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Key Points:

- Outlet glacier changes are heterogeneous and result in large uncertainties in future sea-level rise contribution from Greenland
- Uncertain understanding of outlet glacier changes is largely due to ice-ocean and ice sheet basal processes
- Future research needs include expanded observations, improved modeling, and greater inclusion of new researchers

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Future Evolution of Greenland's Marine-Terminating Outlet Glaciers

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Abstract Mass loss from the Greenland ice sheet (GrIS) has increased over the last two decades in response to changes in global climate, motivating the scientific community to question how the GrIS will contribute to sea-level rise on timescales that are relevant to coastal communities. Observations also indicate that the impact of a melting GrIS extends beyond sea-level rise, including changes to ocean properties and circulation, nutrient and sediment cycling, and ecosystem function. Unfortunately, despite the rapid growth of interest in GrIS mass loss and its impacts, we still lack the ability to confidently predict the rate of future mass loss and the full impacts of this mass loss on the globe. Uncertainty in GrIS mass loss projections in part stems from the nonlinear response of the ice sheet to climate forcing, with many processes at play that influence how mass is lost. This is particularly true for outlet glaciers in Greenland that terminate in the ocean because their flow is strongly controlled by multiple processes that alter their boundary conditions at the ice-atmosphere, ice-ocean, and ice-bed interfaces. Many of these processes change on a range of overlapping timescales and are challenging to observe, making them difficult to understand and thus missing in prognostic ice sheet/climate models. For example, recent (beginning in the late 1990s) mass loss via outlet glaciers has been attributed primarily to changing ice-ocean interactions, driven by both oceanic and atmospheric warming, but the exact mechanisms controlling the onset of glacier retreat and the processes that regulate the amount of retreat remain uncertain. Here we review the progress in understanding GrIS outlet glacier sensitivity to climate change, how mass loss has changed over time, and how our understanding has evolved as observational capacity expanded. Although many processes are far better understood than they were even a decade ago, fundamental gaps in our understanding of certain processes remain. These gaps impede our ability to understand past changes in dynamics and to make more accurate mass loss projections under future climate change. As such, there is a pressing need for (1) improved, long-term observations at the ice-ocean and ice-bed boundaries, (2) more observationally constrained numerical ice flow models that are coupled to atmosphere and ocean models, and (3) continued development of a collaborative and interdisciplinary scientific community.

Plain Language Summary Increasing mass loss from the Greenland ice sheet (GrIS) in response to changes in global climate has motivated the scientific community to understand how much sea level rise will happen in the coming decades. Observations now indicate that the impact of a melting GrIS are more widespread than just sea-level rise and include changes to ocean properties and circulation, nutrient and sediment cycling, and ecosystem function. Major uncertainties still hamper accurate predictions of these impacts, particularly for outlet glaciers in Greenland that terminate in the ocean because their flow is strongly controlled by multiple processes that alter their boundary conditions at the ice-atmosphere, ice-ocean, and ice-bed interfaces. Many of these processes change on a range of overlapping timescales and are challenging to observe. Here we review the scientific progress in understanding how GrIS outlet glaciers respond to climate and how our understanding has changed over time as observations have increased. We conclude with recommendations for (1) improved, long-term observations at the ice-ocean and ice-bed boundaries, (2) more observationally-constrained ice flow models that are linked to atmosphere and ocean models, and (3) continued development of a collaborative and interdisciplinary scientific community.

1. The Importance of Greenland's Outlet Glaciers to Society

The Greenland ice sheet (GrIS) is the second largest reservoir of land-based ice in the world with $\sim 2 \times 10^6$ km³ of ice and the ability to increase global sea level by 7.42 m (Morlighem et al., 2017). The total ice sheet mass balance is an important measure of its “health” with two interconnected components contributing to mass balance changes: (1) solid ice discharge (through iceberg calving) via dynamic changes that occur as a result of atmospheric, oceanic, and other processes and (2) ice surface mass balance (SMB) changes in response to changing atmospheric conditions (see Glossary). While surface accumulation within the interior areas of the GrIS has increased slightly in recent years (Noël et al., 2018), large mass loss is concentrated around the periphery of the GrIS. This mass loss includes both large surface mass losses and changes to marine-terminating outlet glaciers, which act as rapid mass conveyor belts moving ice from the interior to the ocean.

Recent observations suggest that during 1972–2018, $\sim 66\%$ of the GrIS mass loss was due to dynamic change associated with marine-terminating outlet glaciers, producing a ~ 9 -mm increase in sea level, with pronounced dynamic losses in NW and SE Greenland and roughly half of this sea level increase occurring in the last 8 years (Mouginot et al., 2019). While estimates of past mass contribution to sea level have low uncertainties, multiple difficulties remain in projecting future GrIS mass change. In part, there is large uncertainty because future human behavior and climate policy is unknown. There also remains a debate about the physics that dominate important processes contributing to dynamic changes, particularly for outlet glaciers that connect to the ocean (Minchew et al., 2019; Pattyn, 2018; Stearns & van der Veen, 2018; Stearns & van der Veen, 2019; Sutherland et al., 2019). In addition, while most of the outlet glacier dynamic response occurs in the terminal zone (at the ocean boundary), contemporary terminus change is proven long-lasting, ultimately affecting the full ice sheet, and is responsible for much of the expected sea-level rise from Greenland (Felikson et al., 2017; Howat et al., 2008; Price et al., 2011). Thus, it is important to understand more than what happens at the ice sheet marine margin alone.

Here we present an overview of the Greenland marine-terminating outlet glacier settings and controls, examined through the lens of observational and modeling capacity growth in recent decades and a view of future needs. This review builds on existing reviews of glacier calving and crevasse mechanisms (Benn et al., 2007; Colgan et al., 2016), submarine melt (Benn et al., 2017; Straneo & Cenedese, 2015; Truffer & Motyka, 2016), and numerous studies that examine the Greenland climate forcing (Fyke et al., 2018; Straneo & Heimbach, 2013) and the heterogeneous outlet glacier response (Carr et al., 2013). The study of Greenland outlet glaciers is especially urgent given that the recent rapid climate warming underway in the Arctic (see section 3) and concurrent rapid changes in GrIS mass loss (Mouginot et al., 2019) portend a strong response in GrIS mass change.

Rapid expansion of observational capabilities, both in-situ and via satellites, has improved our understanding of outlet glacier changes (see section 4) and the processes responsible (see section 5). Recent attention has focused on ocean forcing, but the response of outlet glaciers to climate forcing is not straightforward. A complex picture has emerged, with interwoven processes controlling outlet glacier dynamics and with outlet glaciers playing a multidimensional role in the interconnected Arctic ice-ocean-climate-biological system (section 6). Given that Greenland's outlet glaciers are important at all scales—locally (e.g., biological productivity and nutrient cycling), regionally (e.g., fjord circulation and ocean stratification), and globally (e.g., ocean thermohaline circulation and sea-level rise)—we conclude with recommendations for future research (see section 7) to expand our understanding of outlet glacier change and associated effects.

