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UNDERSTANDING THE DYNAMIC RESPONSE OF GREENLAND'S MARINE TERMINATING GLACIERS TO OCEANIC AND ATMOSPHERIC FORCING

A WHITE PAPER
BY THE U.S. CLIVAR WORKING GROUP ON
GREENLAND ICE SHEET-OCEAN INTERACTIONS (GRISO)

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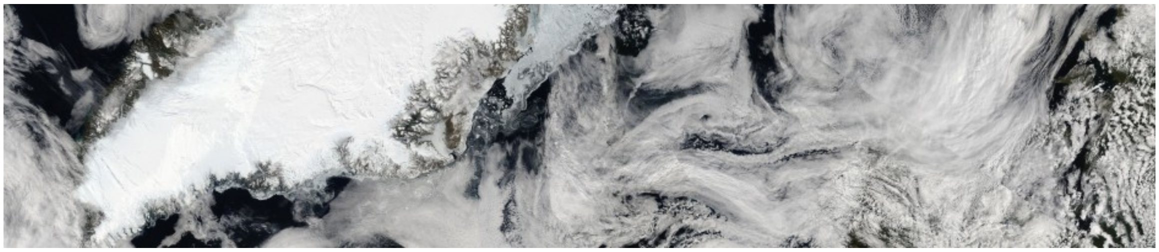

Challenges to Understand the Dynamic Response of Greenland's Marine Terminating Glaciers to Oceanic and Atmospheric Forcing

A Whitepaper by the U.S. CLIVAR Working Group on
Greenland Ice Sheet-Ocean Interactions (GRISO)

1. Introduction

The recent retreat, acceleration, and thinning of glaciers in Greenland has led to a doubling of the ice sheet's contribution to equivalent global mean sea level rise (SLR) over the past two decades. It has also increased the freshwater input to the North Atlantic, where it could impact the global ocean circulation. The synchronous and widespread glacier retreat, and its coincidence with a period of oceanic and atmospheric warming, suggest a common climate driver. Evidence points to the marine margins of these glaciers as the region from which changes propagated inland. The implication is that rapid mass loss from the Greenland Ice Sheet (GrIS) can be triggered from perturbations at the ice front (or the underside of floating ice) in contact with ocean waters. These forcings and the mechanisms driving the dynamic responses must be included in global climate models, either explicitly or in parameterized form, to reduce uncertainties in SLR projections and the impact of GrIS changes on the climate system. The spread of the projected SLR contributions from Greenland by 2100, from 0.06 to 0.54 m, gives a measure of such uncertainties.

Even though a similar scenario is invoked to explain recent changes in Antarctica, a number of considerations call for special attention to Greenland. First, while ice sheet-ocean interactions have been studied for a longer time around Antarctica, it is not evident that Antarctic-derived results can be applied to Greenland's marine terminating glaciers, given the different coastal and climate (atmosphere and ocean) setting at the two poles. Second, the proximity of Greenland to the North Atlantic's dense water formation regions imply that an increasing discharge of freshwater from Greenland can potentially impact the large-scale overturning circulation of the North Atlantic, a major player in the global oceanic heat transport, with far-reaching climatic implications. Third, no community platform comparable to the "Forum for Research into Ice Shelf Processes" (FRISP), a sub-committee of the "Scientific Committee on Antarctic Research" (SCAR), currently exists for Greenland, even though it is very much needed, as we will argue in this report.

Under the mandate of U.S. CLIVAR, a Working Group on GReenland Ice Sheet Ocean interactions (GRISO), composed of representatives from the multiple disciplines involved, was established in

January 2011 to develop strategies to address this problem. This document synthesizes efforts to summarize the state of knowledge, identify the most pressing problems/issues, and make recommendations on how to move forward collectively. It incorporates feedback from additional scientists to an earlier, publically distributed version.

The U.S. CLIVAR GRISO Working Group concludes that ice-ocean-atmosphere interactions in Greenland represent a new research frontier that is critical to understanding glacier evolution and ice sheet mass balance. Recent observed changes in Greenland show that these processes are important in the context of decadal-to-centennial climate variability. Addressing these processes is challenging and will require a concerted and interdisciplinary effort. Key observations need to be collected from the marine margins of Greenland's glaciers, many of which are not easily accessible, to guide and constrain the representation of the relevant dynamics and boundary conditions in ice sheet and coupled Earth system models used for climate projections. This represents both a new scientific endeavor and a technological one: it goes beyond what traditional technology and remote sensing techniques have been able to address. Long-term monitoring and paleo-reconstructions will be key to providing the appropriate temporal context. A synthesis of the science that supports these conclusions and a detailed set of recommendations are provided below.

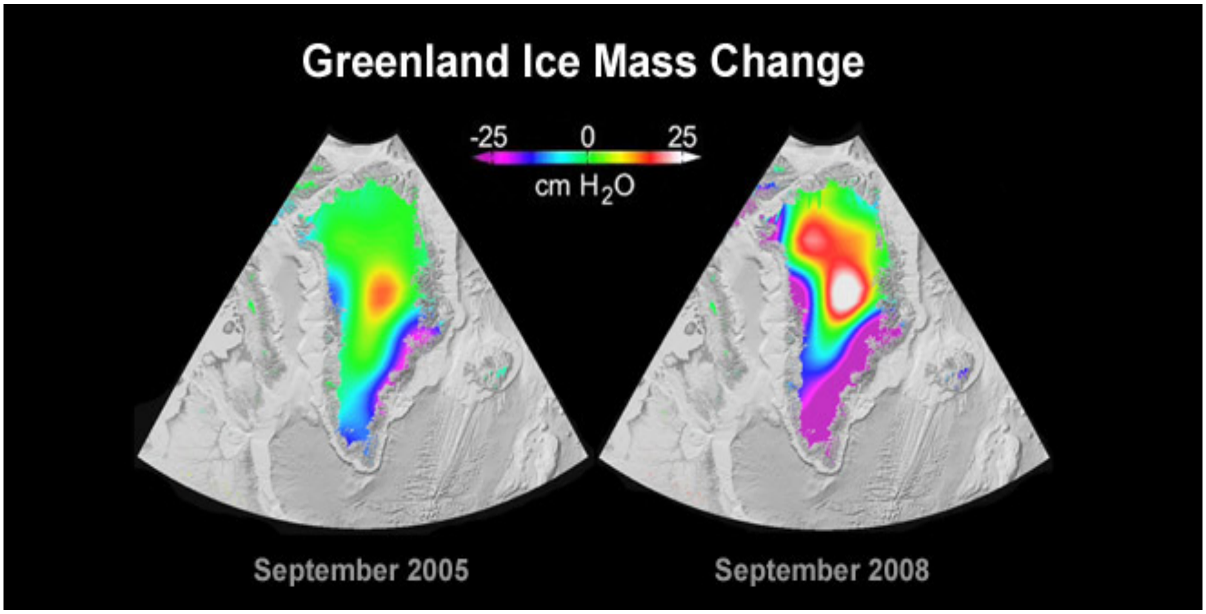

Figure 1: Gravity Recovery and Climate Experiment (GRACE) satellite observations showing recent mass loss from the Greenland Ice Sheet along the western and southeastern marine margins (from NASA/JPL; Khan et al., 2010).

