Establishing a Greenland Ice Sheet Ocean Observing System (GriOOS)

Report from an International Workshop

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Executive Summary

Rapid mass loss from the Greenland Ice Sheet has raised interest in glacier/ocean interactions for two main reasons. First, increased submarine melting of marine terminating glaciers, in part associated with changes in the ocean, has emerged as a likely trigger of the observed dynamic ice loss. Second, increased freshwater and nutrient discharge from Greenland is impacting air-sea exchanges, the regional ocean circulation and marine ecosystems. Progress has been made over the last decade in understanding glacier/ocean exchanges of heat and freshwater in Greenland's glacial fjords. Yet challenges remain to understand the climatic controls on submarine melting, iceberg calving, and the delivery of meltwater and nutrients to the large-scale ocean. These knowledge gaps translate into an inability to appropriately represent these processes in models (even in parameterized form) aimed at future prediction. Progress has been hindered by the lack of concurrent and long-term records of glaciological, oceanic, and atmospheric parameters at the ice sheet/ocean margins – where the exchanges of heat, nutrients and freshwater are occurring.

The need to establish a Greenland Ice Sheet Ocean Observing System, as a means of providing long-term data at a number of key sites around Greenland that can inform understanding and provide boundary conditions and validation for models, was discussed at an International workshop held in San Francisco, on December 12-13, 2015. The workshop was attended by 47 participants from the USA, Canada, Greenland, Denmark, Norway, United Kingdom and Japan covering a wide range of expertise (oceanography, glaciology, climate and ice sheet modeling, marine ecosystems, paleoclimatology). Specific goals of the workshop were to:

1. Re-evaluate the need for GrIOOS
2. Identify the essential variables to be measured
3. Establish what measurements exist already.
4. Determine how many and which sites should be covered
5. Identify appropriate instrumentation
6. Identify the relevant timescales that GrIOOS should address
7. Discuss means of uniformly quality controlling the measurements and distributing the data
8. Identify potential funding sources

Overarching conclusions from the workshop are summarized here. The limited ability of both ocean and ice sheet models to capture the ongoing changes in Greenland, their drivers and their impact on the ocean underlines the need for obtaining long-term measurements at sites around Greenland to

provide constraints on our understanding and ability to model these systems. The establishment of a Greenland Ice/Ocean observing system thus continues to be a key priority for understanding Greenland Ice Sheet variability. Numerous long-term projects/activities have already laid the foundation for an observing system by collecting ocean/atmosphere/glaciology measurements at specific sites around Greenland. At present, however, these observing efforts are largely uncoordinated and have failed to identify a minimum, common set of measurements, data protocols and data sharing policies which would benefit the broader community. In addition, the continuation of these observing efforts is typically at stake since they are largely seen as isolated, often project based sites.

GrIOOS should build on these existing sites by defining a common set of essential measurements and providing a data management model to be employed by all. Essential measurements to be collected at these sites include oceanic (temperature, salinity, pressure in the fjord and nearby shelf), glaciological (ice velocity, thickness, meltwater runoff, mélange characteristics, terminus variations, calving behavior) and atmospheric (local winds and air temperature on the glacier and nearby fjord). Bathymetry and bedrock are needed inputs for any GrIOOS site. Paleo measurements to provide temporal context are strongly desired. A series of ~10 sites were identified based on a number of criteria including existing and ongoing programs, proximity to network nodes and relevance to the motivation described above.

The development and maintenance of GrIOOS will require close international collaboration. GrIOOS implementation will need to be coordinated amongst different countries, paying close attention to minimizing costs and optimizing shared logistics. It is unlikely that GrIOOS will be funded by a single country or union. Instead, GrIOOS should identify a minimum set of measurements for a GrIOOS site and provide key data collection, quality control and processing protocols for such measurements. Sharing practices and experience will be key to the success of the program. Quick and centralized access to data is key, though there should be flexibility so that countries are not excluded from the GrIOOS process for embargo reasons.

Introduction

Mass loss from the Greenland ice sheet 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 [Shepherd et al. 2012]. A third to a half of this loss [van den Broeke et al. 2009; Enderlin et al. 2014; van den Broeke et al. 2016] resulted from the speed up and retreat of marine-terminating glaciers that began in the late 1990s [Rignot and Kanagaratnam 2006] and continues to this date [Moon et al. 2012; Joughin and Smith 2013]. The glacier acceleration and retreat is not well understood and not fully captured by models [e.g., Vieli and Nick 2011]. It is thought to have been triggered in part by ocean forcing [Vieli and Nick 2011; Joughin et al. 2012], but the lack of measurements from the oceanic margins of Greenland has made it challenging to reconstruct the chain of events that led to glacier retreat [Straneo et al. 2013; Straneo and Heimbach 2013].

In addition to the impact of the ocean on the Greenland ice sheet, increased freshwater discharge from the land ice has the potential to affect the ocean and its ecosystem in a number of important ways. Freshening of the ocean around Greenland can affect North Atlantic dense water formation, with a potential impact on the meridional overturning circulation of the North Atlantic, its associated heat transport, and hence the regional climate over the North Atlantic sector and beyond [Marsh et al. 2010; Weijer et al. 2012; Bamber et al. 2012; Lenaerts et al. 2015]. Furthermore, meltwater from glaciers and the associated chemical fluxes, including the export of labile organic carbon, iron and other nutrients, can impact Arctic and sub-Arctic ecosystems [Arrigo et al. 2017; O'Neel et al. 2015].

A multi-disciplinary International Workshop on "*Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing*" was held in Beverly, MA, in June 2013, to bring together the scientific community and identify strategies to move forward on understanding the Greenland ice-ocean system. One of four key recommendations that emerged from the 2013 workshop, and the ensuing report which was widely circulated to include community feedback [Heimbach et al. 2014], is the establishment of a Greenland Ice-Ocean Observing System (GrIOOS). GrIOOS would collect long-term in situ time series of critical glaciological, oceanographic, and atmospheric variables at key locations in and around Greenland. The research community recognized that such measurements are needed to provide information on the time-evolving relationships between the different climate forcings and the glacier flow. In particular, these measurements will provide an assessment of the ocean variability within the fjords, the atmospheric conditions at the terminus, and the variability of glacier dynamics. The lack of such data has hindered our ability to explain and model the recent glacier acceleration, creating weaknesses in our ability to project future changes. These data are critical not only to validate hypotheses but also to provide boundary conditions, forcings, and a point of comparison for both ocean and ice model simulations.

GrIOOS Design and Requirements

Following the recommendations made in the 2014 report, the Study of Environmental Arctic Change (SEARCH) Land Ice Action Team in collaboration with the Greenland Ice Sheet Ocean Interaction (GRISO) Science Network organized a workshop to make progress on the design and implementation of GrIOOS.

The workshop took place in San Francisco on December 12-13, 2015, and was attended by 47 participants from the USA, Canada, Greenland, Denmark, Norway, United Kingdom and Japan (Figure 1). A steering committee selected participants on the basis of expressions of interest submitted in response to a workshop announcement widely circulated on relevant list serves and websites. Selections were made to ensure the appropriate disciplinary expertise (oceanography, glaciology, climate and ice sheet modeling, marine ecosystems, paleoclimatology), gender balance, and representation from early-career scientists. Other attendees included agency program managers (NSF, NASA) and a representative of the Greenland government. The workshop was co-located with the ISMIP-6 (*Ice Sheet Model Intercomparison Project*) meeting, which allowed ice sheet modelers to attend the first half-day and enabled cross-disciplinary discussions at breaks.

Figure 1. GrIOOS Workshop participants, San Francisco, December 2015.

Presentations during short plenary sessions set the stage for detailed brainstorming among participants in a mixture of breakout clusters and whole group discussions. These discussions focused on defining the essential measurements to be collected by GrIOOS, which glacier-fjord systems should be studied, and mechanisms for implementing and maintaining the network. Among the recommendations were support for ongoing remote sensing of glacier variability, the deployment of a suite of relatively low-cost, yet rugged and proven, instruments to collect the essential measurements, and consideration for co-locating the network sites close to other observing platforms where possible.

Key questions addressed at the workshop included:

9. Why establish GrIOOS?
10. What are the essential variables to be measured?
11. What measurements exist already?
12. How many and which sites should we study?
13. What is the optimal instrumentation and GrIOOS design?
14. How will measurements and data be quality controlled and distributed?
15. How will GrIOOS be funded?

A synthesis from the workshop discussions is presented below. Discussion was focused on questions 1 through 5, with a few notes from more limited discussions on questions 6 and 7 also included.

1. Why establish GrIOOS?

Notwithstanding the advances in understanding ice/ocean interactions in Greenland, many challenges remain in modeling the ice dynamics, the ice/ocean boundary and the oceanic shelf and fjords that connect the large-scale ocean to Greenland. In particular, modeled exchanges at the ice/ocean interface are still strongly dependent on parameters that have not been validated by field measurements including drag coefficients and turbulent exchange parameters for heat and freshwater. Coupling of ice sheet and ocean/atmosphere models is limited and, where in place, it relies on ocean models which do not resolve the shelf and fjord processes. Parameterizations of these processes are needed to link ice sheet models (ISMs) with atmosphere-ocean general circulation models (AOGCMS).

The impact of meltwater discharge on the ocean and the marine ecosystems is still largely unknown. The export of Greenland meltwater into the ocean occurs in the form of glacially modified waters that are a mixture of meltwater and ambient waters. The characteristics of glacially modified waters depend on the details of processes at the ice/ocean boundary, which include turbulent upwelling plumes driven by the release of surface melt at depth, submarine melting, and the shape of the ice/ocean interface. These waters are subsequently further modified by fjord processes before being exported onto the shelves. None of these processes are currently represented in the ocean models. Ecosystems around Greenland are also sensitive to variations in the local water mass composition; changes lower down in the food chain can lead to dramatic changes higher up.

2. What are the essential variables to be measured?

Ocean: Essential variables are temperature, salinity, and pressure in the fjord and nearby shelf. Bathymetry is also a needed input.

Ice: Essential variables are meltwater discharge (surface and subglacial), ice velocity, ice thickness and surface elevation, surface mass balance, mélange characteristics, calving behavior, and terminus position.

Atmosphere: Essential variables are local winds and air temperature in the fjord and regional atmospheric forcing of the ocean and ice.

A discussion of the extent to which these observations can be derived from existing networks and/or remote sensing is presented below.

3. What measurements exist already?

This section describes existing networks and projects that are collecting long-term data around Greenland. GrIOOS will build on these networks by incorporating relevant available data and potentially leveraging shared logistics. The networks are described below and shown in Figure 2.

A. Atmospheric

Asiaq Greenland Survey is a two-thirds government funded enterprise that conducts monitoring of hydrology, meteorology, ice surveys, and topographic mapping around Greenland, with an emphasis on the southwest coastal region. They maintain a network of automatic weather stations, mostly located at airports, but also in some mining locations and a few research sites. Location of the sites is dictated by hydropower needs, monitoring of drinking water for communities, and ecological research (www.g-e-m.dk). It was noted that there is opportunity to leverage Asiaq's annual summer maintenance trips for sharing logistics.

PROMICE is a Danish government-funded monitoring network with the goal of providing consistent long-term observations to calculate mass loss by the energy budget method. It consists of >23 automated weather stations (AWS) distributed in the ablation zone around the Greenland Ice Sheet since 2007. The network has large spatial coverage and it is expected that it will be maintained long-term for monitoring mass loss of the ice sheet. The main component of PROMICE is the free online database (www.promice.org) that includes historical mass balance data, documentation of recent change, and outreach efforts. In addition to the AWS, PROMICE has conducted repeat airborne LIDAR/radar surveys around the ice margin in 2007, 2011, and 2015 that have provided velocity mapping and an authoritative ice mask.