2. Context and Setting

2.1. Greenlandic Marine-Terminating Outlet Glacier Characteristics

Outlet glaciers act as arteries for ice flux from the ice sheet interior; their topographically controlled high rates of ice flow allow them to drain interior ice to the marine margin where they terminate in the ocean. Across the globe, the character of marine-terminating outlet glaciers spans a range from the wide and deep, ice-shelf-buttressed outlet glaciers of Antarctica to the thin, well-grounded and relatively warm glaciers of Svalbard, Alaska, and other Arctic regions. Greenland's glaciers fill a unique central range on this spectrum, with many narrow, deeply grounded outlet glaciers and examples both of ice-shelf-buttressed outlets (in the north) and thin, well-grounded glaciers (e.g., much of the east). Most GrIS outlet glaciers have bedrock mar-

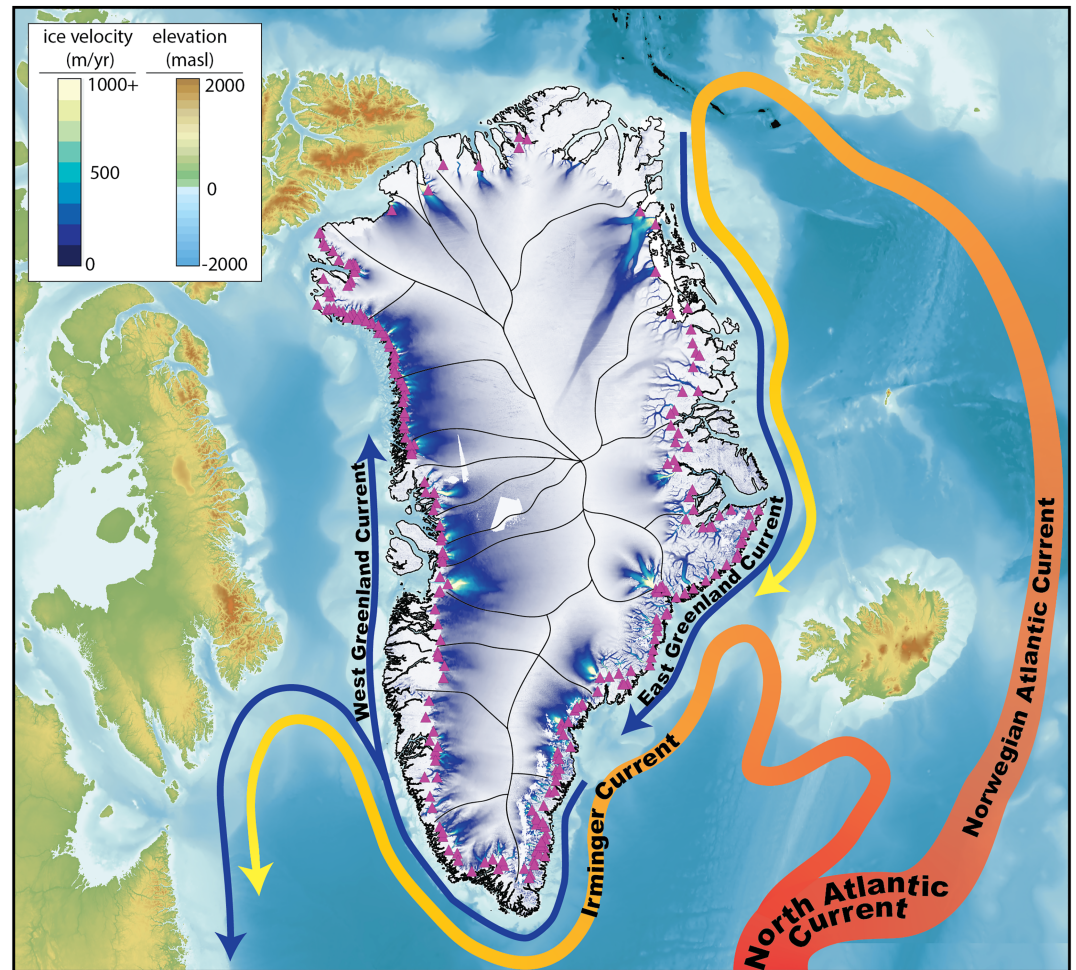


Figure 1. The Greenland Ice Sheet situated in the Arctic showing ocean currents. The size of ocean current arrows indicates water mass; color of arrows indicates heat transport. Surface ice flow speed from (Joughin et al., 2010) highlights the numerous fast-moving outlet glaciers around the periphery of the ice sheet that drain ice from the interior. Purple triangles indicate outlet glaciers identified with flow rates above 50 m/year. Bathymetry data from the GEBCO Grid (GEBCO Compilation Group, 2019) show the deep troughs created on the sea floor from the extent of past ice streams to the continental slope.

gins and deep central troughs carved through erosion, similar to their marine-terminating mountain-glacier counterparts in Alaska and the Antarctic Peninsula. However, some outlet glaciers in Greenland have fast surface flow speeds that reach far into the ice sheet interior (e.g., Jakobshavn Isbrae and the Northeast Greenland Ice Stream) with similarities to the large ice streams draining the Antarctic ice sheet. For these glaciers, lateral boundaries of fast flow are constrained by slow-moving ice in the interior and bedrock towards the ice sheet margin. Greenland's outlet glaciers are narrower than their Antarctic counterparts, but compared to outlet glaciers in the rest of the Arctic, many GrIS outlet glaciers are deeper and connected to a much larger supply of inland ice.

While increasing air and ocean temperatures are driving higher mass loss from outlet glaciers around the globe, the unique character of climate forcing in different regions alters outlet glacier dynamic response. In the Antarctic Peninsula, solid ice discharge via calving is the dominant outlet glacier ice loss process, likely exacerbated by ice shelf weakening from surface and submarine melt (Glasser & Scambos, 2008; Khazendar et al., 2007; Scambos et al., 2004, 2009). Other regions around Antarctica (like the Amundsen Embayment) show large concentrations of dynamic mass loss associated with warm subsurface ocean temperatures suggesting that, like Greenland, the ocean exerts a strong influence on Antarctic mass loss (Cook et al., 2016; The IMBIE team, 2018). Outside of the GrIS, widespread retreat and dynamic acceleration is evident across the Arctic, though SMB is a more dominant contributor to mass loss than dynamics. Changes in discharge

only account for ~20% of mass loss outside the GrIS (McNabb et al., 2015; Van Wychen et al., 2016). While the ocean likely plays an important role for some glaciers outside the GrIS, most of these systems are more responsive to atmospheric changes because they are well-grounded or have shallow regions of ocean contact (Cook et al., 2019).