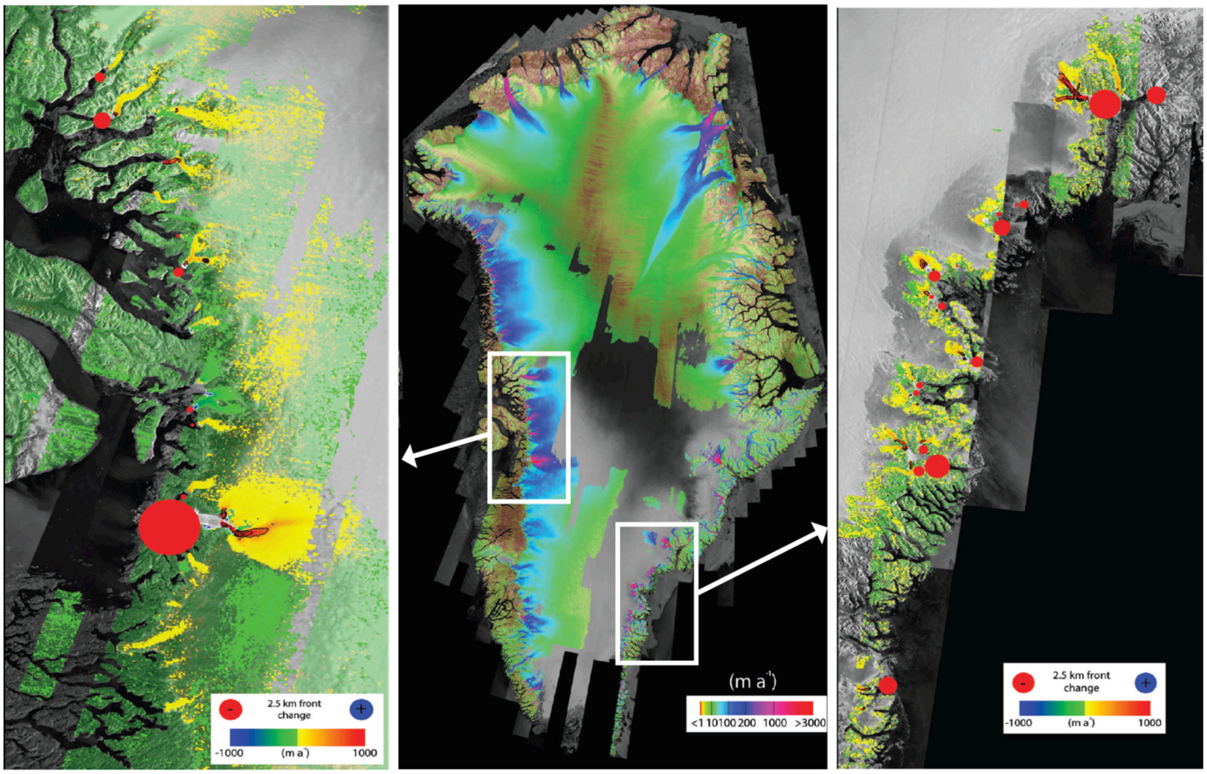

Figure 2. Center: Surface flow speed showing how Greenland's fast flowing outlet glaciers terminate into long, narrow fjords. Left and Right: Acceleration of outlet glaciers between 2000/2001 and 2005/2006 in western and southeast Greenland, (Joughin et al., 2010).

2. Scientific Motivation

2.1 Mass Loss from the Greenland Ice Sheet and Sea Level Rise

Mass loss from the Antarctic and Greenland ice sheets increased rapidly since the mid-1990s[1]. The combined loss from the two ice sheets now accounts for one-third to one-half[2] of sea level rise, roughly equally partitioned between the two [Milne et al., 2009; Cazenave and Llovel, 2010; Church et al., 2011; Rignot et al., 2011]. Geodetic measurements of continental uplift and Earth rotation, while not entirely independent, support these observations [e.g., Wu et al., 2010; Jiang et al., 2010; Nerem and Wahr, 2011]. In Greenland, the loss is due both to increased surface melting and to the acceleration, retreat and thinning (Figures 1 and 2) of marine terminating outlet glaciers [Howat et al., 2007; Luckman et al., 2006; van den Broeke et al., 2009]. The significance of this latter dynamic response, also observed in Antarctica, has only recently been appreciated and, as such, it is not represented in current-generation ice sheet models [Little et al., 2007]. In the 2007 IPCC AR4 report, this shortcoming was identified as *the* largest source of uncertainty in SLR projections [Lemke et al., 2007].

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[1] This period roughly coincides with the advent of quasi-continuous spaceborne measurements of ice velocities from Interferometric SAR (ERS-1 since 1991), ice thickness from laser altimetry (ICESat-1 since 2003), and ice mass changes from gravimetry (GRACE since 2002).

[2] The partition between contributions from thermal expansion in the ocean, mass loss from the polar ice sheets and drainage from glaciers and ice caps (G&ICs) is subject to significant inter-annual to decadal variability. Until the mid-2000s the partition appeared roughly one-third for each of the three, but with a recent shift toward zero net thermal expansion and equal partition between mass loss from the polar ice sheets and that from G&ICs.

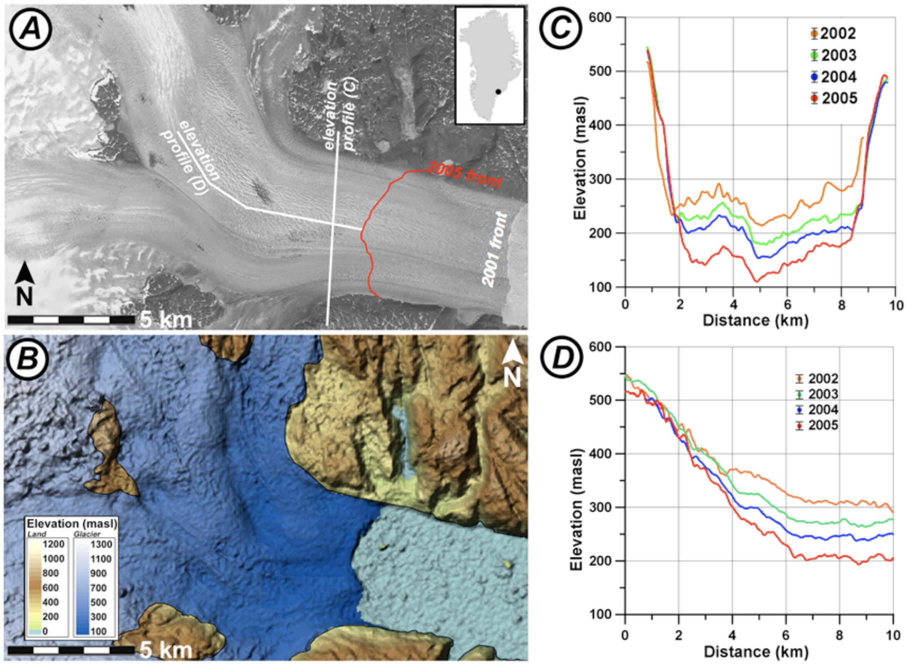

Figure 3. Retreat and thinning of Helheim Glacier, in SE Greenland (from Stearns and Hamilton, 2007). a) ASTER image acquired August 29, 2005. b) Surface topography derived from the image a. c) Surface elevation change on the along-flow elevation profile labeled in image a (0 km is the terminus). d) Surface elevation change on the across-flow elevation profile labeled in a).

Projections of SLR contribution from Greenland by 2100 vary greatly, reflecting a poor understanding of the processes involved. Meier et al. (2007) estimate 0.047-0.245 m depending on whether mass loss rates remain constant or present day acceleration is assumed. Pfeffer et al. (2008) arrive at a range of 0.165-0.539 m by assessing which glacier dynamics are physically tenable. Similar estimates emerge from semi-empirical studies linking future rates of SLR to global mean surface temperatures [Rahmstorf, 2007; Vermeer and Rahmstorf, 2009]. Finally, current-generation ice sheet models estimate 0.006-0.045 m [Price et al., 2011]. "Regime changes" in ice dynamics are not considered in these studies.