The **Danish Meteorological Institute** (DMI) maintains a network of meteorological stations with assistance of aviation companies around the margins of Greenland (and at Summit Station). The data is available at www.research.dmi.dk/data and includes historical archives back to 1784.

B. Seismic and Geodesy

The Greenland GPS Network, **G-NET** (polenet.org)**,** system monitors the earth's elastic adjustment to ice loading and vertical accelerations. GNET began in 2007 and provides data on continental uplift rates that can leverage other more expensive ice mass balance methods (GRACE gravimetric inversions, repeat altimetry, and 'Input-Output' methods). The network consists of >50 nodes throughout Greenland and anyone with a GPS installed at a field site is invited to join the network.

The **Greenland Ice Sheet Monitoring Network** (GLISN; www.glisn.info) is comprised of a network of 33 seismometers that can be used to detect glacial earthquakes and calving events, and seiche events resulting from iceberg calving. Most stations are located in settlements near power and communication resources and thus are generally >50 km from glacier termini and can only detect the largest events. The data are available in near real-time and work is ongoing to improve understanding of iceberg calving mechanisms and magnitude from seismic records.

C. Ocean

Monitoring of ocean properties around the continental shelves of Greenland, and in the fjords, is limited. The Greenlandic fisheries industry has records from 1990 of bottom temperature collected during bottom trawler shrimp density surveys off the southwest coast. Approximately 50 percent of the stations are reoccupied from year to year. The Icelandic mackerel survey on the east coast has hydrographic measurements starting from 2013 that extends from Greenland to Iceland and Norway.

Monthly hydrographic transects have been conducted in Godthabsfjord since 2007 by **GINR** (Greenland Institute of Natural Resources) and include measurement of physical and biological variables. Ice-free conditions in the fjord mean this survey is conducted year-round from small vessels. At one station (GF3) near Nuuk there is a suite of ecosystem sampling conducted in concert with the hydrographic observations. Ecosystem monitoring is being carried out only at a few other sites around Greenland, but resources are limited and marine ecosystem observations only begin in 2002.

The **mooring array in Fram Strait** to measure Arctic Outflow was deployed in 1997 as a government funded monitoring system collaboration between Norwegian Polar Institute (Norway) and the Alfred Wegner Institute (Germany). The array records temperature, salinity, currents, ice thickness and ice drift, and is complemented by annual CTD/LADCP and tracer transects in August and September. It is expected that it will be maintained for at least another 10 years. The mooring array is concentrated in deeper water and lacks moorings on the Greenlandic continental shelf (due to ice hazards), however repeat CTD transects are conducted onto the shelf whenever possible. The mooring array position was shifted in 2002 causing a jump in the ocean temperature time series.

A **mooring array across Davis Strait** was deployed in 2004, as a USA-Canada collaborative project, to measure Arctic outflow west of Greenland. The mooring array spans across the continental shelves and measures velocity, temperature, salinity, sea ice thickness, and marine mammal acoustics and is supplemented by year-round glider observations and annual or biennial hydrographic sections. The future of the network is uncertain and dependent on funding.

Overturning in the SubPolar North Atlantic Program (OSNAP; www.o-snap.org) is an international trans-basin observing system to measure the Atlantic Meridional Overturning Circulation (AMOC) through mooring arrays, repeat hydrographic transects, and glider deployments. The observing network, which includes two mooring arrays on the southeast and southwest Greenland shelves and slopes, was installed in 2014 and currently funded through 2018. It is expected that it will be maintained for 10 years.

Large scale ocean properties can be obtained from the **ARGO float program** that, since 2002, maintains a global array of more than 3000 free-drifting profiling floats that measure hydrographic properties in the upper 2000 m of the ocean. These floats are not useful on the Greenland continental shelf but do provide boundary conditions to monitor long-term average ocean basin property changes around Greenland.

The **Oceans Melting Greenland** (OMG) project is a 5-year program that began in 2015 to observe water temperatures around the coast of Greenland and measure how marine terminating glaciers react to the presence of Atlantic Water. The project consists of annual aerial ice topography measurements and gravimetry of glacier margins and the deployment of 250 Airborne eXpendable Conductivity Temperature- Depth probes (AXCTDs) to measure the properties and extent of Atlantic Water around the coast. As bathymetry is critical to understanding pathways to glacier termini, the fjords and continental shelf will be mapped with airborne gravimetry and multibeam sonar from surface vessels. This campaign will only provide a summer snapshot of water properties, but will greatly improve the spatial extent of measurements around Greenland.

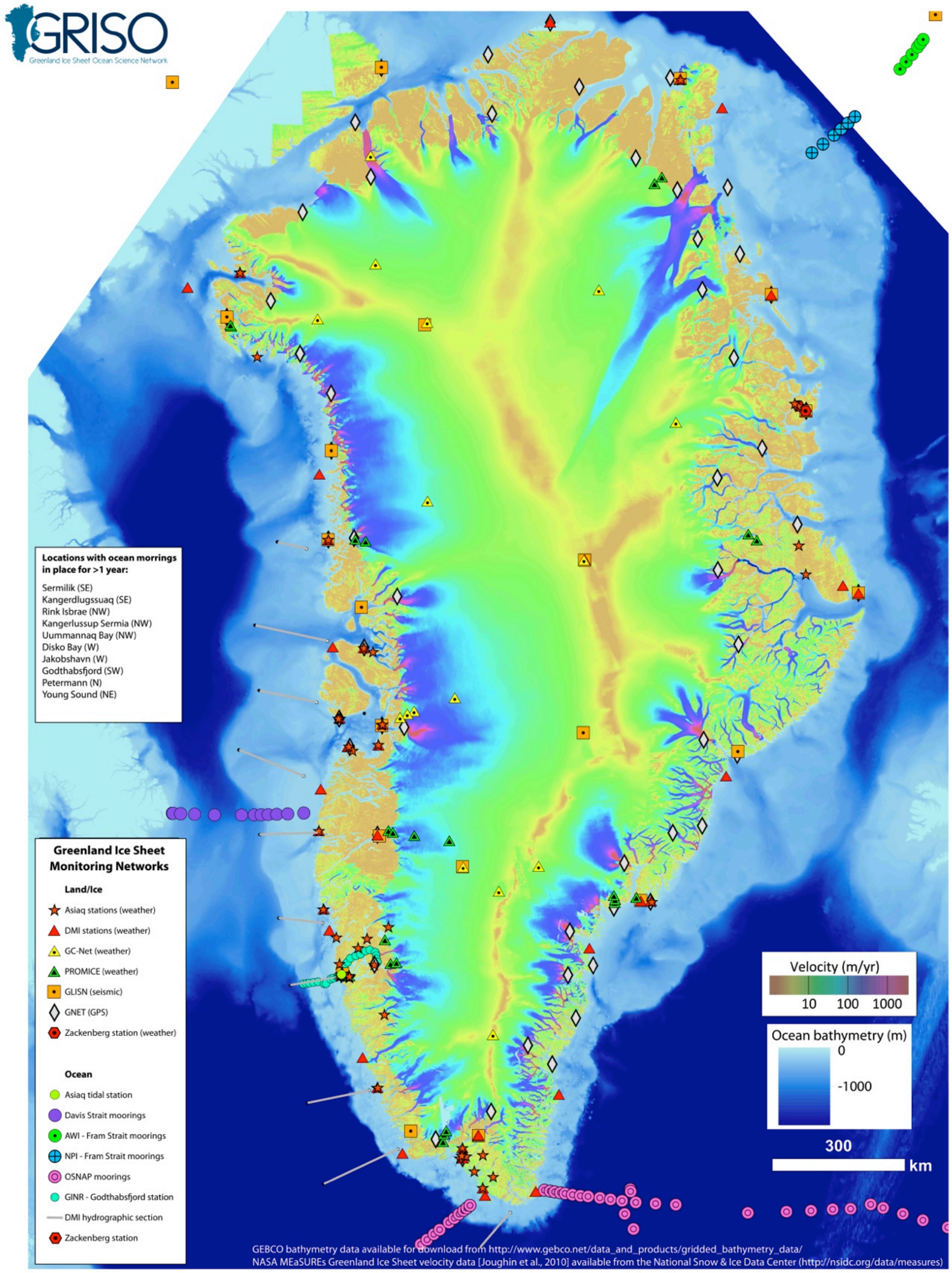

Figure 2: Existing networks on and around Greenland.

D. Remote Sensing

Greenland Ice Mapping Project (GIMP) provides annual DEM and ice velocity datasets of the Greenland Ice Sheet through the use of radar acquisition (e.g., RADARSAT1, TerraSAR-X). Complete coverage of all major outlet glaciers exists from 2010-2012, and ice sheet velocity maps are available through 2009/10 and 2012/13. Data are available online from the National Snow and Ice Data Center (NSIDC).

Landsat 8 data can be used to derive ice surface velocities over a large spatial area with a 16-day repeat period, however the optical satellite is dependent on atmospheric conditions (unlike the GIMP radar products). Acquisition is expected to ramp up in 2014 and the project is working on producing near real-time data streams, but future funding is uncertain at present.

Mass balance estimates of the Greenland Ice Sheet can be obtained from various sources, including gravimetry, geodetic, input-output and hybrid models. There are approximately 2.5 decades of data with each method having different strengths and weaknesses. Observations begin in 1930s from aerial surveys and continue, with significant gaps, to present from satellite imagery and high-resolution laser and radar altimetry surveys, which can isolate glacier change from surface mass balance versus outlet glacier dynamics.

Remote sensing products can be used to assess ice sheet accumulation and albedo. Airborne surveys with Operation IceBridge are useful but with low spatial coverage and a relatively short time series (began in 2010 in Arctic). Changes in albedo are provided by **MODIS satellite data** collected almost daily (250 m resolution). The MODIS data is limited by cloudy conditions and by image geometry at high-latitudes, however it is a useful tool for understanding surface mass balance processes.

Operation IceBridge is the largest airborne polar survey and was designed to fill the gap between the IceSat and IceSat-2 satellites. A variety of datasets are collected including LIDAR altimetry, radar, physical mapping, surface temperature, gravimetry and magnetism (for bed inversions), and atmospheric conditions. There is a large pre-melt (April-May) campaign, and a smaller post-melt (October) campaign, and these are expected to continue until 2019. All data are available online at NSIDC.

The **European Space Agency** (ESA) has a strong focus on creating and maintaining data products. Key parameters that are monitored include surface elevation change, ice velocity, grounding line locations, calving front position, and gravity mass balance. Early products include high-resolution velocity maps from Jan-Mar 2015, complemented by repeat 12-day acquisitions of the margins since June 2015.

Remote sensing data products for oceanographic purposes include surface salinity at 60 km resolution (Aquarius), and sea surface temperature (MODIS Aqua/Terra, AVHRR, Landsat 8, and blended products like OSTIA). It was noted that some of these products are useful for fjord-scale processes, such as subglacial outlet plumes, sea-ice cover, iceberg drift and biological productivity. Sea surface height can be measured via JASON-1/2/3, TOPEX-POSEIDON, ENVISAT/ERS, with limited coverage at high latitudes. Sediment plumes can be monitored by MODIS Aqua/Terra and Landsat 8, and ocean color by SeaWIFS, MERIS, and VIRS.

