Freshwater fluxes from the Greenland Ice Sheet

Report from an international workshop

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Executive Summary

The Greenland Ice Sheet (GrIS) is a large store of freshwater in the global climate system. At present, the GrIS has an approximate water equivalent of 7 m of sea level rise potential (Aschwanden et al., 2019; Morlighem et al., 2017), second only to the 57 m of the Antarctic Ice Sheet (Rignot et al., 2019). Freshwater is discharged from the GrIS into the ocean in three forms: **1) solid ice**, through the calving of icebergs; **2) surface melt and runoff**, as liquid water through above-sea-level melt and supraglacial streams or subglacial discharge of glaciated areas, and rivers draining watersheds of non-glaciated areas; and **3) submarine melt** on the fronts and undersides of marine-terminating glaciers and ice shelves. Since the 1980s, the GrIS has lost approximately 5000 Gt of ice, equivalent to a sea level rise of 13.7 ± 1.1 mm (Mouginot et al., 2019) at an accelerated rate. Beyond sea level rise, the increasing GrIS freshwater flux is raising concerns due to its impacts on global ocean circulation given its proximity to dense water formation sites in the North Atlantic, on marine ecosystems in local and regional waters surrounding Greenland, and on local communities and industries that must navigate rapidly changing ice-related hazards.

Notwithstanding its importance, estimates of the timing, magnitude, and distribution of freshwater discharge around Greenland are imperfect due to scarce observations and a limited understanding of how the freshwater is transformed by ice/ocean processes at the ice margins. To tackle this problem, we organized an international workshop to understand the current state of knowledge and identify the critical gaps and next steps in quantifying the future GrIS freshwater flux. The workshop was held prior to the 2018 American Geophysical Union Fall Meeting, included ~40 participants from nine countries, and focused on four goals:

1) connect the communities needed to quantify freshwater input from the GrIS to the ocean;
2) identify the needs of ocean/climate models for oceanic boundary conditions at GrIS margins;
3) define community needs and science gaps; and
4) prioritize how to improve estimates of the freshwater input from the GrIS to the ocean.

We found that the oceanographic and glaciological communities have made significant progress on quantifying the various components of freshwater flux from Greenland, as well as in parameterizing these inputs in numerical simulations that range from local to regional to global. Although the workshop was successful in connecting several key communities interested in GrIS freshwater flux, the needed expertise to understand the impacts of GrIS freshwater flux on ecosystems and local stakeholders was largely missing. Furthermore, many challenges remain and the workshop identified the specific gaps from observations (both in situ and remotely-sensed), theory, and models (e.g., surface mass balance models, oceanic models of varying resolution, etc.) across all the distinct freshwater flux components. To continue making progress, we must regularly meet across disciplines and make a concerted effort to connect to local stakeholders. We identified three broad recommendations to guide our future efforts:

- quantify near-terminus freshwater flux components across multiple space/time scales;
- understand freshwater transformation from its source to its export into the open ocean; and
- identify the effects of present and future GrIS discharge on coupled ice sheet-ocean-marine ecosystem dynamics.

1. Motivation and background

The Greenland Ice Sheet (GrIS) is a large store of freshwater in the global climate system. At present, the GrIS has an approximate water equivalent of 7 m of sea level rise potential (Aschwanden et al., 2019; Morlighem et al., 2017), second only to the 57 m of the Antarctic Ice Sheet (Rignot et al., 2019). Freshwater is discharged from the Greenland continent into the ocean in the form of: 1) solid ice, through the calving of icebergs, and 2) as liquid water through above-sea-level melt of glaciated and non-glaciated areas, surface melt and runoff respectively, including rivers draining watersheds and supraglacial streams or subglacial discharge fed by surface melt and runoff; and 3) submarine melt on the fronts and undersides of marine-terminating glaciers and ice shelves. Since the 1980s, the GrIS has lost approximately 5000 Gt of ice, equivalent to a sea level rise of 13.7 ± 1.1 mm (Mouginot et al., 2019), which implies an additional freshwater discharge into the ocean. Estimates of the total freshwater flux from Greenland range from 800 km^3/yr in the 1970s to 1100 km^3/yr in the mid 2010s (Bamber et al., 2018). Spatially, this freshwater flux is distributed around the island with peak discharge coinciding with the location of large outlet glaciers (Bamber et al., 2012). Given the projected warming over the Atlantic and Arctic sectors over the next century (Yin et al., 2011), mass loss from Greenland and the associated freshwater discharge are expected to increase. While the GrIS freshwater flux is smaller than the net freshwater discharge from the Arctic Ocean through Fram Strait (~5000 km^3/yr; Haine et al., 2015), it has a major impact on the regional oceans around Greenland, including on the marine ecosystems, and the increasing trend is raising concerns on long-term impacts on the North Atlantic circulation.

Specifically, in addition to sea level rise, we identify four main areas (A1–A4) where the GrIS freshwater flux has an important impact:

A1) *Global ocean circulation*: on a global scale, the input of buoyant freshwater into the subpolar North Atlantic has the potential to affect convection occurring in the Labrador and Irminger Seas (Lazier, 1980), possibly leading to changes in the Atlantic Meridional Overturning Circulation (Bakker et al., 2016; Böning et al., 2016; Frajka-Williams et al., 2016; Marsh et al. 2010; Thornalley et al., 2018; Yang et al., 2016).

A2) *Ice-ocean interactions*: on a local to regional scale, the amount, timing, and location of freshwater flux can modify ambient fjord water properties, changing the stratification and leading to feedbacks on glacier dynamics, submarine melting (see reviews by Straneo & Cenedese, 2015; Truffer & Motyka, 2016, and references therein), and sea ice formation.

A3) *Ecosystems*: freshwater flux from Greenland can affect local and regional marine ecosystems through localized upwelling inside its glacial fjords, which indirectly affects primary productivity and food web dynamics (Cape et al., 2019; Hendry et al., 2019; Hopwood et al., 2018), and triggers blooms downstream (Arrigo et al., 2017; Oliver et al., 2018).

A4) *Human-ice interactions*: on a local to regional scale, the changing magnitude and timing of iceberg calving can increase hazards to communities or offshore shipping and infrastructure (e.g., Bigg et al., 2019). More uncertain is how sea ice cover will respond to increased freshwater input; sea ice is critically important to local communities and ecosystems surrounding Greenland.

Notwithstanding its importance, estimates of the timing, magnitude and distribution of freshwater discharge around Greenland are imperfect due to scarce observations and a limited understanding of how the freshwater is transformed by ice/ocean processes at the ice margins. State-of-the-art datasets, at present, quantify the ice and meltwater discharge at the ice sheet-ocean margins (Bamber et al., 2012; Bamber et al., 2018), but cannot account for the rapid transformation that this solid ice or meltwater undergoes both at the edge of glaciers or within the glacial fjords (Beaird et al., 2015; Beaird et al., 2018; Enderlin et al., 2016; Moon et al., 2018; Mortensen et al., 2018) and beyond on the continental shelf and into the open ocean. However, these data sets are being used to force models, which typically do not resolve either the ice/ocean boundary processes, the glacial fjords, or icebergs, thus raising questions about whether simulations can reproduce the impact of Greenland's discharge on the ocean.

To tackle this problem, we organized an international workshop of scientists from multiple disciplines to assess the current state of knowledge, identify the critical gaps, and determine the next steps in quantifying the future GrIS freshwater flux. The workshop was a natural next step for a growing community of scientists interested in understanding the connections between the GrIS and its surrounding ocean. This community developed out of an initial international workshop focused on *"Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing",* organized by the US Climate and Ocean Variability, Predictability, and Change (US CLIVAR) Working Group on Greenland Ice Sheet-Ocean interactions in June 2013 (Heimbach et al., 2014; Straneo et al., 2013). Further development continued with a second workshop focused on establishing a long-term observing system of oceanic, atmospheric, and glacier variables around Greenland – that took place in December 2015 – and whose outcome is, in part, summarized in a Community White Paper for the Ocean Observations 2019 Conference (Straneo et al., 2019). Taken as a whole, these workshops, reports and community-wide efforts have contributed to the establishment of a multidisciplinary, international community focused on Greenland ice/ocean exchanges (e.g., including glaciologists, oceanographers, paleoclimatologists, biological oceanographers, atmospheric scientists, et al.) that we build upon in the workshop described here.

