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Glacier/ocean interactions in Greenland and their impact on the climate system

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Rapid mass loss from the Greenland Ice Sheet has increased interest in glacier/ocean interactions for two reasons. First, increased submarine melting of marine terminating glaciers is a likely trigger of the observed dynamic ice loss. Second, the increased freshwater discharge from Greenland has the potential to affect the regional and large-scale ocean circulation. While extensive progress has been made, over the last decade, in understanding glacier/ocean exchanges of heat and freshwater in Greenland's glacial fjords, an in-depth knowledge of these exchanges is hindered by the models' inability to resolve the wide range of dynamical scales involved and by the fact that observations that can only provide a partial description because of the intrinsic challenges of working at the glacier margins. Specifically, major challenges remain to understand the dynamics in the near-ice zone, which controls submarine melting and iceberg calving, and the different drivers of the fjord circulation that delivers heat to the glacier. On the ocean side, much progress has been made in showing how Greenland's meltwaters are exported into the ocean in the form of highly diluted glacially modified waters whose properties depend on the details of the glacier/ocean/iceberg interaction. Major challenges remain, however, to parameterize these processes in order to provide appropriate boundary conditions to ocean/climate models.

Keywords: Glacier/ocean interaction, Greenland, glacial fjords, submarine melt, Arctic freshwater

1. Introduction

Ice loss from the Greenland Ice Sheet (GrIS) quadrupled from 1992-2001 to 2002-2011 and contributed 7.5 ± 1.8 mm to sea level rise from 1992 to 2011 (Shepherd et al., 2012). The ice loss is focused around the marine margins (Pritchard et al., 2009) and is due to a combination of changes in surface mass balance (i. e. increased net melt; Hanna et al., 2011) and dynamic changes associated with the thinning, retreat and speed-up of marine terminating glaciers (Howat and Eddy, 2011; Rignot and Kanagaratnam, 2006). While changes in surface mass balance have been largely attributed to rising air temperatures over Greenland (Box et al., 2009) and positive feedbacks associated with changes in albedo (Box et al., 2012), there is less of a consensus on the triggers for the dynamic changes (Fig. 1; Straneo et al., 2013). Amongst the likely players, however, is increased submarine (or subaqueous) melting at the marine margins of the glaciers (Holland et al., 2008; Motyka et al., 2011; Straneo et al., 2013; Straneo and Heimbach, 2013; Sugiyama et al., 2015). This hypothesized role of the ocean in driving major changes in mass loss from the Greenland Ice Sheet (GrIS) has focused interest on the heat and freshwater exchanges at the margins of Greenland's glaciers and set the stage for rapid advances in a relatively new, interdisciplinary field: 'glacier/ocean interactions'. In parallel, there is growing interest for the fate of Greenland meltwater which,

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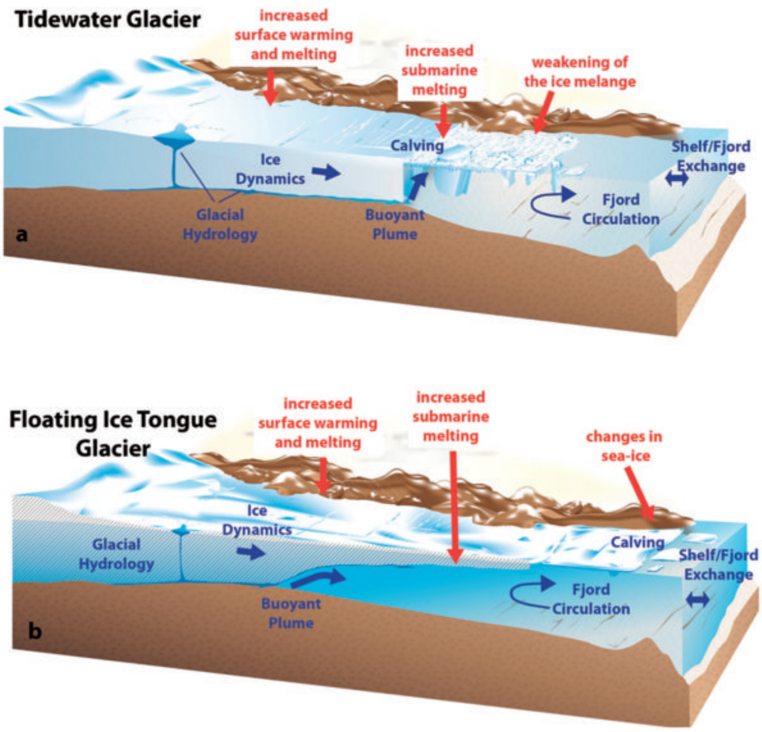

