The need to address ice sheet/ocean interactions in Greenland

By GRISO – U.S. CLIVAR Working Group on Greenland Ice Sheet/Ocean Interactions

F. Straneo, P. Heimbach, O. Sergienko, C. Bitz, D. Bromwich, G. Catania, R. Hallberg, G. Hamilton, A. Jenkins, I. Joughin, S. Price, E. Rignot, M. Spall

Mass loss from the Antarctic and Greenland ice sheets increased rapidly over the last decades and now accounts for roughly one-third to one-half of sea level rise [Milne et al. 2009; Cazenave and Llovel 2010; Church et al. 2011]. Much of the increased discharge is attributed either to enhanced surface melting in Greenland or to retreat of the grounded ice in both Greenland and Antarctica. This was not predicted by ice sheet models which, mostly, do not represent ice dynamics adequately. Indeed this shortcoming was identified as *the* largest source of uncertainty in sea level rise projections in the latest IPCC AR4 report [Solomon et al. 2007; Lemke et al. 2007]. For each ice sheet the changes were spread across wide areas and multiple glaciers or ice streams, but mostly confined to their marine margins, suggesting a common larger-scale regional driver – e.g. atmospheric and/or oceanic variability. Amongst those proposed, one plausible trigger is increased submarine melting at the ice/ocean interface due, for example, to warming ocean waters [Payne et al., 2004; Bindschadler 2006, Thoma et al., 2008]. The widespread lack of data from the ice/ocean boundary, our limited understanding of the processes involved, and their crude representation (or absence) in ice sheet models, however, makes it difficult to test this hypothesis, and to determine what role submarine melting changes may play in future ice sheet variability. This situation is exacerbated in Greenland, since what little is known about ice sheet/ocean interactions applies to Antarctica – where these processes have been studied for a longer time. However, that knowledge cannot be directly applied to Greenland marine terminated glaciers. There are major differences in the ice/ocean environment at the two poles: the coastal configuration, the ocean circulation, the degree of surface melting, the shape of outlet glacier termini vs. floating shelves, etc. Thus, Greenland ice sheet/ocean interactions need to be addressed specifically.

A U.S. CLIVAR Working Group on GReenland Ice Sheet Ocean interactions (GRISO), composed of representatives from many of the disciplines involved and supported by various funding agencies (including NSF, NASA, NOAA, DOE), was established in December 2010 to address this gap. Its goals are to promote interaction between the diverse communities, to develop research strategies and recommendations, and, through this, to advance our understanding of the relevant processes and improve their representation in models. Here, we present a synthesis of the GRISO efforts aimed at 1) summarizing the present state of knowledge, 2) identifying the most pressing questions, and 3) making initial recommendations on how to move forward on this problem.

The doubling of mass loss from the Greenland Ice Sheet (GrIS) over the last decade [Rignot and Karagantnam 2006, Khan et al. 2010] is mainly attributed to the acceleration and retreat of outlet glaciers in western and southeast Greenland [Howat et al. 2008; Stearns and Hamilton 2007]. The precise chain of events that led to the glaciers' acceleration is unclear, but evidence points at increased melting at the glacier/ocean interface ('submarine melting') as a dominant trigger of the acceleration. This is consistent with data and models indicating that the acceleration began at the marine termini of the glaciers [Pritchard et al. 2009; Sole et al. 2008; Price et al 2008; Nick et al. 2009]. The leading mechanism invoked is a reduction in buttressing to ice flow as a result of the thinning or collapse of the floating ice tongue or the calving front [Joughin et al. 2004; Thomas 2004] driven by increased subsurface melting [Motyka et al. 2011; Holland et al. 2008; Murray et al. 2010; Rignot et al. 2010]. Limited available observations indicate subsurface warming of ocean waters around southern and western Greenland at the time when the glaciers accelerated [Bersch et al. 2007; Holland et al. 2008; Murray et al. 2010; Motyka et al. 2011]. Additional support for this hypothesis comes from 100-year paleo reconstructions showing correlations between glacier retreat/calving and nearby ocean properties (Lloyd et al. 2011; Andresen et al. 2011). Thus, increasing evidence points at changes in submarine melt rates as one of the main ways in which ice/ocean processes affect outlet glaciers. While this finding is not surprising in itself – it has long been recognized that melting is important for Antarctica's broad ice shelves or glaciers in northern Greenland, where it may be the major term for mass loss (e.g. Mayer et al. 2000; Rignot and Steffen 2008) – the notion that ice sheets can respond rapidly to changes in submarine melting on inter-annual or decadal time scales, with potentially dramatic implications for sea level rise, is new and warrants attention.