2.2 Dynamic Response of Marine Terminating Glaciers

About half of the doubling of Greenland's mass loss over the last decade [Rignot and Kanagaratnam, 2006; Khan et al., 2010] is attributed to the acceleration and retreat of outlet glaciers in western and southeast Greenland [Howat et al., 2007; Luckman et al., 2006; Stearns and Hamilton, 2007; van den Broeke et al., 2009; Howat et al., 2011]. The accelerating glaciers are marine-terminating or 'tidewater' glaciers, such as Helheim (Figure 3), Kangerdlugssuaq Glaciers and Jakobshavn Isbrae, which end in Greenland's long, narrow fjords (U-shaped valleys whose bottoms are below sea level). Their mass balance is largely controlled by seasonal calving and they are characterized by relatively short floating ice tongues[3] (Figure 4a). This contributes to the presence of an ice mélange, a mixture of sea ice and icebergs, at the front of the glacier's terminus, [Figure 4a; Amundson et al., 2010]. For such glaciers, the ice flow at the front, as well as the circulation of ocean waters and of ice in the mélange are strongly constrained by the fjord setting [e.g., MacAyeal et al., 2012]. Since the initial acceleration, several of the glaciers have slowed down (e.g., Helheim and Kangerdlugssuaq), but continue to flow at a rate that is faster than prior to the acceleration; others, such as Jakobshavn, continue to flow at fast speeds [Howat et al., 2011]. In general, the details of the spatial and temporal variability of the glaciers' acceleration are complex, likely reflecting influence from a combination of forcings [Moon et al., 2012].

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[3] Jakobshavn Isbrae likely had a 10-20 km ice tongue which disintegrated prior or during the acceleration [Motyka et al., 2011].

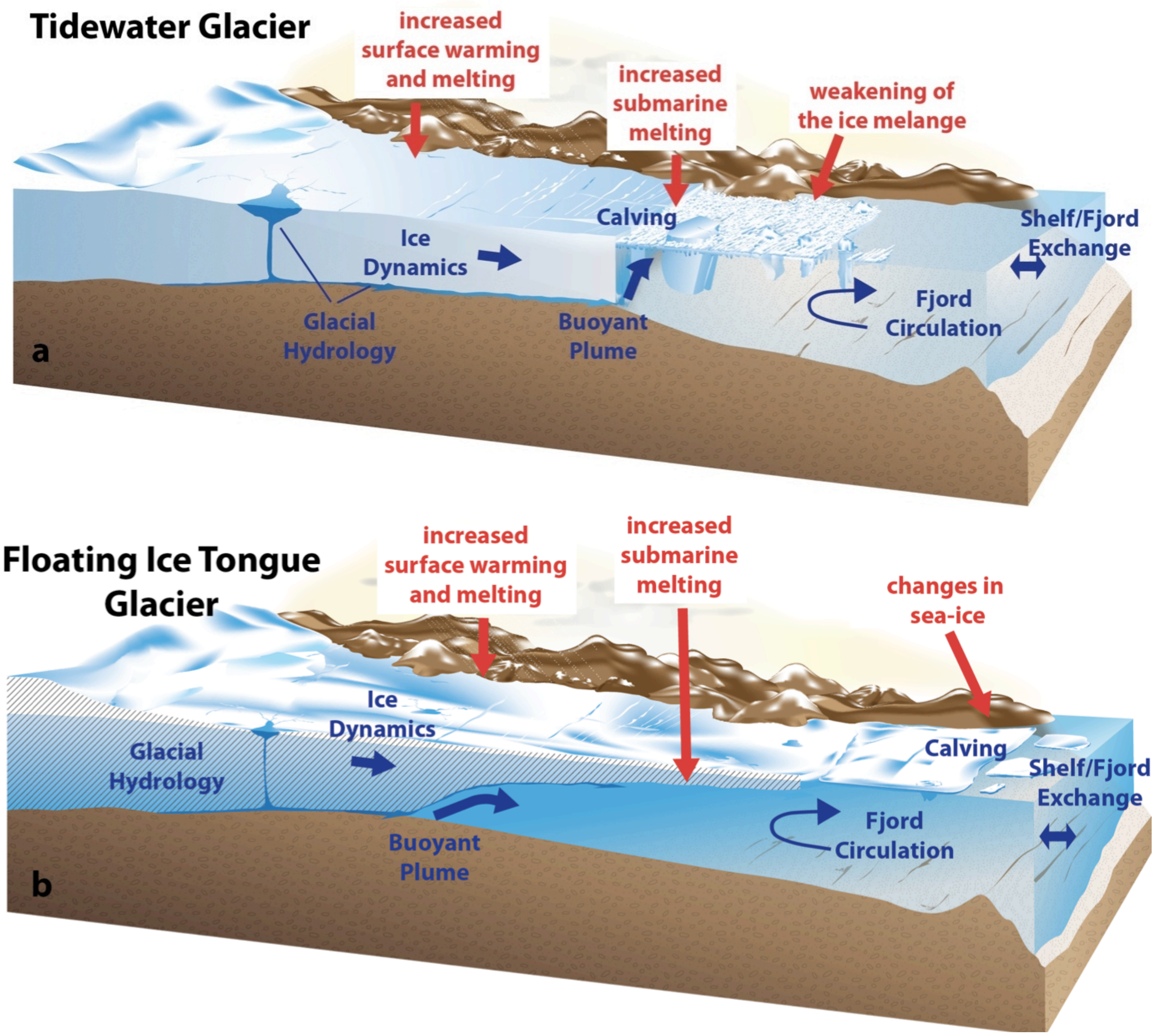

Figure 4: Schematic of a) Tidewater and b) Floating tongue Glacier. The proposed mechanisms for the glacier retreat and ensuing glacier acceleration are shown in red (section 2.3). The key processes needing to be addressed are identified in blue (section 3).

No clear accelerating trend is found for Greenland's northern glaciers[4] [Moon et al., 2012], some of which are characterized by long floating ice tongues (10-90 km; Figure 4b), e.g., Petermann Glacier [Rignot and Steffen, 2008] and Nioghalvfjerdsbrae/79 North Glacier [Mayer et al., 2000; Joughin et al., 2001]. These glaciers still calve but, unlike the accelerating glaciers discussed above, their mass balance is largely controlled by surface and submarine melting.

The synchronous nature of glacier accelerations and their clustering in the western and southeastern sectors [Figures 1 and 2; Howat et al., 2007; Rignot and Kanagaratnam, 2006] suggest that the glaciers responded to a common climate forcing. The precise chain of events that led to the glaciers' acceleration is not fully resolved, but recent work indicates that the acceleration began at the marine termini of these glaciers [Pritchard et al., 2009; Sole et al., 2008; Price et al 2008, 2011; Nick et al., 2009] with a similar sequence of events occurring in all cases. An initial retreat of the

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[4] Petermann Glacier lost about 25% of its tongue in August 2010; whether this triggered a dynamic response upstream is subject to ongoing research [Falkner et al., 2011; Nick et al., 2012].

marine terminus resulted in a loss of buttressing, acceleration, rapid surface thinning, increased calving, and, likely, amplification due to positive ice-dynamics feedbacks [Joughin et al., 2004; Thomas, 2004; Price et al., 2008; Vieli and Nick, 2011]. Hence, the climatic forcings of Greenland's dynamic mass loss are those responsible for the initial glacier retreat. **Thus, the leading hypothesis is that glaciers accelerated and retreated in response to forcing at the marine terminus due to oceanic or atmospheric variability, or both.**

The implication is that understanding the coupled glacier/sea-ice/atmosphere/ocean system is key to improving predictions of ice sheet variability and sea level rise. This is especially true in the light of the predicted changes in the atmosphere and ocean around Greenland. For example, using 19 climate models, Yin et al. [2011] estimate a warming of 1.7-2°C of the upper ocean around Greenland by 2100, almost double the global mean. Additional concern is due to the fact that several of Greenland's large ice streams, including the Northeast Greenland Ice Stream, and its two principal outlet glaciers 79 North Glacier and Zacharie Isstrom [Fahnestock et al., 2001] and Jacobshavn Isbrae [Herzfeld et al., 2011], are located in deep troughs (below sea-level) that extend far into the ice sheet. Destabilization of these ice streams could lead to rapid and large mass losses [Hughes, 1986].