Figure 1 : Schematic of a) tidewater and b) floating tongue glaciers. The proposed mechanisms for the glacier retreat are shown in red and the key processes in blue. (Reproduced from Straneo et al., 2013.)

given the increasing discharge, has the potential to affect both the regional and large-scale ocean circulation, including the Atlantic Meridional Overturning Circulation (Boning et al., 2016; Lenaerts et al., 2015) and the regional marine ecosystems through the nutrient discharge (Bhatia et al., 2013). Given that both the ocean and air temperatures around Greenland are projected to increase over the next century, understanding glacier/ocean interactions is relevant to studies of ice sheet variability and its impact on the climate system including the biosphere. Here I summarize what we have learned over the last decade on ice sheet/ocean interactions in Greenland and outline what questions remain ahead.

2. Submarine melting of Greenland glaciers

Greenland glacier/ocean exchanges occur inside glacial fjords, which act as the connectors between the ocean waters flowing around Greenland's continental shelves and the ice sheet margins. As a result, glacier/ocean exchanges of heat and freshwater are regulated not only by the far-field ocean and glacier, but also by the ice/ocean boundary layer as well as the fjord dynamics. Key to understanding these dynamics is knowledge of the fjord's geometric characteristics including the presence of a sill, the width, the length, and the geometry of the glacier terminus. In Greenland, the terminus can vary from a floating ice tongue, similar to Antarctica's floating ice shelves, which covers most or all of the fjord (e.g. Nioghalvfjerdsbrae or 79 North Glacier) to mostly vertical glacial termini (e.g. Helheim Glacier in southeast Greenland). Depending on these characteristics (Fig. 1), the dynamics at the ice/ocean interface and within the fjord can be vastly different. In summarizing the relevant dynamics for glacier/ocean exchanges, we consider three different regions: the turbulent ice-ocean 'mixed' layer, the fjord system and the large-scale ocean. Processes within the near-ice zone regulate the exchange of heat and mass across the ice-ocean interface. The fjord dynamics supply the warm water to the glacier and export the freshwater from the fjord to the continental shelf region.

2.1 Oceanic heat content

Submarine melting is a result of a heat flux from the ocean to the glacier. Its magnitude is thus controlled by the available heat in the ocean waters next to the glacier and by the turbulent processes which affect the heat exchange across the oceanic boundary layer at the ice edge (Jenkins, 2011). The available heat in the ocean is expressed in terms of the thermal forcing, ΔT, a measure of the temperature above freezing of the ocean waters in contact with the ice:

$$\Delta T = T_a(x,y,z) - T_f(z,S),$$

where T_a is the spatially varying ocean temperature adjacent to the boundary layer and T_f is the freezing point temperature which varies mostly with pressure and weakly with salinity, S.

