.nasa.gov/view.php?id=44524

BACK COVER IMAGE:

An iceberg from a Greenland glacier drifts equatorward in the East Greenland Current on the East Greenland shelf. Increased ice discharge from the Greenland Ice Sheet has contributed to sea level rise and a freshening of the subpolar North Atlantic. Photo credit: Fiamma Straneo, Woods Hole Oceanographic Institution.

INTERNATIONAL WORKSHOP ON UNDERSTANDING THE RESPONSES OF GREENLAND'S MARINE-TERMINATING GLACIERS TO OCEANIC AND ATMOSPHERIC FORCING

Challenges to improving observations, process understanding and modeling

Report from a US CLIVAR and NSF Polar Programs-sponsored International Workshop

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http://www.usclivar.org/meetings/griso-workshop

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Executive Summary

A US CLIVAR-sponsored international workshop was convened in June 2013 to discuss the problem of *"Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing"* and the challenges to improving observations, process understanding, and modeling. The rationale for holding the workshop derives from observations over the last decade of increased mass loss from the margins of the Greenland ice sheet (GrIS). The widespread, regionally synchronous acceleration, and thinning of some of its major marine-terminating outlet glaciers point to a common climatic driver, consistent with the observed warming of the North Atlantic subpolar gyre and near-surface atmospheric warming. Detailed process understanding, however, is currently lacking. This hampers assessment of the impact of increased freshwater flux from the GrIS, not only on regional and global sea level, but also on the North Atlantic circulation and its effect on climate over the Atlantic sector.

The workshop brought together oceanographers, glaciologists, atmospheric, paleo, and climate scientists, including observationalists, modelers, and theoreticians. The 90 attendees included 47 US scientists funded by many research-funding US agencies and 40 non-US experts from 10 countries. Specific meeting goals were:

1. Advancing the science, through improved communication, coordination, and collaboration between the diverse communities;
2. Establishment of the foundation for multidisciplinary efforts that will lead to deeper understanding of physical processes, better representation of these processes in climate models, and, consequently, more reliable projections of the Greenland Ice Sheet contribution to sea level;
3. Training and network building across disciplines for scientists at all career levels, with specific focus on advanced graduate students and early career scientists.
4. Identification of synergies of national and international projects;
5. A document describing a prioritized set of recommendations to advance this urgent and complex interdisciplinary problem.

The workshop was structured into sessions covering the following themes: *Evidence from Glacier Variability; What are the proposed Mechanisms? Evidence from the Paleo Record; The Ice-Ocean Boundary; The Role of (Sub) glacial Hydrology; Oceanic Forcing; Continental Shelf and Large-Scale Ocean Circulation; Glacier Calving and Ice Mélange*; *Modeling Glaciers, Ice Sheets, and Climate; Role of Bottom Topography.*

In discussing a research strategy to move the science forward, workshop attendees identified six basic components:

1. *Improved Bottom Topography* – Subglacial bedrock, sediment, and seafloor bathymetry are of fundamental importance for both glacier and ocean modeling efforts. It is the leading source of uncertainty in simulations that attempt to conduct centennial ice sheet projections. A dedicated effort targeted at obtaining high-accuracy bottom topography of key outlet glaciers, connected fjords, and adjacent continental shelves is crucial.

2. *Data Compilation and Sharing* - The challenges involved in advancing the science and the cross-disciplinary nature of the subject require special emphasis to ensure ease of access of crucial data sets. Efforts should focus on collating and providing all existing data in consistent, easily accessible formats, in particular those data required to conduct model simulation and validation.

3. *Process Studies* – A set of targeted studies are required to provide an understanding of the dynamics of specific processes (e.g., submarine melting, calving, fjord circulation, ice mélange, proglacial sedimentation, etc.), especially coupled processes between two systems. The rationale is that their dynamics may be easier to study in isolation. Special attention should be paid to processes that lead to improved dating of paleo proxy records.

4. *Megasites* – In depth studies of all components (glaciological, oceanographic, and atmospheric) of a few key glacier-fjord-shelf systems is needed to provide an understanding of the interconnectedness of the system and a platform for interdisciplinary studies. Field experiments at these sites should include: a glacier node, a fjord/cavity node, a continental shelf node, and an atmosphere node. A list of ideal characteristics for megasites is proposed.

5. *Greenland Ice-Ocean Observing System (GrIOOS)* - Long-term in-situ time series of critical glaciological, oceanographic, and atmospheric variables at a number of key locations are needed to provide information on the time-evolving relationships between the different climate forcings and the glacier flow. A further goal is the ability to capture potential events in locations that, at present, exhibit little glacier activity, but may do so in the future. Roughly 10 sites will be chosen and measurements sustained for at least a decade. A list of ideal characteristics for megasites is proposed.

6. *Linkages to other programs* - Planning of megasites, process studies, and a Greenland-wide observing network should take into account the availability of existing data from complementary networks. It should also assess existing satellite and airborne remote sensing capabilities and required new technologies.

I Introduction

Mass loss from the Greenland ice sheet (GrIS) quadrupled from 1992-2001 to 2001-2011, resulting in a net contribution to sea-level rise of approximately 7.5 mm over the 1992-2011 period, roughly twice the Antarctic contribution [*Shepherd et al. 2012*]. Half of this loss is associated with the increased melt and run-off associated with rising air-temperatures over the ice sheet and is well reproduced by models [*van den Broeke et al. 2009*]. The remaining half resulted from the speed up and retreat of marine-terminating glaciers located in SE and W Greenland that began in the late 1990s [*Howat et al. 2007; Rignot and Kanagaratnam 2006*] and continues to this date [*Moon et al. 2012; Joughin et al. 2013*]. Unlike changes in surface mass balance, the glacier acceleration and retreat is not well understood and not fully captured by models [*Vieli and Nick 2011*]. Beyond the challenges of understanding and representing the complexity of the glacial dynamics that lead to the retreat [*Price et al. 2008*], one important issue that remains to be resolved is to identify the external (oceanic and/or atmospheric) forcing that triggered the initial retreat and the mechanisms through which it acted. Amongst those proposed, oceanic forcing has emerged as a leading, plausible mechanism [*Vieli and Nick 2011*], making ice sheet-ocean interactions in Greenland a new research frontier that is critical to understanding the ice sheet's evolution and its contribution to global sea level rise [see reviews by *Straneo et al. 2013; Joughin et al. 2012; Vieli and Nick 2011*]. Ice sheet-ocean interactions are likely behind recent changes in Antarctica [*Joughin and Alley 2011*], but several considerations suggest that Greenland requires special attention. First, the coastal and oceanographic setting and the climatic conditions differ between the two ice sheets, as well as the ice flow [*Truffer and Echelmeyer, 2003*]. Second, Greenland's ice loss is contributing to a freshening of the North Atlantic's dense water formation regions, where it can potentially impact the meridional overturning circulation of the North Atlantic, its associated heat transport, and through it the regional climate over the North Atlantic sector and beyond [*Marsh et al. 2010; Weijer et al. 2012; Bamber et al. 2012*].

Understanding ice sheet-ocean interactions in Greenland and incorporating them in models used for sea level rise projections, however, are far from trivial. Greenland's largest glaciers terminate in deep, long fjords, which are remote, inaccessible, and choked with large icebergs whose calving and drift pose a major challenge to scientists and instrumentation. The records of oceanic and sedimentation changes near the glaciers (or even on Greenland's continental shelves where the fjords terminate) are almost non-existent, especially from the period preceding the glaciers acceleration. Furthermore, the processes through which the ocean may impact the glaciers, including submarine melting or weakening of the ice mélange or sea-ice in front of the terminus, are complex, involving a wide range of temporal and spatial scales as well as multiple components (including the ocean, atmosphere, sea-ice, proglacial seafloor sediments, and glacier). Thus, progress on this complex topic will require a cross-disciplinary and multi-faceted approach that involves a broad international community and pools a wide range of resources.

Previous reports have highlighted the importance of studying the role of mass loss from polar ice sheets in sea level rise in the coming centuries [*Bindschadler et al. 2011*]. The need to address ice sheet-ocean interactions in Greenland is described in detail in a white paper by the US CLIVAR Working Group on Ice Sheet-Ocean Interactions [*Straneo et al. 2012*] and in an article based on the white paper [*Straneo et al. 2013*]. One major recommendation from the Working Group was a workshop that would bring together the different communities involved in studying the problem of ice sheet-ocean interactions in Greenland, to discuss the problem, and to develop strategies to address it. The present report summarizes the outcome of a cross-disciplinary International Workshop on *"Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing."* The workshop took place at the Wylie Inn & Conference Center outside of Beverly, MA, on June 4 - 7, 2013. Its main sponsor was US CLIVAR, representing four major US funding agencies (NASA, NOAA, NSF, DOE), with additional support from NSF Division of Polar Programs.

1.1 Workshop Goals

The workshop was initiated as a result of recommendations published by members of the US CLIVAR Working Group on Greenland Ice Sheet-Ocean Interactions (GRISO) in the Working Group white paper [*Straneo et al. 2012]*. Its primary purpose was to bring together observationalists, modelers and theoreticians from the oceanographic, glaciological, meteorological, and climate communities to discuss the challenges and requirements for improving observations, process understanding, and modeling of this problem. Specific meeting goals were:

1. Advancement of the science, through improved communication, coordination, and collaboration between the diverse communities interested in various aspects of ice/ocean/atmosphere interactions in Greenland;
2. Establishment of the foundation for multidisciplinary efforts that will lead to improved understanding of physical processes, better representation of these processes in climate models, and, consequently, more reliable, physically based, projections of the Greenland Ice Sheet contribution to sea level;
3. Training and network building across disciplines for scientists at all career levels, with specific focus on advanced graduate students and early career scientists;
4. Identification of synergies of national and international projects;
5. A document describing a prioritized set of recommendations to advance this urgent and complex interdisciplinary problem, including a plan for a long-term Greenland observing system.

Similar goals were formulated by the US "Study of Environmental Arctic Change " (SEARCH) in their 5-year research program released in April 2012 (see http://www.arcus.org/search/land-ice).

1.2 Workshop Structure

i. Organizing and Scientific Steering Committee

The Organizing Committee was tasked with the organization of the workshop and with chairing the Scientific Steering Committee (SSC). The SSC comprised 17 members (including the Organizing Committee, see Appendix A). It was in charge of planning the workshop format, selecting invited speakers, and reviewing the submitted abstracts. It included experts from the multiple disciplines, who were tasked to act as liaisons to the diverse communities (see Appendix). The committee included international representatives from many of the countries that are most active in research in Greenland, including Greenland itself. The committee had a balanced representation across scientific communities, agency affiliation, genders, and seniority level.

ii. Meeting Format

An overarching goal of the meeting was to ensure that the best up-to-date knowledge was reflected in the meeting presentations, and to engage the workshop participants in focused discussions on how to test the existing hypotheses, identify major unknowns, and formulate requirements for key observations and process studies.