The GrIS contains ~280 fast-flowing (>100 m/year) marine-terminating glaciers (Figure 1) with a high degree of heterogeneity across a range of parameters (Mankoff et al., 2019). Ice discharge from these glaciers is ~500 Gt/year total, with large variations in individual glacier ice discharge associated with interglacial differences in width (1–30 km), thickness (~100–2,000 m), terminus basal conditions (grounded, partially floating, fully floating), terminus conditions (open water, mélange—a granular matrix of icebergs, bergy bits, and sea ice—or ice shelf presence), basal substrate (bedrock, sediments, water), and other topographic controls (Enderlin et al., 2014; King et al., 2018; Mankoff et al., 2019). In the far north and northeast, there are relatively few outlet glaciers; most of which terminate in perennial floating ice shelves. In the northwest, ice flow is less restricted by topography further inland, and there exists a larger abundance of narrower outlet glaciers draining the ice sheet. Here many glaciers develop ephemeral floating termini each winter, which are lost when calving rates increase each spring. Southeastern and western outlet glaciers typically lack floating ice shelves and are fully grounded at their termini, with the exception of the largest glaciers (Enderlin & Howat, 2013; James et al., 2014).

3. Climate Setting in Greenland

The last several decades have seen substantial changes in atmospheric and oceanic conditions around Greenland (Bevis et al., 2019; Straneo & Heimbach, 2013). Large-scale and multidecadal processes as well as local and short-term changes in natural and anthropogenic forcings influence outlet glaciers. Recent rapid Greenland mass loss cannot, however, be explained by natural variability alone. Current changes are closely aligned with significant acceleration in anthropogenic warming, which is altering small to large-scale processes critical to ice sheet mass balance (Aschwanden et al., 2019).

Large-scale atmospheric variations influence surface mass balance across the full ice sheet. Annual to multidecadal GrIS SMB correlates, at varying significance, with the North Atlantic oscillation (NAO), Greenland blocking index (GBI), and Atlantic multidecadal oscillation (AMO) (Hanna et al., 2012, 2016). A negative summer NAO phase is associated with high annual mass losses via enhanced summertime warming and reduced snowfall, particularly in western Greenland (Bevis et al., 2019). High values of the GBI, which measure and describe mean 500 hPa geopotential height for the 60–80° N, 20–80° W region, are also associated with large, ice-sheet-wide melt events (Delhasse et al., 2018; Hanna et al., 2013; Hofer et al., 2017). The decadal-scale periodicity of the NAO and GBI, and the approximately 60-year periodicity of the AMO, are evident in multicentury Greenland ice cores (Trusel et al., 2018). The summer NAO and annual surface mass balance have been predominantly negative since the early 2000s (van den Broeke & Lenaerts, 2014), punctuated by a strong positive index and a pause in surface mass loss in 2013 (Bevis et al., 2019). Although the summer GBI was generally slightly negative from the 1960s–1980s, it increased throughout the 1990s–2000s, reaching a peak during the extreme melt season in 2012 (Hanna et al., 2016). Since the late 1990s, the AMO has been in a positive phase that has been amplified by global warming and currently exceeds AMO values during the period of Greenland warming in the 1930s and 1940s (Enfield et al., 2001).

Along with approximately decadal-scale atmospheric forcing, shorter-term variations are also important. For example, commonly occurring low-level clouds can enhance downwelling infrared flux without obstructing solar radiation, inducing short-term melt events (Bennartz et al., 2013). Atmospheric rivers, which can transport warm, moist air from North America can also enhance short-term melt events, particularly in western Greenland (Mattingly et al., 2018). Short-term variations may also be affected by the broad-scale atmospheric state. For example, the occurrence of atmospheric rivers over Greenland has increased since the late 1990s, in part connected to the negative NAO phase (Mattingly et al., 2018).

On the oceanic side, GrIS outlet glaciers are influenced by ocean properties (e.g., temperature, salinity, and velocity) at the ice-ocean interface, and these ocean properties are in turn modulated by regional ocean circulation around Greenland. (Details of the oceanographic controls on Greenland's outlet glaciers are covered in the review papers of Straneo and Heimbach (2013) and Straneo and Cenedese (2015).) Greenland lies at the confluence of the export pathway of waters from the Arctic and the recirculation of subtropical Atlantic Waters (AW). The East Greenland Coastal Current carries cold, fresh polar-origin water (PW) southward

along the east coast and meets the Irminger Current south of Denmark Strait (Figure 1). As an extension of the North Atlantic Current, the Irminger Current forms a key subpolar gyre boundary current and carries warm AW toward Greenland. Together, the merged East Greenland-Irminger Current travels along the southeast coast, wraps around the southern end of Greenland at Cape Farewell, and continues northward as the West Greenland Current towards Baffin Bay.

Transported via this system of currents, AW is an important source of heat for outlet glaciers. On the Greenland continental shelves, the colder PW is generally found in the surface layer (upper ~200 m) and near the coast, blocking AW surface pathways towards glaciers. However, AW is typically found below and offshore of PW on the shelf (Sutherland & Pickart, 2008) and fills the deep basins within most Greenlandic fjords (Straneo et al., 2011, 2012). The relative offshore thickness of PW and AW layers can modulate water mass access to outlet glaciers, influencing ice-ocean interface melting. For example, in the mid-1990s, the AW layer thickened offshore of Greenland (Våge et al., 2011), possibly in response to combined upper ocean warming since the 1950s (Levitus & Antonov, 2005) and decadal-scale natural ocean variability (Straneo & Heimbach, 2013). This AW layer thickening might have increased the ocean heat available at glacier termini and enhanced submarine melting, as suggested by a correlation between large-scale ocean properties and glacier behavior (Holland et al., 2008; Straneo & Heimbach, 2013). However, there are many critical but poorly resolved links between large-scale ocean variability and glacier response, including fjord circulation and submarine melt dynamics.

To influence submarine melting at glacier termini, Atlantic-origin waters must cross the continental shelf, transit through fjords, and come into contact with glacier termini. Bathymetry is one important control on ocean heat transport towards glacier termini. On the continental shelf, deep valleys or troughs—carved by the past expansion of glaciers during the Last Glacial Maximum (O’Cofaigh et al., 2013)—form a pathway for warm AW to cross the shelf and reach the fjord mouth. Fjords, in turn, form deep, narrow conduits between the ocean at the shelf and the glacier termini. Some fjords contain bathymetric sills (most commonly at the mouth) that can limit the encroachment of warm waters at depth, likely making glaciers within those fjords less vulnerable to ocean warming (Carroll et al., 2016; Millan et al., 2018).