4. How many and which sites should we study?

It is envisioned that 5 to 10 GrIOOS sites will be chosen and that measurements will continue for at least a decade. Choice of the sites should take into account existing measurements and sites that are already being monitored that could become GrIOOS sites with minimum additional measurements. There was general consensus that the chosen sites should span a range of geometries that take into account the glacier/fjord depths, fjords with and without sills, glaciers with and without floating termini, and different oceanic basins. Preferred sites are in close proximity to other observing networks (PROMICE, GNET, etc.), close to inhabited or regularly serviced centers for accessibility at reduced costs, and are of interest to multiple disciplines. There should be a focus on the largest contributors to Greenland Ice Sheet mass loss. Additionally, several of the sites should be selected to build on sites currently targeted for process studies so that they are simply upgraded to satisfy standard GrIOOS requirements. The proximity of paleo records should also be taken into account.

A voting conducted during the workshop identified the following sites. The top three sites selected were Helheim/Sermilik, 79 N/NEGIS, and Jakobshavn, with additional priority sites listed here in order of voting (Figure 3):

1. **Helheim/Sermilik** – SE Greenland. Pros: representative of southeast Greenland, easy access, stabilizing geometry, experience at site and relatively extensive existing record, close to OSNAP moored arrays and OOI Irminger Sea node. Cons: complex geometry on shelf and in fjord, large mélange.
2. **79N and NEGIS (Northeast Greenland Ice Stream)** – NW Greenland. Pros: science community expects large changes, major ice stream, existing and planned observations, close to Fram Strait array, floating tongue which can be used as a platform, an upstream ice core. Cons: remote, complex geometry, difficult logistics, accessibility and lack of community engagement, unusual geology.
3. **Jakobshavn** – W Greenland. Pros: most potential for retreat and contribution to sea level rise, easy access to ice, simple geometry, good long-term history. Cons: no high topography that provides an elevated view of the terminus, sill that limits Atlantic water, large and atypical mélange, inaccessible by boat.
4. **Petermann** – NW Greenland. Pros: existing data and ongoing work, easier to access than 79N (debated), simple geometry, long-term record from paleo studies, ice shelf as platform, good cliff viewing geometry for cameras. Cons: similar to 79N (debated), hard to access, small sea level rise contributor, Nares Strait moorings are gone, atypical of Greenland.
5. **Rink** – W Greenland. Comment: extensive existing measurements, currently stable but poised for retreat.
6. **Kangerdlugssuaq** – E Greenland. Comment: relatively close to Iceland, close to Denmark Strait, no local community, existing measurements.
7. **Upernavik** – W Greenland. Comment: ongoing measurements are occurring.
8. **Qanaaq** – NW Greenland. Comment: ongoing Japanese program, local community involved.
9. **GodthabsFjord** – SW Greenland. Comment: has ongoing program by GINR.

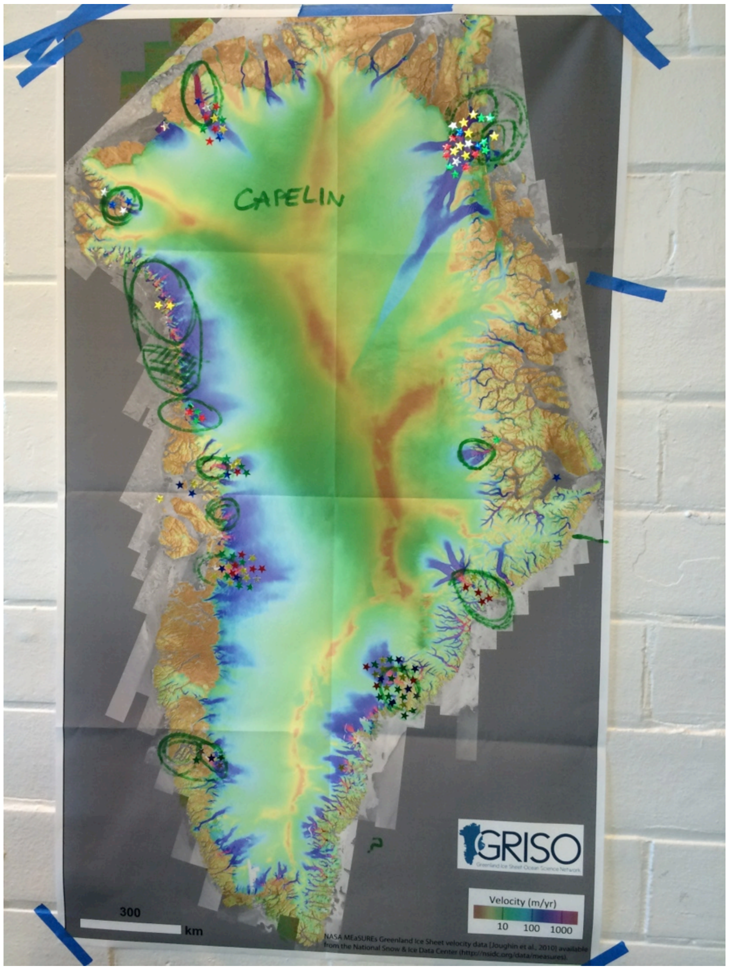

Figure 3 – Site selection by voting at GrIOOS Workshop.

5. What is the optimal instrumentation and GrIOOS design?

Instrumentation

Ocean: Oceanic instrumentation will vary from site to site depending on the configuration of the fjord and the glacier. Moorings ($100-200k) will need to be deployed either anchored to the bottom or suspended from a floating ice tongue, if appropriate. Pressure-inverted echosounders (PIES, $35k) provide an integral measure of heat content. Tagged seals carrying CTD sensors (conductivity, temperature, salinity) may be a good option for some sites, although they last at most one year due to molting.

Ice: ("F" indicates needed for floating termini, "G" indicates needed for grounded or near-grounded termini, $ are price per unit) cameras (15 min repeat interval) with infrared capability (G, $2-10k), seismic (1-3) for calving and subglacial discharge (F/G, $40k), Terrestrial Laser Scanner (TLS, G, $450k), GPS (F, $5k), phase-sensitive radio echo sounding (pRES) (F, $10k).

Atmosphere: Automated Weather Station (AWS, $20k) – 3 potentially, with one each on the ice (~1000m), at the terminus, and at the fjord mouth.

High temporal resolution measurements are required since it is unclear which timescales govern both the oceanic forcing and the glacier response. The proposed instrumentation is in addition to data already provided by existing networks and remote sensing.

Design

The group heard about and discussed lessons learned from previous observation programs, such as PROMICE. One resource document referenced is the NASA Framework for Ocean Observing. Within the discussion, several potential key characteristics were identified:

- Light is sustainable: Logistically or instrumentally expensive observing systems are very difficult to maintain over time. Simple logistics, and ones that would make use of interested communities, are best. However, previous efforts (e.g., USGS monitoring for mountain glaciers) have shown that it is best to aim for oversampling during the first several years of the observing system, with the objective to identify key sites for sustained observations, accommodating potential needs to scale down the observing system over time.
- Monitoring requires proven technology: Although testing new technology is an interesting prospect if it can reduce later costs, an observing system is not the best place to implement new technologies.
- Build on available logistics and programs: Although programs that are already running would not easily scale up, they can provide logistical support for additional instrumentation deployment, if necessary.

6. How will measurements and data be quality controlled and distributed?

There was a discussion of governance and data sharing. Minimum requirements for an observing network include a framework for: 1. key variables to be measured, 2. data quality policies and 3. data sharing policies. Several different possible frameworks were discussed. AON requires data to be immediately available. PROMICE demonstrates that this is important, valued and successful. Quick and centralized access to data is key, though there should be flexibility so that countries are not excluded from the GrIOOS process for embargo reasons. It was also pointed out that it might not be worthwhile to be rigid about rules before there is even any funding.

Discussion recognized that an observing system needs to have strong data server capabilities where observations can be exchanged, as well as means of defining the success and impact of the observing system itself. Cloud solutions were mentioned as a potentially useful tool. Apart from typical academic measures such as publications and citations, it was proposed to introduce other measures of success, for example by recording the uptake of data from the data server, and recording who is using the observations (e.g., academia, industry, other stakeholders).

7. How will GrIOOS be funded?

Workshop attendees heard from Eric Lindstrom (NASA) and William Ambrose (NSF Arctic Observing Network) about recommendations for funding strategies, but did not lay out specific plans for GrIOOS funding. Eric Lindstrom emphasized the importance of interdisciplinary research and development of data management and analysis plans that also incorporate previously collected data and data collected by other funded projects. William Ambrose discussed the AON Program, which is meant to compliment and provide context for process studies. AON is a proposal driven program and, at this time, roughly a quarter of the projects (by number) are physical oceanography, a quarter atmospheric sciences, and a very small fraction land ice. He also discussed the potential value of partitioning GrIOOS efforts into standalone projects, the value of involving young investigators, and the opportunities and challenges in transatlantic coordination.

Summary

Rapid ice loss from the Greenland Ice Sheet is, in part, attributed to ocean forcing at the marine margins of Greenland's outlet glaciers. Yet our understanding of the mechanisms leading to the observed glacier retreat (and hence the ice loss) are poorly understood. On the ocean side, increased ice and freshwater discharge from the Greenland ice sheet is contributing to sea level rise and a freshening of the North Atlantic, with important consequences for ocean circulation and the marine ecosystem. Understanding and predicting the impact of ocean and atmosphere changes on the ice sheet and, vice versa, of ice sheet changes on the ocean is hindered by our limited understanding and ability to model processes at the glacier/ocean boundary and their connection to the larger scale ocean, ice and atmospheric. One important gap identified by the community working in and around Greenland is the lack of the long-term data from glacier/fjord systems around Greenland. Thus, it has been proposed that a Greenland Ice Sheet/Ocean Observing System (GrIOOS) be established with the goal of collecting long-term data at a number of key sites around Greenland. The goal of GrIOOS is to inform understanding and provide boundary conditions and validation for models.

Here, the preliminary conclusions on how to design and establish such a network, following an international workshop held in December 2015, are presented. GrIOOS will consist of ~10 sites whose characteristics will cover a range of glacier/fjord configurations, different oceanic basins and climatic regimes. Essential measurements to be collected at these sites include oceanic (temperature, salinity, pressure in the fjord and nearby shelf), glaciological (ice velocity, thickness, meltwater runoff, mélange characteristics, terminus variations, calving behavior) and atmospheric (local winds and air temperature on the glacier and nearby fjord). Bathymetry and bedrock are needed inputs for any GrIOOS site. Paleo measurements to provide temporal context are strongly desired. A series of ~10 sites are proposed based on a number of criteria including existing and ongoing programs, proximity to network nodes and relevance to the motivation described above.

The development and maintenance of GrIOOS will require close international collaboration. GrIOOS implementation will need to be coordinated amongst different countries, paying close attention to minimizing costs and optimizing shared logistics. Data processing protocols and data sharing practices will be identified. Quick and centralized access to data is key, though there should be flexibility so that countries are not excluded from the GrIOOS process for embargo reasons.