2.3 Proposed Mechanisms and Forcings

Leading hypotheses proposed to explain the initial glacier retreat are:

i. Structural weakening of a floating ice tongue by thinning from excessive submarine melt [Motyka et al., 2011];
ii. Decrease in backpressure exerted by a thinning, decreasing ice mélange leading to increased calving [Joughin et al., 2008b; Amundson et al., 2010; MacAyeal et al., 2012];
iii. Effects of the increased surface melting on the ice flow [Zwally et al., 2002; Joughin et al., 2008a; see also Bell, 2008; Andersen et al., 2010; Hoffman et al., 2011];
iv. Effects of the subglacial hydrological systems on ice flow [Pfeffer, 2007; Schoof, 2010; Sundal et al., 2011];
v. Weakening of lateral shear margins due to cryo-hydrologic warming of subsurface ice [Phillips et al., 2010; van der Veen et al., 2011];
vi. Hydro-fracturing and calving of the floating tongues leading to reduced buttressing [Sohn et al., 1998; Post et al., 2011].

These, in turn, could have been triggered by one, or a combination, of three mechanisms (see also the review by Vieli and Nick, 2011):

1. **Increased submarine melting at the ice/ocean interface (#i, #vi)**
2. **A reduction or weakening of the ice mélange in front of the glacier (#i, #ii)**
3. **Increased crevassing and reduced structural coherence and strength due to surface warming and increased surface melt (#iii, #iv, #v)**

Understanding the way in which these mechanisms may act to perturb the ice sheet is key to elucidating the chain of events that led to the glaciers' acceleration. Here, we review these mechanisms and their links to oceanic and/or atmospheric forcings, highlighting both what is known as well as what is not known.

2.3.1 Submarine melting at the ice/ocean interface

Increased submarine melting at the tidewater front or under the floating ice tongue of Greenland's southern glaciers could have led to increased calving and/or the terminus retreat and eventual disintegration of the ice tongue. This would explain the initial glacier retreat, which then led to the glacier acceleration [Vieli and Nick, 2011; Motyka et al., 2011; Holland et al., 2008]. Recent surveys of major glacial fjords around Greenland have shown that these fjords contain enough warm waters to melt significant amounts of ice [e.g., Holland et al., 2008; Johnson et al., 2011; Straneo et al., 2012] but, also, that the circulation transporting heat to the glacier is complex and highly variable. While preliminary estimates indicate that summer melt rates could be on the order of 1-2 km/yr (for the mostly vertical faces of the southern tidewater glaciers) – these estimates are largely uncertain given the intrinsic challenges of measuring heat transport in highly variable, iceberg-choked fjords [Rignot et al. 2010; Motyka et al., 2011; Sutherland and Straneo, 2012]. In general, our understanding of how submarine melt rates vary as a function of the regional oceanic and atmospheric forcing is presently too limited to include these processes in models, albeit in parameterized form.

Submarine melting occurs when excess ocean heat is present at the ice/ocean interface. The exchange of heat and mass across the ice/ocean boundary is regulated by molecular processes and on scales not resolved either by field observations (mm to cm) or by models. Hence these transfers are typically quantified as a function of the outer boundary layer parameters [e.g., Hellmer and Olbers, 1989; Holland and Jenkins, 1999]. The submarine melt rate (SMR) is expressed as a function of the velocity and temperature (and to a lesser extent salinity) in the oceanic boundary layer [Jenkins et al., 2010]. The boundary-layer flow is conceptualized as a melt-laden, buoyant plume rising at the ice/ocean interface [Jenkins, 1991], tens of meters thick, and with dynamics influenced by a number of glaciological, oceanic and atmospheric parameters. Amongst these are:

(a) *Ice geometry and roughness* – For example, one expects very different plume behavior along Antarctica's mostly horizontal ice shelves [e.g., Little et al., 2009], or northern Greenland's long floating ice tongues versus southern Greenland's mostly vertical tidewater glaciers (Figure 4). Furthermore, SMR varies spatially due to the presence of features such as channels originating from features in the bedrock near the grounding line or localized subglacial discharge – such as those observed under the floating ice tongues of Nioghalvfjerdsfjorden/79 North [Seroussi et al., 2011], or Petermann [Rignot and Steffen, 2008], as well as for glaciers with smaller tongues such as Jakobshavn [Motyka et al., 2011].

(b) *Oceanic properties and circulation* – Both the heat and at least part of the turbulence that modulates the SMR depends on the 'ambient water' properties and circulation, i.e., the waters near the glacier, which the plume progressively entrains. SMR studies typically focus on the temperature of these waters as the main controlling factor, but other parameters including the stratification, which can limit the vertical extent of the plume [Straneo et al., 2011; Huppert and Turner, 1980], and the circulation (including tides, wind-forcing, shelf-driven exchanges), which can supply turbulent kinetic energy, can also have a first order effect on the plume and SMR.

(c) *Subglacial discharge of surface melt and basal melting* – Surface melt water delivered to or near the grounding line depth by the glacier's hydrologic system as well as basal melt water can strongly influence the behavior of the upwelling plume and therefore of the SMR [Andersen et al., 2010; Jenkins, 2011; Rignot et al., 2010; Xu et al., 2012]. In Greenland, recent data show that the seasonality of the subglacial discharge can have a large impact on the distribution of properties near the glacier and, by inference, on the SMR [Straneo et al., 2011; 2012]. A similar scenario likely occurs for glaciers in Alaska [Motyka et al., 2003] and marine terminating glaciers at low latitudes. It is likely not important in Antarctica where surface melting has been limited so far.

2.3.2 Variability of the ice mélange or land-fast sea ice in front of the glacier

Changes in the ice mélange found at the edge of many of Greenland's calving tidewater glaciers (Figure 4a) can affect the rate of calving and hence the glaciers' stability [Amundson et al., 2010]. In some places, the mélange is ephemeral and its removal may be responsible for seasonal acceleration of outlet glaciers [Howat et al., 2010]. In other places the mélange is permanent with a seasonally varying rheology. The presence of a 'solid' boundary at the surface near the ice can affect the circulation of sub-surface waters (and thus SMR) by damping externally forced fjord circulation [e.g., MacAyeal et al., 2012] or by reducing the dynamic and thermodynamic forcing of the ocean near the glacier front. For marine terminating glaciers with a long floating ice-tongue, the presence of land-fast sea ice at the glacier's front (Figure 4b) can similarly impact calving, and has been indicated as a potential trigger of glacier instability [e.g., Reeh et al., 2001].

The buttressing of the glacier's calving front provided by the ice mélange or sea ice is likely to depend on:

(a) *Ice properties* – Including thickness, extent to which the sea ice is land-fast, and susceptibility to break up.