The initial plan to achieve these goals consisted of a mix of (i) invited talks presenting overviews and competing hypothesis statements, (ii) in-depth talks on various aspects of the problem, and (iii) poster presentations. Following intense deliberations within the SSC, it was decided to give more room to discussions, and to elevate the role of posters in the workshop. Broad consensus within the SSC emerged for the following format:

1. a total of 10 topical sessions (see Section 1.3);
2. two to three invited overview talks for each session;
3. 3-minute introductory talks by each science presenter who had a poster;
4. poster sessions;
5. extensive discussion sessions led by members of the SSC.

Following the topical sessions, the SSC met to attempt aligning what had been learned and discussed during the workshop with the meeting goals. Four focus topics emerged, for which statements were prepared to be discussed in the concluding discussion sessions on Friday. These emerging focus topics will be described in detail in Section 3.

iii. Attendees

The workshop brought together oceanographers, glaciologists, atmospheric, paleo, and climate scientists, including observationalists, modelers, and theoreticians. The 90 attendees included 47 US scientists funded by many research-funding US agencies (NASA, NSF, NOAA, DoE, ONR), related observation and modeling projects and centers (in the US, e.g., ASOF, CReSIS, CESM, GFDL, ECCO, JPL, LANL), 40 international experts from 10 countries who are studying processes in Greenland, adjacent ice caps (especially Alaskan tidewater glaciers) and surrounding seas (especially Nordic Seas and the subpolar North Atlantic), and 3 program managers. Among these were 32 early career scientists (graduate students or less than 5 years since graduation). By fostering participation of these early-career scientists, the workshop contributed to the training of a new generation of multidisciplinary scientists that are well-versed in their fields but also well-educated and aware of problems in collateral fields. A complete list of attendees is provided in Appendix D.

iv. Venue

The workshop took place at the Wylie Inn & Conference Center (http://www.wyliecenter.com/) in Beverly, MA, USA, a resort 20 minutes north of Boston. The main selection criteria for this place were (1) its easy accessibility from a major international airport (Boston Logan Airport) to accommodate the expected attendance of participants from Europe, (2) its sufficient remoteness to ensure close interaction among the participants throughout their stay, (3) reasonable costs, and (4) disabled-accessibility according to the Americans with Disability Act.

2 Topical Sessions

The workshop covered a number of key themes, which were organized in topical sessions. Each session is summarized in the following. More detailed session reports are provided in Appendix D.

Session 1: Overview of the Problem of Ice Sheet-Ocean Interactions

The session summarized the scientific rationale for holding the workshop and laid out the workshop goals.

Session 2: Evidence from Glacier Variability

Outlet glacier systems around Greenland, while exhibiting regionally synchronous behavior, also show large spread, even for nearby systems. There is currently a serious lack in understanding of the basic dynamics of outlet glacier variability that prevents skillful projections of their behavior. More observations are needed on a variety of spatial and temporal scales that include all possible modes of observation - remote sensing, in situ, near situ, etc.

Session 3: What are the Proposed Mechanisms?

The community's leading hypothesis is that changes in submarine melting or in the ice mélange (mixture of ice bergs and sea ice typically found in fjords near the glacier termini) may have triggered the retreat of Greenland's glaciers. However, our present understanding of how glaciers respond to these forcings is too crude to draw any conclusions. Improved high-resolution modeling of tidewater glaciers will require better constrained parameters, forcings, and processes - including botton topography (with careful consideration of bedrock vs. sediment characteristics), submarine melt rates, and the back-stress due to the ice mélange. At present, too little is known to appropriately incorporate these processes in predictive models. Further studies are needed to determine whether the ice mélange have any influence on tidewater glacier dynamics. Submarine melting on tidewater glaciers occurs both in Alaska and in Greenland and can be studied at both locations. Its quantification is complex for tidewater glaciers and involves assumptions about the circulation in the fjords and subglacial discharge - neither of which are well known. Furthermore, we acknowledge that very little is known about the shape of the seafloor or the sedimentation rate in front of Greenland's tidewater glaciers. In Alaska, the prevailing conceptual model for tidewater glacier behavior involves a strong connection between evolving submarine moraines and terminus stability [*Post et al., 2011*]. It remains to be seen whether this conceptual model can also explain the contrasting response of neighboring tidewater glaciers in Greenland [*Moon et al. 2008*].

Session 4: Evidence from the Paleo Record

Joint reconstructions of paleo-ice stream and outlet glacier retreat histories in relation to changes in ocean (and atmospheric) properties may add valuable information to understanding ice-sheet/ocean interactions. Better understanding of the required spatio-temporal sampling is needed, with implications for collection of new records, in particular along the continental shelf outside of the LGM limit. Challenges in making progress involve (1) understanding driving mechanisms on sub-millennial time scales; (2) improved spatial data coverage on the continental shelf, in particular in paleo-ice stream troughs and inter-stream areas; (3) understanding local records in terms of ocean temperatures; (4) temporal correlation of proxy records of East and West Greenland to test relative timing of retreat histories; (5) improved data/model synthesis and sensitivity analysis; (6) reducing geochronology error margins in order to resolve differential glacier retreat rates.

New geochemical and proxy methods begin to resolve glacier margin positions with sub-centennial accuracies. Other proxy records are even reaching sub-decadal resolution and so can resolve forcing changes related to the NAO or AMO. Reconstructions covering the last 1000 to 100 years, e.g., the transition from the medieval warm period to the Little Ice Age to present-day provide important baseline states for contrasting climatic settings. A reconstruction work seeks to link the last several thousand years to the present-day instrumental record.

The last deglaciation also provides an interesting paleo-test where major forcings caused major responses of marine outlet glaciers. These periods of study can enlighten on the roles of ocean warming versus topographic controls and on the maximum rates that ice margins can discharge ice.

Session 5: The Ice-Ocean Boundary

Most insights into the processes of ocean circulation and melting beneath slanting ice shelves have been provided by meltwater plume theory, with meltwater as a source of buoyancy (melt-driven buoyancy). In contrast, dynamics at the vertical ice fronts in fjords are significantly influenced by the relative strength of buoyancy and inertia of the freshwater discharge at the bottom of the glacier (buoyancy-driven melting). High resolution, non-hydrostatic ocean models are required to capture the processes, which is challenging for large-scale climate models and requires the development of suitable parameterizations. There are very few observations to test the parameterizations due to the difficulty of accessing the base of ice shelves and the challenges in sampling near a calving ice face. Observational capabilities need to be improved, in particular with respect to measuring ice-ocean boundary processes of tidewater glaciers.

Session 6: The Role of (Sub)glacial Hydrology

Subglacial hydrology affects ice flow on a variety of timescales - from days to years. Surface runoff is the dominant source of water in the ablation zone and it has increased substantially in recent years. Direct observations of subglacial hydraulic systems are very limited, and that hinders progress in understanding subglacial hydrology. In such circumstances, a statistical approach, using regression relationships between surface melting and sliding speed, may be an alternative.

Session 7: Oceanic Forcing

Ocean-induced changes in glacier dynamics are presently supported only by statistical/heuristic arguments - we still lack a basic understanding of the processes at play that can inform model simulations which, in turn, can help shed light on this link. Key to improving this situation is understanding what governs the circulation within the glacial fjords and, in particular, the submarine melt rate. Some progress has been made in mapping the properties of multiple fjords around Greenland, but our understanding of the leading order dynamics and how this may vary from fjord to fjord are still limited. Submarine melt rates are needed to force ice sheet and glacier models, but melt rates estimated from oceanic data are highly uncertain and likely to remain so until we understand the degree of variability and the circulation within the fjords.

Session 8: Continental Shelf and Large-Scale Ocean Circulation

The warming of waters around Greenland (in the sub-polar North Atlantic) is not simply attributable to modes of variability or to long-term trends due to climate change. Likely, it results from a combination of these processes. High-resolution ocean models are needed to resolve the oceanic processes that bring the warm water onto the continental shelves towards the mouth of the fjords. Yet this resolution is still insufficient to resolve the fjords. Accurate bottom topography is one key element that is needed to model the ocean circulation around Greenland; also, higher resolution models that can include the fjords are needed.

Session 9: Glacier Calving and Ice Mélange

Calving operates on a range of spatial scales from mm to km. An accurate "calving law", i.e., a unifying physical formulation that allows specification of the calving of small pieces of ice continuously detaching from ice fronts and large tabular icebergs detaching roughly twice a century from large ice shelves, has been elusive for the past fifty years and, so far, remains out of reach. Some progress in understanding calving has been made using laboratory and modeling studies. New approaches are needed to utilize already available data (terminus positions and rates of their movements) and collection of new information useful for advancing understanding of calving.

Session 10: Modeling Glaciers, Ice Sheets, and Climate

Despite significant improvement in ice sheet modeling (ranging from representing full-Stokes ice dynamics to development of parameterization of physical processes within ice sheets, in particular glacial hydrology and calving), ice sheet models still lack predictive capability. Improved observations (spatio-temporal coverage and quality) and their better utilization (time-evolving or time-snapshot fields as opposed to time-mean fields) are needed to resolve inter-annual to decadal evolution. Increasing emphasis is put on optimal estimation of ice sheet model parameters and the construction of ice sheet initial states that are suitable for prediction. Different initialization strategies lead to rather large disagreements in ice sheet volume, even in control runs. A serious issue, which exacerbates model initialization, remains the physical inconsistency between different data sets (e.g., bedrock versus flow velocities versus thickness evolution). Coupling the components in Earth system models (glacier, ocean, atmosphere) requires consideration of disparate spatio-temporal scales, the use of spatial downscaling (surface mass balance and atmospheric forcing), and asynchronous time-stepping techniques. The impact of changing ice geometries on the climate components is currently crudely represented, limiting the assessment of feedback mechanisms. Required model improvements include: energy and mass conserving ice-ocean and ice-atmosphere two-way couplings; glacial hydrology representation; radiation/albedo feedbacks; and addressing biases introduced through inaccurate coupling.

Session 11: Bottom Topography (Subglacial Bedrock, Sediment and Seafloor Bathymetry)

It is paramount to improve measurements of bottom topography (with careful distinction between bedrock vs. sediment signatures) under outlet glaciers, of the fjords, and on the continental shelf. Higher-resolution is critical to test regional ocean and outlet glacier models. Observations need to resolve features well below the kilometer scale. Measurement techniques include radar for grounded ice, standard and swath acoustic mapping for bathymetry, charting by instrumented marine mammals, and gravity measurements to use in inversions that yield information about bottom topography of fjords and beyond on the continental shelf. It is also vital to have all data sources open, quality-controlled, and freely available.