The workshop summarized in this report was held on December 9, 2018, prior to the American Geophysical Union (AGU) Meeting in Washington, D.C., USA. About 40 participants from nine countries (USA, Canada, Denmark, France, Italy, Germany, Greenland, UK, Netherlands) convened for a full day of discussions and talks focused on freshwater flux components, how we observe them, and how we simulate and predict them moving forward. Participants included graduate students, program managers, and scientists (see Appendix 1 for pre-workshop survey results). For the workshop agenda and a full list of participants see Appendices 2 and 3, respectively. The workshop focused on four main goals (G1–G4):

G1) Connect the communities needed to observe, quantify, parameterize, and model the exchange of freshwater (and heat) between the GrIS and the ocean.
G2) Identify the variables, and spatial-, and temporal-scale needs of the ocean and climate modeling community in prescribing oceanic boundary conditions at Greenland's margins.
G3) Define community needs and science gaps.
G4) Prioritize and strategize about how to move forward in improving estimates of the exchange of freshwater (and heat) between Greenland and the ocean.

We started the morning with talks aimed at bringing the whole group up to speed on the various freshwater flux components and state of knowledge, before using the entire afternoon for interactive discussions and brainstorming activities. The meeting sessions, and breaks, were joint with the Ice Sheet Modeling Intercomparison 6 (ISMIP6) meeting – held at the same location – which provided the complementary context of how to force ice sheet models using both oceanic and atmospheric conditions.

In this report, we outline the results from the workshop, starting with an overview of how GrIS freshwater flux is estimated and then discuss the gaps and challenges identified by the participants (before the workshop in Appendix 1, and during the workshop in Section 3). We end with recommendations for the community that aim to improve our future estimates of the GrIS freshwater flux, particularly in regard to its impact on global ocean circulation (A1) and local ice/ocean interactions (A2). Even though the workshop was advertised to the best of our ability, we acknowledge that the needed expertise to fully grapple with the present status and future needs of understanding the impacts of GrIS freshwater flux on ecosystems (A3) and to local stakeholders (A4) was largely missing (Appendix 1, 2, and 3). Making concrete connections to these communities is a pressing need.

2. Estimating the freshwater flux from Greenland – present status

The necessary spatial and temporal resolution of a freshwater flux estimate from Greenland into the ocean depends on the problem being addressed. For example, to understand the fjord-scale circulation that controls the transformation of freshwater near the GrIS, we need to quantify freshwater discharge at the glacier/ocean interface including subglacial discharge plumes that span over spatial scales of meters to hundreds of meters and sub-daily temporal variability. In contrast, to understand the impact of increasing GrIS freshwater input into the subpolar North Atlantic on interannual and longer timescales, we need accurate representations of the total freshwater at monthly time scales spread around the continent at relatively coarse spatial resolution with a vertical structure (i.e., at the model resolution) likely not resolving any details of in-fjord transformation. Thus, the challenge of estimating the GrIS freshwater flux is not only in its interdisciplinary nature, but also in the feedbacks across spatial and temporal scales that might not match the needed resolution of the problem being addressed. Observationally, freshwater from the ice sheet is not readily distinguishable from freshwater exported from the Arctic Ocean, circulating around Greenland's perimeter, except via expensive and complex trace element measurements (Beaird et al. 2015; Rhein et al. 2018). Thus using observations to quantify the freshwater transport from Greenland is challenging. This is in addition to the fact that ocean waters surrounding Greenland are choked with ice, both icebergs and sea ice, making observations difficult to obtain, especially in the near-surface layers where freshwater is often found.

Nevertheless, the oceanographic and glaciological communities have made progress in quantifying the various components of freshwater flux from Greenland, as well as in parameterizing these inputs in numerical simulations that range from local to regional to global. Much work needs to be done, but we start here with an overview of the current state of knowledge. It is a rapidly evolving field given the significant leaps in remote-sensing capabilities over the last decade, as well as refinements in modeling capabilities and recent observational campaigns targeted around Greenland.

To quantify the GrIS freshwater flux at the ice/ocean or land/ocean perimeter of Greenland, we have to estimate three main components:

- *Solid ice*: the portion of ice flux of Greenland's outlet glaciers that calves as icebergs.
- *Surface melt and runoff*: Melt that occurs at the surface of glaciers in the ablation zone is largely routed into supraglacial streams and enters the ocean at the surface or drains to the glacial bed and enters the ocean as subglacial discharge. In addition, some portion of runoff may be stored in firn or englacially.
- *Submarine melt*: Along the fronts of tidewater glacier and on the undersides of floating ice shelves, fresh melt water is input directly into the ocean throughout the water column.

If we are interested in the GrIS freshwater flux onto the continental shelf (i.e., at the mouth of the fjords), then it is important to take into account the melting of icebergs within the fjords, and the resulting decrease in solid freshwater flux and increase in liquid freshwater flux.

2.1. Solid ice

Roughly half of the long-term ice loss from Greenland is in the form of solid ice discharge across the grounding line (van den Broeke et al, 2017). This grounding line flux is not the same as the iceberg discharge flux because of submarine and frontal melting of marine ice. In northern Greenland the difference between solid-ice discharge and calving flux can be as much as a factor four (Rignot, 1996). As a result, solid ice discharge, submarine melt, and subsequent iceberg melt are key components in the full freshwater budget for Greenland fjords and coastal regions. Despite the importance of solid ice in the freshwater budget, detailed measurements across space and time are lacking for iceberg production and for iceberg melt.

Iceberg production happens through calving, a complex process with many suggested parameterizations but no universal calving law or 'best fit' model (e.g., Enderlin & Bartholomaus 2019). Calving can be tracked by satellite measurements of the glacier termini, combining measurements of terminus position, ice flow speed, and glacier thickness to determine solid ice discharge. However, all of these measurements can be challenging to acquire for marine-terminating glaciers, which are usually heavily crevassed, flanked by steep fjord walls, and often have high surface slopes. As a result, measurements can have high uncertainties. In light of these challenges, the most common method to determine solid ice discharge is to define 'flux-gates' further up-glacier, in a location where surface speed and ice thickness are easier to measure, and assume that all solid ice passing this flux gate is eventually discharged into the ocean (e.g., Enderlin et al., 2014; King et al., 2018; Mankoff et al., 2019). While this method produces a useful first order approximation, it does not account for surface thinning downstream of the flux-gate, partition between calving events (timing and magnitude) and submarine melt at the terminus, and assumes full-thickness calving at the ice front. Nonetheless, these estimates are continuously refined through the use of increasingly high resolution glacier ice thickness and ice velocity data that allows us to resolve seasonality, calving styles, terminus characteristics (e.g., floating or grounded), and through improved estimates of submarine melt (via ambient and concentrated plume melt).

2.1.1. Melting of icebergs prior to reaching the continental shelf

Assessing the transformation of Greenland's calving flux into liquid form at any location downstream of the calving front (for example at the continental shelf boundaries), requires the additional step of knowing the timing and location of iceberg melt. Iceberg melt is a particularly vexing problem because it depends heavily on subsurface ocean temperatures and currents, which require in situ observations that are difficult to collect in the challenging Greenland coastal environment. Yet, ongoing research has yielded a variety of useful results. For example, repeat satellite images allow characterization of the map-view size and distribution of icebergs (Enderlin et al., 2016; Sulak et al., 2017). Applying basic width-to-keel depth ratios, total iceberg size can be approximated and iceberg melt models used to examine potential subaerial and submarine ice melt (Moon et al., 2018). Satellite images can also be used to create map-view digital elevation models (DEM) of the iceberg tops (Enderlin & Hamilton, 2014). By differencing repeat DEMs, one can calculate average iceberg melt based on surface elevation changes. In addition, laboratory experiments informed by observations have provided means of improving melt parameterizations for icebergs in the fjords (FitzMaurice et al., 2016, 2017, 2018). Icebergs are now also beginning to be included in ocean simulations (e.g., Bigg et al. 1997; Martin & Adcroft 2010; Stern et al., 2016; Wagner & Eisenman, 2017; Marsh et al., 2018), with a variety of parameterizations used to determine melt (iceberg fragmentation is ignored), though icebergs remain absent in most general model studies.