Ocean conditions near or under Greenland's marine terminating glaciers are largely unknown because of the challenges associated with making measurements next to the ice edge; however, some inferences can be made by considering water properties on Greenland's continental shelves and, where measurements exist, near the glaciers. Water properties around Greenland's continental shelves are characterized by the confluence of cold, relatively fresh water of Arctic origin (Polar Water, PW) carried by the East and West Greenland Currents (Sutherland and Pickart, 2008; Myers et al., 2007), and of warm, salty water of Atlantic origin (Atlantic Water, AW) initially carried poleward by the North Atlantic Current (Fig. 2; Straneo et al., 2013). Depending on the distance from their Atlantic or Arctic source, the properties within these water masses vary but, generally speaking, PW are thicker and colder along the eastern coast of Greenland and Atlantic waters are warmer in southeast and western Greenland. PW are lighter than AW due to differences in salinity and, therefore, are found closer to the surface all around Greenland. Seasonally, PW warms due to solar insolation giving rise to a third, surface water mass 'Warm Polar Water' (Beaird et al., 2015).

Ocean properties inside glacial fjords with sills deeper than the Polar/Atlantic Water interface resemble those on the nearby continental shelves, with cold PW overlying warm, salty Atlantic waters. These deep-silled fjords include all of Greenland's largest glaciers including Jakobshavn Isbrae, Helheim, Kangerdlugssuaq, Petermann and 79 North Glaciers

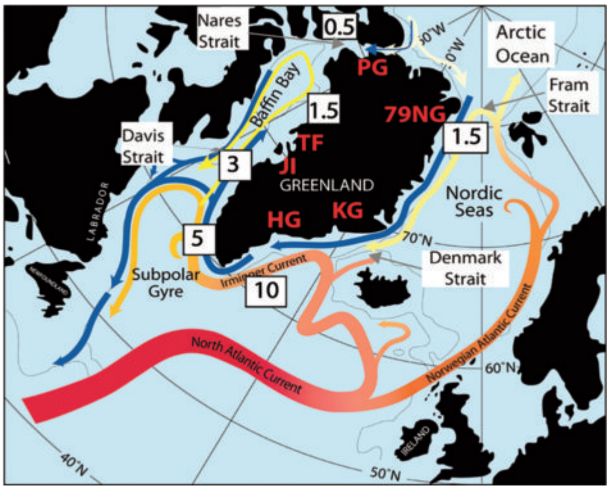

Figure 2 : Schematic circulation of warm Atlantic (red to yellow) and cold Arctic (blue) water masses around Greenland. Numbers indicate the mean temperature (℃) of the Atlantic water on the shelf. (Redrawn from Straneo et al., 2012.)

(Fig. 3; Holland et al., 2008; Straneo et al., 2010; Christoffersen et al., 2011; Johnson et al., 2011; Wilson and Straneo, 2015). For fjords whose outer or inner sills are shallower than the Atlantic/Arctic water interface, we expect the near-glacier properties to be closer to the PW layer since these sills effectively prevent the Atlantic waters from reaching the glacier (e.g. Beaird et al., 2015).

The thermal forcing defined above requires knowledge of the ocean temperature distribution along the entire glacier face, which is challenging to obtain. Instead, to compare thermal forcings for several Greenland glaciers I estimate these in two approximate ways. For the first estimate, I assume that the ocean temperature near the glacier face is horizontally uniform and vertically varying like that of the closest profile of temperature (and salinity) obtained near the glacier. For most glacial fjords this is a profile taken 5 to 80 km from the glacier face (see Straneo et al., 2012). For the second estimate, I assume that the temperature near the glacier face is uniform and equal to the temperature at the grounding line depth observed closest to the grounding line (effectively the grounding line depth temperature from the profile used in the first method). The need for these partly empirical formulations reflect the lack of appropriate data in the near-ice zone.