Other fjord circulation processes—including freshwater buoyancy forcing, atmospheric forcing, tides, and coastal-trapped waves—also control ocean heat transport towards the glacier and glacial freshwater export out to the coastal ocean. During the summer, subglacial meltwater discharges at the outlet glacier grounding line, driving vigorous upwelling plumes and setting up a fjord exchange flow that helps draw AW toward glacier termini (Carroll et al., 2015; Motyka et al., 2003; Rignot et al., 2010; Sciascia et al., 2013). Other freshwater sources, including surface runoff and submarine glacier and iceberg melting, also contribute to the buoyancy forcing that drives a fjord exchange flow. In addition, wind forcing—both locally within the fjord and remotely on the shelf—can drive energetic fjord flows and vigorous exchange between fjords and shelf ocean (Carroll et al., 2017; Cowton et al., 2016; Fraser & Inall, 2018; Jackson et al., 2014, 2018; Spall et al., 2017). These wind events, often associated with atmospheric low pressure systems, are strongest during winter and have a seasonal cycle that is opposite to the seasonality of freshwater forcing (Harden et al., 2011; Oltmanns et al., 2014). Freshwater forcing, wind forcing, and other fjord processes (tides, internal waves, etc.) all contribute to the net exchange of heat, salt, and freshwater between the shelf and the fjord and in combination control the near-glacier ocean properties that influence the GrIS.

4. Evolving Understanding of GrIS Outlet Glaciers

Despite nearly a century of ice sheet observations (Bjørk et al., 2012; Gabel-Jorgensen, 1935), only in recent decades has the importance of GrIS outlet glaciers been fully recognized. This is largely due to the improved spatial and temporal resolution of observations from air and space-borne instruments, particularly since the 1990s (Figure 2). These observational improvements have been proven pivotal for quantifying the mass balance state of the ice sheet and for improving our understanding of outlet glacier controls. As an example, the ice sheet was thought to be close to a balanced state during the 1970s and 1980s but, until recently, we lacked the observational data to demonstrate this within measurement uncertainties (Mouginot et al., 2019).

In the 1990s, NASA’s Program for Arctic Regional Climate Assessment was the seed for several observational ground and air campaigns aimed at improving ice sheet mass balance estimates. NASA’s Airborne Topographic Mapper began flying over Greenland with regularity during this time and revealed peripheral thinning rates in excess of 1 m/year (Frederick et al., 2000; Krabill et al., 2004), which were subsequently

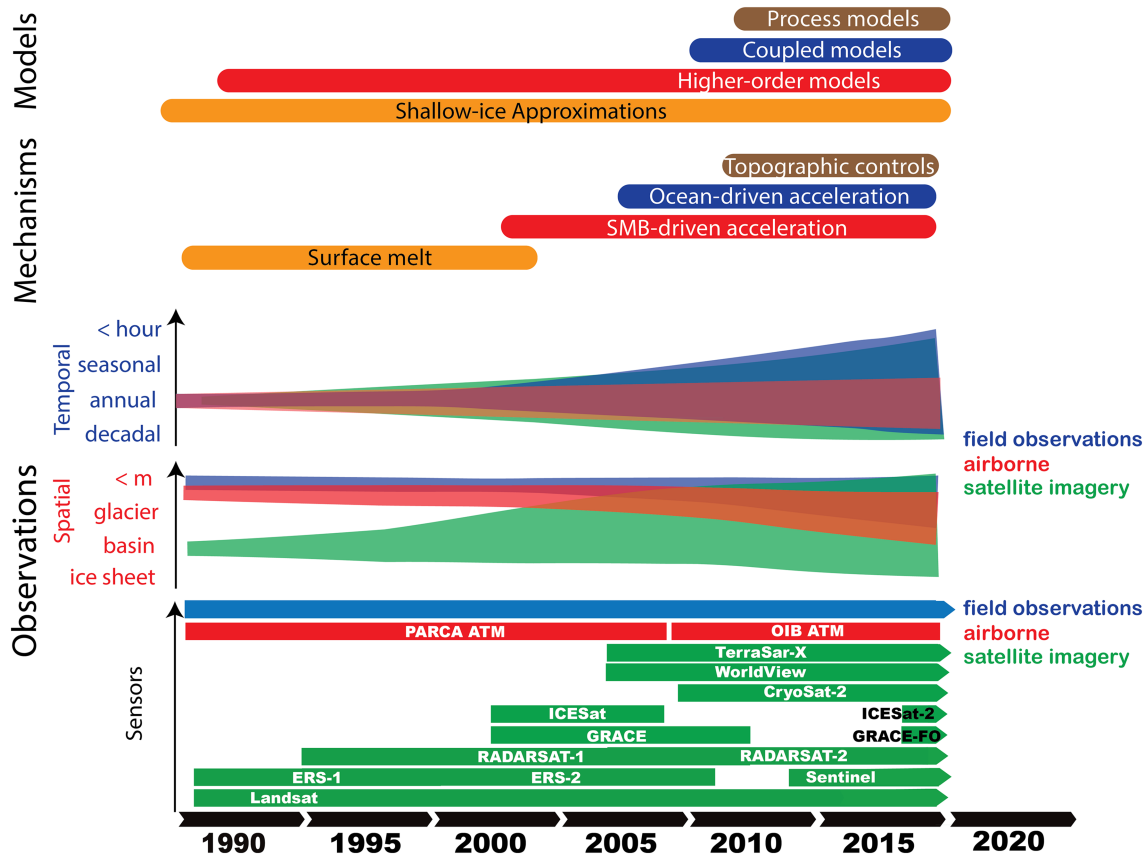


Figure 2. Qualitative interpretation of progress in the field of outlet glaciers in Greenland showing rapid gains in observations (both sensor type and scales have expanded), understanding of important mechanisms, and model capabilities with time.

validated by NASA's ICESat mission launched in 2003 (Pritchard et al., 2009). Although the relative contributions of the observed thinning from ice dynamics or surface mass balance changes were unknown at that time, more recent reconstructions of terminus position (Catania et al., 2018; Howat & Eddy, 2011; Murray et al., 2015) and discharge (Mouginot et al., 2019; Rignot & Kanagaratnam, 2006) support the hypothesis that the onset of dynamic flow acceleration occurred in the 1990s. These changes coincided with increases in atmospheric warmth and oceanic heat content as described above.