2.2. Surface melt and runoff

Ice sheet surface melt and associated runoff, both via surface streams and subglacial discharge, are the primary liquid freshwater sources. Surface melt can be observed using microwave satellite data, which can help identify the presence and extent of melt but cannot provide information on melt volume (Mote, 2007). In situ weather stations can provide information on solar radiation, air temperatures, wind, and surface conditions (van As et al., 2011), which can be used in the creation of melt models, but these detailed in-situ measurements are spatially limited. As a result, forcing regional climate models (RCMs) with reanalysis data is the current standard for obtaining comprehensive surface melt data across space and time. The most commonly used RCMs (e.g., RACMO and MAR) include atmospheric processes and ice sheet surface processes like refreezing and runoff (Fettweis et al., 2017; Noël et al., 2016). Despite the widespread use of RCM output, it is difficult to validate these model simulations and local uncertainties can be high (Vernon et al, 2013) depending on how runoff is routed and stored subglacially.

Runoff reaches the ocean in two ways: 1) as surface streams; and 2) via subglacial discharge as surface melt routes through the ice and along the ice-bed interface. The majority of runoff that is routed through outlet glaciers emerges subglacially. There are a handful of river gauges in Greenland (particularly in the southwest region), that can validate runoff from land-terminating ice (van As et al., 2018), but most surface streams are not directly measured. Subglacial discharge beneath outlet glaciers is even more difficult to measure because they terminate into the ocean at depth. Direct measurements at the subglacial interface are extremely difficult, though some headway has occurred by sampling ocean water properties or water plume characteristics (Jackson et al., 2017). Other indirect measurements include the use of seismic tremor data to reveal the volume flux of subglacial discharge (Bartholomaus et al., 2015).

2.3. Submarine melt

Submarine melt at the edge of glaciers is regulated by ocean temperature and circulation, where changes in either variable influences the heat flux across the ice/ocean boundary layer (Jenkins, 2011; Magorrian & Wells, 2016). For rapidly calving glaciers, such as Jakobshavn, Kangerdlugssuaq or Helheim, the ice discharge is thought to be largely determined by calving (with a smaller contribution from submarine melting – given the smaller surface area exposed to ocean waters). For the few remaining floating ice tongues in northern Greenland, however, as well as the numerous thin, small ice flux glaciers around the GrIS, submarine melting tends to be the main ice loss term (Rignot 1996; Wilson et al., 2017; Fried et al. 2018). While submarine melt occurs year round, it is strongly enhanced in summer by subglacial discharge emerging at the grounding line of outlet glaciers in discrete outlets driving localized plumes of enhanced melt (Fried et al., 2015; Mankoff et al., 2016; Slater et al., 2018).

For mostly vertical tidewater glaciers, melt rates have been estimated using a combination of melt parameterizations and buoyant plume theory (Morton et al. 1956; Jenkins, 2011; Magorrian & Wells, 2016). Application of this theory has been improved by adapting from a point source to a line source for discharge plumes (Jackson et al., 2017) to produce the ocean water properties that best explain near-terminus observations, and through the use of ocean models that account for ambient melting outside the discharge plumes (Magorrian & Wells, 2016; Slater et al., 2018). However, in reality, we are uncertain about many aspects of plumes at present, i.e., point source versus line source, or details of the boundary layer adjacent to the ice surface (e.g., shear vs. convection). The morphology of the submarine terminus can give information about the spatial variability in processes at play at the terminus. Deeply undercut outlets have been revealed at the terminus (Fried et al., 2015; Rignot et al., 2015; Sutherland et al., 2019) that are the sources of subglacial water and high melt rates. Fried et al. (2015) inferred high melt rates associated with small discharge outlets and that deeply undercut channels can enhance calving via sloughing as surface crevasses connect to the undercut roof.

Sutherland et al. (2019) directly estimated submarine melt rates using repeat scanning of the glacier face, finding that ambient melt rates predicted by theory are two orders of magnitude too low compared to the observed values (one order of magnitude too low for terminus-wide melting). The underprediction of submarine melt rates by theory is also suggested by modeling studies (Slater et al., 2018) and attempts to estimate calving fluxes (Wagner et al., 2019). At the same time, the flux of submarine meltwater calculated via oceanographic methods (i.e., the flux-gate method in Section 2.4.1; Jackson & Straneo, 2016; Motyka et al., 2003), is of the same order of magnitude as the estimated submarine melt rate values (Sutherland et al. 2019). Unfortunately, the flux-gate method does not differentiate iceberg melt from terminus melt, and cannot provide spatial structure to the melt rate at the termini. The latter is important if there are feedbacks between submarine melting and calving.

Indeed, calving losses also occur at outlet glacier termini and there is great uncertainty in the role that submarine melt plays in controlling the location, rate, and style of calving that occurs. Both modeling studies (Benn et al., 2017; Ma & Bassis, 2019) and remote-sensing observations (Fried et al., 2018) suggest a link between submarine melting and retreat patterns. Even the much-higher than anticipated directly measured submarine melt rates (Sutherland et al., 2019) only equate to ~30% of the ice flux, implying that the greatest impact of submarine melting might be the feedbacks on calving and subsequent glacier dynamic response.

For floating ice tongues, estimates of submarine melting can be derived using remote sensing data and calculating the Lagrangian ice flux divergence (e.g., Wilson et al., 2017). This represents an improvement over earlier estimates based on Eulerian ice flux divergence, or assumptions that the ice flux is balanced by melting under the ice tongue (Enderlin & Howat, 2013; Münchow et al., 2014; Seroussi et al., 2011). At present, it is still challenging, however, to resolve seasonal or interannual variations in melt rates using these methods. Ocean models coupled to an ice/ocean boundary layer can, in principle, provide melt rate estimates under floating ice tongues, but at present, challenges remain in validating the melt parameterizations used in these models, in obtaining the bathymetry under the floating ice needed for the ocean simulations and in formulating appropriate lateral boundary conditions.

2.4 Putting it all together

Because of the complexity of the processes involved and challenges in quantifying the various freshwater inputs from observations alone, progress on this topic must come from combining different methodologies and including theory, models, and observations. In particular, estimates of freshwater discharge from Greenland used in modeling studies, typically as a boundary condition for ocean models vary greatly depending on the application. Commonly, the time and space scales needed co-vary, such that global models might need relatively coarser resolution products of the GrIS freshwater flux (e.g., monthly time scales and 10 km space scales), while regional and local models necessarily need finer resolution to examine processes occurring at subdaily to daily to weekly timescales in fjords typically narrower than 5 km and on sub-minute timescales and sub-meter spatial scales to resolve plumes.

2.4.1. Observations

From an observational perspective, estimates of glacial fjord freshwater budgets typically use in situ water property and velocity measurements to infer subglacial discharge, ice discharge, and submarine melt rates (Jackson & Straneo, 2016). Indeed, the ocean-only observational approach that uses conservation of mass, salt, and heat, is one of the only methods that can directly estimate the distinct freshwater fluxes in the waters surrounding the GrIS (Jackson & Straneo, 2016; Motyka et al. 2003; Sutherland et al. 2019), as well as provide information on water mass transformation inside the fjords. However, very few interannual records exist of ocean properties inside glacial fjords (Boone et al. 2017; Carroll et al. 2018; Mortensen et al.,2014; Straneo et al. 2016). Oceanographically-observed estimates of freshwater flux can be compared with model-derived estimates, e.g., subglacial discharge that is typically estimated from regional atmospheric models coupled to a snowpack model (e.g., Noël et al., 2018) or submarine melting. Ice discharge is obtained from remote sensing flux-gate estimates (e.g., Enderlin et al., 2014; King et al, 2018). Submarine melting is typically a small fraction of the ice flux for strongly calving systems, though challenges remain to estimate the relative partitioning of the two (Sutherland et al., 2019; Wagner et al., 2019).

One of the most promising observational techniques to quantify the freshwater export from a glacial fjord system is through the use of ocean velocity measurements (e.g., from ship-based surveys or moored measurements) combined with noble gas measurements that permit the separation of glacial meltwater input into melt above the sea-surface, melt below the sea-surface and, potentially, basal melt over the bedrock (Beaird et al., 2015; Beaird et al., 2018). Noble gas measurements, however, are costly and only provide snapshots of the glacial meltwater distribution. The hope is that they can be combined with other properties and tracer measurements to provide a more continuous and less expensive estimate of the meltwater pathways within and at the mouth of the glacial fjords (e.g., Cape et al., 2019). Beyond the glacial fjords and nearby shelf-regions, glacial meltwater becomes strongly diluted and much harder to track (Rhein et al 2018), though it has been done successfully using noble gases around Antarctica away from the surface layer (e.g., Hohmann et al 2002).