The results of this calculation for profiles taken close to Greenland's five largest systems are shown in Fig. 3

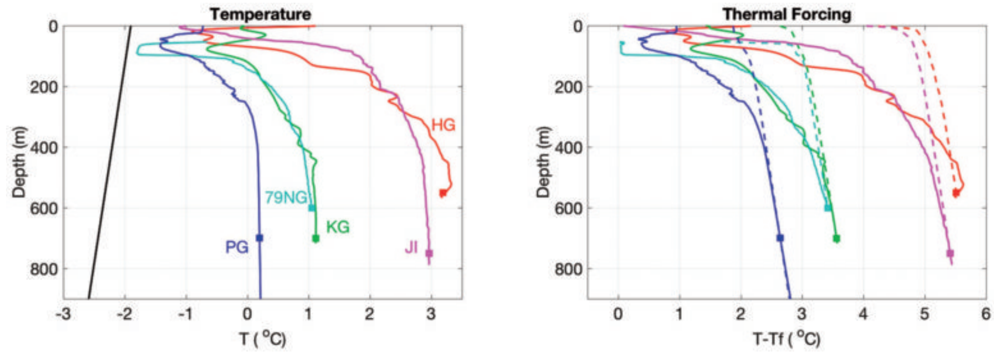

Figure 3 : Left: Temperature profiles near Greenland's largest glaciers: HG (Helheim Glacier), JI (Jakobshavn Isbrae), KG (Kangerdlugssuaq Glacier), 79NG (79 North Glacier), PG (Petermann Glacier). Black line shows freezing point temperature for constant salinity of 34.9. Right: Temperature above freezing for the 5 glaciers above for the same profile as shown in left (solid) or for a constant temperature equal to that at the grounding line depth (dashed). Squares show grounding line depths. Data described in Straneo et al. (2012).

(see Straneo et al., 2012, for a more in-depth description of the profiles). Clear from the figure is that all of these large systems are associated with maximum temperatures at depth (the AW) and that the AW characteristics vary around Greenland depending on the distance and transformation from the Atlantic source. For example, waters at Helheim Glacier are the warmest and those at Petermann Glacier are the coldest. In terms of thermal forcing, this is largest at depth both because of the maximum ocean temperatures at depth but, also, because of the decrease in the freezing point temperature with pressure. Broadly speaking, differences in thermal forcing (estimated as described above) around Greenland are largely set by the temperature of the inflowing Atlantic waters but are also sensitive to changes in the freezing point temperatures. The two methods provide fairly different results except at the grounding line (where they are forced to be equal, Fig. 3). This highlights the need to improve our understanding of what governs melt rates at the margins of Greenland's glaciers. In general, the extent to which thermal forcing alone is responsible for differences in melt rate at Greenland's glaciers, however, is unknown. Likely dynamical factors such as the flow speed, the ice topography and the ocean stratification also play an important role.

2.2 Circulation at the glacier edge and in the fjord

Observations near the glacier fronts are scarce, but the dynamics is conceptualized as follows. Within a few meters of the ice, the ice-ocean boundary layer consists of a turbulent region (a few meters thick) where the turbulence is unaffected by the boundary and, closer to the ice, a viscous sublayer (a few millimeters thick) where the turbulent eddies are suppressed and molecular processes dominate the exchanges (Holland and Jenkins, 1999; Jenkins, 2011). Farther away, the flow is given by a system of rising buoyant plumes driven by submarine melting and subglacial discharge (surface melt above sea level). The seasonality in the discharge of surface melt, in particular, is thought to impart a large seasonal cycle to the dynamics at the ice/ocean edge. This discharge enters the fjord waters through channels discharging at the base of the glacier fronts whose number, sizes, and geometries are mostly unknown and possibly influenced by the complex networks of drainage channels and crevasses in the glaciers (for a review, see Chu, 2014). Observations of plumes consist of visual observations of turbid waters that surface at the edge of a glacier (e.g. Chauché et al., 2014) and a limited number of surveys of plume characteristics (Chauché et al., 2014; Bendtsen et al., 2015; Mankoff et al., 2016). A recent study of a west Greenland glacier mapped the volume flux within a surfacing plume and showed that, within 100 m of the glacier face, the plume's characteristics matched those predicted by plume theory (Mankoff et al., 2016). The study also highlighted, however, that the plume itself is very narrow (~30 m) compared to the width of the glacier (~5 km), raising the question of how much submarine melt actually occurs in the plume/glacier contact area. More likely, the important contribution is how the plumes influence the fjord-scale circulation and, as such, the supply of ocean heat to the glacier face. No doubt, however, plumes also play an important role in glacier mass balance by impacting calving processes (O'Leary and Christoffersen, 2013).