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Appendix I: List of Attendees

<u>Steering Committee Members</u>

1. Abermann (Asiaq, Greenland)
2. Ahlstrom (GEUS, DK; glaciologist)
3. Hamilton (U Maine, USA; glaciologist)
4. Heimbach (MIT/U Texas USA; ocean modeler)
5. Nowicki (GISS, NASA, USA; ice sheet modeler, ISMIP)
6. Scambos (NSIDC, USA; SEARCH; remote sensing, Antarctica)
7. Straneo (WHOI, USA; SEARCH, oceanographer, Greenland ice/ocean)
8. Sutherland (U. Oregon, USA; oceanographer, Greenland ice/ocean)

<u>Facilitator</u>

9. Bob Bindschadler (SEARCH, glaciology, NASA, USA)

<u>Others</u>

10. Mike Bevis (Ohio SU, USA; GNet)
11. Laura de Steur (NPI, NO; ocean, Fram Strait, Greenland ice/ocean)
12. Aqqalu Rosing-Asvid (GINR, Greenland; marine biologist)
13. Holland D (NYU, USA; ice/ocean)
14. Mortensen J. (GINR, Greenland; oceanographer)
15. Ian Joughin (APL-UW, USA; ice remote sensing)
16. Beatha Csatho (U. Buffalo, USA; remote sensing)
17. Marco Tedesco (CUNY, USA; surface mass balance)
18. Asa Rennermalm (Rutgers, USA; hydrology)
19. Alun Hubbard (Aberystwth, UK; glaciologist)
20. Mark Inall (SAMS, UK; oceanographer)
21. Adrian Jenkins (BAS, UK; ice/ocean)
22. Leigh Stearns (Kansas U, USA; glaciologist)
23. Ginny Catania (U. Texas, USA; glaciologist)
24. Shin Sugiyama (Hokkaido, Japan; glaciologist)
25. Erin Pettit (UAF, USA; acoustics for ice)
26. Dave Finnegan (CRREL, USA; engineering; LIDAR)

27. Sridhar Anandakrishan (PSU, USA; glaciology)
28. Alan Mix (Oregon SU, USA; paleo)
29. Christian Rodehacke (DMI, DK; ice sheet modeling)
30. Lora Koenig (NSIDC, USA; hydrology, Icebridge)
31. Irina Overeem (NSTAAR, USA; sediment plumes)

Early Career (S indicate students, P postdoc)

32. Dave Porter (LDEO, USA; ice/ocean)
33. Pierre Dutrieux (APL-UW, USA; ocean/ice, Davis Strait)
34. Ian Fenty (JPL, NASA; USA, OMG NASA)
35. Twila Moon (U. Oregon, USA; glaciology/remote sensing) (P)
36. Andrew Hamilton (UBC, CA; glacier/ocean, AUVs, Canadian glaciers) (S)
37. Tim Bartholomaus (UTIG, USA; seismic, radars, glaciology)
38. Alistair Everett (Swansea, UK; glaciology) (S)
39. Kristin Schild (Dartmouth, USA;, remote sensing, sediment) (S)
40. Rebecca Jackson (WHOI/MIT, USA; oceanography) (S)
41. Ellyn Enderlin (U. Maine, USA; glaciers, icebergs, remote sensing)
42. Tom Cowton (U. Edinburgh, UK; ocean modeler) (P)
43. Maureen Walczak (Oregon SU, paleo) (P)

Program managers

44. Eric Lindstrom (NASA)
45. William Ambrose (NSF)

Greenlandic Government Representative

46. Inuuteq Holm Olsen (Minister Plenipotentiary for Greenland to the USA)

Arcus on site coordinator

47. Lisa Sheffield Guy

Appendix II: Meeting Agenda

Saturday December 12th

ISMIP6 participants will join us in the morning sessions.

8:30-9:00 breakfast

9:00-10:40 Session 1: Why an Observing System

Review of basic understanding of ice forcing ocean and vice versa; identify the long-term needs.

Chairs: Patrick Heimbach; Ian Joughin

Note takers: Alistair Everett, Ian Fenty

1. Introduction and Goals (Straneo, 20 min)

2. Glacier retreat/advance – (G. Hamilton/T. Moon – 10 min)

3. Ocean forcing glaciers

i) Theory/Modeling/Observations of submarine melting (A. Jenkins; 10 min)

ii) Ice sheet Modeling: Impact of ocean variability (T. Payne, 20 min)

4. Glaciers forcing ocean (Sutherland/Heimbach, 10 min)

5. Atmospheric forcing of glacier setting – (A. Ahlstrom, 10 min)

6. Impact of glacier changes on the marine ecosystem – (A. Rosing-Asvid, 10 min)

10:40-11:00 Coffee Break

11:00-12:30 Session 2: What have we learned - glacier/fjord projects?

Chairs: Fiamma Straneo; Gordon Hamilton

Note takers: Tom Cowton, Kristin Schild

Brief reviews (3 slides max) of glacier/fjord experiments

- Ummanaq (**Catania**)
- Nuuk Fjord/Glacier (**Mortensen)**
- Store Glacier (**Hubbard)**
- Upernavik (**Ahlstrom)**
- Bowdoin (**Sugiyama**)
- Alison/Hayes (**Porter**)
- Qanaaq –(**Rodehacke** DMI)
- Helheim/Sermilik F. (**Straneo/Hamilton**)
- 79 North – (**Straneo**)
- Kangerlugssuaq (**Inall)**

- Jakobshavn (**Holland)**
- Petermann – (**Mix)**

Lunch 12:30-1:30

1:30 to 3:00 Session 3: Existing Measurements

Summary of existing networks, monitoring sites, airborne and remote sensing (2 slides per program)

Chairs – Dave Sutherland and Twila Moon

Note takers: Maureen Walczak and Andrew Hamilton

In situ:

- Asiaq (Abermann)
- PROMICE/GCNET (Ahlstrom) w. airborne work
- GNet (Bevis)
- DMI Met Stations (Rodehacke),
- Fisheries data (Rosing-Asvid),
- Fram Strait (de Steur),
- Davis Strait (Dutrieux)
- OSNAP (Straneo)
- ARGO (Straneo)
- GLISN (Bartholomaus)
- Nuuk/Zackenberg monitoring sites (Mortensen)
- Baffin Bay Observatory (Future Canadian/EU/Greenland) – (Mortensen)
- Denmark Strait (?) – Inall future plans

Remote sensing/airborne assets

- Landsat/SAR (Moon/Joughin)
- Mass balance/elevation changes (Csatho)
- Surface Mass Balance/Surface Melt (Tedesco)
- Oceanic remote sensing (Sutherland/Heimbach)
- Icebridge (Koenig)
- ESA's Climate Change Initiative (Alhstrom)

Mixed

- OMG – NASA (Fenty)

Coffee Break 3:00-3:30

3:30-5:00 Session 4: Breakout I

Three group brainstorming for GrIOOS.

What measurements are needed? Where, how many and how do they tie to existing networks.

5:00-8:00 – Reception Joint with ISMIP (Ice Sheet Modeling Intercomparison Project)

Sunday December 13th

8:30-9:00 breakfast

9:00-10:00 Session 5 Summary from previous day including Breakout I

Chairs Jakob Abermann; David Sutherland

Note takers: Ellyn Enderlin, Pierre Dutrieux

10:00- 11:00 Session 6 Program managers Input (TBA)

Chair P. Heimbach

Note takers: Rebecca Jackson, Kristin Schild

10:30-11:00 Coffee

11:00- 12:30 Session 7 Measurement Techniques

Review instrumentation/measurement techniques including feasibility/costs.

Chairs: Gordon Hamilton, Ted Scambos, Andreas Ahlstrom

Notetakers: Andrew Hamilton; Dave Porter

12:30-13:30 Lunch

13:30 – 15:00 Session 8 Breakout Session II

Breakout again into three groups and continue brainstorming GrIOOS.

What is feasible, what instrumentation, what will it cost?

Contrast what is easy to measure/what is important

Produce table of easy versus important (include costs)

Discuss what technology is missing

15:00-15:30 Coffee

15:30 – 17:00 Session 9 Summary Discussion/presentation of the 3 groups

Discussion lead Bob Bindschadler

Notetakers: Rebecca Jackson and Tim Bartholomaus

Appendix III: Notes from each session

Session 1 - *Alistair Everett and Ian Fenty*

1. Introduction and Goals (Straneo, 20 min)

FS highlighted the aims of GrIOOS. GrIOOS follows on from the previous GRISO workshop, and represents one of the four priorities outlined in the current GRISO report. Importantly, GrIOOS should improve understanding of the links between the ice, ocean and atmosphere; help to improve boundary conditions for models; and leave a useful legacy of data for future generations.

With this in mind FS posed a number of questions:

- What measurements are essential?
- What is already there?
- How many and which sites should we study?
- How will data be quality controlled?
- What options are there for funding?
- What timescales should GrIOOS be interested in?
- How will measurements and data distribution be coordinated?

2. Glacier retreat/advance – (G. Hamilton/T. Moon – 10 min)

GH highlighted remote sensing as a key tool in understanding spatial and temporal patterns of advance and retreat in Greenland's glaciers. We now have a record spanning a few decades, with spatial resolutions ranging between ~15-250 metres/pixel. Many techniques have been developed for extracting ice front positions and velocities from these images.

Moon and Joughin (2008) show a record of terminus positions separated into two epochs 1992-2000 and 2000-2006. More glaciers were in retreat during the later period. The overall retreat is contemporaneous in the SE and NW sectors. A relatively large seasonal cycle is also found in many glaciers. Longer term records (eg. Bjork et al., 2012) also show a period of retreat in the 1930s and '40s, followed by some advance through the '70s and '80s.

TM highlighted existing research on forcings such as climatic (eg. ocean/atmosphere) and environmental (eg. fjord bathymetry, melange). TM showed an inverse relation between speed and terminus position.

East Greenlandic behaviour is divided around the 69N latitude (Seale et al.,2011), with different behaviour to the N and S, likely related to divergence of the Irminger Current at the Denmark Strait. TM summarised recent behaviour of floating tongues: Zachariae Isstrom recently lost its ice shelf, TM suggested that 79N might be the next to go, Peterman is characterised by large crevasses and may soon see an additional shelf breakup.

3 Ocean forcing glaciers

i) Theory/Modeling/Observations of submarine melting (A. Jenkins; 10 min)

AJ presented a review of current understanding of the ocean-ice interface. Physics of the turbulent ice-ocean boundary layer beneath sea ice is fairly well observed and understood. Vertical and horizontal ice faces work on broadly similar principles and theory should be generally applicable. Melt rates can be calculated from the three equation parameterisation which includes the balance of heat and salt across the ice-ocean boundary layer and constrains the ice surface to be at the pressure melting point. The three equation model can be incorporated into plume theory to model melt rates driven by the convection of subglacial discharge.

AJ highlighted three characteristic regimes which occur at a vertical ice face, where we would generally expect melt on the scale of Greenlandic glaciers to be in the highest region – on the order of $z > \sim 100$m. In this regime melt rates increase with height. AJ highlighted the difficulty of carrying out lab scale experiments within this regime, and therefore on validating current models.

AJ outlined a number of unknowns which are currently assumed for application of plume theory. These include the entrainment of the plume, the drag coefficient, and the turbulent exchange parameters for temperature and salinity. Due to the difficulty of lab scale experiments and limited observations these parameters are effectively untested.

Observations of basal melt rates exist on floating ice tongues using high precision radar, but vertical faces are much more difficult. Acoustic sounding seems like the only option, but there are questions about whether it is sufficiently accurate to capture melt rates, and high-temporal resolution will be necessary to resolve changes. Other questions remain about the coupling of plume theory to the melt rate parameterisation, currently this relies on the bulk temperature and salinity of the plume, but this may not accurately represent 'far-field' conditions for the ice-ocean boundary layer

Recent studies (Xu et al, 2012; Sciascia et al, 2013; Kimura et al, 2014) have applied high resolution, non-hydrostatic ocean models to the vertical ice face problem, but in the absence of observation, results are tuned to match plume theory.

ii) Ice sheet Modeling: Impact of ocean variability (Tony Payne, 20 min)

TP summarised current efforts to bring ice sheet modelling to the CMIP [coupled-model intercomparison project] process, currently ISMIP6. At present, CMIP models have a very poor representation of ice sheets. Important feedbacks between the ice sheets and the ocean are not captured which limits the utility of CMIP model projections of sea level rise.

Two methods are currently used: ice sheet forced by atmospheric and oceanic boundary conditions and ice sheet coupled within an atmosphere/ocean model with feedbacks between the two. Boundary conditions are particularly difficult to parameterise in ice sheet models (ISMs), AOGCMs do not resolve shelf and fjord processes, therefore a parameterisation is necessary to link ICMs to AOGCMs.