(b) *Atmospheric mechanical or thermodynamic forcing* – Thermodynamic forcing from above (surface heating) as well as mechanical forcing by wind, including katabatic winds, likely have a first order impact on the stability of the ice mélange or sea ice.

(c) *Oceanic mechanical or thermodynamic forcing* – It is likely that thermodynamic forcing from below (e.g., by warming surface waters) as well as mechanical forcing (waves and currents) has a first order impact on the stability of the ice mélange or sea ice. Some of the ocean forcing is indirectly due to the glacier and includes the impact of calving on the ocean (and hence the ice mélange/sea ice) and the impact of subglacial discharge (e.g., via its impact on turbulent plumes at the ice-edge).

2.3.3 Increased crevassing, calving, and reduced structural coherence and strength due to surface warming and increased surface melt

Unlike initially thought, recent studies suggest that enhanced lubrication at the bed, from increased surface melt, is likely not a major player in the retreat of the fast flowing glaciers [Joughin et al., 2008b; Nick et al., 2009; Schoof, 2010]. Instead, increasing evidence from both modeling and observations [Phillips et al., 2010; Van der Veen et al., 2011; Colgan et al., 2011] show that crevassing associated with basal and lateral shear, along with enhanced surface melting that provides melt water to fill crevasses, leads to a weakening of lateral shear. This weakening mechanism has several aspects that include cryo-hydrologic warming of subsurface ice due to presence of melt water in crevasses; structural weakening of ice due to melt water runoff; changes in subglacial hydrological system due to delivery of the surface melt water to the bed. Combined effects of the reduction in the lateral shear with delivery of surface melt water to the bed through crevasses and fractures are neither apparent nor well understood. Weakening of the lateral shear results in ice flow acceleration. Additional melt water delivered to the bed may result in ice flow deceleration [e.g., Schoof, 2010; Sundal et al., 2011; Hoffman et al., 2011]. The connection between calving activity and climate forcings is not a straightforward one [Post et al., 2011].

A comprehensive description of calving remains a glaciological challenge. It plays a crucial role in both direct ice loss at the terminus and indirect effects on inland ice flow acceleration (Nick et al., 2010; Vieli and Nick, 2011). In addition to ongoing efforts to establish a "universal calving law", i.e., a law that describes episodic calving of large tabular icebergs from Antarctic ice shelves and more or less continuous calving of smaller icebergs from Greenland outlet glaciers (e.g., Benn et al., 2007;

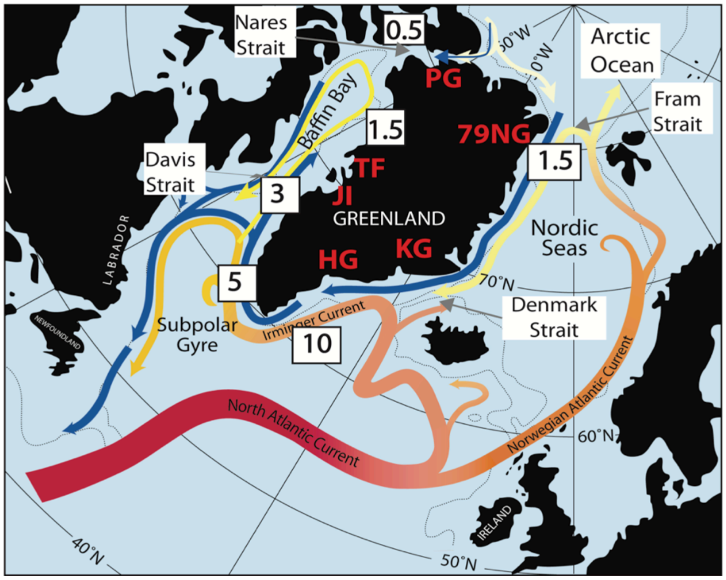

Figure 5. Schematic circulation of warm Atlantic (red to yellow) and cold Arctic (blue) water masses around Greenland. Numbers indicate the mean temperature (°C) of the Atlantic water on the shelf (from Straneo et al., 2012).

Amundson and Truffer, 2010; Bassis, 2011) efforts of all kinds (observational, theoretical, experimental, modeling) have to be made to develop understanding and, if possible, parameterizations of tidewater and outlet glaciers calving.

2.4 Oceanic Forcing of Greenland's Glaciers

Greenland's large outlet glaciers terminate in fjords which are typically 5-10 km wide, ~100 km long and hundreds of meters deep. These fjords connect the ice sheet margins to Greenland's continental shelf, where cold waters of Arctic origin flow along side (or above) warm waters of Atlantic origin (Figure 5). A review of limited data from major glacial fjords around Greenland shows that these contain cold, fresh Arctic waters in the upper layer and warm, salty Atlantic waters at depth. As for the shelf, the properties of the Atlantic waters in the fjord vary depending on the nearby oceanic basin [Straneo et al., 2012]. Specifically, the warmest Atlantic waters (2-5°C) are found in Southeast and Southwest Greenland, and are fed by the North Atlantic's Irminger Current and its extension into Baffin Bay. The next warmest waters (~1.5°C) are found in Northeast Greenland, and are fed by the Norwegian Atlantic Current and the branch which retroflects in Fram Strait. North and Northwest Greenland's fjords are fed by Atlantic water that has circulated all around the Arctic Ocean with temperature around 0.5°C. The circulation of the deeper Atlantic waters is facilitated by the presence of deep troughs which steer the warm water across the shelf [Sutherland and Pickart, 2008] and by the fact that most of these fjords have sills well beneath the Atlantic/Arctic water interface, which only minimally constrain the inflow of the Atlantic Water, unlike smaller glacier/fjord systems ([e.g., Mortenson et al., 2011]).

An analysis of the water properties from the fjords suggests that melting is primarily driven by the warm Atlantic waters [Johnson et al., 2011; Straneo et al., 2012; Rignot et al., 2012] and influenced seasonally (and potentially on shorter time scales) by subglacial discharge at depth [Straneo et al., 2011; Xu et al., 2012]. The surface layers of the fjord are warm in summer, due to surface heating [Murray et al., 2010; Christoffersen et al., 2010] but it is unclear whether these warm waters reach the glaciers and affect the ice mélange or sea ice.

In terms of dynamics, the circulation inside the fjords and at the ice edge are likely to be influenced by the large density and temperature contrast between the Arctic and Atlantic waters [e.g. Straneo et al., 2011] as well as by a number of externally driven flows [Sutherland and Straneo, 2012; Mortensen et al., 2011]. These, in turn, are likely driven both by local winds and shelf processes and it is unclear how they interact with the slower circulation driven by melting and subglacial discharge from the glacier [Motyka et al., 2003; Rignot et al., 2010]. Coupling of these different externally forced modes may, for example, provide the turbulent kinetic energy for submarine melting at the ice-ocean interface.

Moving farther away from the ice/ocean boundary towards the open ocean, the ambient properties in the fjord are controlled by continental shelf/fjord exchanges and by shelf properties. The former are controlled by local wind events such as katabatic winds, tip jets and barrier winds [Moore and Renfrew, 2005; Klein and Heinemann, 2002], as well as coastally trapped waves, eddies and other variable shelf processes. The shelf properties, in turn, are controlled by the large-scale Atlantic and Arctic coupled atmosphere-ocean variability as well as smaller-scale processes at the shelf edge [Haine et al., 2009].

The accelerating glaciers are primarily located in the Subpolar Gyre of the North Atlantic and Baffin Bay. Here, the ocean-driven hypothesis is consistent with oceanographic observations showing a generalized warming of this oceanic region roughly at the same time as the glaciers started accelerating [Zweng and Münchow, 2006; Bersch et al., 2007; Holland et al., 2008; Murray et al., 2010; Motyka et al., 2011]. The warming is primarily due to changes in the large-scale ocean circulation but, also, to decreased atmospheric forcing [Hakkinen and Rhines, 2004; 2009] both of which could have led to a warming and volume increase in the subtropical waters around Greenland.