3 How to Move Forward

3.1 Overview and Proposed Strategy

A major goal of the workshop was to develop a research plan to significantly improve our understanding and projection of the Greenland Ice Sheet's dynamic changes. The implementation time scale addressed here is 5-10 years, with some key observations needing to be continued for at least a decade. We envision that the results from this research plan will primarily be used to inform future model simulations of ice sheet and climate variability, to address current uncertainties in the ice-sheet's contribution to sea-level rise, and also to understand the impact of freshwater discharge from Greenland on ocean circulation and consequences for the climate over the North Atlantic sector (including, but not limited to continental US and Europe). Key to these questions is to identify which ocean-related processes may have led to the recent dynamic changes in Greenland. Several (not necessarily distinct) mechanisms for "how the ocean impacts Greenland's glaciers" emerged from the workshop. In order of (perceived) importance (in the context of affecting the dynamics of Greenland's glaciers) these are: submarine melting; changes in the ice mélange; and mechanical forcing by waves or tides.

To make progress over the next decade on the question of how the ocean impacts Greenland's glaciers, the workshop identified an emerging research strategy. It involves five basic components (which are discussed in detail in the following sub-sections):

1. Improved Bottom Topography - a dedicated effort targeted at obtaining high-accuracy sub-glacial bedrock, sediment, and seafloor topographies of key outlet glaciers, connected fjords, and adjacent continental shelves;
2. Data Compilation and Sharing - to provide the necessary ancillary data needed to address this problem, quality-controlled and with error bars, and to make them easily accessible in a consistent format;
3. Process Studies - to provide an understanding of the dynamics of specific processes, in particular of coupled processes in isolation;
4. Megasites - to provide an understanding of the interconnectedness of the system and a platform for interdisciplinary studies;
5. Greenland Ice-Ocean Observing System - to provide temporal and spatial context for ice sheet-ocean interactions - including sites that are not megasites.

Modeling will be an integral part of the research implementation, both in terms of aiding the design of process studies, megasites, and observing systems, as well as being a target for transferring *process understanding* to suitable *process parameterization* in large-scale Earth system and climate models.

3.2 Improved Bottom Topography

Subglacial bedrock, sediment, and seafloor bathymetry – collectively referred to here as bottom topography – are of fundamental importance for the both glacier and ocean circulation modeling efforts. It has been shown to be the leading source of uncertainty in simulations that attempt to conduct centennial ice sheet mass loss projections. A dedicated effort should, therefore, be devoted to collecting vastly improved bottom topographic data from underneath outlet glaciers, underneath floating ice tongues, in fjords, and on adjacent continental shelves. Such data should be collected

- for the key glacier/fjord/shelf systems that are candidates for megasites (section 3.5);
- for systems that will be part of a proposed Greenland Ice Ocean Observing System (section 3.6);
- for all glacier/fjord/shelf systems that are considered to be among the 10 to 20 most important (in ways to be properly defined) systems in Greenland.

Some of these surveys should be carried out in concert with efforts to identify modern sedimentation rates and assessments of how actively any submarine terminal moraines may be prograding. This information is important for interpreting sediment records and deducing the glacial history from those. It can be used to inform process-based studies examining the links between sedimentation and glacier stability (section 3.4).

Some of these dedicated surveys may be achieved as part of "megasite" campaigns; others should be undertaken as focused efforts. Resolution requirements for high-resolution modeling are well below 1 km (somewhere between 100 and 500 m?).

In terms of available measurement techniques, aero-gravity is identified as a potentially effective means of obtaining coastal bathymetry. It allows dense coverage compared to sparsely sampled shipboard measurements, and it is significantly cheaper than ship-borne multi-beam echo sounding. However, it cannot yet obtain the sub-km spatial resolution required for modeling, and inversion uncertainties due to geophysical limitations such as unknown sediment thickness lead to elevation errors of several 10's of m. In the fjords, detailed bathymetric information has been retrieved from instrumented seals. AUV's offer the possibility to provide much improved bathymetric information.

To plan and coordinate the bottom topography data collection and compilation, a study group should be formed, consisting of glaciologists and oceanographers with relevant expertise (e.g., use of aero-gravity, ship-borne echo-sounding, AUV deployment) and end user interests (in particular, ice sheet modelers). The group should lay out a concrete plan of what is required technically, logistically, and financially to achieve a "complete mapping" (in a way to be defined) in the coming 5 to 10 years.

3.3 Data Services, Synthesis, and Transparent Modeling

The challenges involved in advancing the science of ice sheet-ocean interactions and the cross-disciplinary nature of the subject require special emphasis to ensure ease of access of crucial data sets. Here "ease of access" refers to actually making the data publicly available, both in raw (where useful) and quality-controlled form, providing its useful documentation, centralizing data archives (one-stop approach), and promoting homogeneous data formats to increase the ease of use. Several data sets are crucial to any effort to understand or model ice sheet interactions - amongst these are

- bottom topography (subglacial bedrock and sediments; fjord/ocean bathymetry);
- meteorological measurements from AWS;
- ocean data from ship surveys and moorings;
- atmospheric reanalyses and ocean state estimates in common format;
- surface mass balance and/or dischargeestimates, e.g., from regional modeling;

- relevant data from dedicated airborne campaigns;
- paleo-reconstructions of ice sheet, ocean, and atmospheric conditions as baseline data sets for ice sheet model spin up.

Often, various related data archives already exist on an individual (PI or project) basis, which store either the data or relevant meta-data (and pointers to the sources). A serious discussion should be undertaken to address the extent to which to rely on existing archives, to re-create archives, or develop sophisticated, up-to-date meta-archives that gather all data sources that are relevant to the science of Greenland ice sheet-ocean interactions. Existing efforts, such as the Arctic Research Mapping Application [*Gaylord et al. 2013*] provides initial steps in this regard.

NSF's Office of Cyberinfrastructure should be involved in developing a comprehensive and integrated plan. A recent report on Cyberinfrastructure for Polar Sciences has highlighted "Data as a Service" (DAAS) as an important activity. It refers to all aspects of data curation, management, services, archiving, discovery, access, analysis, and modeling [*Pundsack et al. 2013*]. In moving forward, that report should be consulted for details.

In defining the archive content and structure, consideration should be given to model input requirements. Essential fields (bottom topography, surface and subglacial boundary conditions, forcings, climatologies, etc.) are especially important. Consideration should be given to developing shared data sets that are appropriate for Model Intercomparison Projects (MIPs). Again, development should be based on, take note of, or learn from what's already available, e.g., from projects such as:

- seaRISE (http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment)
- CORE-II (http://data1.gfdl.noaa.gov/nomads/forms/core/COREv2.html)
- MISMIP (http://homepages.ulb.ac.be/~fpattyn/mismip/)

In surveying the existing diverse data sets, efforts should be devoted to their synthesis into a coherent dynamical framework. Models play two important roles in this regard: (1) serving as dynamical interpolators of the heterogeneous data (disparate sampling and different variables that are linked through known physical relationships); and (2) supporting the design of field campaigns (in particular with regard to spatial and temporal sampling). Judicious use of models in the context of observing system simulation experiments (OSSEs) assigns them an important quantitative role in the portfolio of decision-making. The OSSE process itself is well-suited to uncover potential model deficiencies and to focus the discussion on important quantities of interest.

Model intercomparison projects already provide common protocols and metrics for assessing model behavior with respect to process variables (or climate indices) of interest. Modeling groups should consider to further raise the level of transparency of published simulations through increased open-source access of the underlying codes and through "publication" (i.e., making available) of simulation provenance (including source code, information on compiler versions, run-time parameter settings, and input data sets used) in order to enable reproduction of the simulations. The difficulty of code portability requires community support. It could initially be tackled through identification of a few reference platforms, such as NSF's TeraGrid.

3.4 Process Studies

The workshop attendees identified a set of process studies to meet the overarching goal of improving our understanding of ice/ocean interactions around Greenland in relation to increased mass loss. The identified processes are glaciological, oceanographic (and atmospheric), and specific to ice/ocean-interactions by their nature.

Glaciological processes

- sub- and supra-glacial hydrology, englacial freshwater drainage systems;
- glacier calving: causes and effects;
- subglacial processes (e.g., sediment transport);
- surface mass balance budgets and their regional contributions;
- fjord sedimentation and submarine moraine development;
- Oceanographic (and atmospheric) processes fjord circulation and heat transport variability;
- connection to large-scale ocean circulation dynamics and climate variability;
- connection to local atmospheric variability;
- Ice/ocean-interaction processes turbulent heat- and mass-transfer at ice/ocean interface;
- melting at the ice front;
- dynamics of plumes fed by submarine melting and/or subglacial discharge;
- sea ice and ice mélange - their role in modulating melting, calving, and fjord circulation (e.g., through mixing).

It was emphasized that basic aspects of the identified physical processes are universal, and their understanding can be achieved not only by field studies at different locations where these processes are most pronounced (e.g., ice-front melting on Alaskan tidewater glaciers), but also by employing various research means - laboratory, numerical and theoretical studies.

A particular challenge is the lack of observational assets that would unravel the processes that control the turbulent flux of heat and mass across the ice-ocean boundary. It underscores the need for developing new capacities to get at the interface. The observational challenge should be tightly linked with a renewed interest on coupled models of the ice-ocean interface.

In addition to "targeted" studies focused on individual processes, it is proposed to conduct investigations of the interactions (possibly nonlinear) of these processes. Results obtained from laboratory, modeling, and targeted field process studies are intended to inform "megasite" campaigns in terms of observing strategy and requirements.

Paleo data provide clear evidence for centennial switches in fjord-water sources in the last several thousand years, adding complementary insights to process understanding. Did ice respond to these switches? Targeted paleo ice sheet reconstructions and fjord reconstructions would provide important insight into the ice-ocean connection on the 100+ year timescale; something observations cannot do.

3.5 Megasites

Workshop participants have identified the need for detailed interdisciplinary studies of a few key glacier-fjord-shelf systems, at which a comprehensive set of measurements could be simultaneously collected. The purpose of what we call "*megasites" is to coordinate the simultaneous collection of the full range of glaciological, oceanographic*, and atmospheric observations necessary to characterize and understand the intrinsically coupled ice-ocean-atmosphere system. Data collected at these megasites will enable us to understand how the key processes (section 3.4) interact with one another by providing a contextual framework, in which to interpret observations collected at a larger number of sites comprising the Greenland Ice-Ocean Observing System (section 3.6). By definition, they will provide a platform for interdisciplinary study, but will require careful planning to make actual cross-disciplinary science happen.

A secondary goal will be to collect data that are useful for process model verification and validation. To this end, a list of required variables and spatio-temporal sampling should be established for each process considered. Resources should be devoted in the planning phase to developing theory and modeling tools that help characterize the glacier/fjord system. Modeling tools, even if imperfect, are valuable ingredients in the decision portfolio to design an observing network, e.g., in terms of required spatio-temporal sampling, investigating sensitivities to various forcings, and required variables to be measured.