To make the link between Greenland freshwater flux and the open ocean requires knowledge of the distinct freshwater components in the fjord, how much exchange the total freshwater flux drives in the fjord (i.e., through entrainment and subsequent drawing in of shelf waters into the fjord), and then the transport of that freshwater across the shelf-edge to the open ocean. On the Greenland shelf, measurements include repeat hydrographic sections, sea mammal-borne measurements, subsurface moorings both east and west of Cape Farewell (Lozier et al., 2019) and across straits, such as Fram Strait, Denmark Strait, and Davis Strait (Curry et al., 2013), and surface salinity from microwave satellites (SMOS, Aquarius). However, hydrographic sections are limited to only summertime due to the challenging environment (Myers et al., 2009; Sutherland & Pickart, 2008); mammal-borne measurements typically only include temperature sensors (Grist et al., 2011; Sutherland et al., 2013); moorings are subsurface to reduce hazards from surface waves, sea ice and icebergs (e.g., Le Bras et al., 2018); and satellite-based measurements of salinity are subject to large uncertainties in cold water and in coastal areas, e.g., on the shelf around Greenland (Köhler et al., 2015). As a consequence, seasonally-resolving measurements of freshwater (e.g., Le Bras et al. 2018) on the Greenland shelf are largely absent.

2.4.2. Modeling the impacts on the fjord scale

Ocean models requiring boundary conditions from Greenland have used a variety of prescribed fluxes depending on the model domain, and the question or time scale investigated. Glacial fjord simulations, to date, have largely focused on the circulation driven by subglacial discharge and/or submarine melt at the glacier front. These are typically specified as a seasonally varying freshwater flux that emerges from one or more pre-imposed channels or as a distributed flux along the entire glacier face (e.g., Carroll et al., 2017; Kimura et al., 2014; Slater et al., 2015; Xu et al., 2013). The magnitude of the freshwater flux is typically estimated from RCMs or in situ measurements, while the submarine melt rate is either derived in the model if an ice/ocean parameterization is used or estimated from an idealized plume model or similar. For floating ice tongues, Shroyer et al. (2017) examined the circulation underneath the Petermann Glacier floating ice tongue, finding that wind effects modulate the shelf-fjord exchange that dominates the model-estimated basal melt rates. To date, no fjord-scale simulation has investigated the impact of iceberg melt distributed along the entire length of the fjord in driving the fjord circulation.

2.4.3. Modeling the impacts on the open ocean scale

Global ocean and climate models have implemented a wide range of freshwater forcings from Greenland, underlining the need for improving and standardizing these fluxes. Global Earth System models addressing timescales of 100 to 1000 years currently do not include ice sheets, thus discharge from Greenland typically only consists of the routing of precipitation over the ice sheet into the ocean. In some models, e.g., CESM (Community Earth System Model), any snow accumulation beyond 10 m is discharged into the ocean as a freshwater flux in specified regions (Kay et al., 2014; Lenaerts et al., 2015). Global ocean-only models used in historical runs, typically from the 1950s to present day, combine forcing from atmospheric reanalyses (CORE II, 1958-2007; Yeager & Large, 2008; or more recently JRA55, 1958-2016; Tsujino et al., 2018– which includes river discharge from Dai et al. 2009)– with more recent Greenland discharge estimates. To date, the most sophisticated of these is that of Bamber et al. (2012, updated and extended in 2018), which includes a spatially variable (on a 5 km grid around Greenland) monthly estimate of freshwater flux (typically all converted as a liquid freshwater flux) from Greenland as separate fields (Bamber et al. 2018) of solid discharge (grounding line ice flux), tundra run-off and surface and subsurface runoff reconstructed using an RCM forced by reanalyses. Examples of regional models forced by the Bamber products include Böning et al. (2016) and Dukhovskoy et al. (2019), both investigating the impact of Greenland freshwater on the freshening of the North Atlantic. The modeling community is actively investigating how vertical and horizontal resolution affects the spreading of freshwater from Greenland (Dukhovskoy et al. 2019), with some groups implementing a vertical distribution of the GrIS freshwater flux at the ice margin instead of using a surface only flux. Ultimately, we need an active interaction between the GrIS freshwater flux, even if implemented accurately in depth, and the fjord/shelf, so that the correct exchange of freshwater (and other variables such as heat, nutrients, etc.) can occur. Furthermore, icebergs have been implemented in several modeling studies (e.g., Martin & Adcroft 2010; Marsh et al. 2015; Marson et al. 2018) to investigate the effect of melting (both in depth and horizontally as they disperse from their source glacier), compared to the common practice of turning all solid ice flux into liquid freshwater at the ice margin.

3. Estimating the freshwater flux from Greenland – gaps and challenges

The community has made considerable progress over the last decade in estimating the GrIS freshwater flux and understanding the important processes that control its magnitude and influence on the surrounding ocean. On the ice side, satellite remote-sensing has provided a wealth of data to estimate the solid ice flux, as well as to quantify iceberg distributions around the ice sheet and onto the continental shelf. In addition, we now have water property time series that span several years from multiple fjords around Greenland (e.g., Uummannaq, Sermilik, Godthåbsfjord) which, hopefully, will in time become part of a long-term Greenland Ice Ocean Observing System (GrIOOS; Straneo et al., 2019). These time series, combined with an increasing number of shipboard surveys, have identified the dominant circulation processes that exchange freshwater and heat between the ice sheet and surrounding ocean. However, challenges remain in monitoring the GrIS freshwater flux at the time and space scales needed for local to regional to global simulations. And, significant gaps in our knowledge still exist across all the freshwater flux components discussed above. At the workshop, disciplinary groups discussed the gaps and challenges, which are summarized below. A final list of overarching recommendations follows in Section 4 below.

3.1. Solid ice

Much work remains to better understand, measure, and parameterize the grounding line flux of ice and the related partitioning of how much is iceberg discharge (i.e., calving flux) versus submarine melting, and the resulting iceberg melt in the fjord, i.e., the space- and time-dependent transformation of solid ice into liquid meltwater.

Solid ice flux

- As mentioned earlier, the grounding line flux (solid ice discharge) is commonly calculated using a 'flux-gate' method that does not incorporate near-terminus surface or partition out submarine melt at the ice front. This is problematic for determining the timing and location of solid versus liquid freshwater production. Observations are needed that can help to partition solid versus liquid freshwater flux at the glacier terminus.
- There is limited knowledge regarding glacier terminus and iceberg geometries, including roughness. It is common practice to approximate iceberg shape (e.g., as a cone or cylinder), but these different shapes can have widely varying surface areas, producing large ranges in melt rate estimates. Roughness is rarely included and may also be significant, but has not yet been well constrained from observations.
- Near-glacier ice mélange (a combination of icebergs, bergy bits, and sometimes sea ice) may also play an important role in controlling the timing of calving and the movement, breakup, and melt of icebergs (e.g., Amundson et al. 2010; Walter et al. 2012). However, this is not well known at this time.
- Improving projections of future solid ice discharge and reconstructing past ice discharge also highlights key challenges. 'How to improve discharge estimate for pre-1990's?' remains an open question. And methods for predicting calving volume into the future also need to be established and refined.

Solid ice transformation (i.e., iceberg melt and breakup)

- Assessing the timing and location of iceberg production and melt also requires detailed knowledge of the spatial distribution of icebergs. Remote sensing, likely combined with machine learning and image classification algorithms, provides a promising path forward for providing these data, but there is not yet an operational product for iceberg distributions.
- Iceberg melt is a complex process that includes subaerial melt, melt from wave erosion, and submarine melt, as well as mechanical breakup. In situ observations are needed to better constrain the balance of these processes (and how it changes in time and for different locations) and to develop more appropriate parameterizations for including these processes in models, since they would inject freshwater at distinct depths in the water column.
- Submarine iceberg melt depends on subsurface ocean conditions, which are sparsely measured around Greenland. There is a need both for more measurement locations and for longer time series, particularly winter and shoulder-season measurements.
- Further remaining challenges in constraining iceberg decay are associated with sea ice-iceberg interactions, grounding events that occur frequently in shallow bathymetry, and iceberg capsizing and decay that is not due to melting (i.e., fragmentation/breakup).

3.2. Surface melt and runoff

Capturing the full range of climate variables needed for the detailed study of surface melt and runoff, and of related processes, remains difficult because Greenland is large, remote, and a harsh environment for capturing in situ and year-round data. Workshop attendees collaborated to outline the gaps in surface melt and runoff data and the most pressing needs that must be addressed. In some cases, the data production methods are established but a consistent and validated data set is not available.