Subsequently, direct monthly GrIS mass estimates became available from NASA's Gravity Recovery and Climate Experiment (GRACE) satellite launched in 2002, producing, for the first time, an ice-sheet-wide picture of the spatio-temporal mass balance pattern. As GRACE data accumulated, complex and time-varying mass loss patterns were revealed. Mass loss was concentrated in the southeast prior to ~2007, but notable acceleration of mass loss into the northwest ultimately allowed the northwest to contribute ~70% of GrIS mass loss during 2003-2013 (Chen et al., 2011; Khan et al., 2010; Velicogna et al., 2014). GRACE data also enabled scientists to fully appreciate the rapidity of GrIS changes. Even seasonal and shorter duration events had an impact on ice mass balance (Velicogna, 2009), meaning that short duration observations could impart bias in mass balance estimates. By comparing regional climate model estimates of ice sheet SMB to the total mass loss data from GRACE, scientists were able to distinguish between SMB and dynamic mass change for the ice sheet on a range of time and space scales (van den Broeke et al., 2016; Velicogna et al., 2014). This work thrust Greenland's outlet glaciers into the spotlight (in terms of both the research priority and the news media) as significant potential contributors to sea level rise.

With a focus on outlet glaciers as an important control of GrIS mass balance, researchers began to identify and understand the underlying mechanisms for the observed changes. While changes to dynamic regime (e.g., stable to retreating) were likely initiated from the ocean (Howat & Eddy, 2011; Murray et al., 2010; Nick et al., 2009; Seale et al., 2011; Straneo et al., 2010), the exact mechanism for ocean-induced retreat remained elusive for several years. For many outlet glaciers, speedup and thinning were hallmark indicators

of dynamic change, demonstrating the sensitivity of outlet glacier dynamics to changes in terminus perturbations (Howat et al., 2008; Joughin et al., 2008). As observations expanded in time and space, however, this simple model of glacier dynamic response to climate perturbation became more complicated. Not all glaciers responded to climate perturbations in the same way, and even glaciers in adjacent fjords exhibited vastly different dynamic changes in elevation (Csatho et al., 2014; Felikson et al., 2017; Howat et al., 2007; McFadden et al., 2011), ice speed (Bevan et al., 2012; Howat et al., 2007; Joughin et al., 2010; Moon et al., 2012), terminus position (Bevan et al., 2012; Catania et al., 2018; Howat et al., 2007; McFadden et al., 2011; Moon & Joughin, 2008; Murray, Scharrer, et al., 2015; Warren & Glasser, 1992), and ice discharge (Enderlin et al., 2014; King et al., 2018). This work made obvious the idea that outlet glacier controls may be regionally or locally variable.

During this time, there was also considerable research into the role of ice sheet surface meltwater in altering ice dynamics. Much research focused on land-terminating glaciers (Bartholomew et al., 2011; Das et al., 2008; Joughin et al., 2008b; Sole et al., 2013; Zwally et al., 2002) because of the relative ease of making observations in these regions compared to heavily crevassed outlet glaciers. This work revealed the ice velocity response to subglacial surface meltwater input on a range of time scales. While ice velocity increases rapidly in response to changes in subglacial water storage (Bartholomew et al., 2008), there are self-regulation processes that permit efficiency to be gained in the subglacial system causing ice velocity slow down to occur over longer time scales (Nienow et al., 2017; Tedstone et al., 2015). Similar controls are expected for outlet glaciers, but observations using correlations between surface melt and ice flow speed in outlet glaciers are sparse (De Juan et al., 2010; Moon et al., 2014). As our attention in recent years shifted to the ice-ocean boundary, the important role of subglacially-routed surface meltwater as a driver of submarine melt and terminus retreat, has emerged (Chauché et al., 2014; Fried et al., 2015; Motyka et al., 2003; Rignot et al., 2010; Slater et al., 2015; Straneo et al., 2013) (see section 5.2.2). This somewhat unexpected mechanism by which surface melt influences glacier dynamics illustrates the importance of examining mass loss processes holistically to account for linkages between processes at the subglacial substrate, the ocean and atmospheric boundaries, and the deep interior dynamics of the ice sheet.

This brief history highlights the importance of improved observations—higher resolution (spatial and temporal) and a wider variety of observation type—to our deeper understanding of Greenland's outlet glacier controls. Simultaneous development has also occurred in ice sheet model methodologies, which permit greater data assimilation, higher resolution, improved model physics, and the development of competing models. In combination, these advances support improved projections of future outlet glacier change.

5. Controls on Outlet Glacier Dynamics

While outlet glaciers extend far into the ice sheet interior, much work has focused on the terminus boundary at the ocean because this is where the changes in mass balance have been the largest. GrIS outlet glacier termini exist in an environment where they are influenced by external climatic factors like ocean and atmospheric properties, as well as internal factors like substrate composition, geometric properties, and inland dynamics (Figure 3; Carr, Stokes, and Vieli (2013)). Because changes in these factors can be superimposed on, and interact with, one another, it is often difficult to attribute an observed glacier dynamic change to a particular forcing factor. In general, however, change in terminus position over time arises from an imbalance between ice flux from the interior and frontal ablation (i.e., the sum of iceberg calving (section 5.2.1) and submarine melting (section 5.2.2)). Glaciers are expected to advance into their fjords if they are supplied more ice from the interior than they lose. This could result from ice flux acceleration towards the marine margin, surface snow accumulation in excess of surface melt (section 5.3), or reduced terminus ablation rates. Glaciers are expected to retreat inland when ice flux from the interior does not match the loss of ice via frontal ablation. This could occur from ice flux deceleration, increased calving and/or submarine melting rates, or greater surface melting than snow accumulation. Terminus retreat usually induces outlet glacier thinning, predominantly in downstream regions. This ice sheet surface steepening subsequently induces an ice flow acceleration, but can also induce ice flow convergence, which may counteract acceleration. While this pattern of outlet glacier dynamic change in response to retreat has been observed around the GrIS, significant spatio-temporal heterogeneity in this response complicates our understanding of outlet glacier controls.