It is anticipated that a minimum of two megasites will be established, with at least one megasite representative of each type of marine outlet glacier (vertical calving and floating tongue). The lifetime of each megasite should be long enough to capture the major modes of variability affecting the interaction of key processes, but the intent is not for them to become long-term monitoring sites. It is anticipated that a megasite will have a lifetime of 2-3 years, after which time the level of effort can be reduced to transition it to a GrIOOS site. Because of their complexity, international cooperation likely will play an important role in establishing and maintaining the megasites.

A comprehensive set of glaciological, oceanographic and atmospheric observations will be collected at each megasite, subdivided into four different nodes:

- A ***glacier node*** will be comprised of sensors to monitor ice-flow speeds near the terminus or grounding line (low-cost GPS receivers, time-lapse cameras, autonomously-operating terrestrial LiDAR or ground-based interferometric radar), changes in terminus position and iceberg calving (time-lapse cameras, seismometers, water-level recorders in the fjord), and surface mass balance (automatic weather stations). The glacier node will also include observations of the ice mélange (time-lapse cameras, low-cost iceberg trackers). On floating tongues, estimates of submarine melt rates can derived from phase-sensitive radar surveys carried out on the ice surface. Regional-scale surveys (covering catchment areas of outlet glaciers) of ice motion and ice thickness changes will be carried out with satellite and airborne remote sensing. Understanding the role of subglacial hydrology on the glacier's behavior and the fjord's hydrography will require hot-water drilling of access holes upstream of the terminus. These holes can also be instrumented with thermistors to measure thermal structure through the glacier, necessary for modeling ice flow.

- A ***fjord (or cavity) node*** will include moored instruments to monitor water properties (temperature, salinity, currents) in the fjord (for vertical calving glaciers) or the subglacial cavity (for floating ice tongues). Instruments will be deployed at several locations spanning the length of the fjord (from the mouth to close to the glacier terminus) or along the floating tongue (from the terminus to the grounding line). Floating tongues offer a stable platform from which to suspend profiling instruments in the subglacial cavity once access has been gained by hot-water drilling. Fjords are more challenging environments to make long-term measurements because deep-keeled icebergs pose a major hazard to bottom-moored instruments. Additional observational approaches will be necessary, such as CTD tags mounted on marine mammals to measure properties through the water column during dives, ice-tethered or drifting instruments for continuous under-ice measurements (currently used in the Arctic), or acoustic sensors to derive integrated heat content along profiles. Autonomous vehicles (underwater and surface) can serve several purposes: bathymetric charting; hydrographic measurements; access to grounding zone. Measurements near the vertical terminus are particularly challenging. Desired observations include melt water discharge plume (e.g., through tracer/isotope measurements); sediment transport; terminus location and shape of the ice front (through sonar).

- A ***continental shelf node*** will be comprised of oceanographic moorings to obtain time series of temperature, salinity, and current velocity across the shelf from the fjord to the continental slope. Instrumented seals will augment the point observations at moorings with a more widely-spaced sampling of water column properties. Satellite data (e.g., sea-surface temperature, sea ice concentration, sea ice drift from radar imagery or scatterometry; ocean salinity observations from Aquarius) will be incorporated where available.

- An ***atmosphere node*** will focus on the collection of standard meteorological parameters (air temperature, wind speed and direction, barometric pressure, radiation fluxes, precipitation). Automatic weather stations will be deployed in the glacier catchments to obtain surface mass balance measurements, and adjacent to each glacier terminus, or on each floating tongue, to provide the atmospheric forcing for changes in the glacier and fjord. Larger-scale synoptic-scale conditions over the whole glacier-fjord-shelf system will be obtained from high-resolution reanalysis products.

Data collection in at least one megasite should be augmented to measuring fjord sedimentation and submarine moraine development to capitalize on simultaneous collection of other variables. In addition, megasite campaigns should incorporate the collection of paleo-proxy data (e.g., sediment cores) targeting various timescales, depending on which paleo proxy data are available (e.g., sediment cores from fjords, sediment cores from epi-shelf lakes). The design of each megasite should be flexible enough to allow changes in observational strategies during the lifetime of the site, or to incorporate new technological advances in instrument design/capability and data telemetry. Previous reports have provided recommendations on the use of paleo-data for understanding ice sheet-ocean interactions (Mix et al. 2012; Carlson et al. 2012) and should be consulted for details.

Participants agreed that the choice of megasite locations should be based on candidate glacier-fjord-shelf systems meeting a defined set of common characteristics. Vertical calving and floating tongue megasites (labeled [*VT*] and [*FT*], respectively) also have some type-specific characteristics, as noted by the symbols:

- Simple geometry for both glacier and fjord (i.e., relatively straight-sided and few tributaries);
- Availability of ice thickness, fjord bathymetry, and cavity geometry (or the ability to obtain this information during the lifetime of the megasite with airborne radio-echo sounding, airborne gravimetry, or autonomous underwater vehicle surveys);
- Availability of pre-existing glaciological, oceanographic, and meteorological observations;
- Deep glacier terminus (~500 m) in contact with warm bottom waters [*VT*];
- Deep fjord sill (below ~150 m) to allow exchange of shelf and fjord waters [*VT*];
- Access to warm water through a trough [*FT*];
- Ease of access (i.e., nearby settlement or research station);
- Leveraging through international collaboration;
- Vulnerability of the regional outlet glacier catchment basin.

For the vast majority of potential megasites, there will be little or no existing paleo data. Once sites are selected, a high-priority task will be to construct decadal to millennial records and proxies of past ice/ocean interaction. This paleo information will be vital for providing context to the modern observations.

3.6 A Greenland Ice-Ocean Observing System (GrIOOS)

Long-term time series of critical in situ glaciological, oceanographic, and atmospheric parameters at a number of key locations are needed to provide information on the time-evolving relationships between the different climate forcings and the glacier flow. These measurements will provide an assessment of the ocean variability within the fjords, of the atmospheric conditions at the terminus, in addition to a record of glacier variability. The lack of such data has greatly hindered our ability to explain and model the recent glacier acceleration. They are critical not only to validate hypotheses but also to provide boundary conditions, forcings, and a point of comparison for both the ocean and the ice model simulations. High temporal resolution measurements are required since it is unclear which timescales govern both the oceanic forcing and the glacier response. Design criteria might involve the calculation of heat transport anomaly budgets toward the glacier termini and freshwater budgets to constrain discharge rates. A further goal of a distributed monitoring network is the ability to capture potential events in locations that at present exhibit little glacier activity, but may do so in the future. The development and maintenance of a GrIOOS will require close international collaboration.

An important use of the network data will be used to constrain various components of Earth system models. Dynamically consistent model-data synthesis frameworks will be required to (i) dynamically interpolate diverse the GrIOOS observations, (ii) put them into context with the basin-scale North Atlantic (and Arctic) satellite and in-situ observing system, and (iii) close heat and freshwater transport changes through time to and from the GrIS.

It is envisioned that approximately 10 GrIOOS sites will be chosen and that measurements will continue for at least a decade. The glacier types associated with the observing system should include a wide range with respect to size, stability, and characteristics. It is envisioned that GrIOOS sites will include both tidewater and floating tongue glaciers. Potentially, several GrIOOS sites could be stripped down versions of megasites, which would benefit from the preceding intensive study. Similarly, several GrIOOS sites could be based on glacier/fjord systems that have already been (or are being) studied, which would allow compilation of a longer time series and would benefit from the existing knowledge of the system.

A basic GrIOOS site could be composed of:

- An ***ocean node*** comprised of a series of oceanic moorings (recording temperature, salinity, velocity, sea-ice and iceberg conditions) both in a fjord and on the shelf. Depending on the fjord/glacier type, the way these measurements are achieved may differ substantially. Floating tongues offer the possibility of suspending instruments from the ice through bore holes that are expensive to drill but provide an ideal platform. Several successful examples of this technology have been used on Antarctic ice shelves. Tidewater glaciers with substantial calving are very challenging because of the deep draft icebergs and general inaccessibility of the region. These require subsurface moorings and potentially proxy measurements for the upper portion of the water column that contains the icebergs. For example, depth averaged heat content measured by acoustic means may help provide information on the temperature of the upper several hundred meters which are not instrumented because of iceberg draft. Complementary measurements such as biogeochemical sensors can be added to the nodes to address problems of interest to different communities. New technologies should be developed to address these challenges.

- A ***glacier node*** including observations of ice flow (low-cost GPS receivers or off-ice time-lapse cameras), terminus position change (time-lapse cameras), and calving (seismometers, water-level recorders in the fjord). For glaciers with no frontal ice mélange, thermal time-lapse cameras should be deployed to monitor the appearance and persistence of subglacial discharge plumes that may reach the surface. For glaciers with a mélange, time-lapse cameras will provide observations of its extent, characteristics, and time-varying behavior. Automated weather stations deployed at locations adjacent to the glacier terminus will collect standard meteorological measurements (air temperature, snow accumulation, barometric pressure, winds, and radiation fluxes).

- As for the megasites, a comprehensive survey should be undertaken for each GrIOOS site to collect appropriate paleo proxy data to establish a historical (decadal to millennial) context for modern observations of past ice-ocean interaction processes.

The following criteria can be used to guide the choice of the GrIOOS sites:

- *Range of glacier types* – including tidewater and floating ice tongue systems and ones where change is/has occurred versus stable systems;
- *Range of oceanic basins* – where the oceanic forcing is likely to differ in terms of variability and amplitude;
- *Proximity to existing observational nodes* – for oceanic, atmospheric, and potentially glaciological long-term measurement sites (see above);
- *Accessibility* – near inhabited regions or regularly serviced regions, which will help both in reducing costs and providing access, if gear needs to be serviced/fixed;
- *Broader interest* – chosen sites should be interesting to other disciplines and incorporate complementary measurements;
- *Local synergy* – linked and of interest to local activities (e.g., of the Greenland Climate Center);
- *International collaboration* – the GrIOOS network should be maintained by an international consortium to help spread the costs and optimize the resources.

3.7 Linkages to Ongoing Programs

Planning of the megasites and the Greenland-wide observing network should take into account the availability of existing data from complementary networks as well as ongoing satellite and airborne remote sensing programs. Existing observing networks include

- DMI meteorological station network (http://www.dmi.dk)
- AWS maintained by GEUS (http://www.promice.org)
- AWS maintained by GCNet (http://cires.colorado.edu/science/groups/steffen/gcnet/map.html)
- Long term oceanic shelf measurements at key locations including Fram Strait (AWI/NPI); Davis Strait (UW/BIO); Cape Farewell (OSNAP); Irminger Sea Node (OOI); Denmark Strait (NACLIM)
- Geodetic (POLENET) and seismic (GLISN) networks (http://polenet.org/, http://www.iris.edu/hq/programs/glisn)
- Greenland GPS network (GNET) (http://www.polar.dtu.dk/english/Research/Facilities/GNET)

In addition, the monitoring sites should be chosen in consideration of existing or planned airborne and satellite remote sensing campaigns. These missions include laser and radar altimetry, SAR interferometry, gravimetry, and optical sensors. Data from these campaigns have broad spatial and temporal coverage that is valuable for constraining many of the controlling processes. Workshop participants made recommendations for campaigns targeting specific measurements (e.g., detailed bottom topography of key outlet glaciers and fjord systems, ice velocity and thickness changes). While NASA's Operation IceBridge furnishes some of these variables and bridges a gap in ice sheet observations between ICESat-1 and ICESat-2, sampling ice-velocity changes at sufficiently high temporal resolution will not be possible without some means to provide a spatially dense field of measurements, as would be possible with interferometric synthetic aperture radar satellite sensors.