TP discussed issues with resolving outlet glaciers and the effects of grid resolution on model predictions. ISMs are now beginning to include improved models of calving and frontal melt. TP highlighted the strong links between GrIOOS and ISMIP6 efforts, and how GrIOOS may be important in informing the parameterisations used to link ISMs to AOGCMs.

4. Glaciers forcing ocean (Sutherland/Heimbach, 10 min)

DS summarized glacier-ocean interactions from the fjord scale (~1 km) to the basin scale (~1000 km).

On the fjord scale, liquid freshwater (eg. Subglacial discharge, surface runoff, submarine melt) and solid freshwater (eg. icebergs) discharges affect fjord circulation patterns, with feedbacks between fjord conditions (eg. buoyancy driven flows, T/S modification) and ice front processes (eg. Calving, submarine melt). Other glacial impacts on fjord circulation include for example a seasonal or permanent ice melange, and mixing driven by deep-keeled icebergs moving within fjords.

On basin scales freshwater affects large scale processes such as the AMOC. While the volume of freshwater released into the arctic ocean from Greenland is small compared to river discharge, the depth and properties of water introduced at the boundaries of AOGCMs has a strong impact on the results, and is currently poorly understood leading to major uncertainty in model results. For example, some AOGCMS have suggested that freshwater input from Greenland can reduce the AMOC by around 50% (10 Sv), while other models with the same forcing show different results.

5. Atmospheric forcing of glacier setting – (A. Ahlstrom, 10 min)

AA outlined a number of feedback mechanisms between the ice sheet and the atmosphere. Atmospheric drivers of increased surface melting include wind, which can also affect the stability of proglacial ice melange, increased rainfall and solar radiation. Other factors, such as crevasse extent, can have feedbacks on surface melting through increases in surface area. Increased surface melt and rainfall can encourage hydrofracture and inputs of meltwater to the bed. The transfer of water to the bed increases basal water pressures leading to sliding, and also drives feedbacks at the terminus, where increased subglacial discharge leads to more rapid submarine melt with potential impacts on calving and terminus stability.

6. Impact of glacier changes on the marine ecosystem – (A. Rosing-Asvid, 10 min)

AR-A discussed impacts of changes in ocean currents and increased freshwater inputs from the GrIS on local ecosystems around the coastline of Greenland. Benthic organisms, at the base of the food chain, vary with distance up-fjord and also between adjacent fjords. Many are sensitive to local water properties, krill for example do not survive in polar water. The changing boundaries of local ocean currents therefore has a strong impact on local ecosystems. Changes lower down the food chain can lead to dramatic changes higher up. In the 1930s the expansion of high arctic conditions led to Capelin moving north which in turn led to increased numbers of Harp Seals. More recently, an increasing number of mackerel have been found off the south east coast of Greenland, in addition to increased numbers of capelin and herring, making these waters more viable for commercial fishing.

It is thought that these recent changes may be driven by the migration of atlantic waters closer to the coastline of Greenland.

AR-A also highlighted the usefulness of seal tagging for gathering oceanographic measurements, successful campaigns have already been carried out around the coastline of Greenland collecting profiles of temperature and salinity on each dive. This technique integrates biological and oceanographic observations and therefore may be desirable for attracting a wider range of stakeholders to an observing system. Testing has also been carried out on herring tagging, which may prove a viable technique in future.

Tom Cowton & Kristin Schild

Ginny Catania – Central West Greenland (Rink/UMI/KS)

Project goals - determine the ocean contribution to the observed heterogeneity in glacier dynamics

Project location- 15 glaciers over the past 3 years on the central west coast of Greenland

Structure:

1. Remote sensing program for entire region (Landsat, Worldview DEMs)
2. Field program on Rink/UMI/KS glacier systems (3 glaciers)
3. Modeling the interface between the ice and ocean systems

Results- highly controlled by geometry

Variability in systems:

- Some in retreat, some show little change
- Some losing mass, some gaining mass
- Some show stable velocity, while others show fluctuations
- KS has a large submarine moraine – might need to resurvey bathymetry
- Multi-beam terminus profiles show that melt rates are larger than models suggest
- Fjord circulation from moorings at Rink and KS
    - Rink has energetic, seasonally fluctuating subsurface outflow
    - KS is shallower, and so has surface outflow
    - Monitoring near surface waters difficult due to icebergs

Lessons learnt:

1. Spatio-temporal variability in these systems is the norm – it may be better to study more systems than one in particular detail
2. It is critical to have bathy/bed data – to understand geometry and its importance and for modeling, and how these local conditions modulate glacier behavior.
3. Improved in-situ observations are needed to determine the spatio-temporal variability in: 1) subglacial discharge; 2) fjord temperature/salinity; 3) submarine terminus geometry *(more than once per year!)*

Alun Hubbard – Store Glacier

Context, glacier background

- Calving front ~5km wide & up to 500 m deep, freeboard at 120 m
- Annual ELA-gate mass flux of ~16 - 18 GT/a
- Calving front flux of ~14GT/a & peak terminus velocity to 30m/d
- Stable ice front position since early 1900s though modulated by seasonal frontal advance/retreat cycle of ~500m
- Dynamic thinning rate of ~1.5m/a since 1990s.
- Modelled, measured & inferred submarine melting ~2 to 8 m/d, some big upwelling areas
- Sill depth of 450 m about 80 km from terminus, fjord depth ~ 800 m
- AW is 2.4-2.8 C year round

Methods

- Borehole drilled 30 km upglacier from terminus (SAFIRE project)
- LIDAR surveying of ice front (hasn't worked well due to laser properties)
- CTD measurements in summer and winter
- Side-scan sonar of calving front (reveals presence of plumes and deeply undercut areas)
- Seismics, radar, and GPS surveys also conducted

Results: Highly heterogeneous across the terminus- lots of variability.

John Mortensen- Godthabsfjord

Background: Permanent station near Nuuk, and multiple CTD (and ADCP?) stations along fjord. Looking at the circulation and tidal mixing in the fjord mouth.

Results:

- Clear signal of buoyancy-driven circulation – fjord outflow is stronger and shallower during summer
- Tidal exchange with shelf (5 m tidal range), and mixing over sill, are important
- Winds blow up-fjord during summer months, which results in extensive melange cover in upper fjord since there are no katabatic winds here.

Andreas Ahlstrom- Upernakik Isstrom (4 glacier system)

Background: 4 glaciers draining into head of same fjord - experiencing a common atmospheric forcing and similar fjord water properties, but show different individual response due to local bathymetry and geometry (e.g. each outlet is at a different depth)

Methods:

- Bathymetric mapping (including from helicopter in melange)

- High-frequency satellite velocity mapping
- 2 PROMICE AWS
- Time lapse camera looking at UP-1
- On-glacier GPS-trackers (down-glacier)
- GNET GPS
- Differential on-glacier GPS (up-glacier)
- CTD and sediment cores
- ISSM modelling (basal friction)

Suggestions:

- Greater sharing of CTD data would be valuable
- Create a collection of sediment cores from the fjord to reconstruct calving rates and water temperature over a 100 year time period (led by Camillla Andresen).
- Also would like to have bathymetry data before core collection.

Shin Sugiyama – Bowdoin Glacier (also Qaanaaq region, NW Greenland, ~20 glaciers)

Background: Qaanaaq village is accessible by Air Greenland flight (1 per week). Study has been ongoing for 5 years, and has been extended for a further 5 years

Results/Future work:

- 20 glaciers in regions, all show retreat from ~2000. Bowdoin Glacier has been stable since at least 1949, but began to retreat in ~1999. The rate of retreat accelerated in 2008.
- The terminus of Bowdoin Glacier is accessible in a small boat. Bathymetry surveyed along fjord centreline and some cross-fjord transects. Aiming to establish a mooring & CTD measurements.
- Glacier surface also accessible to within ~1km of calving front. Hot water drilling 2 km from ice front.

David Porter – Alison Glacier

Background: Pilot study conducted in July 2014, to work with the community (village of Kullorsuaq) to take oceanography measurements. Relatively accessible (in range of Air Greenland helicopter). Fjord is typically melange-filled. Big retreat in 2003.

Methods/Results:

- Local knowledge used to map fjord depth (later corroborated by OMG multi-beam soundings). Gravity inversion indicates sill ~ 15 km from calving front. The local fishermen estimated the fjord depth to be ~1000 m, which is very close to gravity results.
- 17 CTD stations taken from a small fishing boat over 2 days. Only obtained to depth of 450 m due to length of rope, but fjord 1000 m deep in places.

- Suggests non-specialists (e.g. fishermen) can measure nearby fjord water properties. In winter, this could be done through seal holes. The community members are interested in continuing the measurements.

Christian Rodehacke – Tracy Glacier (North Greenland/Qaanaaq region fjords)

Background: Sampled Late winter (April/March) hydrography since 2011 through collaboration with Danish military

Science question: What are the conditions at the end of winter/beginning of summer near Tracy Glacier?

Plan (August/September 2015-17):

- Simple CTD program, limited water sampling.
- Rely on support from the Danish Arctic Command (not yet approved 2016-17)
- Focus on the late summer heat content and stratification (pre-conditioning)
- Possibility to cover further glacier systems in the Nares Strait: Humboldt and Petermann glacier
- Will use turbidity as a measurement of glacial water

Example results – can identify turbid meltwater jet at ~50 m depth at Bowdoin Glacier. Shallow warm surface water is flowing down fjord. Sediment plumes exist at the surface in front of the glacier- subglacial discharge is buoyant enough to reach the surface.

Mark Inall – Kangerdlugssuaq Fjord

Summary of studies (lots of measurements in the fjord):

- 1993: CTD
- 2004: CTD, AUV abs vel, LADCP (v. limited), bathy mapping, O_{18} (unpublished)
- 2008: CTD + 75kHz VMADCP, trough section only
- 2009/10: CTD/XBT, Mooring T 150-300 m
- 2010: CTD, microstructure – shelf only (unpublished)
- 2011: CTD, microstructure, 0-30m abs. vel.
- 2015: Seaglider, outer shelf only
- NSIDC seaice 1992 – present
- Various SST products
- Glacier front / speed (Luckman, unpublished) 1985 - present
- More recent in situ obs ? Straneo group?
- Hydrodynamic models:
    - BOM, 3D (2012, Cryosphere Discussions)
    - MITgcm 2D (2013, JGR 2013) – idealised, not specifically Kangerd.

- ➢ MITcgm 3D (2015, unpublished)

Summary of findings

- SGD can vary melt by factor 10 (seasonal, model)
- 4 cell circulation scheme can/does exist (obs+model)
- Estimates of AW-induced melt rates vary by factor of ~10 (obs + model)
- PSW is very important in a number of ways
- Shelf flows are highly 3D (model)
- Fjord entrance flows are 3D (obs + model)
- Trough: important topographic steering (obs), and large trough exists at KGL.
- Wind response is complex and 3D – pulsing of AW and PSWw by wind (obs + models) – a few CTD casts may not be representative of conditions

- The complexity of ocean water traveling to the fjord is still TBD.

David Holland – Jakobshavn Isfjord

State of Knowledge:

- Deep water inside fjord is replaced by less dense water from outside fjord. This wouldn't happen in a non-glacial fjord, and is likely due to entrainment into plumes at ice-ocean interface.
- Fjord water properties are determined by water properties at sill depth. In summer, AW is thicker but cooler than winter. It is this water that flows over sill into fjord. The amount of warm water in the fjord varies every season.
- A lighter water mass can come into the fjord and replace the denser water. This flushing occurs because the subglacial discharge results in buoyant plumes.