Although there are no long-term measurements from the fjords that can confirm changes in water properties and/or circulation, some support for the ocean-driven hypothesis is found in recent paleo reconstructions. Specifically, Lloyd et al. (2011) links changes in the terminus position of Jakobshavn Isbrae over the last ~100 years to changes in water temperatures on the West Greenland shelf reconstructed from paleo-proxies. Andresen et al. (2012) links the calving activity of Helheim Glacier over the last 120 years (reconstructed using sediment cores from the fjord) to variations in several oceanic and atmospheric indices including a proxy for the properties of ocean waters on the Southeast Greenland shelf.

The bulk of Greenland's accelerating glaciers are located in Southeast and West Greenland where the warmest subsurface ocean waters flow along the coast and, also, where historical data indicate we should expect to see the largest amplitude variability [Straneo et al., 2012]. Climate model projections, furthermore, predict that this is where the most pronounced ocean warming will occur, roughly 2°C in the upper 500 m by 2100, which is almost double the global mean and much stronger than around Antarctica [Yin et al., 2011]. If oceanic variability is a trigger for glacier retreat, it is unlikely that dynamic changes in Greenland will be confined to one region. Indeed, both recent data [e.g., Schauer et al., 2004; Polyakov et al., 2004] and climate model predictions [Yin et al., 2011] indicate present and future warming of the waters in the Nordic Seas and Arctic Ocean, raising the question of whether the glaciers in northeast and northern Greenland may start to retreat in the near future.

2.5 Atmospheric Forcing at the Marine Margins of Greenland's Glaciers

Of the many impacts of atmospheric variability on the ice sheet, we focus here on the impact on the near terminus region. Key atmospheric quantities considered here are (1) surface heating (e.g., due to rising air temperatures) which will affect the amount of surface melting as well as the structural integrity of the glacier, and (2) surface wind-stress which can affect both the ocean and the glacier in the near terminus region.

(a) *Surface heating* – Changes in coastal air temperatures around Greenland affect surface melting of glacial ice thereby generating meltwater and also, potentially, modifying the surface roughness, and hence the albedo, and the glacier structure [Cathles et al., 2011]. Increased surface melt water can lead to enhanced crevassing and calving (and as a result glacier retreat), but also it will increase the subglacial discharge delivered to the base of the glacier, which – as indicated above – can affect submarine melting and/or the ice mélange or sea ice in front of the glacier.

(b) *Surface stresses* – Greenland's high orography generates strong wind forcing in the form of barrier winds, katabatic winds, tip jets, etc. (e.g., Moore and Renfrew, 2005). These result in strong variations in wind speeds and heat fluxes (e.g., Vage et al., 2009). In turn, these phenomena have the potential to strongly affect the coastal region near the glacier as well as the glacier's margins. Such wind stress variability has numerous effects on coastal currents and fjord dynamics as well. Consequent changes affect mélange dynamics and characteristics (e.g., Walter at al., 2012) as well as glacier terminus dynamics.

2.6 Summary

Recent dynamic mass losses from the GrIS are primarily due to the retreat of tidewater glaciers, such as Helheim (Figure 3), Kangerdlugssuaq Glaciers and Jakobshavn Isbrae, following a perturbation at the marine terminus. Three trigger mechanisms have emerged as leading hypotheses (Figure 4):

1. Increased submarine melting at the ice/ocean interface;
2. Reduction or weakening of the ice mélange in front of the glacier;
3. Increased crevassing and reduced structural coherence and strength due to surface warming and increased surface melt.

The proposed mechanisms are supported by the observed ocean warming off southeast and western Greenland [Holland et al., 2008; Bersch et al., 2007; Zweng and Münchow, 2006] and the general warming of air temperatures around coastal Greenland [Box et al., 2006]. Warming of the ocean waters (or increased heat transport to the glaciers) could conceivably drive an increase in submarine melting and/or a decrease in the ice mélange (mechanisms #1 and #2). Warming air temperatures could drive a change in the ice mélange through melting from above (#2), an increase in crevassing (#3), and also an increase in submarine melting at the ice-ocean interface due to increased subglacial discharge (#1). Limited data from the marine margins and a poor understanding of how changes in the ocean or atmosphere impact Greenland's glaciers make it difficult to establish the actual chain of events that lead to glacier retreat.

In terms of submarine melting, recent surveys of the glacial fjords have shown that these contain enough warm Atlantic waters to melt significant amounts of ice. Yet the temporal and spatial distributions of the melt rate depend on the details of the circulation at the ice edge which, in turn, is likely influenced by a number of glaciological parameters (including the ice edge slope and the subglacial discharge of melt water), oceanic processes (including tides, fjord modes, shelf-fjord exchange and large-scale oceanic variability), and atmospheric forcing such as local or regional winds). Until these connections are clarified, one cannot predict how melt rates may vary in response to large scale oceanic and atmospheric variability.

In terms of the ice mélange, recent studies suggest that it can affect the rate of calving and, hence, glacier stability. Yet the extent to which its rigidity is controlled by mechanical (e.g., wave action, katabatic winds) or thermodynamic (e.g., ocean/air temperatures) processes is unclear – as is its response to climate forcing.

In terms of increased surface warming or melt and their impact on the glaciers, recent studies suggest that enhanced lubrication at the bed, from increased surface melt, is likely not a major player in the retreat of the fast flowing glaciers. Yet, a number of other mechanisms tied to increases in surface melt may act to weaken the ice and cause enhanced calving. Limited knowledge of the controls on both glacial hydrology and calving, however, make it difficult to link the glacier retreat to atmospheric changes.

In general, the oceanic, atmospheric and glaciological data from the terminus region prior to the acceleration are scarce or non-existent, and remain so to date for many sites. From the modeling perspective, the mechanisms linking oceanic or atmospheric variability to terminus changes remain too poorly understood to be included in the models. These gaps prevent reliable interpretation of past changes and prediction of future ones.

3. Strategy and Recommendations

The gap in our understanding of the mechanisms linking climate forcings, perturbations at marine glacier margins, and their dynamic responses constitutes a major obstacle to reducing uncertainties in Greenland's projected mass change, its contribution to SLR, and its impact on the climate system. Progress on this problem must be achieved both by facilitating research within each discipline (to provide the appropriate input to the coupled ice/ocean/atmosphere system), and by promoting cross-disciplinary research which addresses the fully coupled system. This document primarily focuses on the cross-disciplinary approach since this is unlikely to occur without a concerted effort by the scientific community and the funding agencies.

A cross-disciplinary and multi-faceted approach is needed, combining fieldwork, remote sensing, long-term observations, laboratory experiments, modeling, data analysis and synthesis. It requires the development of existing systems as well as the establishment of new systems in a number of spheres:

- **Methodology**: new approaches, theories, numerical methods to study ice/ocean coupled system at various spatial and temporal scales;
- **Technology**: new methods and instrumentation systems (e.g., capable of monitoring ice and sea-water properties in harsh environments on a continuous basis);
- **Human**: close collaboration between diverse communities of scientists, (oceanographers, glaciologists, sea ice and atmospheric scientists, observationalists, theoreticians and numerical modelers) and across international borders; and
- **Organizational**: proposal review and project coordination among the funding agencies may unleash a leveraging effect, especially in terms of field campaign coordination; this is particularly the case on an international level where no obvious field coordination mechanisms exist.