The picture is complicated, however, by numerous competing hypotheses concerning increased glacier flow, which have been formulated over the last decade. Briefly, these are:

(1) Effects of the increased surface melting on the ice flow [Zwally et al. 2002; but see also Bell 2008; Schoof 2010; Sundal et al. 2011];

(2) Effects of the subglacial water pressure variability on ice flow [Pfeffer 2007];

(3) Weakening of lateral shear margins due to cryo-hydrologic warming of subsurface ice [Truffer and Echelmeyer 2003; Phillips et al. 2010; van der Veen et al. 2011];

(4) Hydro-fracturing and calving of the floating tongues leading to reduced buttressing [Sohn et al. 1998, Anderson et al. 2010];

(5) Seasonal stress modulation of the ice mélange and suppressed calving [Amundson et al. 2010; MacAyeal et al. 2011].

The larger subject is reviewed by Vieli and Nick [2011]. In the context of ice sheet-ocean interactions it is thus crucial that observation design for process studies and theory-testing take into account potential contributions from the listed processes.

With a main focus on the problem of submarine melting-induced increase in glacier flow and mass drainage, the GRISO working group addresses two related questions:

1) What local and regional factors control the submarine melt rate, including its spatial and temporal distribution?

2) How can this information be used to provide appropriate boundary conditions to ice sheet/glacier models?

Submarine melting occurs when excess heat is present at the ice/ocean interface, and is controlled by variety of processes occurring on molecular to ocean-basin scales. Models and observations typically do not resolve the smaller scales and parameterizations of the turbulent heat and salt transfer at the ice-ocean boundary are used to link melting with the larger scale fields [e.g. Hellmer and Olbers 1989; Holland and Jenkins 1999]. In these parameterizations, 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 thought to be dominated by a melt-water, buoyant plume rising at the ice edge [Jenkins 1991]. Unlike for Antarctica, where the plume is mostly governed by submarine melting, recent studies suggest that in Greenland the subsurface discharge of the extensive surface summer melt is a major driver of the upwelling plume [Jenkins 2011; Straneo et al. 2011]. The implication is that increasing air temperatures and the resulting increase in surface melt could lead to an increase in SMR during summer even if the ocean conditions are unchanged. The question arises as to which (if any) of these processes dominates the plume dynamics.

One further complication in estimating local SMR concerns its spatial variability. Localized subglacial discharge or features in the bedrock near the grounding line can result in channels which may continue to grow if the melting becomes concentrated in them. Such channels have been observed in glaciers with a substantial floating ice tongue, e.g., at Nioghalvfjerdsfjorden/79 North [Seroussi et al. 2011], or Petermann [Rignot and Steffen, 2008]. In general, the topography under the ice affects the plume structure and the SMR. At present this effect is barely, if at all, represented as a drag coefficient in the turbulent flux parameterizations.