Methods: Have had success with CTD from boat and helicopter, but not moorings (issues with icebergs and fishery). Glider from boat and tagged mammals could have potential.

Ian Joughin – Jakobshavn Isbrae

State of Knowledge:

- Glacier thickens 10-15 m in winter and thins ~30 m in summer, net -15m/yr.
- The fastest Jakobshavn velocities (2010-2015, peak 2012) occurred due to ungrounding of the glacier terminus and subsequent retreat across a topographic low.

Different modes of retreat are important:

1. Transient triggering – forcing drives retreat of terminus from stable position, beyond which retreat is self-sustaining and may not reflect ongoing forcing. Lateral resistance is responsible for a slowdown.
2. Sustained forcing – ongoing forcing required to drive retreat of glacier

Alan Mix – Peterman Glacier

Project Goal: to study not just triggers of past retreat (using Paleo methods and Sediment cores) but also dynamics during this retreat.

Overview of study location/new datasets:

- Peterman has well-constrained, simple geometry: Floating ice shelf 50-km x 15-km, high-resolution bathymetry (*NEW),* deep Canyon 750-km into interior.
- Ice topography & drainage: Basal channels 1-2 km x 40 km long, surface ponds, streams, crevasses, similar to West Antarctic systems
- Documented viability of paleo records: Paleo grounding lines (*NEW*), Paleo sea-level rapid retreat (*NEW*), ~60 Sediment cores (*NEW*), document decadal variability.
- Manageable Logistics: Thule Air Force Base as science hub, *New* Danish investments, Access via Air National Guard, Within Range; Helicopter, Twin Otter

Results:

- IceBridge altimeter & radar reveals ice shelf thinning <5 m/year 2003-2010, >5 m/year 2007-2010. Calving in 2010, 2012 removed 28 km ice shelf (36 +4 Gt)
- Warming bottom waters, freshening of surface waters (pop-up moorings, ~20 units, popping up over next few years then turn into drifters): Regional scale- Warming along isopycnals 2003-12, Local scale- warmer and saltier Atlantic inflow 2012-15. Water has warmed ~0.1 C since 2003. The glacier response: cooler fresher outflow 2012-15
- Can identify old grounding line and sediment wedge with bathymetry data- the rebound is much faster than in existing models. Also found clam shells where the ice was supposed to be during the LGM according to reconstructions, so LGM reconstructions are also inaccurate.

On-going data collection:

- Observations on and below ice shelf (AWS): 3 through-ice stations with ocean moorings, On-going real-time ocean properties (>100 days, hourly measurements), Bi-monthly variability in ice-ocean boundary layer
- Also dating of raised beaches used to reconstruct isostatic rebound

Fiamma Straneo – 79N Glacier, draining NE Greenland Ice Stream

Background: Largest floating ice tongue in Greenland- grounded in 600 m, with ocean cavity 80 km long. Glacier is hard to access due to landfast sea ice. CTD casts undertaken in 1992 and 2009, with some by helicopter.

Future work: Measurements are planned for trough, cavity and land ice in 2016/17 with AWI, NPI, WHOI…

Fiamma Straneo – Sermilik Fjord

Methods: X-CTD casts and moorings within fjord (March survey and summer survey)

Results/Suggestions:

- There is a greater spatial variability in summer. Need to be careful with where measurements are taken. For measurements taken distant from the calving front, need a transfer function to convert for near glacier properties. Measurements taken near glacier already include the effects of ice-ocean interaction, so need to be careful that these properties aren't duplicated. We need to be know what we are sampling and what we are not sampling.
- Also much temporal variability – can't just rely on summer measurements, as they tend to be snapshots sensitive to external forcing and glacier discharge and are not adequate or representative of the system.
- Argues that we don't yet know what we need to monitor as we don't fully understand processes of ice-ocean interaction – much data may become more useful as we improve this understanding.
- Presently, unbiased measurements of the glacier-ocean link and realistic submarine melting measurements are not trivial.

Summary of Session 3: Existing Measurements

Rapporteurs: *Maureen Walczak and Andrew Hamilton*

Special presentation prior to commencing Session 3

Eric Lindstrom (NASA, USA)

Eric is the Project Manager for the Global Ocean Observing System (GOOS). He stressed the need for an independently initiated observing system to get organized in order to make the best case possible to obtain funding, and he recommended that GrIOOS utilize the Framework for Ocean Observing (FOO; http://www.ioccp.org/foo) as a guide for best practices, essential ocean variables to monitor, and as a template for common language utilized in observing systems. He stressed the need to translate the quality science currently being conducted into a comprehensive observing system that provides sustained interdisciplinary (physical/biological/chemical) observations to address societal needs. It is important that all stages of the project are included in the development of the observing system, especially the critical need for data management and development of end products that close the loop back to answering the original questions that motivated the creation of the observing system.

Session 3: Existing Measurements

Summary: Eighteen speakers gave a brief introduction to measurement that are currently being collected around Greenland that could be leveraged and/or included in GrIOOS. The presentations were divided into 4 groups: 1) Atmospheric, 2) Seismic and Geodesy, 3) Oceanographic, and 4) Remote Sensing.

1. Atmospheric

Jakob Abermann (Asiaq, Greenland): Asiaq/GEM

Asiaq Greenland Survey is a two-thirds government funded enterprise that conducts monitoring of hydrology, meteorology, ice surveys, and topographic mapping around Greenland, with an emphasis on the region focused on the southwest coast. They maintain a network of automatic weather stations, mostly located at airports, but also in some mining locations and a few research sites. The sites are dictated by hydropower needs, monitoring of drinking water for communities and ecological research (www.g-e-m.dk). It was noted that there is opportunity to leverage Asiaq's annual summer maintenance trips for sharing logistics.

Andreas Ahlstrom (GEUS, DK): PROMICE

PROMICE is Danish government funded monitoring network with the goal of providing consistent long-term observations to calculate mass loss by the energy budget method. It consists of >23 automated weather stations (AWS) distributed in the ablation zone around the Greenland Ice Sheet since 2007. The networks have large spatial coverage and are expected to be maintained long-term for monitoring mass loss of the ice sheet. The main component of PROMICE is the free online database (www.promice.org) that includes historical mass balance data, documentation of recent change, and outreach efforts. They conducted repeat airborne lidar/radar surveys around the ice margin in 2007, 2011, and 2015, as well as provide velocity mapping and an authoritative ice mask.

Christian Rodehacke (DMI, DK): Meteorological and Remote Sensing from DMI

The Denmark Meteorological Institute (DMI) maintains a network of met stations with assistance of aviation companies around the margins of Greenland (but also at Summit Station). The data is available at www.research.dmi.dk/data and includes historical archives back to 1784. It was noted that it is especially important for users to notify the networks if they use the data as this improves chances for continued funding, particularly for the stations in the NE Greenland that are difficult and expensive to access.

2. Seismic and Geodesy

Mike Bevis (Ohio State U, USA): GNET

The GNET GPS system was presented and discussed how it is utilized for glacier-ocean interaction monitoring by sensing earth's elastic adjustment to ice loading and vertical accelerations. GNET began in 2007 and provides data on continental uplift rates that can leverage other more expensive ice mass balance methods (GRACE gravimetric inversions, repeat altimetry, and 'IN-OUT' methods). The network consists of >50 nodes throughout Greenland and anyone with a GPS installed at a field site is invited to join the network. The utility of the GNET network as meteorological sensors was also presented.

Tim Bartholomaus (UTIG, USA): GLISN

The Greenland Ice Sheet Monitoring Network (GLISN) is comprised of a network of 33 seismometers that can be used to detect glacial earthquakes and calving events, and seiche events resulting from iceberg calving. It was noted however that most stations are located in settlements near power and communication resources and thus are generally >50 km from glacier termini and can only detect the largest events. The data is available in near real-time and work is ongoing to improve understanding of iceberg calving mechanisms and magnitude from seismic records.

Discussion: Eric Lindstrom commented that there was significant overlap between the GLISN and GrIOOS names, which could cause confusion among the funding agencies, and a potential name change for GLISN to include the term 'seismic' would be worth considering.

3. Oceanography

Aqqalu Rosing-Asvid (GINR, Greenland): Fisheries and Marine Biology

The Greenlandic fisheries industry has records from 1990 of bottom temperature collected during bottom trawler shrimp density surveys off the southwest coast. Approximately 50 percent of the stations are reoccupied from year to year. It was noted that the Icelandic mackerel survey on the east coast has hydrographic measurements starting from 2013 that extends from Greenland to Iceland and Norway. Overall there is not a lot of oceanic monitoring occurring around Greenland.

John Mortensen (GINR, Greenland): GINR Oceanography and Greenland Ecosystem Monitoring

Monthly hydrographic transects have been conducted in Godthabsfjord since 2007 and include measurement of physical and biological variables. Ice-free conditions in the fjord mean this survey is conducted year-round from small vessels. At one station (GF3) near Nuuk there is a suite of ecosystem sampling conducted in concert with the hydrographic observations. Ecosystem monitoring at a few other sites around Greenland, but resources are limited and marine ecosystem observations only begin in 2002.

Laura de Steur (NPI, Norway): Fram Strait Mooring Array

The mooring array in Fram Strait to measure Arctic Outflow was deployed in 1997 as a government funded monitoring system collaboration between Norwegian Polar Institute (Norway) and the Alfred Wegner Institute (Germany). The array records temperature, salinity, currents, ice thickness and ice drift, and is complemented by annual CTD/LADCP and tracer transects in August and September. It is expected to be maintained for at least another 10 years. The mooring array is concentrated in deeper water and lacks moorings on the Greenlandic continental shelf (due to ice hazards), however repeat CTD transects are conducted onto the shelf whenever possible. It was noted that the mooring array position was shifted in 2002 causing a jump in the ocean temperature time series.

Pierre Dutrieux (APL, USA): Davis Strait Mooring Array

A mooring array across Davis Strait led by Craig Lee (APL, USA) was deployed in 2004 to measure Arctic outflow west of Greenland. The mooring array spans across the continental shelves and measures velocity, temperature, salinity, ice thickness and marine mammal acoustics and is supplemented by year-round glider observations and annual or biennial hydrographic sections. The future of the network is uncertain and dependent on funding.

Fiamma Straneo (WHOI, USA; SEARCH): OSNAP, ARGO

Overturning in the SubPolar North Atlantic Program (OSNAP; www.o-snap.org) is a multinational transbasin observing system to measure the Atlantic Meridional Overturning Circulation (AMOC) through an extensive mooring array, repeat hydrographic transects and glider deployments. The observing network, consisting of two mooring arrays extending west and east from the southern coast of Greenland, was installed in 2014 and is expected to be maintained for 10 years.

The ARGO float program initiated in 2002 is a global array of more than 3000 free-drifting profiling floats that measure hydrographic properties in the upper 2000 m of the ocean. These floats are not useful on the Greenland continental shelf but do provide boundary conditions to monitor long-term average ocean basin property changes around Greenland.

Ian Fenty (JPL, NASA, USA): Ocean Melting Greenland (OMG)

The OMG project is a 5-year program to observe water temperatures around the coast of Greenland and measure how marine terminating glaciers react to the presence of Atlantic Water. The project consists of annual aerial ice topography measurements and gravimetry of glacier margins and the deployment of 250 Airborne eXpendable Conductivity Temperature- Depth probes (AXCTDs) to measure the properties and extent of Atlantic Water around the coast. As bathymetry is critical to understanding pathways to glacier termini, the fjords and continental shelf will be mapped with airborne gravimetry and multibeam sonar from surface vessels. A desire to coordinate with other projects to strategize deployment locations was expressed. It was noted that the campaign will only provide a summer snapshot of water properties, but will greatly improve the spatial extent of measurements around Greenland.