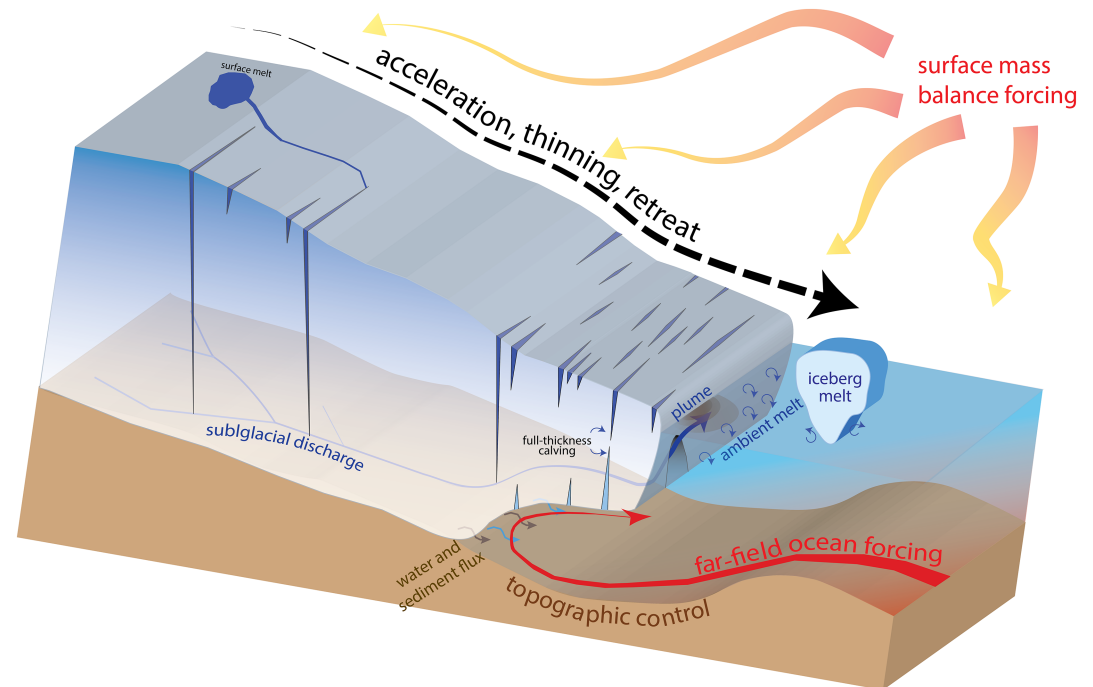


Figure 3. Conceptual diagram of outlet glacier processes at play in the terminal zone where the atmosphere, ice sheet, substrate and ocean interact. Red arrow indicates the ocean heat forcing that is at depth in fjords. Black arrow indicates that dynamic changes of outlet glaciers are more pronounced toward the glacier terminus. Blue arrows indicate subglacial water, which upwells at the submarine terminus and rises along the terminus face carrying sediment and nutrients (brown arrows) with it as well. Subglacial plumes, iceberg melt and far-field ocean circulation all act to influence fjord circulation.

5.1. Morphological Controls

The geometry of an outlet glacier (width, surface, and bed topography) exerts a first-order control on dynamics by influencing the force balance that governs ice flow (van der Veen & Whillans, 1989). Here we use the term bed topography to mean the topography beneath the glacier and bathymetry to mean the topography beneath the ocean within an outlet glacier fjord. Morphological controls on GrIS outlet glaciers include geometrical effects and effects related to bed characteristics. This includes the presence or absence of till, till rheology during deformation, and water pressure variations at the ice-bed interface. Little direct observation of bed characteristics exists for the GrIS as a whole, with even fewer in outlet glacier regions owing to the difficulty, and expense, in obtaining such observations. The basal regime beneath outlet glaciers is expected to be thawed (MacGregor et al., 2016), although the exact relationship between bed conditions and ice flow remains elusive (Minchew et al., 2019; Stearns & van der Veen, 2018; Stearns & van der Veen, 2019). Borehole observations for a land-terminating region near the ice sheet edge confirm the presence of liquid water at the base of the ice sheet at high-pressure conditions, enabling fast ice motion by reducing effective pressure at the bed (Andrews et al., 2014). We expect similar processes to occur beneath outlet glaciers. Evidence from seismic experiments also suggests that thick till is present in places (Walter et al., 2014) and is highly porous (up to 40%) and thus weak (Dow et al., 2013; Walter et al., 2014), although this till is not ubiquitous across the ice sheet (Harper et al., 2017).

Initial surveys of basal topography beneath GrIS outlet glaciers (e.g., Jakobshavn Isbrae) revealed that, unlike the ice streams in Antarctica, most GrIS outlet glaciers flow in narrow (<10 km), deeply incised (<3 km) submarine troughs that are laterally constrained by bedrock, with flow driven by steep surface slopes (Clarke & Echelmeyer, 1996; Truffer & Echelmeyer, 2003). Thanks to coordinated, long-term effort to complete extensive ice-penetrating radar surveys, the basal topography has been constrained across a large portion of the GrIS (Bamber et al., 2013; Gogineni et al., 2014; Studinger et al., 2010). Similarly, multibeam surveys within several fjords near glacier termini have been collected to determine fjord bathymetry (Fenty et al., 2016). These and other observations have been combined via the principle of mass conservation to produce a spatially complete GrIS subglacial topography map, including estimates across the terminal zone of many

outlet glaciers (Morlighem et al., 2017). This valuable map has been used to refine our early understanding of the important role of topography on outlet glacier behavior (Hughes, 1975; Mercer, 1978; Weertman, 1961). For example, observations of recent glacier terminus position changes suggest near-terminus topography is a critical determinant of terminus stability (Brough et al., 2019; Bunce et al., 2018; Catania et al., 2018). Although not the case for all glaciers, outlet glacier termini that rest on retrograde slopes of terminal moraines (termed sills in the oceanographic literature) are generally more susceptible to retreat given an external forcing, and, once retreat begins, it may continue unabated until the terminus reaches a region of prograde bed slope (Catania et al., 2018; Schoof et al., 2017; Haseloff and Sergienko, 2018). Uncertainties in bed topography remain in under-sampled regions (Morlighem et al., 2017), however, and because outlet glaciers are sensitive to even small-scale (less than a kilometer scale) topographic variations (Catania et al., 2018; Enderlin et al., 2013), large uncertainties remain in projections of future outlet glacier behavior.

The deep subglacial trough that defines most GrIS outlet glaciers is likely formed through bed erosion over multiple glacial cycles. Deeper troughs are formed in steeper regions of Greenland as a result of greater flow convergence contributing to enhanced erosion (Kessler et al., 2008). This erosion both lowers the bed of outlet glaciers and produces sediment that is transported to the grounding line where it can be deposited in the form of a terminal moraine (Dowdeswell & Vásquez, 2013; Jaeger & Koppes, 2016). The presence of a terminal moraine or sill helps to stabilize the terminus by (1) providing additional flow resistance (Brinkerhoff et al., 2017; Morlighem et al., 2016), (2) limiting the warm water access to the terminus at depth (Bartholomaeus et al., 2013), and (3) reducing buoyancy effects on calving (Enderlin et al., 2018; Post et al., 2011). In fact, the presence of a moraine at the glacier terminus exerts such a profound control on dynamics that the coupling between ice and sediment dynamics is considered to be solely responsible for the tidewater glacier cycle, a pattern of slow advance and rapid retreat for marine-terminating glaciers that occurs in the absence of climate forcing (Brinkerhoff et al., 2017; Post et al., 2011). Rapid retreat occurs as a result of instability of the terminus position resting on a retrograde bedslope, as described above. Advance is controlled by, amongst other things, the rate of sediment transport and is thus related to surface melt. The advance process is slow because sufficient mass must be accumulated and transported to the terminus. To advance into an overdeepened fjord area, a glacier must also bulldoze enough sediment into the overdeepening to sufficiently inhibit frontal ablation and promote terminus advance (Brinkerhoff et al., 2017; Motyka et al., 2006; Nick et al., 2009).