On the ocean side, the plume's properties depend on the 'ambient waters', i.e. the waters near the glacier, which it 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, etc…), which can supply turbulent kinetic energy, can also have a first order effect on the plume and SMR. In Greenland, the relevant ambient waters are those at the head of the deep, long fjords where the major tidewater glaciers are grounded hundreds of meters below sea level. These fjords were virtually unexplored prior to the glaciers' acceleration, but recent surveys have revealed a commonality of features. Mostly, the fjords associated with the major glaciers have no sills or deep sills. This means that the exchange with the continental shelf occurs over a thick layer and involves both the upper, cold, fresh Arctic waters and the deeper, warm, salty waters present on the shelf [Azetsu-Scott and Tan 1997; Holland et al. 2008; Johnson et al. 2011; Straneo et al. 2010]. The large density and temperature contrast between these waters affects the plume structure and dynamics, and likely contributes to a SMR which varies greatly with depth [Straneo et al. 2011]. Recent synoptic and moored observations show that the fjords are characterized by fast, sheared flows, highly variable in time, by multiple overturning cells, by slower tides, and by even slower estuarine-like modes [Sutherland and Straneo 2011; Mortensen et al. 2011] that are driven by a combination of local winds, glacier and shelf processes. The extent to which these flows affect the plume, the properties near the glacier, or provide energy for turbulent mixing at the ice-ocean boundary layer remains unclear.

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 strongly controlled by strong 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 latter is likely controlled by the large-scale Atlantic and Arctic coupled atmosphere-ocean variability. The recent warming of waters on the SE and W shelves [Holland et al. 2008; Murray et al. 2010; Motyka et al. 2011], for example, was likely due to a slow-down of the subpolar Atlantic circulation driven by large-scale atmospheric changes [Hakkinen and Rhines 2007/2009]. A recent study suggests that variability in the Arctic export also influences the shelf and through it glacier activity [Andersen et al. 2011]. The presence/absence of sea ice in the fjord and/or on the shelf may modulate each of the considered processes.

On the glacier side there are numerous unresolved questions. Dynamic and thermodynamic effects of the increased SMR on glaciers with substantial floating tongues (e.g., 79 North and Petermann) are clearly different from those effects on glaciers with no or seasonally developing tongues (e.g., Jakobshavn, Amundson et al, 2010). Understanding these effects on either of these systems (with and without floating tongues) is far from complete. The differences lie in the perturbation of the stress-balance either across the ice front (in case of the glaciers with seasonal or no floating tongues), or at the lateral margins (in case of the large floating tongues). Additionally, in the latter case, SMR could significantly affect locations of the grounding line, with the potential of triggering a Marine Ice-Sheet instability (note that the Northeast Greenland Ice Stream, and some outlet glaciers at other locations are partially grounded below sea level). Despite existing studies (e.g., Price et al 2008, Nick et al, 2009) which have tried to address questions of the upstream propagation of the stress perturbations at the glacier terminus, questions remain, and detailed theoretical and modeling studies are urgently needed. The marine-terminating glaciers in the south of Greenland are significantly more crevassed than the ones in the northern part. This presents considerable challenges to gathering field and remote sensing observations, as well as to modeling approaches. The modeling requires new approaches, different from those based on continuum mechanics. Remotely sensed data have ambiguities due to strong inhomogeneity of the ice surface.

In addition to the ocean's direct effects on glaciers through enhanced melting, indirect effects either due to extra heat delivered from the lower latitudes to the Greenland boundaries (e.g. increased atmospheric temperature, absence of sea ice and mélange) or due to mechanical impacts (increased storminess and wave activity) may promote ice loss. Currently, there are neither comprehensive assessments of these aspects of ice/ocean interaction, nor clear understanding of physical origins of these processes.

Key questions

We have shown that submarine melting is the end product of a complex chain of processes ultimately connecting the large-scale oceanic and atmospheric circulation around Greenland with small-scale processes at the ice-ocean boundary. Several key questions must be addressed to make progress on this complex problem:

1. Ice/Ocean Boundary Dynamics

Current parameterizations for the turbulent transfers at the ice/ocean interface have not been validated, largely due to the absence of direct local SMR and turbulence measurements. Validation and improvement of these parameterizations is thus a key target. A related problem is the appropriate choice of large-scale variables in these parameterizations.

2. Plume

Plume dynamics are poorly understood, under-observed, and ill-represented in models whose scales are usually much greater than the expected plume thickness. Processes including entrainment, rotational constraints and the influence of the ambient fjord circulation and properties need to be understood and included in the plume representation for a correct assessment of the oceanic boundary layer properties that influence melting.