John Mortensen (Greenland): Baffin Bay Observatory

The Baffin Bay Observatory is a proposed collaboration between Canada, the EU, and Greenland that would consist of a mooring array and cabled observing system. It is an observational system designed to compliment satellite data with a focus on biogeochemical cycling. Little information on the funding and timeframe was available.

Mark Inall (SAMS, UK): OSNAP

This is a proposal to extend the Ellet Line (E3L; North Atlantic Circulation and Climate) transect from 2018 using surface vessel every two years and gliders each year in the winter. The section would be an extension of the O-SNAP project across the Denmark Strait between Iceland and Greenland. An overview of existing observations was given, including a note that observations began in 1975.

4. Remote Sensing

Ian Joughin (APL-UW, USA): Greenland Ice Mapping Project (GIMP)

Through the use of radar acquisition (RADARSAT1, TeraSAR) the project provides annual DEM and ice velocity datasets of the Greenland Ice Sheet. There exists complete coverage of all major outlet glaciers from 2010-2012, and ice sheet velocity maps are available through 2009/10 and 2012/13.

Data are available online from NSIDC.

Twila Moon (U. Oregon, USA): LandSat8 Surface Velocities

Provide ice sheet surface velocities over a large spatial area with a 16-day repeat period, however the optical satellite is dependent on atmospheric conditions (unlike the GIMP radar products). Acquisition is expected to ramp up in 2014 and the project is working on producing near real-time data streams, but future funding is uncertain at present.

Beatha Csatho (U. Buffalo, USA): Greenland Mass Balance

An overview of mass balance estimates of the Greenland Ice Sheet were given from various sources, including gravimetry, geodetic, input-output and hybrid models. There are approximately 2.5 decades of data with each method having different strengths and weaknesses. Observations begin in 1930s from aerial surveys and continue to present from satellite imagery and high-resolution laser and radar altimetry surveys, which can isolate glacier, change from surface mass balance and outlet glacier dynamics.

Marc Tedesco (CUNY, USA): Surface Mass Balance and Melt

A summary of remote sensing of products to assess ice sheet accumulation and albedo were given, with a relation of the strengths and limitations of the methods. Airborne surveys with Operation IceBridge are useful but with low spatial coverage and a relatively short time series (began in 2010 in Arctic). The point was raised that surface mass balance models require snow density which is not acquire with these datasets. Also presented were changes in albedo provided by MODIS satellite data collected almost daily. The MODIS data is limited to cloud-free conditions and by geometry of images at high-latitudes, however it is useful part of understanding surface mass balance processes.

Lora Koenig (NSIDC, USA): Operation IceBridge

A summary of IceBridge with a focus on radar products was presented. IceBridge is the largest airborne polar survey and was designed to fill the gap between IceSat and IceSat-2. A variety of datasets are collected including LIDAR altimetry, radar, physical mapping, surface temperature, gravimetry and magnetism (for bed inversions), and atmospheric conditions. It was related that there is a large pre-melt (April-May) campaign, and a smaller post-melt (Oct) campaign, and these are expected to continue until 2019. All data are available online at NSIDC.

Andreas Ahlstrom (DEUS, DK): European Space Agency

The presentation provided a summary of European Space Agency (ESA) remote sensing products and climate change initiative. It was emphasized that there is a strong focus on creating and maintaining data products (not just data repository). Key parameters that are monitored include surface elevation change, ice velocity, grounding line locations, calving front position, and gravity mass balance. Early products include high-resolution velocity maps from Jan-Mar 2015, complimented by repeat 12-day acquisitions of the margins since June 2015.

Dave Sutherland (U. Oregon, USA): Remote Sensing for Oceanography

A brief summary of various remote sensing data products for oceanographic purposes was given, including surface salinity at 60 km resolution (Aquarius), and sea surface temperature (MODIS Aqua/Terra, AVHRR, LandSat8, and blended products like OSTIA). It was noted that some of these products are useful for fjord-scale processes, such as subglacial outlet plumes, sea-ice cover, iceberg drift and biological productivity. Sea surface height can be measured via JASON-1/2/3, TOPEX-POSEIDON, ENVISAT/ERS, with limited coverage at high latitudes. Sediment plumes can be monitored by MODIS Aqua/Terra and LandSat 8, and ocean colour by SeaWIFS, MERIS, and VIRS.

Discussion:

Bob Bindschadler (SEARCH, USA)

The group was encouraged to keep in mind other stakeholders that would be interested in the data products (beyond the glacier and ocean scientific community) and alternative funding sources for GrIOOS to leverage. There was a recommendation to consider other value added products the monitoring system could produce, with a particular note for predictive products – which could be informed by what the ocean-ice/climate modelers need to improve their models.

Notes from Session 5 – Summary from previous day including breakouts

Pierre Dutrieux

The assembly was first reminded that a document summarizes best practices/policy for proposing observing system and networks: the Framework for Ocean Observing (NASA document).

A discussion on lessons learned from previous programs (e.g. PROMICE) followed. A list of key characteristics for a successful program is:

- 'Light is sustainable' : logistically or instrumentally expensive observing systems are very difficult to maintain over time. That being said, it might be wise to start the first few years of the observing system with oversampling (as has been done by USGS for monitoring mountain glaciers, for example) with the objective to identify key sites for sustained observations and to scale down the observing system after a few years.
- 'Monitoring requires proven technology' : although testing new technology is an interesting prospect if it can reduce costs further down the line, an observing system is not the best place to implement new technologies.
- 'Build on available logistics and programs' : although programs that are already running would not easily scale up, they provide logistical support for additional instrumentation deployment, if necessary.
- Simple logistics, and ones that would make use of interested communities, is best.

To motivate progress in understanding and provide answers relevant to society, the issue of the observing system integration with modelling activities was raised. So: what would the modellers want?

- What would be needed to predict/forecast/increase our understanding of the system over decadal time scales? Impact of ocean forcing on the ice? Impact of ice melting on the ocean? The problem is that the answer to this question strongly depends on our still limited understanding of the processes themselves.
- What would biological modellers need?

The assembly fell short of defining answers to those questions.

Finally, it was recognised that an observing system needs to have strong data server capabilities (Cloud solutions?) where observations can be exchanged, as well as means of defining the success and impact of the observing system itself. Apart from typical academic measures (publications and citations), it was proposed to introduce other measures of success, for example by recording the uptake of data from the data server, and recording who is using the observations (academia, other stakeholders?).

Notes from Becca Jackson & Kristin Schild

Eric Lindstrom – NASA (presented Sat 12 December 2015)

Tips for getting proposals funded (specifically monitoring proposals):

- Show/tell what you've done and why you need to continue monitoring
- The proposal needs to be interdisciplinary
- Good words to include/what they like to see is time devoted to "data management and analysis". They would fund a proposal just to do this. There is a lot of collected NASA imagery/data that is just sitting there- collected by their missions and funded projects.
- The science traceability matrix (FOO [add website]) outlines what to include in a NASA proposal.

William Ambrose – director of Arctic Observing Network (AON) at NSF.

AON's mission: detect and quantify Arctic change, with a broad range of programs including indigenous community, physical and biological oceanography, permafrost, etc.

AON Program & what they fund:

- It is a proposal driven program, so vision is elusive. The program is not really a network, and there is mission flexibility.
- PIs need to have questions in mind as they develop their proposals, but it is ***not*** for hypothesis-driven research or data analysis. It does fund support for observing infrastructure, adding observing infrastructure, innovative observing technology, etc.
- AON is meant to compliment and provide context for process studies. Currently there are AON sites all around the Arctic and Greenland, and there is a database online [add website] – all the data is openly available immediately after collection.

Funding statistics:

- Currently AON's portfolio is, by number of proposals: about a quarter physical oceanography, a quarter atmospheric sciences, and a very small fraction land ice. The small number of land ice projects is likely due to few proposals submitted.
- There was a large jump in AON funding in 2009 from ARRA. Many of the proposals funded during this period and coming up for renewal now. A lot of AON's current budget is tied up in "mortgage" for ongoing projects, but hopefully this will be reduced in future. In current funding round, AON has received $75 million in funding requests, with on $5-6 million to spend.

Suggestions for getting proposals funded:

- GrIOOS has to be partitioned and pitched to various funding agencies. NSF likes grassroots efforts and workshops. Proposals should be able to stand alone, while also being part of a coordinated GrIOOS effort. NSF recognizes the value of long-term measurements, but they need to have good questions.
- Young investigators are encouraged to be involved, make connections and write joint proposals with other young investigators, in the US and abroad (UK mentioned)
- Issues raised about transatlantic coordination and joint programs, especially the timing and outcomes for proposals. There is a NERC agreement that allows them to let NSF do the review and decide on funding decision for joint proposal (US and UK).

Question about road map for big projects and proposals: how to cobble together pieces? There is no formal mechanism for joint review, even between US agencies. It is suggested to talk to program managers. Leveraging co-funding is good (e.g. between NSF and NASA) and everybody wins, but proposals also need to be able to stand alone.

Question: why is land ice such a small piece of AON funding? Likely not many proposals funded, other sources of funding for these things.

Summary of Session 7: Measurement Techniques

Rapporteurs: Andrew Hamilton and Dave Porter

Summary:

In this session 12 speakers presented an overview of measurement techniques used to study glacier-ocean interactions in Greenland. The advantages and disadvantages of each instrument were discussed, and logistical and budgetary considerations related. There was an emphasis on relatively inexpensive but essential instruments and measurement techniques that could be included at existing field sites to record key variables for the observing system. When available costs have been included in the instrumentation summary. The presentations were divided into two groups depending on the focus of observation: 1) Ice and 2) Ocean.

1. Ice Measurement Techniques

Ted Scambos (NSIDC, USA): AMIGOS-II

A prototype glacier-ocean observing node, AMIGOS-2, was presented. The node consists of an Iridium satellite telemetered surface station with met/GPS/camera linked to a through-ice Distributed Temperature Sensor (DTS fiber optic cable), and oceanographic sensors below the ice, including 2 CT-cells and 2 current meters and a hydrophone. The system is powered by Li-ion batteries and solar panels and is deployed with an adjacent ADIOS GPS pole that links to the surface station. The unit is intended to be deployed through an ice shelf with a hot water drill and there are currently 15 of its predecessor (AMIGO-I) deployed across Antarctica and have functioned for 3-4 years.

Cost: $160k (additional CT/current meter sensor clusters $30k each)

Sridar Anandakrisnan(PSU, USA): Active seismometers

Small self-contained active seismic systems were presented, useful for mapping ice shelf cavities, bathymetry, and sediment structure (required for gravimetry inversions). The systems are easily deployable from helicopters, appropriate for crevassed glacier terrain, and useful for obtaining sediment thickness, sound velocities (that can inform density estimates), ground truth gravity inversions, and identify grounded or floating ice. Over 150 systems have been deployed worldwide.

Cost: unknown

Tim Bartholomaus (UTIG, USA): Passive Seismic Stations

The utility of passive seismometers at glacier termini for detecting subglacial drainage signals and calving events was presented. The systems are relatively low cost and robust, requiring at most annual servicing, yet have the ability to improve understanding of very poorly observed subglacial drainage processes and can detect even small calving events when deployed close to the terminus. Work is ongoing to calibrate tremors with drainage volume or intensity. When combined with hydrophones, timelapse cameras and tide gauges the seismometers would give a complete picture of episodic events in glacial fjords.The seismic stations are battery and solar powered and only require 3-4 hours for installation with one hour of annual servicing.