Although frictional resistance to flow provided by a terminal moraine/sill can help to stabilize glacier termini, generally little frictional resistance is provided at the glacier bed where the ice is close to flotation (Enderlin, Carrigan, et al., 2018; Shapero et al., 2016; Stearns & van der Veen, 2019). As a result, the variable width of the glacier fjord and the changes in width that accompany terminus movement also impact glacier dynamics (Carr et al., 2013). Enderlin et al. (2013) found that, all else equal, glaciers with wider termini and/or with geometries that widen inland of the terminus are more sensitive to climate perturbations than their narrower counterparts. In fact, inland widening of the fjord may exert stronger control over retreat than the presence or absence of a terminal moraine (Åkesson et al., 2018).

The geometry up-glacier of the terminus region also exerts control over outlet glacier dynamics. Following terminus retreat, interior losses of ice occur as a result of terminus-induced diffusive thinning that propagates into the interior (Price et al., 2011). Diffusive thinning is understood with kinematic wave theory (Nye, 1960; Pfeffer, 2007; van der Veen, 2001), which relates how a glacier dynamically adjusts to perturbations. The extent of inland thinning for individual glaciers was recently shown to correlate to glacier geometry via the Peclet number, a nondimensional number relating the rate of advection of a perturbation at the terminus to the rate of diffusion (Felixson et al., 2017). Thinning limits occur at the heads of outlet glacier submarine troughs where steep bed slopes restrict diffusive thinning from propagating farther inland, placing important limits on the ability of some glaciers to contribute significantly to near-term sea level rise (Felixson et al., 2017). Inland thinning observations following the near-synchronous 2005 retreat of SE Greenland glaciers support a strong diffuse thinning dependence on surface slope: Up to 10s of meters of thinning were observed along the steep, confined, fast-flowing outlet glaciers within years of terminus retreat with much lower rates of thinning across the flatter interior Howat, Joughin, et al. (2008). Estimates of dynamic mass loss from ice sheet models suggest that mass loss due to such diffusive thinning far outweighs mass loss that directly results from terminus retreat, with 75% of estimated sea-level rise as the result of interior thinning (Price et al., 2011).

5.2. Oceanic Controls of Outlet Glaciers

5.2.1. Calving of Icebergs

Calving is a two-step process involving both the fracture and mechanical detachment of icebergs from the glacier (Bassis & Jacobs, 2013). Although the precise mechanisms driving calving may vary in space and time, observations and models of Greenland's glaciers suggest that three major processes influence the calving volume flux: (1) buoyancy at the terminus, (2) buttressing provided by ice mélange, and (3) undercutting via submarine melt (section 5.2.2). The relative importance of these processes likely varies widely with glacier geometry, which broadly controls the ice flux towards the terminus, the stress balance at the terminus, and the access of warm water to the terminus face.

Glaciers occupying deeply incised channels tend to approach buoyant conditions at their termini. Increases in basal water pressure with subglacial channel depth (such that ocean water does not penetrate the glacial hydrologic system) and the hydrostatic pressure imbalance at the terminus support a generally extensional flow regime that promotes buoyancy at the terminus (Murray et al., 2015). Buoyant flexure at the grounding line (Logan et al., 2013) likely supports basal crevasse formation (James et al., 2014; van der Veen, 1998). Basal crevasses can propagate upwards via tidal pumping to connect to existing surface crevasses and create large volume, full-thickness, laterally extensive iceberg calving events (Amundson et al., 2010; Bassis & Jacobs, 2013; Fried et al., 2018; James et al., 2014; Murray, Selmes, et al., 2015). This buoyant-flexure-driven style of calving can disrupt fjord stratification (Burton et al., 2012) and produce icequakes that are large enough to be recorded globally (Ekstrom et al., 2006; Murray, Selmes, et al., 2015) as the iceberg rotates backwards during detachment and scrapes the new terminus face and/or the subglacial substrate (Amundson et al., 2010). Since buoyancy-driven calving typically requires capsizes of the full-thickness icebergs that detach from the glacier; the rate of calving via this mechanism is sensitive to buttressing provided by the mélange that occupies many Greenland fjords seasonally to perennially (Amundson et al., 2010; Amundson & Burton, 2018; Fried et al., 2018; Robel, 2017). Glaciers that terminate in deep fjords containing seasonal mélange are prone to larger seasonal oscillations in terminus position that are more directly correlated with changes in mélange presence or strength (Cassotto et al., 2015; Fried et al., 2018; Howat et al., 2011; Moon et al., 2015).

Outlet glaciers that are thinner and well-grounded appear to be less sensitive to mélange presence and more sensitive to terminus melt (section 5.2.2), which can dramatically undercut portions of the terminus face (Fried et al., 2015). Eventually, undercutting becomes sufficiently large and torques the overhanging ice (which is typically heavily crevassed) to drive mechanical failure via iceberg sloughing (Bartholomaus et al., 2012; Fried et al., 2015; O'Leary & Christoffersen, 2013). This calving style produces local terminus embayments associated with regions where subglacial discharge emerges at the grounding line (Chauché et al., 2014; Fried et al., 2018). The amount of seasonal terminus change associated with this calving style appears to be directly controlled by the glacier surface melt volume flux via subglacial discharge (Fried et al., 2018). A number of Greenland's outlet glaciers are thin and calve via sloughing, making this an important calving mechanism.

5.2.2. Submarine Melting of Glacier Termini

Submarine melting of glacier termini—the direct mechanism by which the ocean can influence outlet glaciers—has garnered increased attention as growing evidence points towards a correlation between Greenland glacier dynamics and ocean conditions. For example, benthic foraminiferal data from Disko Bay in western Greenland show a close correlation between Jakobshavn Isbrae terminus positions over the last 100 years and subsurface ocean temperatures (Lloyd et al., 2011). Further, modern observations indicate widespread terminus retreat and thinning occurring when climate conditions promote elevated submarine melt rates (Catania et al., 2018; Holland et al., 2008; Rignot et al., 2016; Straneo & Heimbach, 2013) and slowing and thickening occurring when subsurface ocean waters cool (Khazendar et al., 2019). However, no simple relationship exists between ocean and ice that is shared across glacier-fjord systems in Greenland (Slater et al., 2019; Straneo et al., 2016). There are also few observational constraints on submarine melting, further complicating the effort to understand the ocean's forcing on glaciers. Instead the field has relied heavily on untested theory and models to estimate melt rates and their variability.