Numerical studies have greatly improved our understanding of buoyant plumes by showing that submarine melt rates are strongly influenced by the volume of subglacial discharge (and hence its seasonality; Sciascia et al., 2013, Xu et al., 2012, 2013) and the distribution of plumes (Slater et al., 2015). In particular, these studies have highlighted one important result: that melting is enhanced in the presence of subglacial discharge. The implication is that submarine melting can increase as a result of increases in surface melting even if the ocean conditions near the margin do not change. To this day, however, quantitative results from these models are largely untested because of the limited data from the ice/ocean interface. In particular, the coefficients used in the melt parameterization have not been validated by direct measurements (Straneo and Cenedese, 2015). In general, estimates of submarine melt from ocean measurements for Greenland's glacial fjords are highly uncertain because of the temporal variability, of the need to compute both heat and freshwater fluxes, and because of our inability to separate glacier and iceberg melt (Jackson and Straneo, 2016).

Key questions remain about the role of plumes in driving the fjord-scale circulation and, in turn, the melting of the glacier. In part these are being addressed by models in which the plumes are being parameterized (Cowton et al. 2015; Carroll et al. 2015) but cross-validation with field experiments will be key to determine if all the relevant dynamics are appropriately resolved.

Beyond the buoyancy-driven circulation resulting from glacial melting and discharge, glacier/ocean interactions are also affected by the fjord circulation forced by local or regional winds and by exchanges with the continental shelves. Examples of external drivers for glacial fjords include along-fjord winds (Moffat, 2014), tidal-mixing and flows (Mortensen et al., 2011 and 2013), shelf-forced flows (Jackson et al., 2014) and buoyancy-driven flows (Gladish et al., 2014). At present there is no simple model that can account for the fjord dynamics or even identify which regime may dominate in one particular fjord (Sutherland et al., 2014a; Jackson and Straneo, 2016). Yet either resolving or understanding how changing atmospheric and oceanic conditions will affect the circulation and properties within a fjord and, in turn, glacial melt will be key to understanding ice sheet variability. To date, studies analyzing correlations between ocean data and glacier variability (where both exist) over 1–10 year timescales show that there is no simple model that can link glacier variability, subglacial discharge variability and oceanic changes (e.g. Straneo et al., 2016). Likely, this is because other factors, including bedrock configuration, surface melt and other glaciological processes, play a role in glacier stability.

3. Discharge of meltwater

One important consequence of GrIS mass loss is an increased discharge of freshwater into the North Atlantic and Arctic Ocean and thus the potential to impact the Atlantic Meridional Overturning Circulation, the regional circulation, sea-ice formation and air-sea exchanges. Key to understanding this impact is our ability to track the pathways of Greenland meltwater into the ocean and, also, to provide appropriate boundary conditions from Greenland to ocean models investigating the impact of increased Greenland discharge (e.g. Boning et al., 2016).

In terms of budget, total discharge from the GrIS is due to the sum of ice discharge (icebergs and submarine melting) and runoff of ice melting above sea level. From 1961 to 1990, the GrIS was mostly stable, with an estimated ice discharge of 497 ± 50 km^3/y and runoff of 416 ± 57 km^3/y (Bamber et al., 2012). Both these components have increased over the past two decades, and a recent study estimated that the additional (ice and runoff combined) freshwater discharge in 2012 was 378 ± 50 km^3/y (Enderlin et al., 2014), resulting in a total freshwater discharge of $1{,}291 \pm 50$ km^3/y.