To move forward we propose three distinct scientific approaches: 1) process studies targeting specific dynamic regimes; 2) long-term monitoring of key systems in Greenland; and 3) inclusion of the dynamics into Earth System Models.

3.1. Process Studies Targeting Specific Dynamic Regimes

The goal of these studies is to identify and understand the relevant processes *and* develop/improve parameterizations for those processes that cannot be resolved in models. Past Climate Process Team (CPT) studies initiated by U.S. CLIVAR may serve as models for organizing such studies. Several of these processes are not Greenland-specific, and, as such, can also be addressed in other settings including Alaska, Patagonia and Antarctica, where accessibility, isolation of the processes or other factors may provide more advantageous conditions. At the same time, some processes that are relevant in Greenland are also relevant to other marine terminating glaciers.

3.1.1. Ice/ocean boundary layer and plume dynamics

Key measurements and modeling of the turbulent processes and their controls are needed to estimate submarine melt rates and develop appropriate melt rate parameterizations. The ice/ocean boundary layer is thought to be dominated by a rising, buoyant plume whose characteristics regulate the melt rate [e.g. Jenkins, 2011]. Basic questions relate to how ice roughness, ice base slope, subglacial discharge, fjord circulation and other local forcings influence the dynamics of the buoyant plume, the turbulent mixing, the circulation and the submarine melt rate (SMR) at the ice/ocean interface. Direct observations of the plume as well as plume-resolving simulations are needed to develop parameterizations to be used in models. Testing existing and new parameterizations by combining direct SMR observations with theory (in the field, the lab, or models) is critical to assessing their validity. Coupled ice/ocean simulations linking plume dynamics to the SMR and the shape of the ice-ocean interface are also needed to determine feedbacks between ice front/submarine topography, plume flow and the resulting spatial variability in SMR. Prerequisite for a correct plume representation is knowledge of the subglacial discharge, including flux, size and location of drainage channels and temporal variability in those properties.

3.1.2. Fjord circulation and exchanges with the continental shelf

Integrated observational, modeling and data analysis efforts are needed to understand how the fjord and shelf dynamics impact properties at the ice/ocean boundary including the sea ice and/or the ice mélange. Large-scale ocean general circulation models are unlikely to resolve the fjord scales (except in nested form or through the use of unstructured grid techniques), so parameterizations of fjord processes that can be used in coupled climate models will need to be developed. Critical to any fjord/shelf modeling is having an accurate fjord and shelf bathymetry. A recent effort shows how these can be constructed, and made publically available, by pooling data collected from multi-disciplinary and international groups (e.g. Schjoth et al., 2012). Meteorological data around Greenland is available from a network of DMI stations and from the Greenland Climate Network. Observational strategies will vary greatly depending on whether the fjord is covered by a floating ice tongue or not. Establishing commonalities and differences in the fjord/shelf dynamics for the large ice tongues in northern Greenland compared with the rapidly calving glaciers in the south is also key to understanding all regimes of fjord/glacier systems. Furthermore, the role of the ocean may change depending on the corresponding oceanic basin since these are characterized by different properties and variability [Straneo et al., 2012]. In general, the ensemble of oceanic processes that control properties at the edge of the ice still need to be fully understood. It is unclear, in particular, if satellite derived products (such as SST on the shelf) are representative of the variability of ocean properties at the ice-edge.

3.1.3. Glacial hydrology

Knowledge of the supraglacial, englacial and subglacial hydrology, including discharge of freshwater into the fjord environment, is key to our understanding of ice flow, submarine melt rate and plume dynamics. Efforts are needed to link both the ice and water drainage regimes of an outlet glacier to hydrological processes (i.e., glacier sliding) within the catchment area feeding that glacier. In addition, links between glacial hydrology and the local atmospheric forcing need to be understood. Regional snow/ice models forced by atmospheric reanalyses/models need to be evaluated with *in situ* observations of both atmospheric and melt conditions.

3.1.4 Glacier dynamics

Process studies need to address the transition in ice flow from large catchment basins to narrow outlet glaciers, in order to understand how the changes in stress-distribution and large-scale bed geometry influence the flow of ice and its supply to the terminus. High-resolution bedrock topography beneath outlet glaciers and their catchment basins are therefore crucial. Models need to be evaluated against observations to ensure that the inland effects of marginal thinning and acceleration are not over- or underestimated. Another key focus should be to understand the physics of the ocean interactions (thermodynamic and mechanical) with grounded and floating ice. These process-oriented studies require combined approaches: theoretical, laboratory, field and modeling studies. Knowledge acquired in these studies has to be synthesized and evaluated by regional (specific outlet glacier) models. Such models need to include adequate representations of physical processes (e.g., surface- and subglacial hydrology, calving, crevassing, non-traditional rheology).

3.1.5 Calving

Calving plays a crucial role in both ice loss at the terminus and (indirectly) on the acceleration of inland ice flow but its description remains elusive. In addition to ongoing efforts to establish a “universal calving law”, i.e., a law that describes episodic calving of large tabular icebergs from Antarctic ice shelves as well as quasi-continuous calving of smaller icebergs from Greenland outlet glaciers, efforts of all kinds (observational, theoretical, experimental, modeling) are necessary to develop a full understanding and realistic parameterizations of glacier calving.

3.2 Long-term Monitoring of Key Systems in Greenland

Understanding the time-evolving relationship between climate forcings, perturbations at the ice/ocean interface, and the responses in terms of glacier flow and mass loss is impossible without long-term monitoring. To complement the process-oriented studies, therefore, essential variables should be collected on a quasi-continuous basis at a few key sites around Greenland. These measurements should capture glacier flow, local meteorology, oceanic conditions near the glacier front, in the fjord and on the continental shelf, and ice mélange conditions, to the extent possible. Data collected should also provide a measure of the heat and freshwater transport into and out of key fjords to enable budget analyses and provide boundary conditions for the ocean general circulation models (GCMs). These data will provide invaluable context for the study and validation of the linkages between key processes operating at vastly differing scales. Unlike in Antarctica, where the ocean has access to almost the entire ice sheet perimeter, a monitoring system that can effectively measure the overall oceanic controls on ice sheet-wide mass balance may actually be feasible for Greenland, where the majority of the drainage across the marine margins is confined to a small number (~10) of major outlet glacier/fjord systems.

We recommend that the following criteria be used to guide the choice of monitoring sites:

1. **Oceanic basins** – The oceanic and atmospheric forcing on glaciers varies depending on the geographic location; therefore monitoring sites should cover the different basins.
2. **Range of glacier types** – Both tidewater and floating ice tongue glaciers should be included.
3. **Proximity to oceanic monitoring sites** – Glacier sites should be close to existing large-scale oceanic monitoring stations (e.g., AON, ASOF, OOI, THOR), which will provide context and a link between the far-field ocean and the regional oceanic variability.
4. **Proximity to atmospheric monitoring sites** – Glacier sites close to existing atmospheric stations (e.g., the DMI network, Greenland Climate Network) will offer context for the regional atmospheric variability and the possibility to link this with glacier activity.
5. **Access** – Chosen sites should be accessible long-term at reduced costs. Proximity to inhabited regions and/or regularly serviced regions is highly desirable.
6. **Local synergy** – Links to local activities (e.g., those of the Greenland Climate Research Centre) and integration with complementary scientific studies (e.g., changes in local ecosystems) will leverage their utility to address a broader range of questions and potentially directly benefit the local people.

A monitoring system should include both *in-situ* as well as air- and space-borne components. Essential variables include ice elevation, mass balance and flow speed, ocean temperature and salinity, and sea ice conditions. Regional Arctic/subpolar gyre high-resolution atmospheric and ocean re-analyses are needed to constrain surface and lateral boundary conditions.