Previous reports have highlighted the value of paleo reconstructions of ice sheet, ocean, and atmospheric conditions during the last deglaciation in the context of Greenland ice sheet-ocean interactions. Specific reports are those by Mix et al. [2012], Carlson et al. [2012)], and activities by the PALeo-constraints on SEA-level rise (PALSEA) working group [see http://eis.bris.ac.uk/~glyms/working_group.html].

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Appendix A: Organizing and Scientific Steering Committee

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Appendix B: List of Review Talks and Poster Presentations

Session 2: Evidence from Glacier Variability

(Rapporteurs: Ellyn Enderlin and Ken Mankoff)
Three talks provided an overview of the topic, followed by discussion.

(a) Twila Moon (U. Washington): '*Spatial and temporal variability of Greenland outlet glaciers*'
On the glacier by glacier level, there is no coherent temporal or spatial connection to each other or local environment. On the regional level, high-frequency temporal and spatial variability smoothes out, and it is possible to see synchronous changes. The marine-terminating outlet glaciers draining the NW and SE portions of the GrIS have undergone widespread acceleration and terminus retreat. Changes in velocity and terminus position are evident but it is hard to compare the dynamic behavior of the two regions because of differences in precipitation, elevation, the inland extent of streaming flow, etc. In North Greenland, several glaciers with floating termini (Ostenfeld, Zachariae Isstrom, and Petermann) have calved-off large floating blocks, but little acceleration is evident. These changes were detected using remote sensing observations. Glacier velocities are derived from InSAR, feature-tracking, and speckle-tracking methods. Terminus positions can be tracked using a variety of optical remote sensing platforms. Therefore, a continuation of satellite missions that are the only means to ensure spatial coverage on the Greenland-wide scale is paramount.

(b) Leigh Stearns (U. Kansas): *'Progress and Challenges: Observing Tidewater Glacier Variability'*
Changes occur on time-scales of seconds to decades, and spatial scales of millimetres to kilometers. Therefore, it is difficult to determine a priori what is the right temporal and spatial scale for observations. Moreover, there are many "unknown unknowns," such that it is impossible to plan to observe phenomena related to them. All modes of observations (remote sensing, in situ, etc.) have their advantages and disadvantages. For instance, remote sensing observations provide spatial coverage, but lack necessary temporal resolution. In situ observations, on the other hand, can have very fine temporal resolution, but are not spatially representative. In order to improve our understanding of glacier behavior, we need to combine the three techniques (in situ, near situ, and remote sensing).

(c) Marin Truffer (U. Alaska): '*Lessons learned from Alaskan Tidewater Glaciers*'
Physical processes are independent of geographic location; therefore, the wealth of knowledge acquired studying Alaskan tidewater glaciers can be used to understand behavior of Greenland tidewater glaciers. There are many examples when the behavior of tidewater glaciers is not synchronous with climate change because different processes (bed topography, ocean interactions, erosion/sedimentation, etc.) have different effects on glacier behavior. Therefore, it is not possible to extrapolate observed behavior from one glacier to others. Changes in glacier behavior are not necessarily coupled to climate change, but ice-ocean interactions have the potential to influence ice flow through submarine melting driven by convection of a buoyant plume ejected from the base of the terminus. Alaskan fjords tend to be very warm; therefore, submarine melting has a strong dominance in glaciers mass balance. These fjords could be a good location to conduct studies aiming to understand submarine melting.

Discussion

Spatial and temporal scales of observed changes as well as physical processes were the main topics of the discussion. It was pointed out that short-term events like calving, ice-, or earthquakes control large-scale and long-term events such as glacier geometry.

Session 3: What are the proposed Mechanisms

(Rapporteur: Yun Xu)

Three talks provided an overview of the topic and a discussion followed after the talks.

(a) Andreas Vieli (Univ. of Zurich, Switzerland): *'Modeling the dynamics of tidewater outlet glaciers'*

Ice sheet models resolve ice flow, surface evolution, and grounding line motions reasonably well. They have problems, however, with processes and forcings requiring high spatial resolution such as calving at the glacier terminus or oceanic melt. Therefore, in order to improve models seeking to represent the dynamics of tidewater glaciers – the following processes/parameters need to be better constrained:

- High resolution bedrock geometry is needed to model glacier dynamics since details of the bed really matter – including possible threshold points.
- The influence of the perturbation at the terminus (e.g., front retreat) on the upstream dynamics (e.g., thinning and acceleration) should be represented in the model.
- The calving model (calving law) should be carefully chosen and implemented because the glacier dynamics is very sensitive to the calving model.
- The response to ocean melt should be implemented, i.e., moving ice boundary,
- Different glaciers are sensitive to different forcing types, which should be considered when generalizing the model result.

Models should be applied to 3D, more complicated conditions to understand realistic cases.

(b) Jason Amundson (U. of Alaska): '*In defense of ice mélange'*

The question of whether the ice mélange really influences glacier dynamics is still being debated. Potentially, the ice mélange can act to buttress/inhabit calving, suppress ocean waves, isolate the atmosphere and ocean, and affect capsizing icebergs and submarine melting. An influence of the ice mélange is supported by studies showing that large-scale calving events are preceded by the break-up of sea-ice. For Jakobshavn Isbrae, calving rates are six times larger in summer than in winter, and abrupt onset of calving is in spring. At Store Glacier a small speed up occurs during clearing of mélange. In many cases, seasonal glacier retreat starts before air temperatures are above freezing and stops while air temperatures are still high, leaving the ice mélange as a possible influence on glacier retreat. The mechanism by which the ice mélange impacts calving might be related to its buttressing effect on the glacier, its suppression on waves and winds, and its 'glueing' to the terminus. Progress in addressing the ice mélange's role can be made by compiling more observations from satellite images, time-lapse photography, and terrestrial radar images, and by simulating the mélange in laboratory experiments and numerical modeling.

(c) R. Motyka (Univ. of Alaska): '*Submarine melting'*

Submarine melting is forced by two factors: available heat in fjords and the convection at the ice front that entrains heat to melt the ice. For Alaskan glaciers, ocean temperatures can be up to 12° C at the outer sill and can become a source of heat to the fjords by tidal mixing. Ocean temperatures in Greenland's fjords are normally 0 - 4° C, and heat makes its way to glaciers through advection by wind-driven, tidal, and/or estuarine circulations. Submarine melting occurs both at vertical faces of grounded tidewater glaciers and beneath (especially at the base of) floating ice tongues. A simple two-layer model of ocean circulation with inflow at depth and outflow at the surface has been used to describe the circulation in front of the grounded tidewater glacier. This simplified circulation can be complicated though by the presence of sills, an ice mélange, and icebergs. T-S analysis, with the help of the Gade line, is helpful to diagnose submarine melting. Estimates of submarine melting under glacier tongues can be achieved via flux divergence, echo sounding scanning, and borehole measurement. This approach is less feasible for grounded tidewater glaciers. Here, flux gates should be carefully selected for melt rate calculations. Modeling studies of submarine melting using plume models or GCMs show a quasi-linear dependence of melt rate on ocean temperature and subglacial freshwater discharge.

Discussion

Questions revolved around the role of subglacial discharge, including its seasonality and distribution. Isotope tracers were discussed as a means of identifying water sources. The differences between Alaska and Greenland's glaciers were briefly discussed – ultimately they share similar physics.

Session 4: Evidence from the Paleo Record

(Rapporteurs: Laura Levy and Kristian Kjeldsen)

Three talks provided an overview of the topic, accompanied by 7 specialized (3-minute intros to posters) science presentations.

(a) Jerry Lloyd (Durham University, UK): *'Long term variability of the ocean around Greenland'*

Lloyd provided a context for water masses around Greenland over the era of the last deglaciation from paleo proxy records. Ocean circulation proxies of surface waters include diatoms, dinoflagellates, forams, and d18O, and for bottom waters include benthic foram fauna, Mg/Ca, and d18O. Ice rafted debris (IRD) are useful indicators of large iceberg discharge and ocean circulation patterns underlying their rafting. Issues covered included the origin of the initial deglaciation in Greenland and the evolution of water mass properties throughout the Holocene. The reconstructions suggest an influence of the ocean, in particular the supply of warm water via the Irminger Current in the detailed history of deglaciation (e.g., Knutz et al. 2011).

Main conclusions are (1) joint paleo-reconstructions of the outlet glacier retreat histories in relation to changes in ocean (and atmospheric) properties may add valuable information to the problem of ice sheet-ocean interactions; (2) quantitative temperature reconstructions should be conducted, based on benthic forams transfer functions and Mg/Ca dating; and (3) a better understanding of the required spatio-temporal sampling is needed and implications for collection of new records, in particular along the continental shelf outside of the LGM limit.

(b) Camilla Andersen (GEUS, Denmark): *'Linking glaciers, ocean and atmospheric variability - lesson from marine sediment archives'*

Key interest was on deciphering the climate drivers behind outlet glacier changes during the last 100 years (e.g., in relation to NAO and AMO indices), with emphasis on the 1930s and early 2000s retreat events. A secondary topic was the inference of fjord circulation intensity changes on inter-annual time scales, e.g., due to changes in local storminess. Ocean and atmospheric temperature reconstructions of the Little Ice Age (LIA) period (onset roughly 1250) provide an interesting and contrasting climatic setting.

(c) David Roberts (Durham University, UK): *'West Greenland ice stream instability during the LGM/Holocene transition'.* A number of high-resolution deglaciation reconstruction records of paleo-ice streams and outlet glaciers have become available in recent years. Despite these, the deglacial dynamics remains poorly constrained or understood. Possible forcing mechanisms are sea level rise, insolation changes, atmosphere/ocean circulation changes, and increasing temperatures. Topographic features (troughs/fjords) are likely dominant controls on marine margin stability and their consideration critical in the context of forcing mechanisms. Asynchronous behavior of nearby ice streams point to a complex interplay of forcings and controls. Different forcings may have dominated during different stages of the deglaciation.