Critical variables for understanding Greenland freshwater flux and for linking observational and modeling studies are:

- *Albedo*: Providing consistent and spatially comprehensive data on albedo, including time series of the (sub)seasonal change, which is mainly determined by surface property changes (e.g., snow vs. bare ice vs. melt pond albedo).
- *Snowline*: The location and movement of the snowline throughout the year.
- *Partitioning of precipitation into rain vs. snow*: Determining the quantity and timing of precipitation events and the type of precipitation is key to understanding accumulation, melt, and retention.
- *Surface melt routing*: Understanding routing includes investigating potential time lags in runoff due to surface (firn layer), englacial, and subglacial hydrologic processes, and the short to long timescale evolution of catchment boundaries.
- *Ice sheet geometry*: Ice sheet geometry changes on subseasonal time scales influence surface melt routing, subglacial conditions (e.g., pressure), and locations of discharge.

Suggested methods or strategies to address these needs include expanding the network of weather stations on the ice sheet and producing targeted validation datasets for testing surface mass balance models. These validation datasets could be developed from a combination of remote sensing and in situ measurements. With regional climate model reanalysis providing the vast majority of widely used surface melt and runoff data, validation of results remains a pressing need.

3.3. Submarine melt

Accurate submarine melt rates are needed for two primary reasons: 1) they directly inject freshwater into the oceans surrounding Greenland and at varying depths, and 2) they can destabilize glacier termini, indirectly leading to variable solid ice flux. The two processes are connected as well, since the injection of freshwater can alter fjord circulation and stratification, which feeds back on further submarine melting and any induced calving activity.

Significant gaps remain in our knowledge of submarine melting primarily because of the difficulty of obtaining measurements at vertical face tidewater glaciers and under floating ice tongues. There is a huge discrepancy between commonly used theory for ambient melt rates (i.e., the melt in regions away from discharge-driven plumes) and melt rates inferred from modeling and snapshots of terminus morphology from ship-based sonar. To make progress on submarine melting, we need process-oriented studies to:

- Test whether melt rate parameterizations are skillful and well-calibrated, and if not, how to either 1) adjust the parameters in the theory (e.g., turbulent transfer coefficients, drag coefficients, and what background velocity to use) or 2) develop new theory with a different functional form (e.g., how does melting over an overcut terminus differ from an undercut terminus given the buoyancy of the fresh meltwater?),
- Combine observational and modeling analyses to test the feedbacks of submarine melt on glacier dynamics, in terms of calving and ice flux response. In particular we need more fjord measurements of temperature, salinity, and velocity for use in the oceanographic budget method (preferably within several kms of the ice front) to constrain model estimates of submarine melt and subglacial discharge.

and GrIS-wide studies to:

- Explore how, on a GrIS-scale, different submarine melt parameterizations influence the freshwater flux to the ocean and recommendations for the modeling community on what parameterizations to use given the resolution of their simulation,
- Test the parameter space of how submarine melt affects fjord water properties around the GrIS, given the range of stratification, grounding line depths, and seasonality known to exist. One way forward here might be to combine box models with existing observations.

3.4. Putting it all together

Much progress has been made over the last decade on quantifying the space and time-dependent freshwater flux from Greenland and its contribution to sea level rise. At the workshop, the discussion focused on how to improve current and future estimates of GrIS freshwater flux with an eye towards its effect on ocean circulation (from local to regional to global) and potential feedbacks on glacier dynamics.

3.4.1. Observations

At the fjord-scale, more observations are critically needed to inform our process-based understanding of how freshwater flux from the ice margin is transformed. Best estimates of ice flux, submarine melt, and runoff should be compared with results from intensive shipboard surveys and high-resolution satellite remote-sensing products in a suite of different glacial fjord environments. These process-based studies are expensive and time-consuming, but are necessary for constraining theory on submarine melt (which is difficult to observe directly), quantifying the solid ice transformation, and, at the fjord mouth, how freshwater is export onto the continental shelf. Building on these new process-based studies, as well as existing time-series data, will enable both 1) a cost-efficient GrIOOS (Straneo et al., 2019) that can be used to monitor exchange between the GrIS and the ocean, and 2) a data product that modelers can use to verify and compare different freshwater forcing products and how they are parameterized across existing spatial resolutions.

Observing the spreading of freshwater from the Greenland ice sheet and its tidewater glacier fjords onto the shelf and into the open ocean is inherently challenging. Sea ice and icebergs present a navigational hazard to research vessels, and make year-round observations near the ocean surface, where freshwater is concentrated, impossible. A further challenge is that the spatial scales involved in the problem are very small: icebergs are typically patchy, under 1 km in scale, and affected by both ocean currents and wind. Transport variability, along the shelf or across the shelf-edge is equally challenging. The shelf-edge around the Greenland continental margin extends over thousands of kilometers and the dynamical ocean processes in the region are relatively small-scale (1 to 10 km). As a consequence, localized areas of high exchange across the shelf-edge may be difficult to assess using traditional oceanographic observations. Along-shelf transport divergence has been estimated from summertime hydrographic sections (Myers et al., 2009) to identify regions of off-shelf transport, while offshore measurements of oceanic properties reveal a seasonal freshening of the Labrador Sea (Holte & Straneo, 2017; Schmidt & Send, 2007), indicating that seasonal freshening or seasonal changes in off-shelf transport may be important. While it may be assumed that ice mass loss from Greenland all eventually makes its way into the open ocean, the response of the large-scale circulation is likely sensitive to the mechanism and location of freshwater inputs (Dukhovskoy et al., 2019).

Some potential ways forward identified were 1) to develop improved satellite products for coastal and partially ice-covered regions (e.g., Ardhuin et al., 2019; Armitage et al., 2017), and 2) to undertake targeted process studies in fjord-shelf-open ocean systems.

3.4.2. Modeling the impacts on the fjord scale

Models are an indispensable tool for building understanding of the physical processes at the ice-ocean interface and for identifying potential future impacts of freshwater inputs to the ocean. At the workshop, primary gaps were identified for both regional, high-resolution fjord-resolving ocean models, and larger-scale climate models.

In fjord-resolving models, the major gaps include:

- The size distribution of icebergs, mélange cover, and amount of sea ice in fjords and their model implementation. The size and shape of icebergs in particular, which has significant consequences freshwater distribution within the fjord, are largely unknown.
- Observations in 1) the winter time, 2) at discharge locations, 3) actual calving vs. grounding line discharge observations, and 4) improved bathymetry.
- Representation of small-scale processes that drive vertical mixing, such as tides, waves and mixing in plumes and the feedbacks on horizontal circulation that drive fjord renewal. In particular, plume-melt theory for vertical face tidewater glaciers is untested and shown to be inaccurate (Sutherland et al. 2019).

3.4.3. Modeling the impacts on the open ocean scale

As these data-based estimates of freshwater discharge from Greenland are implemented in ocean models, important questions remain regarding how this freshwater is distributed in time and in the vertical around Greenland. Observations and modeling studies from the fjords show that the meltwater from Greenland (whether from surface melt or melt of glaciers and icebergs) is distributed over a layer that can be several hundreds of meters thick (e.g., Beaird et al., 2018; Moon et al., 2018) depending on the depth at which this water enters the ocean and on the mixing associated with its spreading. In the past, most modeling studies applied all freshwater inputs at the surface, which generates a strongly buoyant fresh layer with greater potential to disrupt air-sea-sea-ice exchanges. Some large-scale ocean models now distribute freshwater inputs over several grid cells in the vertical, in layers up to 200 m thick, however this distribution is usually constant in space and time. The Estuary Box Model approach is one method to physically parameterize the vertical distribution of freshwater and allow for it to vary in space and time, which is under development for implementation in CESM2 (Sun et al., 2017). Methods for implementing freshwater fluxes from mobile icebergs in large-scale ocean models are also under development (e.g., Martin & Adcroft 2010; Marsh et al 2015). An initial implementation of icebergs that melt at the surface found that icebergs are more likely than liquid freshwater to enter the Labrador Sea, where freshwater will likely have a more significant impact on large-scale ocean circulation and climate (Marson et al., 2018). Hence, in addition to accurate vertical distribution, implementing solid and liquid freshwater components explicitly is critical.