Furthermore, there is evidence that the plume's structure and properties are highly sensitive to the characteristics of subglacial drainage, including its spatial and temporal variability, thus knowledge of these boundary conditions is key to a correct plume representation.

3. Fjord and Continental Shelf Dynamics

A suite of fjord circulations is forced at the continental shelf, by local winds and by the glacial melting and discharge. It is unclear how these interact to affect the ambient properties and circulation at the ice front – both of which influence SMR. Understanding what processes govern the leading variability and how they can be represented as a function of the continental shelf, the glacier and atmospheric forcing is key for any modeling study which will not resolve the fjord processes. In addition, cross-shelf processes must be understood in order to provide the appropriate conditions at the fjord's mouth. These are strongly influenced by local forcing, by the far field coupled atmosphere/ocean (and sea ice) variability and by the shelf bathymetry, which must include the numerous troughs present on the shelf. Understanding, resolving or representing these processes is thus key to providing appropriate boundary conditions at the glaciers edge.

4. Marine-terminated outlet glaciers without permanent floating tongue

Dynamic and thermodynamic effects of the submarine melting at the ice front are poorly understood on local and catchment spatial scales. Although advances in these directions could be done independently from the ocean circulation studies (e.g., through prescribing SMR at the glacier terminus), ultimately, they have to be based on results of the studies described in point 1 (Ice/ocean boundary dynamics). Establishing spatial and temporal scales that control propagation of the terminus perturbations upstream of the glacier to the interior of the GrIS is imperative for projections of ice mass loss and Greenland's contribution to sea level.

5. Marine-terminated outlet glaciers with permanent floating tongue

Outlet glaciers *with* floating ice tongues are arguable very different from those *without*. From an ice dynamics perspective they might resemble ice shelves in Antarctica. However, in contrast to Antarctic shelves floating into wide embayments, they are separated from the open ocean by narrow fjords, whose dynamics strongly modulates ice flow conditions. Presence of the floating tongue allows the ocean waters to reach ice masses near the grounding line where their effect on the grounded ice fluxes is stronger than near the ice front. There is a potential of the Marine Ice Sheet Instability at several locations in the northern part of Greenland. Such ice/ocean configurations (ice shelves connected by the narrow fjords) have not been studied before, and even basic understanding of these systems will make significant advances.

Strategy and Recommendations

Submarine melting is controlled by a wide range of oceanic, atmospheric, and glaciological processes. Its impact on marine terminating outlet glaciers remains poorly understood. Improving our understanding of the mechanisms involved and our ability to model them will require a cross-disciplinary and multi-faceted approach. Three strategies are highlighted here:

A. Process studies targeting specific dynamic regimes.

These should include combined field, modeling, data analysis and laboratory experiments, which should be aimed at identifying the relevant processes, their controls, and at improving/developing parameterizations for processes which are not resolved in the models. The goals of these process studies are to (a) improve our basic understanding of the ice/ocean mutual effects around Greenland, (b) develop and test skillful parameterizations for use in coupled ice sheet-ocean general circulation models, and (c) provide the connections between the ice sheet models and the climate/Earth system models. The process studies should target the following components through adequate observations and simulations:

1. Ice/ocean boundary layer – Key measurements and modeling of the turbulent processes and their controls are needed to establish the characteristics of this layer, including the ice roughness. Testing of existing and new parameterizations by combining direct SMR observations with theoretical predictions (in the field, the lab or models) is key to assessing their validity.

2. Plume – Key questions include addressing its speed, width, variability as a function of the ambient fjord and subglacial discharge forcing. Direct observations of the plume as well as plume resolving simulations are needed to develop parameterizations to be used in models which cannot resolve the relevant turbulent scales. Coupled ice/ocean simulations linking the plume dynamics to the SMR and the shape of the front are also needed to determine feedbacks between front topography. Prerequisite for a correct plume representation is knowledge of the subglacial discharge, including flux, size of drainage holes and temporal variability.