Challenges in making progress involve (1) difficulty understanding driving mechanisms on sub-millennial time scales; (2) improving spatial data coverage on the continental shelf, in particular in paleo-ice stream troughs and inter-stream areas; (3) understanding local records in terms of ocean temperatures; (4) testing relative timing of retreat histories using temporal correlation of proxy records of East and West Greenland; (5) improving data/model synthesis and sensitivity analysis; and (6) reducing geochronology error margins in order to resolve differential glacier retreat rates.

Session 5: The Ice-Ocean Boundary

(Rapporteurs: Thomas Millgate and Satoshi Kimura)
Two talks provided an overview of the topic, accompanied by 6 specialized science presentations.

(a) Adrian Jenkins (BAS): *'Ice-Ocean Boundary Dynamics'*
Jenkins covered the physics of the turbulent ice-ocean boundary and meltwater plume beneath the ocean experienced during ice shelf melting. Its parameterization in ocean models is based on fully-developed, unstratified turbulent flow over hydraulically smooth surfaces. Three important assumptions are made: (1) an unstratified ocean beneath the ice shelves; (2) a smooth ice base morphology; and (3) a fully-developed turbulent flow regime. While functional forms of parameterizations are thought to be well known, parameter values (such as drag coefficient, transfer coefficient, entrainment rates) are poorly constrained. There are only very few observations to test the parameterizations due to the difficulty of accessing the base of ice shelves and the challenges in sampling near a calving ice face. Nevertheless, some data are beginning to be collected beneath ice shelves (see Keith Nicholls below).

Most insights into the processes of ocean circulation and melting beneath slanting ice shelves have been provided by meltwater plume theory, with meltwater as a source of buoyancy (melt-driven buoyancy). In contrast, the dynamics at the vertical ice front in fjords is significantly influenced by the relative strength of buoyancy and inertia of the freshwater discharge at the bottom of the glacier (buoyancy-driven melting). High resolution, non-hydrostatic ocean models are required to capture the processes, which is challenging for large-scale climate models, and requires the development of suitable parameterizations.

(b) Keith Nicholls (BAS): '*Observations from the ice-ocean boundary*'
Collecting observations at the ice-ocean boundary is inherently difficult as it means either drilling through or getting underneath an ice shelf or getting dangerously close to the calving front of a

tidewater glacier. There are no direct observations of the ice-ocean boundary of a tidewater glacier. Observations underneath ice shelves have predominantly focused on the whole cavity beneath an ice shelf, however some recent efforts have succeeded in focusing data collection from the boundary layer. The instrumentation available to make measurements within the ice-ocean boundary is improving. ROV's and AUV's potentially hold the future in terms of obtaining measurements, however the cost/risk balance needs to be assessed when using them near active ice fronts.

Observations of the boundary layer were taken by lowering vertical microstructure profilers, current meters and thermistor chains through boreholes. In-situ precision radar can be used to measure ice shelf basal melting to a high level of precision. The microstructure profilers measure shear at high precision, which is used to estimate the turbulent kinetic energy dissipation rate. The thermistor chains record the history of temperature within the ice-ocean boundary layer as the ice-ocean migrates. This measurement can be used to infer the heat flux within the ice-ocean boundary layer, which is broadly consistent with the melt rate of ice shelf measured by the radar. Most observations are from Antarctic ice shelves surrounde by cold or moderately warm (compared to Greenland fjord) water.

Session 6: The Role of (Sub)glacial Hydrology

(Rapporteur: Andrew Taylor)
Two talks provided overviews of the topic.

(a) Ian Hewitt (Oxford Univ., UK): *'Modeling glacial hydrology & implications for submarine melting and discharge'*
He introduced basic ideas of how water moves at the base of glaciers and described two distinct hydrological systems - distributed (water films, micro-cavity networks, canals, linked cavities and Nye channels) and channelized system (Röthlisberger channels). Observations suggest that glacier sliding is proportional to the rate of water pressure change. However, direct measurements are sparse. The existing ice-flow models heavily rely on assumptions of the type of sliding (e.g., over hard rock vs. deformable sediment). There are attempts to link ice flow models with subglacial hydraulic models, but the lack of data to constrain parameters make these coupled models impractical. The subglacial water discharge is spatially and temporally variable, and depends on runoff input in strongly nonlinear ways. Therefore, it is difficult to estimate or develop simple parameterizations useful for assessments of the effects of subglacial runoff on submarine melting at the terminus or grounding line.

(b) Tim Creyts (LDEO/Columbia University): '*Seeing what condition the condition is in: Characteristics of Greenland drainage in englacial and subglacial systems*'
In the ablation zone, there are numerous observations of glaciers' seasonal speed-ups, preceded by strong surface melting. Supraglacial water can reach the bed in numerous ways, e.g., through moulins. Such seasonal speed-ups are widely observed on mountain glaciers in low latitudes and suggest a switch between distributed and channelized hydraulic systems. Seasonal speed-ups extend hundreds of km inland.

Session 7: Oceanic Forcing

(Rapporteurs: Carl Gladish and Rebecca Jackson)
Two summary talks were followed by 7 brief science presentations and discussion.

(a) F. Straneo (WHOI): *'Observations at the margins of Greenland's glaciers'.*
The ocean can directly force outlet glaciers by thermodynamic (melting at the terminus and under ice shelves and melting of the ice mélange) and mechanical (wave and tidal action, energy for mixing) means. Over the last 5-6 years, observations from Greenland's large glacial fjords have shown that these contain waters of both polar (cold, fresh, at the top) and Atlantic (warm, salty, subsurface) origin - and that they are strongly stratified because of the two water masses. Temperature and salinity data provide evidence of melting along the glacier front and the injection of subglacial freshwater at depth. Melting is primarily driven by the Atlantic Water layer. Fjord and shelf properties tend to be fairly similar which suggests rapid exchange between the shelf and the fjord. Limited non-summer data shows differences that can be partly attributed to the seasonal variation in subglacial discharge. In Sermilik fjord, the meltwater plume emerges at mid-depth and at the surface - and there is a large high-frequency variability associated with along-shore wind variability. Recent data indicate that the circulation is not just buoyancy-driven but also driven by shelf-fjord exchange. Estimates of submarine melt rates from oceanic heat transport (flux gates) often assume a circulation pattern and that the entire heat flux goes to melt the ice. These are not necessarily appropriate assumptions.

(b) David Sutherland (U. Oregon): *'Connections between continental shelf circulation and fjord circulation'*
Understanding the circulation in the fjords is key to addressing the problem of ice sheet-ocean interactions in Greenland. The relevant fjord dynamics include (1) estuarine circulation (as in river outflow), (2) intermediary circulation (driven by external baroclinic forcing), and 3) mixing processes.

Estuarine circulation operates on greater than tidal timescales and consists of an outflow near the surface and inflow below, with a resulting exchange flow through the estuary being significantly larger than the amount of freshwater influx. Fjords can be considered as estuaries above the sill depth, if a sill exists. Deep fjord basin waters may be renewed by episodic inflow of denser water.

Intermediate (also known as intermediary) circulation is a two-layer baroclinic flow driven by changes in coastal density profiles. A classification of fjords based on the expected importance of estuarine versus intermediary circulation was proposed. Modeling of fjords has been mostly 2-dimensional, with flow driven by subglacial discharge. Challenges in this approach include: the need to carry out appropriate sensitivity studies, the need for careful attention to mixing, caution in calculating melt rates.

Discussion

Bob Bindschadler asked: 'What do glaciologists need from oceanographers, and vice versa?'
There was general agreement that melt rates were important and that end-member glacier/fjord interactions need to be studied to advance beyond heuristic or statistical or non-physically based relations between calving, melting, glacier advance, mélange and so on. It is unclear what the end-members would be and to what extent one can borrow from studies in Alaska or Antarctica. Modelers need to tell us what they need, but also, processes need to be understood before they are parameterized. Other issues that were discussed are 1) uncertainties in applying the flux-gate method for estimating melt rates, 2) sediment transport at the ice front.

Session 8: Continental Shelf and Large-Scale Ocean Circulation

(Rapporteurs: Ben Harden and Marilena Oltmanns)
This session included three invited talks and 6 short science presentations, followed by discussion.

(a) Ruth Curry (WHOI): '*Variability in the North Atlantic Ocean 1950-2010*'
Greenland subpolar waters are an important cross-road between the Arctic and the subtropics. Most of the action is concentrated in the North Atlantic subpolargyre which influences the location of the storm track and air-sea exchange. Much of its variability is described by the North Atlantic Oscillation (NAO) - where a high NAO corresponds to a cool subpolar gyre. However, the heat content of the entire subpolar gyre has been rising since the mid-1990s and this variability cannot be explained by the NAO anymore - likely there is a contribution from the global rise in oceanic heat content. Curry also noted that the Arctic Ocean has been accumulating freshwater since the mid-1900s.

(b) I. Fenty (JPL/Caltech): '*Ocean Variability around Greenland: Insights from Observations and a Coupled Ocean-Sea Ice Model*'
Warm waters from the subtropics gradually cool along well-defined paths, but the processes that drive the cooling, as well as its seasonal and interannual variability, are not well understood. The heat loss to the atmosphere requires a lateral transport of heat from the mean boundary currents into the interior of the basins. This is done by eddies. Bathymetry is very important for the circulation of the warm water around the slope, onto the shelves and in the fjords.

(c) T. Haine (Johns Hopkins Univ.): *'Modeling the large-scale ocean circulation around Greenland'*
Rich and highly variable shelf/slope ocean dynamics is observed off of southeast Greenland - with numerous eddies along the shelf-break. Topographic steering and mixing (by eddies) mostly along isopycnals is key to dispersion between the polar and the Atlantic waters. Runoff, winds, tidal rectification along bathymetry might be important too, but are not studied with model presented. Troughs are important conduits for channeling warm Atlantic water to fjord mouths. Greenland runoff is still small compared with other freshwater sources and, especially, compared to the large fresh anomaly that has been accumulating in the Beaufort Gyre of the Arctic Ocean.

Discussion
Much of the discussion was about oceanic processes at the basin scale and on the modes of climate variability (e.g., the NAO). Key inputs needed to model the fjord/shelf connections are accurate bathymetry and more ocean measurements that can be used to validate the models (including lagrangian measurements). It is still unclear whether the recent warming of the North Atlantic is attributable to modes of variability or to long-term trends due to climate change.

Session 9: Glacier Calving and Ice Mélange

(Rapporteurs: Ryan Cassotto and Timothy Bartholomaus)

(a) Jeremy Bassis (U.Michigan): *'Bound to fail – calving laws'*
He provided a review of the calving process, the various types of calving, approaches used to describe calving, and a modeling efforts aimed to reproduce some of the salient features of iceberg calving. Calving is a mechanical removal of ice mass from a glacier terminus or ice front, and should be distinguished from

melting. In practice, however, it is difficult to accurately parse between melting at ice front, above and below the water line and calving as all processes take place simultaneously. Currently, there are two ways to consider calving. (i) The big picture and detail-oriented approaches: they are both valuable and have informed efforts to identify broad “calving laws” that can predict the calving rate across a range of glaciers, as well as studies of ice fracture mechanics. Several factors may be important to both approaches, including water-filled crevasses, variations in friction at the glacier bed, submarine melting, and ocean waves. (ii) The relationship between ice thickness at the glacier front and water depth: stemming from this relationship is the apparent dichotomy of floating termini, from which large, tabular icebergs can rift, and grounded termini, from which relatively smaller icebergs can crumble or overturn. The geographic distribution of grounded (e.g., most of Greenland and Alaska) and floating (e.g., northernmost Greenland and Antarctic) termini suggests that temperature, or surface water availability, may be important to the terminus configuration. The imbalance of static normal stresses acting on the glacier front controls the height of the glacier front.