Space- and airborne data, such as laser and radar altimetry, SAR interferometry, gravimetry, and optical sensors, provide valuable information to constrain many of the controlling processes because of their broad spatial and temporal coverage; recommendations are sought targeting specific measurements (e.g., detailed bathymetry of key outlet glaciers and fjord systems, ice velocity and thickness changes). While NASA's Operation IceBridge furnishes some of these variables and bridges a gap in ice sheet observations between ICESat-1 and ICESat-2, sampling velocity changes at sufficiently high temporal resolution will not be possible without NASA's DESDynI mission (a top-tier mission of the National Research Council's 2007 Decadal Survey, but currently on hold).

An ice-sheet-wide observing system sustained over decadal timescales, while ambitious, might be within reach through a closer coordination of the international scientific effort already focused on Greenland outlet glaciers, fjords, and adjacent Arctic and subpolar seas, some investment in key science infrastructure (oceanographic moorings, weather stations, GPS networks, etc.), and pooling of the available logistical infrastructure. Complementing the monitoring program, a compilation and evaluation of relevant geochemistry and paleo-proxy information should provide extremely valuable context of long-term outlet glacier evolution. A whitepaper by Mix et al. [2012] discusses the specific needs to gather new key paleo-proxy records and exploit existing ones.

3.3 Synthesis of the Results into Earth System Models

Results of process-oriented studies and observations collected in targeted campaigns and by long-term monitoring systems have to be integrated into large-scale circulation and Earth-system models in several ways including (but not limited to) the following:

3.3.1 Physically based parameterizations of unresolved processes

With characteristic widths on the order of few kilometers, comprehensive representation of the dynamics of Greenland outlet glaciers and fjords (at spatial resolution on the order of 100 m or less) is beyond the capabilities of large-scale climate models, currently operating at 100 km grid spacing. Key physical processes identified and explored in the process studies need to be incorporated into global circulation and Earth system models using a suite of parameterization techniques. This will require new developments in the ice, ocean, atmosphere and sea ice physical parameterizations and numerical methods capable to implement them in a computationally efficient manner. A close cross-disciplinary collaboration has to be established to ensure progress.

3.3.2 Data assimilation and parameter optimization constrained by observations

The margins of the GrIS and its adjacent seas remain strongly under-sampled. A large range of parameters required for simulations of glacier and ocean dynamics cannot be determined through direct observations for a number of reasons (e.g., technological and logistical). Drawing on experience from ongoing oceanographic data-assimilation efforts (e.g., the "Estimating the Circulation and Climate of the Ocean" – ECCO project) and in parameter inversion efforts within the ice sheet-modeling community (e.g., optimization for ice basal drag parameters), 'cross-pollinating' activities between different scientific communities have to be established to ensure the most efficient data use in models. New methodologies capable of assimilating data of diverse nature and from a variety of sources in a meaningful way need to be developed or shared across disciplines. All these efforts will require development of comprehensive, well-structured and sophisticated databases and data formats to allow rapid access and optimal use of the hard-won data. Maintaining and distributing these data sets will require adequate data management infrastructures, a task best taken on by experienced data centers (e.g., NSIDC, NODC).

3.3.3. Coupling of the various components of the Earth System Models

Representing feedbacks between GrIS variability and the large-scale ocean/atmosphere circulation or other climate system components, requires interactive (two-way) coupling between ice sheet and climate models or components thereof. Although there are several ongoing efforts to develop such Earth system models, no such fully-coupled model currently exists that captures the processes relevant on decadal to centennial time scales. The ongoing coupling efforts are uncovering numerous hurdles that must be overcome. The nature of these obstacles is diverse – from fundamental assumptions of various modeling components (e.g., fixed boundaries in atmospheric and ocean GCMs *vs.* evolving boundaries in the ice sheet models), to disparity of the characteristic temporal and spatial time scales (e.g., minutes to hours for atmospheric GCM *vs.* days to years for ocean GCMs *vs.* decades to millennia and beyond for ice-sheet models). In order to make progress, a closer interaction between the different communities involved and the model developers needs to be established. Given the multitude of disciplines involved, the emergence of a new generation of scientists with a cross-disciplinary background would greatly benefit this problem.

3.3.4 Model testing, analysis and intercomparison

The hierarchy of modeling approaches described above is required as a quantitative basis for model assessment, identification of systematic biases and guiding of future observing systems. The hierarchy covers small-scale process modeling for the purpose of developing parameterizations for inclusion into large-scale Earth system models, to model-data synthesis frameworks to integrate available observations with models, both small-scale and global-scale. A feedback loop is needed to link on the one hand large-scale model-data misfits or biases, e.g., subpolar gyre hydrographic properties, to those at key locations (fjord exits and glacier termini), and on the other hand the discrepancies of parameterized versus observed fjord properties. All of these ultimately affect fjord/glacier systems and the GrIS response.

Observing system studies are required to assess which processes have the strongest impact on constraining ice mass loss, and where, with what accuracy, and at which frequency these should be sampled. In conjunction with synthesis/data assimilation systems this can be achieved through observing system simulation experiments (OSSEs). The large scale-small scale and observation-model feedback loops should ultimately point to more targeted field campaigns to close the major gaps in linking process understanding and climate model representation. The synthesis/data assimilation systems also provide suitable frameworks for quantifying uncertainties in the link between climate forcings of the glaciers on the one hand and glacier responses on the other hand.

3.4 Interagency and International Program Coordination

U.S. funding agency program support by NSF, NASA, NOAA and DOE of oceanographic, atmospheric, hydrologic, and cryospheric research has been critical to the current scientific understanding of the response of Greenland's glaciers to oceanic and atmospheric forcing outlined in this paper. Not only is continued agency program support crucial to addressing the gaps in our understanding, new, more highly integrated cross-disciplinary opportunities for research are needed to address the coupled system more completely.

A number of international groups already have field programs in different parts of Greenland investigating various aspects of ice/ocean interaction. In numerous occasions, efforts are duplicated due to lack of coordination and communication between groups. In order to make research activities more efficient and productive, we recommend creation of an international, community-based platform with specific focus on research in Greenland. The primary goal of such organization is to facilitate coordination and interaction of various research groups. As experience of the recent International Polar Year shows, highly focused and well-coordinated efforts have high payoffs [Polar Research Board, 2012]. Establishing connections with existing programs and committees (e.g., CLiC, AMAP/SWIPA, SeaRISE, AON/ADI, ARCUS, U.S. AMOC, SEARCH) will facilitate collaboration and coordination of research efforts among scientific communities.

4. Conclusions

This document provides clear evidence that understanding of ice-sheet/ocean interactions is a fundamental requirement for providing realistic projections of Greenland's future behavior over decadal-centennial timescales, which, in turn are key to reducing uncertainties in sea level rise projections and freshwater discharge into the climate-sensitive North Atlantic and Arctic Oceans. Critical aspects of Greenland's coupled ice-sheet/ocean system are identified, and a research agenda is outlined which will yield fundamental insights into how the ice sheet and ocean interact, their role in Earth's climate system, their regional and global effects, and probable trajectories of future changes. Key elements of the research agenda are focused process studies, long-term monitoring efforts at key sites and inclusion of the relevant dynamics in Earth System Models. Cross-disciplinary and multi-agency efforts, as well as international cooperation, are crucial to making progress on this novel and complex problem. Integration of this new knowledge into a comprehensive picture of the coupled North-Atlantic/Arctic/Greenland ice sheet system will be a significant step towards fulfilling the goal of credibly projecting sea-level rise over the coming decades and century.

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