In climate models, freshwater fluxes are implemented on the continental shelf of Greenland, so that the main problem they face is converting disparate freshwater fluxes entering the ocean through fjord systems to fluxes on the shelf. With increasing grid resolution there is opportunity to better identify water properties on the shelf and at individual fjord openings, which force melt at the ice-ocean interface and mix with the meltwater and runoff inside the fjord. However, typical ocean grids (climate projections >0.5˚, observational period 1/4˚, process studies <1/10˚) do not provide the resolution to actually simulate the fjord circulation nor the ice-ocean interface. Nevertheless, boundary currents and shelf processes are greatly improved at resolutions of 1/10˚ and higher.

The climate modeling community identified several potential approaches for addressing this issue, including:

- A transfer function which could transform freshwater inputs into open ocean freshwater forcing values. Ideally, this would also take into account feedbacks of the ocean onto the ice sheet.
- A physics-based fjord module or Estuary Box Model, which would represent freshwater transformations with fjords in a simple but physically motivated manner. Fjord-resolving models could be used to inform this approach.
- A systematic way to test the sensitivity of the ocean response to the vertical distribution of freshwater inputs.

4. Moving forward: recommendations for the community

The workshop was successful in connecting several key communities interested in GrIS freshwater flux. Since the questions involved cross disciplinary boundaries, we recommend that the communities continue to meet and discuss ways to integrate observations and modeling across the ice-ocean-atmosphere interfaces and across multiple time scales. We lay out several recommendations below that will lead to significant progress in estimating future GrIS freshwater fluxes. We believe these recommendations will aid sea level rise predictions, improve our understanding of freshwater flux effects on global ocean circulation, and detailing the ice-ocean interactions that control feedbacks between the ocean and glaciers/ice sheets. Finally, we end with broader recommendations that underscore the need for more engagement with biological oceanographers and fisheries scientists to understand impacts on ecosystems, as well with stakeholders in local towns and government agencies that interact with ice every day.

1) *Quantifying near-terminus freshwater flux components across multiple space/time scales:*
We need to build upon numerous ongoing projects looking at the separate freshwater flux components to quantify the complete time- and space-varying freshwater flux near the terminus of a GrIS tidewater glacier. That is, we need integrated, multi-disciplinary process studies that use ocean observations of the freshwater flux components, with coincident observations and modeling of the individual components from the ice (calving flux, submarine melt, surface runoff/melt). These process studies would lead to enhanced knowledge of where and when surface runoff/melt enters the ocean as subglacial discharge, as well as constrain current submarine melt parameterizations used to quantify both terminus melt and iceberg melt.

2) *Understanding the transformation of freshwater from its source to its export to the open ocean:*
Although many models are of increasingly high resolution, there will remain a pressing need for GrIS freshwater flux at coarser resolution (i.e., distributed around the continent and not inside the fjords at the outlet glaciers themselves) for many years to come (including for a possible CMIP6 follow-on). Thus, we need process-oriented studies that combine modeling and observations to quantify the transformation of the freshwater flux components from the ice margin to the fjord mouth (and into wherever the open ocean begins), which allows future work to leverage the relatively sparse observations to better represent the freshwater system state. These process studies should be able to partition the freshwater flux in time and space with a particular emphasis on the vertical structure and resulting water mass exchange and transformation, exploring the range of glacier/fjord types around the GrIS to develop parameterizations for large-scale simulations of the ocean and climate.

3) *Identifying effects of present and future GrIS on coupled ice sheet-ocean-marine ecosystem dynamics:*
Recent studies have highlighted a number of mechanisms through which the discharge from the ice sheet can affect fjord water properties and circulation in addition to nutrient distributions and marine ecosystems as a whole within the fjords and downstream regions. The impact of projected GrIS changes on these ecosystems, however, is largely unknown. More system-oriented observational and modeling studies that address the inter-linkages of the physical oceanographic and glaciological processes, the ocean biogeochemistry and the marine ecosystem components (and eventually the ecosystem services provided to the local communities) are needed to address these questions. In particular, process understanding validated by observations is key to including these dynamics in ocean models. An assessment is needed of what biological and ecosystem variables need to be observed, what is being observed already (inventories), and how to develop multidisciplinary observing systems.

4.1. Societal benefits

A diverse set of stakeholders use information about fjord water properties, iceberg distributions, and sea ice conditions for a variety of activities, including hunting, transportation, shipping, and fishing, both recreational and commercial (e.g., Vorosmarty et al., 2018). In local communities, most of this information is based on personal experience and shared by word of mouth or social media. For coastal navigation and shipping, the ice service at the Danish Meteorological Institute has a long history of mapping sea ice and icebergs hazards, especially around southern Greenland, for navigation purposes. Improvements in the partitioning of GrIS freshwater flux components, as discussed above, will directly benefit these stakeholders through improved knowledge and datasets on present conditions and how they might change in the future. However, engagement with these stakeholders is key, so we recommend supporting projects that emphasize coordination and communication of results to local communities. Several entities are already engaging in the communication of environmental conditions relevant to GrIS freshwater flux, including the Asiaq Greenland Survey (www.nunagis.gl) and the Government of Greenland. On a regional scale, icebergs from Greenland move beyond its boundaries and can affect shipping, tourism, and offshore infrastructure along the Canadian and US coastlines (e.g., Bigg et al., 2019; Marsh et al., 2018). International shipping routes through the Northwest Passage are not in the future anymore, but happening more frequently each year. International efforts are also essential for Inuit engagement in the integration of science and traditional knowledge in ice sheet-ocean research. The Pikialasorsuaq partnership (pikialasorsuaq.org) is a new collaboration between Greenland, Denmark, and Canada that provides a valuable example. The Pikialasorsuaq is the Inuit name for the North Open Water (NOW) Polynya. The governments of Canada, Greenland, and Denmark are currently discussing how to manage the Pikialasorsuaq region as an international shared resource.

With the Arctic warming at two to three times the global average (Box et al., 2019), it is certain that substantial changes will occur in the Greenland coastal region – from ice sheet to ocean – that will include changes in freshwater flux (e.g., magnitude, timing, and location). Extending current observational work and filling gaps as soon as possible will provide the critical data needed to quantify these changes and project their impact on society-relevant parameters. These long-term baseline data are vital across multiple areas to: 1) establish baseline seasonal to interannual variability, 2) detect secular change, 3) quantify the character of change, 4) provide data needed to ground truth model results, including reanalysis and projection models, and 5) support short- and long-term research (e.g., process studies) that can improve models and support statistical or empirical research and projections. A well-established observation system can also better support research development, by providing a consistent publicly available dataset, and data use across scientific and user groups with varying levels of additional resource support.