Discussion

Physical aspects of calving (e.g., stress regime and its changes) were the main subject of discussion. It was emphasized, once again that on glaciers with strong melting, it is very difficult to distinguish between melting and calving, since both processes occur simultaneously. It was pointed out that the balance between calving and glacier ice flux to its front could be used as a zero-order parameterization for fjord circulation models.

Session 10: Modeling Glaciers, Ice Sheets, and Climate

(Rapporteurs: Saffia Hossainzadeh and Nicole Schlegel)
Two overview talks were provided, accompanied by 7 specialized science presentations.

(a) Helene Seroussi (JPL/Caltech) *‘Modeling Greenland Ice Sheet Dynamics’*
Recent advancements include implementation of higher-order and full-Stokes solvers, scalability through parallelization, finite element/volume unstructured mesh discretization, and progress in better understanding the physical processes. Improved observations for validation include InSAR velocities, ice thickness from Operation Icebridge, and mass changes from satellite gravimetry (GRACE). Better utilization of time-evolving or time-snapshot fields as opposed to time-mean fields is needed to resolve inter-annual to decadal evolution. Increasing emphasis is put on the estimation of ice sheet model parameters and construction of ice sheet initial states that are suitable for prediction. Model sensitivities to parameters and forcing have been compared within the US SeaRISE project. Sensitivity tests included changes to climate, sliding, and melting at the ocean boundary. Models showed rather different sensitivities. Their different initialization strategies leads to rather large disagreement in ice sheet volume, even in control runs. A serious issue which exacerbates model initialization remains the physical inconsistency between different data sets (e.g., bedrock versus flow velocities versus thickness evolution). Constraining initial conditions and model parameters requires far more and/or improved quality observations than presently available. On “short” time scales (100 years) ice temperatures seem unimportant for simulating volume changes. Inverse modeling approaches are powerful tools to establish consistent model states from inconsistent heterogeneous observations.

(b) Stephen Price (LANL): *‘Land Ice Modeling in Earth System Models’*
The talk was with a focus on the Community Earth System Model (CESM). Coupling the components requires consideration of disparate spatio-temporal scales, requiring the use of spatial downscaling (surface mass balance and atmospheric forcing) and asynchronous time-stepping techniques. The impact of

changing ice geometries on the climate components is currently crudely represented through dump & restart techniques, limiting the assessment of feedback mechanisms. Required model improvements include: energy and mass conserving ice-ocean and ice-atmosphere two-way couplings; glacial hydrology representation; radiation/albedo feedbacks; biases introduced through inaccurate coupling.

Session 11: Bottom Topography (Subglacial Bedrock and Seafloor Bathymetry)

(Rapporteur: Winnie Chu)

(a) Robin Bell (LDEO, Columbia Univ.): *'Airborne Measurements of Glaciers and Fjords'*
She highlighted the effectiveness of aero-gravimetry data in constraining coastal bathymetry. It allows dense coverage compared to sparsely sampled shipboard measurements, and it is significantly cheaper compared to shipborne multi-beam echo sounding. There are new instrumentation developments that allow one to combine multiple sensors and install them on an aircraft, increasing the scope of observations that can be done in one mission. IcePod, such a multi-sensor device that includes optical instruments, radar, gravimeter, etc., will be used in a near future campaign in Greenland and will collect detailed information on ice surface elevation, surface temperature, evolution of water storage within the ice sheet as well as gravity-based fjord bathymetry around Greenland. Such observations can be taken seasonally.

Poster presentations by C. Tinto and D. Porter focused on inversions of bathymetry from gravity measurements.

Discussion

A follow-up discussion session was dedicated to examining the potential of gravity inversion and the future of IceBridge gravity and IcePod campaigns. A common message emerging from the discussion is that of the importance of open data sources. Greenland gravity data collected by Operation IceBridge campaign up to 2017 will be publically available from the NSIDC website in the near future (http://nsidc.org/data/iggrv1b.html). Furthermore, the community suggested that a user-based updating scheme for the data source would be more appropriate in capturing the seasonal and inter-annual changes in marine-terminating glaciers, such as ice thickness and grounding line migration. Other noteworthy suggestions were also made in regard to running more individual gravity surveys along the fjords, in order to minimize the problem of obtaining gravity-derived bathymetry in narrow and steep sided fjords. This could perhaps be achievable in smaller campaigns using a Twin Otter plane.

Session 12: A Programmatic Perspective – Opportunities and Challenges

(Rapporteur: Roberta Sciascia)
Five invited speakers in this session provided feedback from agency and program perspectives.

(a) William Wiseman (Arctic Natural Sciences Program, NSF)
He pointed out that Greenland and the Arctic region and their environmental changes offer to the scientific community opportunities and challenges. The opportunities come from the visibility both inside and outside NSF. NSF's Arctic Science Program has many activities planned over the next 5 years, among which include sea level rise, ice and climate, fjord, outlet glaciers. In the current environments of budget cuts, it is necessary to justify: methods, sites, instruments, and to promote scientific collaborations among different groups.

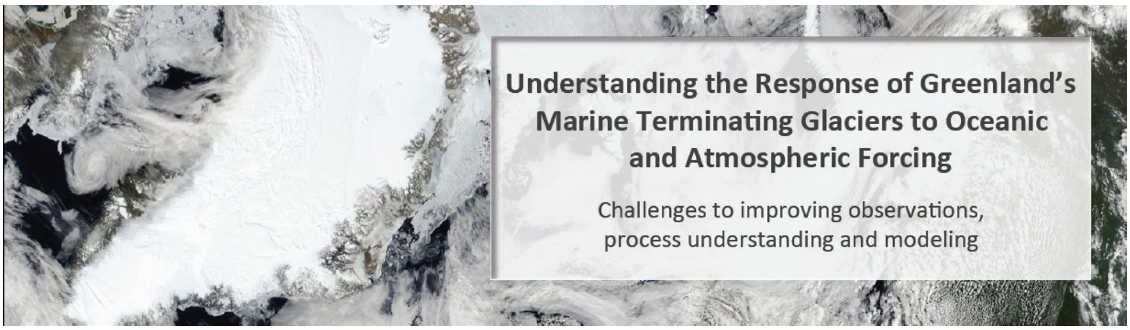
(b) Marco Tedesco (Polar Cyber-infrastructure Program, NSF)
He emphasized that data management and sharing (i.e., publicly available data sets) is an important part of the scientific collaboration and can help address complex scientific problems. The increasing interest in the polar regions (both Arctic and Antarctic) by different research groups results in a great variety of data and requires an informatics infrastructure. The Polar Cyberinfrastructure Program seeks to provide tools for scientists to accelerate and ease their research. This includes data acquisition, storage and management, integration, and visualization. In order to move forward in this direction, it is crucial to closely collaborate with computer scientists and help them develop the most efficient and useful technologies for science research in the polar regions.

(c) Michael Studinger (Operation IceBridge, NASA/GSFC)
He provided the current status of the Operation IceBridge. Its mission is to bridge the gap in data collection between the satellite missions ICESat and ICESat-2. The project is invaluable to obtain new data of ice thickness and bottom topography of Greenland outlet glaciers and fjords, especially through mapping of the major fjord/glacier systems. The main challenge is the bottom topography. Fjords are inaccessible and remote sensing techniques aren't available. It is also important to turn observations into data products and quality control is crucial to obtain comprehensive data sets.

(d) Michael Patterson (US CLIVAR Project Office)
He gave an overview of activities carried out by the US CLIVAR program, and a place that the GRISO Working Group occupies in the contexts of the program. He described opportunities and possibilities of continuing GRISO activities beyond the lifetime of the Working Group as part of the US CLIVAR.

(e) Thomas Wagner (Cryospheric Science Program, NASA HQ)
He pointed out that ice/ocean interaction in Greenland is a large and complicated problem, and although it is indeed driven by societally relevant questions, casting it in terms of sea level rise alone might be too limiting. There are many interesting questions (e.g., impact of glacier's melting on biology; impact of increased freshwater discharge on climate in the Atlantic sector) that must be explored in addition to the sea level rise question.

Appendix C: Workshop Agenda



Date: June 3-7, 2013
Location: Wiley Inn, Beverly MA, (http://www.wyliecenter.com/)
Meeting Website: *http://www.usclivar.org/meetings/griso-workshop/*

Description:
The widespread retreat and speedup of marine-terminating outlet glaciers in Greenland over the past two decades has led to a doubling of the ice sheet's contribution to sea level rise and increased the freshwater input to the North Atlantic. Its coincidence with a period of oceanic and atmospheric warming suggests a common climate driver. Yet the forcings and mechanisms behind these dynamic responses are poorly understood and either missing or crudely parameterized in climate and ice sheet models. Progress on this complex topic requires a collaborative, international, cross-disciplinary and multi-faceted approach. With this workshop, we seek to bring together oceanographers, glaciologists, atmospheric and climate scientists, including observationalists, modelers, and theoreticians, working on all aspects of this problem. A whitepaper initiated by the *U.S. CLIVAR Working Group on GReenland Ice Sheet Ocean interactions (GRISO)* serves as background to this workshop. It can be downloaded at *http://www.usclivar.org/working-groups/greenland-ice-sheet-ocean-interactions/*

Meeting Format:
This workshop seeks to promote a deeper understanding of the physical processes involved in ice/ocean/atmosphere interactions in Greenland including a better representation of these processes in climate models. It is structured around three elements:

- Review talks by invited speakers to summarize the state of knowledge in a specific area (especially for non-experts) laying the foundation for the scientific discussions;
- Science presentations by the participants -- consisting of a 3 – slide (3 min) introduction to the problem and a poster which will be on view during poster sessions and throughout the meeting;
- Discussion sessions throughout the meeting led by Steering Committee Members including two final discussion sessions on Friday when the prioritized agenda will be set.