Cost: <$40k/yr per station

Erin Pettit (UAF, USA): Acoustic Observations of Glacial Fjords

Passive hydrophones have been utilized for applications related to submarine melt rates, calving events, subglacial discharge, seiche events, and marine mammals. The hydrophones are relatively low cost but do require annual servicing due in large part to memory capacity limitations due to the large dataset produced (e.g. marine mammal frequencies require sampling at > 5 kHz).

Cost: $6-10k ($20k for broader spectrum systems)

Dave Finnegan (CRREL, USA): Automated Terrestrial Laser Scanner (ATLAS)

A stand-alone automated LiDAR system with 6-11 km range used to create high resolution DEMS was presented. The ATLAS system provides a 60^{o} field of view (with environmental enclosure), 15 mm accuracy and 10 mm precision (spots density falls to 1 m in far-field). The system requires 24 VDC and 600 Watt Hrs per scan but will be powered solely by methanol fuel cells sufficient for 1-year operation. The system provides a massive dataset (~30 million points) useful for analyzing terminus advance, tidal motion, ice mélange, and calving events. A system was installed in July 2015 at Helheim Glacier, set at 30 min scan every 6 hours resulting in compressed 200 Mb file. Data storage over a year deployment would be an major issue

Cost: $450k

Gordon Hamilton (U. Maine, USA): Timelapse Cameras and Thermal Imaging

A brief presentation of timelapse cameras was presented, noting the low-cost systems are useful to measure calving events, terminus position, presence of subglacial plumes, and condition of ice mélange. The systems a StarDot 5 MP webcam and/or FLIR and are Iridium telemetered for real-time viewing and powered by 12DC solar. For infrared other information is required, including humidity, calibration temperatures, and optical depths.

Cost: $2-10k (visible vs infrared)

Alistair Everett (Swansea, UK): Remote Sensing of Subglacial Plumes

A photogrammetric method of using sea surface height anomalies to estimate discharge and volume flux of subglacial plumes that rise to the surface was presented. The method requires some CTD water column data but utilizes existing remote sensing products and as such requires no additional investment or infrastructure. The method is limited in that it requires a visible surface expression of the plume, and is therefore impacted by ice mélange and fjord stratification, and results in a probability of discharge maximum that must be constrained with other data.

Cost: none

2. Ocean Measurement Techniques

Dave Sutherland (U. Oregon, USA): Oceanographic Moorings and Iceberg Tracking

Deep subsurface ocean moorings were described with modifications for the challenging environment of glacial fjords with iceberg hazards and high sedimentation rates. Moorings include various sensors such as current profilers (ADCPs), temperature sensors, conductivity-temperature sensors, pressure sensors, and Iridium beacons, but are fully adaptable for inclusions of other sensors. Some adaptations included dual acoustic release mechanisms for redundancy, weak links in the upper part of the mooring in case of iceberg encounters, and mid-water flotation to reduce likelihood of drag by iceberg keels. The significant challenges of maintaining moorings in glacial fjords were emphasized, and icebergs generally prohibit measurements in the upper 50-100m of the water column. Moorings are usual deployed for 2 years and sampling intervals depend on sensors but are usually <1 hr. Deep water moorings require large vessels to deploy with associated ship-time costs.

Cost: $100k-$300k

Shallow pop-up moorings were described which consist of temperature sensors, conductivity-temperature sensors, and pressure sensors. These instruments are deployed in shallow, low-sedimentation, protected waters near the fjord walls and enable a way to record surface water properties in iceberg fjords.

Cost: <$10k estimated

Also presented was the utility of small GPS devices for iceberg tracking, which can be used to constrain circulation in the upper water column. These are inexpensive instruments but expensive to deploy and limited to fjord-scale speeds due to their low precision, so cannot be used for vertical motion.

Cost: $200

Fiamma Straneo (WHOI, USA; SEARCH): PIES and ITPs

An instrument that uses acoustics to derive a depth-integrated temperature of the water column was described. The Pressure Inverted Echo Sounder (PIES) instruments are bottom anchored, easy to deploy and last 4-5 years, but must be retrieved for data recovery. It was noted that there remain issues with sediment accumulation in glacial fjords with regards to a solid substrate for deployment.

Cost: $35k (+$7k to add a CT)

Also presented were Ice-Tethered Profilers (ITPs), satellite telemetered moored CTD profilers that are deployed through ice. ITPs are a robust and tested technology in the Arctic and are proposed as instruments that could be deployed through glacier tongues or fast ice to provide temperature, salinity, velocity and optical properties from 10-700 m depth in the ice cavity. They have a nominal 2-year lifetime and the data is telemetered daily, eliminating the loss of data in event of instrument loss.

Cost: $150k

John Mortensen (GINR, Greenland): Hydrographic Transects in Godthabsfjord

Monthly hydrographic sections from small surface vessels were described for the waters around Nuuk, Greenland. The method requires personnel on site year-round. Open water conditions and few icebergs provide relatively easy access to Godthabsfjord and allow streamlined mooring that can extend to the surface.

Cost: $10k/day

Christian Rodehacke (DMI, Denmark): Oceanographic Expeditions in NW Greenland

A series of hydrographic profiles collected near Qaanaaq Fjord, NW Greenland, in late winter (March/April) since 2011 were described, as well as sections across Nares Strait in 2015. Future plans for CTD profiling in August/September 2016-17 were related but are dependent on support from Danish Arctic Command, which has not yet been approved. Installation of moorings through sea ice with an automated weather station near Qaanaaq was described.

Costs: unknown

Aqqalu Rosing-Asvid (GINR, Greenland): Satellite-linked Data Loggers on Seals

A method for obtaining ocean temperature and salinity profiles from seals tagged with small expendable data loggers was presented. The instruments are satellite telemetered and send data daily over the average 10-month span of the tag (July-May, between seal molting each spring). Seals generally dive 4-12 times per day to depths of several hundred meters (up to 600 m), with ranges varying from a single fjord to hundreds of kilometers, species dependent. The loggers sample at 1 Hz during deep dives, and although the accuracy and resolution of the sensors is somewhat poorer than traditional oceanographic instruments they provide a means to collect quality water column profiles from otherwise inaccessible regions. The feasibility of capturing and tagging seals was discussed and a recommendation was given to start with small pilot program in a new fjord to determine behavior of seals. Plans were discussed to tag Greenlandic halibut that sample the deep benthic waters, although the 5-10% recapture rate reduces data return. Some concerns were raised about biased sampling using tagged marine creatures and the inherently unpredictable nature of nature.

Cost: $8k/tag + seal tagging costs (minimum $8k-16k to tag 3 seals each year)

Summary discussion, led by Bob Bindschadler

Note takers: Timothy Bartholomaus & Rebecca Jackson

What are the key variables to be measured at GrIOOS sites?

1. Ocean, presented by Dave Sutherland.

- Essential measurements: temperature, salinity, pressure in fjord; winds in fjord; moorings on shelf (maybe desirable?); bathymetry.
- Desirable measurements: water properties on shelf (maybe essential); Pressure Inverted Echo Sounder (PIES) for heat content; velocity; turbidity; biological measurements.
- Essential instruments: moorings (through ice for floating tongues), Automatic Weather Station (AWS) near the fjord surface and within fjord walls, PRES for floating tongues.
- Desirable instruments: seals.
- Open questions that were discussed but not resolved: How much structure in depth should the moorings have? What sort of redundancy? Are seals biased samplers? How important is it to have moorings on the shelf? This might be especially important for shallow-silled fjords.

2. Glaciology, presented by Twila Moon.

- Essential measurements: discharge runoff, ice velocity, ice elevation, surface mass balance, melange, calving, terminus position
- Essential instruments ("F" indicates needed for floating termini, "G" indicates needed for grounded or near-grounded termini, $ are price per unit) : cameras (15 min repeat interval) with infrared capability (G, $2-10k), Automatic Weather Stations (Potentially three: on the ice ~1000 m, at the terminus, and at the fjord mouth) F/G ($20k), seismic (1-3) for calving and subglacial discharge F/G ($40k), Terrestrial Laser Scanner (TLS, G $450k), GPS (Floating $5k), Phase-sensitive radio echo sounding (pRES) (Floating, $10k).
- Essential to support: satellite observations of ice surface elevation and ice speeds.

3. Discussion points.

What are the timescales at which we need these observations? The ocean and glacier observations should be synced for optimal monitoring.

What should be the spatial focus of these observations? How much of the glacier and fjord should be monitored? For example, do cameras need to cover the whole melange and fjord, or just focus on the terminus?

There was debate over how important it is to instrument the shelf. Mark Inall argued that monitoring the Atlantic waters on the shelf is a crucial component for this overall effort.

This led into a discussion of various larger-scale oceanic monitoring efforts at Denmark Strait, Davis Strait and Fram Strait. It was agreed that GrIOOS should attempt to leverage the ongoing work surveying the fluxes through these straights.

Choosing GrIOOS sites

The discussion of site selection was guided by a vote, where all workshop participants cast three votes for their preferred sites around Greenland. The top three winners were Helheim, Jakobshavn and 79N. The runners up were, in order, Petermann, Rink, Kangerdlugssuaq Glacier, Upernavik, Qanaaq, KNS. The pros and cons of each site were discussed and summarized here.

- ***Helheim***. Pros: representative of southeast Greenland, easy access, stabilizing geometry, experience at site and relatively extensive existing record. Cons: complex geometry on shelf and in fjord, large melange.
- ***Jakobshavn.*** Pros: most potential for retreat and contribution to SLR, easy access to ice, simple geometry, good long-term history. Cons: no high topography that provides an elevated view of the terminus, sill that limits Atlantic water, large and atypical melange, inaccessible by boat.
- ***79N***. Pros: science community expects large changes, an ice stream, existing observations (though limited), close to Fram St array, floating tongue which can be used as a platform, an upstream ice core. Cons: remote, complex geometry, difficult logistics, accessibility and lack of community engagement, unusual geology.
- ***Petermann***: existing data and ongoing work, easier to access than 79N (debated), simple geometry, long-term record from paleo studies, ice shelf as platform, good cliff viewing geometry for cameras. Cons: similar to 79N (debated), hard to access, small SLR contributor, Naires St. moorings are gone, atypical of Greenland.
- ***Other sites***. KNS has good ocean measurements but needs ice. Qanaaq also has ongoing measurements from Japanese and a well connected local community. Rink has extensive existing measurements and is currently stable, but is poised for retreat.

There was some confusion and debate about whether it is a pro or con for a site to already have ongoing funding when considering GrIOOS site selection.

Discussion of how to proceed

How much is GrIOOS steering people towards certain sites versus just a framework for getting measurements at sites? Should there be a menu of sites that countries can choose from? Is GrIOOS an umbrella that groups can work under, or is it really trying to emphasize key sites? This point is unclear.

There is a tradeoff between number of sites and the extent of observations at each site. Ute suggests that it is better to have a larger list of candidate glaciers and include smaller glaciers.

How will this be funded? No one country is going to fund the whole thing. Being part of GrIOOS should increase one's chances of getting funded. The NSF Arctic Observing Network provides an opportunity to begin funding in the USA.

What are the key components of an observing system? There was a discussion of governance and data sharing. Minimum requirements for an observing network include a framework for: 1. key variables to be measured, 2. data quality policies and 3. data sharing policies. Several different possible frameworks were discussed. AON requires data to be immediately available. PROMICE demonstrates that this is important, valued and successful. Quick and centralized access to data is key, though there should be flexibility so that countries are not excluded from the GrIOOS process for embargo reasons. It was also pointed out that it might not be worthwhile to be rigid about rules before there is even any funding.

Bob suggests that the group should read the Framework for Ocean Observing (FOO) as a guide. A workshop report will be written, though it is not yet clear where it should be published. Presentations from workshop will be available on the GRISO website.