Most of Greenland's freshwater is discharged at the margins of the subpolar North Atlantic and the connected Baffin Bay (Bamber et al., 2012) and enters the ocean through calved icebergs, submarine melt, and subglacial discharge occurring in the glacial fjords. Thus, the fjords are the conduits through which this freshwater reaches Greenland's continental shelves. It is important to note that this freshwater discharge is not distributed evenly around Greenland but is localized into discrete locations, corresponding to the glacial fjords. Furthermore, a significant fraction is discharged at depth (either because of subglacial discharge or deep submarine melt) and, as such, behaves in a very different manner from a surface freshwater discharge like a river.

Tracking Greenland meltwater is challenging because its fresh signature is rapidly lost due to mixing with ocean waters. Some progress has been made by taking into account that melting of ice transforms ocean waters in specific ways given the thermodynamic change associated with the phase change (Jenkins, 1999). A comparison of winter and summer water temperatures and salinities in one major fjord have shown, furthermore, the large impact of the seasonal addition of subglacial discharge (Straneo et al., 2011). In general these studies show that Greenland meltwater is exported in the form of glacially modified waters which are distributed over a thick upper layer (at times ~200 m) and with salinities close to those of the PW (e.g. Beaird et al., 2015; Straneo et al., 2011; Jackson and Straneo, 2016; Mortensen et al. 2011, 2013). Quantitative tracking of meltwater requires additional tracers, however. One promising avenue is the use of noble gases (Beaird et al., 2015) which, for a mid-sized glacier in West Greenland, show that glacially modified waters contain fractions of subglacial discharge and submarine melt that are less than a few percent even within a kilometer of the glacier's terminus.

In order to provide appropriate boundary conditions to the large-scale ocean models, the mixing processes that dilute Greenland's meltwater must be understood and accounted for. For models which do not resolve the ice/ocean boundary layer dynamics, the plumes and even the fjords, this means that they need to be parameterized. Based on our present knowledge, one expects Greenland's meltwater to be exported in a strongly diluted form, over the upper 100–200 m, and that this export have a strong seasonal modulation (given the summer release of subglacial discharge). Icebergs released from Greenland are also highly problematic for models. Recent studies show that a significant fraction of the icebergs melt inside some of the fjords (Enderlin et al., 2016) but, also, that many icebergs are exported from the fjords after a non-trivial time lag (Sutherland et al., 2014b).

4. Summary

Major advances in understanding glacier/ocean interactions in Greenland have been made over the last decade as interest for the role of the ocean in triggering Greenland's dynamic changes and the impact of increased Greenland freshwater discharge into the ocean has grown. These studies collectively have shown that Atlantic waters reach the margins of large glaciers at depth and drive substantial submarine melt. They have also shown that the glacier/ocean exchange is strongly modulated by the seasonal release of surface melt which, in turn, has a big impact on submarine melt. In terms of melt-water export, these studies have shown that Greenland's meltwater is exported in the form of highly diluted glacially modified waters and that their properties are set by the processes at the ice edge, including subglacial discharge, and by fjord processes. In general, we expect the meltwater export to have a strong seasonality and the meltwaters to be distributed over the upper 100–200 m.

Key questions pertaining to glacier/ocean interactions in Greenland remain, however, and we are far from being in a position to provide submarine melt rates to ice sheet models or meltwater forcing to ocean models. Specific issues that need to be addressed include:

1. Testing of melt rate parameterizations using high-resolution models and data.
2. Establishing the patterns and rates of subglacial discharge for marine terminating glaciers.
3. Understanding the role of externally forced fjord circulations in setting the submarine melt rate magnitude and in regulating the meltwater export.

In addition, it is important to remember that submarine melt rates affected, for example, by oceanic or atmospheric variability, are only one of the multiple factors influencing glacier stability. Thus prolonged measurements of multiple systems is key to unraveling the different dynamics at play and improving our understanding of ice sheet variability.

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