TUESDAY June 4th

9:00 - 10:15 Session 1. Introduction and Big Picture Motivation

F. Straneo - Introduction – Meeting Structure and Goals (20 min)
B. Bindschadler – Staying Ahead of the Greenland Ice Sheet (20 min)
I. Joughin – Recent Greenland Ice Sheet Variability (20 min)

10:15 - 10:45 Coffee Break

10:45 - 12:15 Session 2. Evidence of Glacier Variability (Chair: I. Joughin)

T. Moon – Patterns of glacier variability in Greenland (20 min)
L. Stearns – Observing Tidewater Glacier Variability: Progress and Challenges (20 min)
M. Truffer – Lessons learned from Alaskan tidewater glaciers (20 min)
Science Presentations and Poster Introductions (3 min each)

- *G. Hamilton – Factors leading to the onset of tidewater glacier terminus retreat*
- *A. Ahlstrøm – Seasonal velocity variations of 11 outlet glaciers from in situ GPS*
- *M. Andersen – Dynamic mass loss of North West Greenland*
- *E. Enderlin – Re-examining the timing of recent dynamic changes in NW Greenland*
- *M. Truffer – Fjord /Glacier Ice Interactions: Nuup Kangerlua (Godthåbsfjord)*
- *V. Miles – Rapid changes in advance–retreat (co) variability of Sermilik fjord glaciers, SE Greenland*
- *S. Foga – Flow variability of Helheim Glacier and potential oceanic forcing*

12:15 - 1:30 Lunch

1:45 - 3:00 Session 3. What are the Proposed Mechanisms? (Chair: R. Bindschadler)

A. Vieli – Modelling the dynamics of tidewater outlet glaciers: approaches, issues, perspectives (20 min)
J. Amundson – In defense of ice mélange (20 min)
R. Motyka – Submarine melting: drivers, measurement, and importance (20 min)
Discussion

3:00 - 3:30 Coffee Break

3:30 - 5:00 Session 4. What can the paleo record teach us? (Chairs: D. Roberts, A. Vieli)

C. Andresen – Linking glaciers, ocean and atmospheric variability – lessons from marine sediment archives (20 min)
J. Lloyd – Long term variability of the ocean around Greenland (20 min)
D. Roberts – West Greenland ice stream instability during the LGM/Holocene transition (20 min)
Science Presentations and Poster Introductions (3 min each)

- *A. Carlson – Paleo influence of ocean temperatures on southwest GIS margins*
- *A. Jennings – The Role of Ocean Warming in Central West Greenland Ice Stream Retreat: LGM through Deglaciation*
- *L. Levy – Constraints on the Holocene extents of the southwestern margin of the GIS*
- *T. Lowell – Late Holocene Expansion of the GIS and implications for Its Current Decay*
- *K. Nisancioglu – Melting of Northern Greenland during the last interglacial*
- *M. Kelly - Late glacial-early Holocene fluctuations of GIS outlet glaciers and adjacent local ice caps*
- *K. Kjeldsen – Mass loss of the southern half of the GIS since the Little Ice Age Max.*

5:00 - 6:00 End of Day Discussion (Moderators: L. Padman, G. Hamilton)
6:00 - 7:00 Poster Session I
7:30 Dinner at the SALEM Beerworks, Salem, MA

WEDNESDAY June 5th

8:30 - 10:00 Session 5. Dynamics at the Ice-Ocean Boundary (Chairs: R. Motyka, D. Menemenlis)

A. Jenkins – Ice-Ocean Boundary Dynamics (20 min)

K. Nicholls – Observations from the ice-ocean boundary (20 min)

Science Presentations and Poster Introductions (3 min each)

- *S. Kimura – An application of plume theory to assess impacts of subglacial discharge on glacier subaqueous melting*
- *T. Millgate – Effect of Basal Channels on Oceanic Ice-Shelf Melting*
- *S. Hossainzadeh – Effects of Greenland's Runoff in a Regional Arctic System Model*
- *R. Sciascia – Seasonal variability of submarine melting and circulation in an East Greenland fjord*
- *A. Wells – Melting-driven evolution of an ice shelf coupled to a buoyant meltwater plume*
- *Y. Xu – Subaqueous melting of Store Glacier, W Greenland from 3D numerical modeling and ocean observations*

Discussion

10:00 - 10:30 Coffee Break

10:30 - 12:15 Session 6. Role of (sub) Glacial Hydrology (Chairs: O. Sergienko, D. van As)

I. Hewitt – Modeling glacial hydrology: implications for submarine melt water discharge (20 min)

T. Creyts – Seeing what condition the condition is in: Characteristics of Greenland drainage in englacial and subglacial systems (20 min)

Science Presentations and Poster Introductions (3 min each)

- *T. Creyts – Fast or slow?: Englacial drainage in the Greenland Ice Sheet?*
- *K. Schild – Understanding the Subglacial Hydrological Environment of a Greenland Tidewater Glacier*
- *W. Chu – Role of subglacial hydrology and basal topography in driving ice flow of Greenland glaciers*
- *D. Lampkin – A Fuel Injected Ice Stream? Melt Water Drainage from Saturated Crevasses, Jakobshavn*
- *D. van As – Increasing meltwater discharge from the Nuuk (SW) region*

Summary/Discussion

12:15 - 1:30 Lunch

1:45 - 3:30 Session 7. Oceanic Forcing at the Glaciers' Edge (Chairs: F. Straneo, J. Mortensen)

D. Sutherland – Connections between continental shelf circulation and fjord circulation (20 min)

F. Straneo – Observations at the margins of Greenland Glaciers (20 min)

Science Presentations and Poster Introductions (3 min each)

- *P. Budgell – A Nested High-Resolution Simulation of Circulation in Sermilik Fjord*
- *R. Jackson – Shelf-forced fjord circulation and heat transport at the terminus of a major outlet glacier*
- *C. Gladish – Sub-annual renewal of a Greenland glacial fjord driven by subglacial fresh water discharge*
- *L. Padman – Decadal Variability of Petermann Gletscher, NW Greenland - Ice, Ocean, and Atmosphere*
- *J. Mortensen – Circulation and heat sources for glacial melt in a subarctic sill fjord (Godthabsfjord)*
- *J. Bentsen – Modeling of intermediate water mass formation and heat transport in Godthabsfjord*
- *R. Motyka – LeConte Glacier, Alaska: Submarine Melting and Proglacial Fjord Dynamics in Sep. 2012*

Summary/Discussion

3:30 - 4:00 Coffee Break

4:00 - 5:00 End of Day Discussion (Moderators: R. Hallberg, O. Sergienko)

5:00 - 6:00 Poster Session II

6:00 Reception at the Wiley

THURSDAY June 6th

8:30 - 10:30 Session 8. Large Scale Ocean/Continental Shelves (Chairs: F. Straneo, P. Heimbach)

I. Fenty - Ocean Variability around Greenland: Insights from Observations and a Coupled Ocean-Sea Ice Model (20 min)
R. Curry – Variability in the North Atlantic Ocean 1950-2010 (20 min)
T. Haine – Modeling the large-scale ocean circulation around Greenland (20 min)
Science Presentations and Poster introduction (3 min each)

- *I. Koszalka – Oceanic variability on the SE Greenland shelf near the Helheim-Sermilik glacier-fjord system*
- *W. Maslowski – Modeling of Ocean Dynamics and Variability near Greenland's Marine Terminating Glaciers*
- *U. Schauer – Decadal warming in the West Spitsbergen Current in Fram Strait*
- *P. Dodd – The Supply of Warm Atlantic Water to Nioghalvfjerdsbræn in North East Greenland*
- *P. Myers – Oceanographic processes in Baffin Bay impacting or being impacted by Greenland*
- *B. Harden – Shelf variability and the forcing of hydrographic changes within Sermilik fjord*

Summary/Discussion

10:30 - 11:00 Coffee Break

11:00 - 12:15 Session 9. Calving and Ice Melange (Chairs: I. Joughin, J. Hamilton)

J. Bassis – Granular model of ice (partially) explains diverse calving patterns from grounded and floating glaciers (20 min)
Science Presentations and Poster Introductions (3 min each)

- *A. Taylor – A physically-based crevasse-depth calving model applied 2D to marine outlet glaciers:*
- *T. Bartholomaus – Does calving matter? Evidence for significant submarine melt*
- *R. Cassotto Observations of tidal and calving impacts on near-terminus ice flow and terminus stability?*
- *M. Dennin – Jamming of Ice Melange: Modeling Ice Melange Dynamics with Particle Rafts*
- *W. Sneed – Norske Oer Ice Barrier: permanent, semi-permanent, or not*
- *C. Richards – Timing and characterization of calving events from surface waves*
- *M. Oltmanns – Forcing of the ice by Katabatic winds – Ammassalik, SE Greenland*

Discussion

12:15 - 1:30 Lunch

1:45 - 3:30 Session 10. Modeling Glaciers, Ice sheets and Climate (Chairs: A. Vieli, S. Price)

H. Seroussi – Modeling of Greenland dynamics (20 min)
S. Price – Land Ice Modeling in Earth System Models (20 min)
Science Presentations and Poster Introductions (3 min each)

- *O. Sergienko – Basal conditions of fast-flowing outlet glaciers and ice streams from 3D inversions*
- *F. Nick – Future sea-level rise from Greenland's major outlet glaciers in a warming climate*
- *A. Humbert – Modelling concepts of the Jacobshavn Isbrae and the Greenland Ice Sheet*
- *R. Hallberg – Adding Coupling between Oceans and Ice-sheet Dynamics to Coupled Climate Models*
- *N. Schlegel – Sensitivity of flow in Greenland glaciers to errors in surface mass balance forcing*
- *C. Rodehacke – Fully coupled ice sheet–earth system simulations: GIS response to CO2*
- *C. Little – Uncertainty in 21st century oceanic heat content near Greenland*

Discussion

3:30 - 4:00 Coffee Break

continued…

THURSDAY June 6th (continued)

4:00 - 5:00 Session 11. Bathymetry (Chairs: J. Mortensen, R. Motyka)
R. Bell – Airborne Measurements of Glaciers and Fjords (20 min)

Science Presentations and Poster Introductions (3 min each)

- *K. Tinto – Bathymetry in fjords of Northwestern Greenland from Operation IceBridge aerogravity*
- *D. Porter – Fjord bathymetry controls on basal melt and glacier retreat in Greenland*

Summary/Discussion

5:00 – 6:00 End of Day Discussion (Moderators: L. Stearns and D. Menemenlis)
6:00 – 7:00 Poster Session III

FRIDAY June 7th

Session timing to be announced soon.

Session 12. A programmatic perspective – opportunities and challenges
Moderators: NSF, NASA, IceBridge Program/Project Managers

DISCUSSION SESSIONS: (How) Can this workshop make a difference for making substantial progress towards achieving the stated goals?

Session 13. Discussion I – What are the prioritized questions?
Leaders: B. Bindschadler, P. Heimbach, R. Motyka

10:00-10:30 Coffee Break

Session 14. Discussion II – What are the key modeling needs?
Leaders: S. Price, A. Vieli

Session 15. Discussion III – What are the key observations and how do we get them?
Leaders: A. Jenkins, G. Hamilton, F. Straneo

12:30 pm Lunch (included)

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