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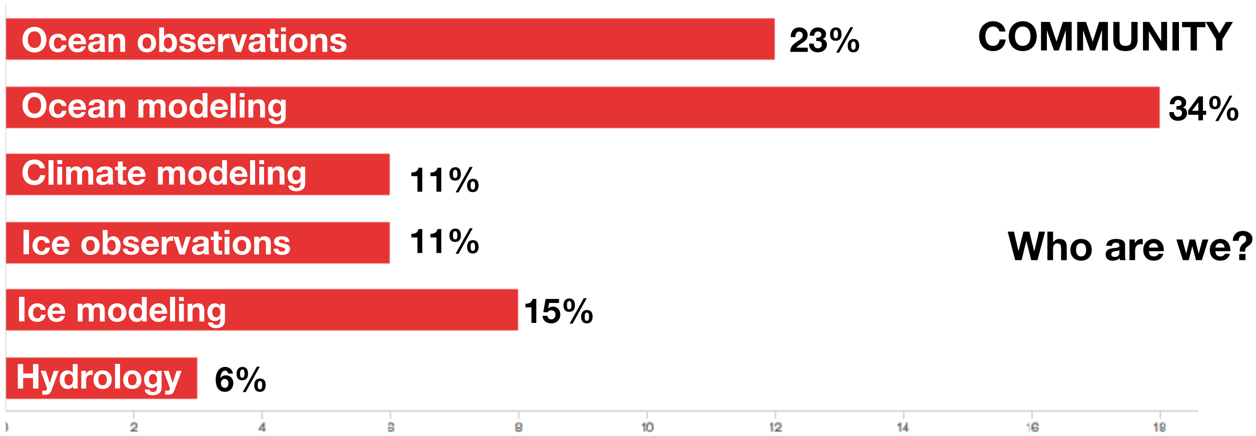
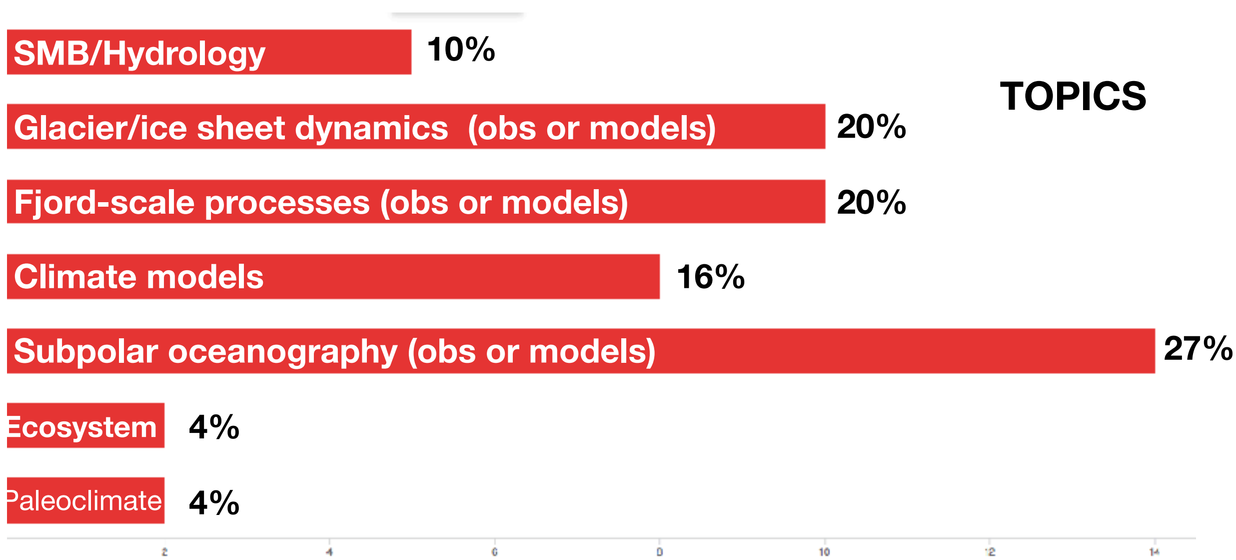
Appendix I – Pre-workshop survey results

Prior to the workshop, a set of survey questions were sent out to participants. The following images outline the results from those surveys, providing context for the workshop outcomes and complement the discussions and recommendations reported here.

Breakdown of scientific communities of participants:



Breakdown of scientific research topics of participants:



(Survey continued...)

What are we missing?

Category	Votes (only 7 total)
1. Sea ice	2
2. ICESat-2	1
3. GPS	1
4. All forms of modeling (e.g., Lagrangian)	1
5. Atmospheric Scientists	2

Who are the primary user groups?

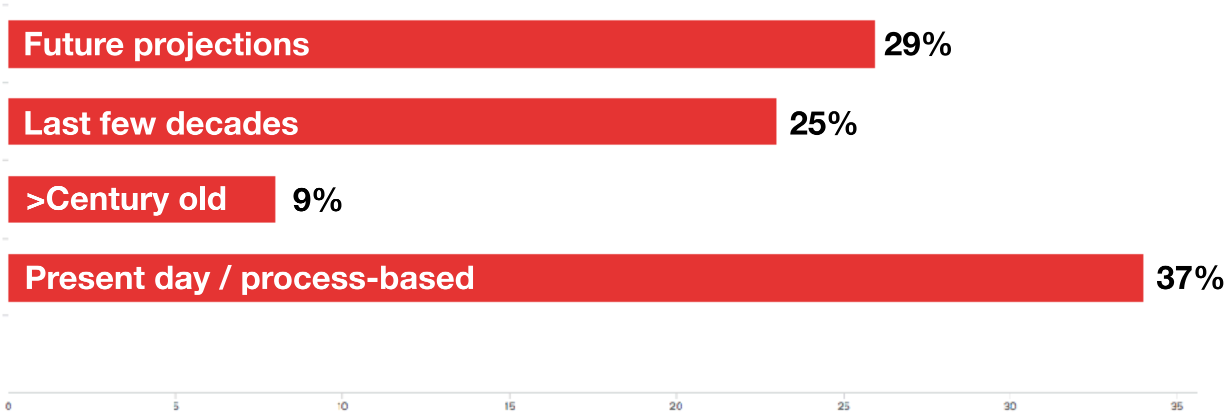
Group	% of Votes (93 total)
1. Ocean modelers (all scales)	**23%**
2. Climate modelers	**19%**
3. Sea level rise/policy makers/IPCC	**12%**
4. Observational oceanographers	9%
5. Glaciologists/ice community	9%
6. Marine Ecosystem Community	8%
7. Governments/Local communities	6%
8. SMB/Atmospheric modelers	4%

What use would you have for FW flux estimate?

Use	% of Votes (42 total)
1. Validation/evaluation of ocean models	**31%**
2. As input into ocean model/product	**24%**
3. Context for fjord-scale observations	**14%**
4. Validation/evaluation for SMB	10%
5. Context for fjord-scale observations	10%
6. Policy/IPCC uses	7%
7. Validation/evaluation for ice models	5%

(Survey continued...)

Over what time scales are FW flux estimates useful?



And at what spatial scale?

Scale	% of Votes (47 total)
1. Individual Glacier/Fjord (process)	**40%**
2. Individual Glacier/Fjord, but around ice sheet	**26%**
3. Ice sheet wide	**23%**
4. Regional scale	11%

**Need to define these spatial scales more explicitly*

What is biggest challenge in building an improved FW flux estimate?

Challenge	% of Votes (46 total)
1. Limited ocean-related observations	**22%**
2. Spatial heterogeneity (lat/lon and depth)	**17%**
3. Producing consistent product in space/time	**17%**
4. Limited runoff/SMB-related observations	**15%**
5. Limited ice-related observations	13%
6. Implementation of FW flux in models	7%
7. Identifying different sources of FW	7%
8. Coordinating disparate communities	2%

**Dependent on the question asked and use, time-resolution, spatial-resolution, etc.*

Appendix II – Meeting Agenda

8:30 – 9:00 **Arrival**

9:00 – 9:20 **Welcome & Introduction**: survey results & meeting goals

9:20 – 10:30 **Morning synthesis talks #1** (shared with ISMIP6)

- The Reverse Example: Ocean Forcing of Ice Sheet Models – ISMIP6
  Sophie Nowicki (NASA/GSFC) and Fiamma Straneo (Scripps)
- Estimating freshwater fluxes from Greenland
  Jonathan Bamber (Bristol)
- How do ocean and climate models handle FW fluxes and what do they want?
  Isabela Le Bras (Scripps)

10:30 – 11:00 **Coffee break** (ISMIP group leaves)

11:00 – 12:30 **Morning synthesis talks #2**

- Greenland Surface Mass Balance and runoff: current state of knowledge
  Brice Noël (Utrecht)
- Synthesis of near glacier transformation processes
  Dustin Carroll (NASA/JPL)
- Greenland icebergs: contribution to freshwater budgets
  Twila Moon (NSIDC)
- Synthesis of fjord dynamics and exchange at the mouth of the fjord
  Rebecca Jackson (Rutgers)
- Ocean observations outside the fjords: what can we learn?
  Femke de Jong (NIOZ)

12:30 – 1:30 **Lunch** (Joint with ISMIP)

1:30 – 1:40 **Summary of IPCC AR6 Chapter 9** (Baylor Fox-Kemper, Brown University)

1:40 – 2:30 **Working groups session #1: addressing needs and gaps**
Interdisciplinary groups identify needs in formulating appropriate freshwater export fluxes across the ice sheet-fjord-ocean system.