3. Fjord and Continental Shelf – Joint modeling, field, and data analysis efforts are needed to understand the shelf/fjord/plume dynamics as well as how the fjord, the shelf and atmospheric variability influence the variability in the ice mélange. Ocean general circulation models are unlikely to resolve the fjord scales (except perhaps in nested form) so parameterizations of fjord processes may need to be developed. Observational strategies will vary greatly depending on whether the fjord is covered by the floating ice tongue (e.g. 79 North, Petermann) or not. Establishing 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 covering all different systems. Furthermore, the role of the ocean may change depending on the Greenland oceanic sector which the fjord/glacier system discharges in since these different basins (Subpolar Gyre, Nordic Seas, Arctic Ocean, Baffin Bay) are characterized by very different properties and forcings.

4. Glacial Hydrology – Knowledge of the supra- and subglacial hydrology, including subglacial discharge, are key both to our understanding of glacial ice flow and to SMR predictions. Efforts are needed to link glacial hydrology regimes of an outlet glacier to hydraulic processes in catchment areas feeding that glacier. In addition, a link between glacial hydrology and the local atmospheric forcing needs to be established. Regional snow/ice models forced by atmospheric reanalyses/models have to be validated by *in situ* observations of both atmospheric and melt conditions.

5. Ice Dynamics – Process studies need to address ice flow transition from large catchment basins to narrow outlet glaciers in order to understand changes in stress-distributions and effects of large-scale variability of the bed geometry (from wide unobstructed areas to narrow outlet geometry) on the ice flow and its supply to the terminus. Another key focus

is to understand the physics of ocean effects (thermodynamic and mechanical) on grounded and floating ice. These process-oriented studies require all possible approaches: theoretical, laboratory and modeling studies. Knowledge acquired in these studies has to be synthesized and validated by regional (specific outlet glacier) oriented models. Such models need to include adequate representations of known physical processes (e.g., surface- and subglacial hydrology, calving, crevassing, non-traditional rheology).

6. Remote sensing – Space- and airborne data (e.g., from satellite altimetry or Operation IceBridge) may provide valuable information to constrain some of the listed processes because of their areal and spatial coverage; recommendations are sought targeting specific measurements (e.g., detailed bathymetry of key outlet glaciers and fjord systems).

2. Monitoring of key systems in Greenland

Until the chain of events linking SMR (and glacier variability) to the oceanic and atmospheric variability is understood – crucial data should be collected on a quasi-continuous basis at a few key sites around Greenland including glacier flow, weather data, oceanic conditions near the glacier front, in the fjord and on the shelf, ice mélange properties to the extent possible. These data will provide invaluable context for the studies above and validation of the link of the different scales. Since the atmospheric and oceanic forcing on the glaciers varies significantly depending on the oceanic basin, it is recommended that a system from each basin (Subpolar Gyre, Nordic Seas, Arctic, Baffin Bay/West Greenland) is chosen as a representative collection for Greenland. Similarly, the systems to be monitored should include a range of different glacier types and, especially, include both rapidly calving glaciers and glaciers with large ice tongues. Unlike Antarctica a proxy-monitoring system measuring controls on ice sheet-wide ice mass drainage may actually be feasible for Greenland. On the ocean side, such a system could be integrated and planned with existing ocean observing system including the Arctic Observing Network, the European Ocean Sites, ongoing long-term observing efforts at the Arctic gateways and contributions from the Ocean Observatories Initiative (where appropriate).

3. Key Ancillary Information & Methods

Several key inputs are required to make progress on this topic:

1) Outlet glacier, fjord and shelf bathymetry / bed rock topography
2) Regional Arctic/subpolar gyre high-resolution atmospheric and ocean re-analyses
3) Ice temperature measurements in logistically accessible areas
4) Internal ice-column structure from radar profiles – and in general, the role of data that is, or can be, obtained from Operation IceBridge.
5) Geochemistry & paleo-proxy information?
6) Data synthesis: Interpretation of the diverse sets of disparate observations will be a challenge and requires tools to synthesize these measurements in a coherent dynamical framework .

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