2:30 – 3:00 **Report out from Working groups session #1**

3:00 – 3:30 **Break**

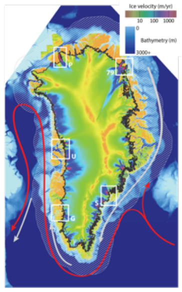
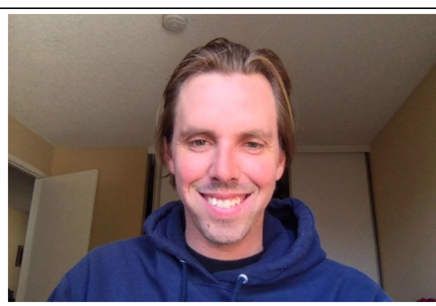
3:30 – 4:20 **Working groups session #2: how do we move forward?**
Disciplinary groups identify gaps from session #1 and a prioritized list of steps for making progress

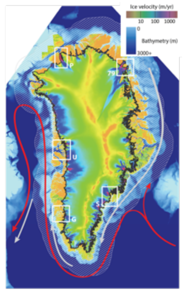
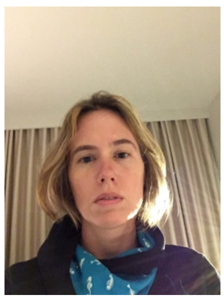
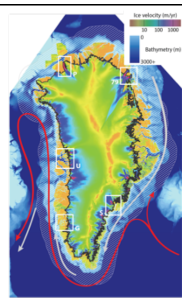
4:20 – 4:50 **Report out from Working groups session #2**

4:50 – 5:00 **Summary & wrap up**

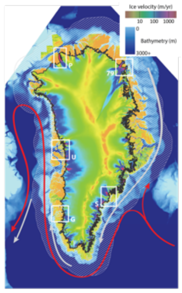
5:00 – 7:00 **Reception** (Joint with ISMIP)

Appendix III – List of Attendees

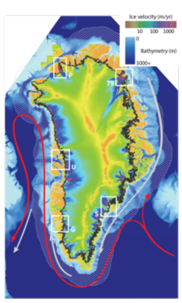
NAME	PHOTO	SHORT BIO
Alistair Adcroft	 *(default photo)*	Princeton University / NOAA GFDL alistair.adcroft@noaa.gov Expertise: Climate models Subpolar oceanography
Surendra Adhikari		NASA / JPL Surendra.Adhikari@jpl.nasa.gov Expertise: Glacier / ice sheet dynamics
Andreas Ahlstrøm		GEUS (Denmark) apa@geus.dk Expertise: SMB / hydrology of Greenland Glacier / ice sheet dynamics
Jonathan Bamber		University of Bristol ggjlb@bristol.ac.uk Expertise: SMB / hydrology Glacier / ice sheet dynamics
Dustin Carroll		NASA / JPL Dustin.Carroll@jpl.nasa.gov Expertise: Fjord-scale circulation Biogeochemical cycling

Ginny Catania* **organizing committee*		University of Texas Institute of Geophysics gcatania@ig.utexas.edu Expertise: Glacier / ice sheet dynamics
Gokhan Danabasoglu	 *(default photo)*	NCAR gokhan@ucar.edu Expertise: Climate models
Femke de Jong		Royal Netherlands Institute for Sea Research (NIOZ) Femke.de.Jong@nioz.nl Expertise: Subpolar oceanography
Roberto Delgado	 *(default photo)*	NSF Arctic Observing Network (AON) robdelga@nsf.gov
Julie Deshayes		LOCEAN-IPSL (France) Julie.Deshayes@locean-ipsl.upmc.fr Expertise: Climate models Subpolar oceanography

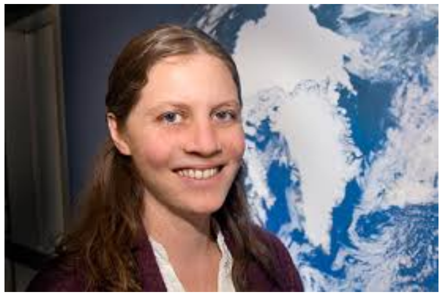
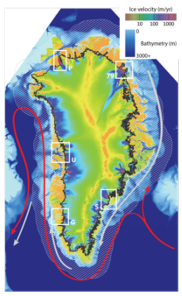
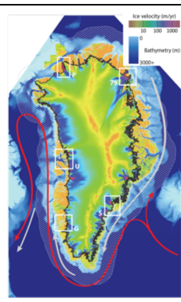
Dmitry Dukhovskoy		Florida State University ddukhovskoy@fsu.edu Expertise: Subpolar oceanography
Ellyn Enderlin		University of Maine / Boise State University (2019-on) ellyn.enderlin@gmail.com Expertise: Glacier / ice sheet dynamics
Denis Felikson		NASA / GSFC denis.felikson@nasa.gov Expertise: Glacier / ice sheet dynamics
Ian Fenty		NASA / JPL Ian.Fenty@jpl.nasa.gov Expertise: Subpolar oceanography
Baylor Fox-Kemper		Brown University baylor@brown.edu Expertise: Climate models Paleoclimate

Eleanor Frajka-Williams		National Oceanographic Centre (UK) eleanor.frajka@noc.ac.uk Expertise: Subpolar oceanography
Feras Habbal	 *(default photo)*	University of Texas - Austin fhabbal@ices.utexas.edu Expertise: Climate models
Alex Hager		University of Oregon ahager@uoregon.edu Expertise: Fjord-scale circulation
Patrick Heimbach* **organizing committee*		University of Texas at Austin heimbach@utexas.edu Expertise: Subpolar oceanography
Dorotea Iovino		Foundation Euro-Mediterranean Center on Climate Change (CMCC) dorotea.iovino@cmcc.it Expertise: Subpolar oceanography

Rebecca Jackson		Oregon State University / Rutgers University (2019-on) rebecca.h.jackson@gmail.com Expertise: Fjord-scale circulation
Michael Jasinski		NASA / GSFC michael.f.jasinski@nasa.gov Expertise: SMB / hydrology
Kristian Kjeldsen		GEUS (Denmark) kkk@geus.dk Expertise: Glacier / ice sheet dynamics Paleoclimate
Inga Koszalka		GEOMAR Helmholtz Centre for Ocean Research Kiel ikoszalka@geomar.de Expertise: Climate models Subpolar oceanography
Isabela Le Bras		Scripps Institution of Oceanography ilebras@ucsd.edu Expertise: Subpolar oceanography

Sasha Leidman		Rutgers University szl9@scarletmail.rutgers.edu Expertise: SMB / hydrology of Greenland
Margaret Lindeman		Scripps Institution of Oceanography lindeman@ucsd.edu Expertise: Fjord-scale circulation
Eric Lindstrom		NASA Physical Oceanography eric.j.lindstrom@nasa.gov Expertise: Subpolar oceanography
Torge Martin		GEOMAR Helmholtz Centre for Ocean Research Kiel torge.martin@gmail.com Expertise: Climate models Subpolar oceanography
Wieslaw Maslowski	 *(default photo)*	Naval Postgraduate School maslowsk@nps.edu Expertise: Subpolar oceanography Climate models Fjord-scale circulation Biogeochemical cycling

Twila Moon* **organizing committee*		NSIDC / University of Colorado, Boulder twila.science@gmail.com Expertise: Glacier / ice sheet dynamics
Theresa Morrison		Scripps Institution of Oceanography t4morris@ucsd.edu Expertise: Fjord-scale circulation
Alexis Moyer		University of Edinburgh a.moyer@ed.ac.uk Expertise: Glacier / ice sheet dynamics
Paul Myers		University of Alberta pmyers@ualberta.ca Expertise: Subpolar oceanography
Brice Noël		Institute for Marine and Atmospheric Research (IMAU), Utrecht University b.p.y.Noel@uu.nl Expertise: SMB / hydrology of Greenland Climate models

Sophie Nowicki		NASA / GSFC sophie.nowicki@nasa.gov Expertise: Glacier / ice sheet dynamics Climate models
Asa Rennermalm		Rutgers University arennerm@geography.rutgers.edu Expertise: SMB / hydrology of Greenland
Nicholas Rome	 *(default photo)*	Consortium for Ocean Leadership, IOOC nrome@oceanleadership.org
Olga Sergienko	 *(default photo)*	Princeton University, GFDL osergien@princeton.edu Expertise: Glacier / ice sheet dynamics
Donald Slater		Scripps Institution of Oceanography daslater@ucsd.edu Expertise: Fjord-scale circulation

Leigh Stearns* **organizing committee*		University of Kansas stearns@ku.edu Expertise: Glacier / ice sheet dynamics
Fiamma Straneo* **organizing committee*		Scripps Institution of Oceanography fstraneo@ucsd.edu Expertise: Subpolar oceanography Fjord-scale circulation
Dave Sutherland* **organizing committee*		University of Oregon dsuth@uoregon.edu Expertise: Subpolar oceanography Fjord-scale circulation
Till Wagner		University of North Carolina Wilmington wagnert@uncw.edu Expertise: Glacier / ice sheet dynamics Climate models
Ken Zhao		UCLA kzhao@atmos.ucla.edu Expertise: Fjord-scale circulation