Submarine melting observations in Greenland are limited and, for the most part, indirect. While the total ice discharge is relatively well constrained at outlet glaciers Enderlin et al. (2014), King et al. (2018), Mankoff et al. (2019), partitioning this ice discharge into calving and submarine melting is an ongoing challenge. Melt rates have been derived from satellite data for floating ice tongues (Enderlin & Howat, 2013; Motyka

et al., 2011; Wilson et al., 2017), but these methods are not possible for the grounded or near-grounded termini that are most prevalent around Greenland. The total submarine meltwater flux can be estimated by measuring the oceanic transports of heat, salt, and mass through a fjord, called the flux-gate or fjord budgets method (Jackson & Straneo, 2016; Motyka et al., 2003, 2013). In Greenland, this method has been applied to synoptic ocean surveys (Inall et al., 2014; Rignot et al., 2010) and long-term moored records (Jackson & Straneo, 2016). However, this approach measures the total submarine meltwater from all upstream icebergs and glaciers and can have substantial errors from limits on the oceanographic record temporal and spatial resolutions (Jackson & Straneo, 2016). Finally, in Greenland, the terminus morphology has been measured with multibeam sonar and used to indirectly estimate or validate melt rates (Fried et al., 2015; Rignot et al., 2015). In Alaska, repeat sonar scans that track the terminus evolution in time—combined with records of ice velocity and calving—have provided a more direct estimate of melt rates (Sutherland et al., 2019), but these new methods have yet to be applied in Greenland.

Without direct measurements of submarine melting, our understanding of the ocean's impact on glaciers is currently limited by three main factors: (1) limited observations and knowledge of the controls on near-glacier ocean conditions in fjords, (2) lack of a validated theory for predicting melt rates based on near-glacier ocean conditions, and (3) unclear impact of submarine melting on calving and upstream glacier dynamics.

Submarine melting is expected to be a function of the near-glacier ocean conditions (temperature, salinity, circulation) and the subglacial discharge flux that forms from surface melt (Jenkins, 2011; Slater et al., 2015). Because of the valley morphology created by outlet glaciers and the large fluxes of surface meltwater delivered seasonally to the glacier bed, meltwater is likely routed to the base of the ice and down the main trunk of the glacier to the grounding line via a few relatively stable subglacial conduits (Fried et al., 2015; Lewis & Smith, 2009). At the terminus, this meltwater is ejected into the fjord at the glacier base and subsequently rises due to buoyancy, forming energetic plumes that entrain warmer ocean waters (Bendtsen et al., 2015; Mankoff et al., 2016; Motyka et al., 2003). Subglacial discharge drives enhanced turbulent transfer of ocean heat across the ocean-ice boundary layer, and thus, the overall rate of ocean heat delivery to the terminus will be function of the subglacial discharge flux and its distribution along the terminus (Carroll et al., 2015; Jenkins, 2011; Sciascia et al., 2013; Slater et al., 2015; Xu et al., 2012). Consequently, submarine melting is expected to be intimately coupled with atmospheric conditions, complicating the task of separating the oceanic versus atmospheric forcing of the GrIS.

The field has relied heavily on theory and models to derive melt rates as a function of the near-glacier ocean conditions and the subglacial discharge flux. A three-equation melt parameterization is typically used to calculate the terminus melt rate as a function of ice-adjacent ocean temperature, salinity and velocity, using empirical coefficients that have been derived from studies of sea ice and ice shelves (horizontal ice-ocean interfaces), and thus are not necessarily applicable to Greenlandic glaciers (Holland & Jenkins, 1999; Jenkins et al., 2010; McPhee et al., 1987; Straneo & Cenedese, 2015). Often this melt parameterization is coupled to a plume model from buoyant plume theory (Jenkins, 2011; MacAyeal, 1985), which is a well-developed theory to describe the evolution of a source of buoyancy (freshwater from subglacial discharge and submarine melt in this case) as it rises through a stratified fluid (Morton et al., 1956). The plume model estimates the ice-adjacent ocean temperature, salinity, and velocity (~ 1 m from ice) based on the far-field ocean properties (>10 – 100 m from the ice) and the subglacial discharge flux. The ice-adjacent conditions are then plugged into the melt parameterization to calculate a melt rate. This coupled plume-melt theory has seen widespread use for estimating melt rates in several ways: on its own (Jenkins, 2011; Magorrian & Wells, 2016; Slater et al., 2016), in numerical ocean models (Carroll et al., 2017; Cowton et al., 2015; Kimura et al., 2014; Sciascia et al., 2013), and in observational studies that measure near-glacier ocean conditions (Jackson et al., 2017; Mankoff et al., 2016). In the last case, melt rates are derived using near-glacier observations, but the resulting melt rates should still be regarded as theoretical or modeled, not observationally validated.

Coupled plume-melt theory has been used to describe two regimes of melting across the terminus: (1) discharge-driven melting where vigorous plumes from subglacial discharge upwell along the terminus and (2) ambient melting away from discharge outlets. Because melting is expected to scale with ice-adjacent plume velocity (Holland & Jenkins, 1999; Jenkins, 2011), energetic discharge plumes should drive elevated melting, while ambient melt rates should be associated with less vigorous velocities and lower melt rates.

As a result, ambient melt is typically assumed to be negligible compared to discharge-driven melting, resulting in a focus on discharge-driven melting (Carroll et al., 2016; Cowton et al., 2015). This has led to recent progress in characterizing subglacial discharge plumes with observations from remotely operated kayaks and tagged seals (Everett et al., 2018; Jackson et al., 2017; Mankoff et al., 2016) and high-resolution ocean models of discharge plumes (Ezhova et al., 2018; Kimura et al., 2014; Xu et al., 2012).

Although models and theory indicate that ambient melt is negligible compared to discharge-driven melt, new observations suggest that ambient melt may play a significant role in the net terminus ablation (Slater et al., 2018; Sutherland et al., 2019; Wagner et al., 2019). If buoyancy from submarine melt and subglacial discharge is the only driver of ocean velocity along the terminus, then the ambient melt regime will be characterized by weak plumes that rise over a short distance (on the order of 1–10 m) and then intrude into the fjord in a series of stacked layers (Magorrian & Wells, 2016). However, this framework neglects the realistic 3-D structure of ocean circulation along the terminus. Slater et al. (2018) combine an ocean model with observed near-glacier velocity to show that horizontal recirculations from the discharge plume will enhance ocean velocity over large swaths of the terminus and likely elevate ambient melt rates, which is corroborated by the surface morphology and ice flux budget in Wagner et al. (2019). At LeConte Glacier in Alaska, direct estimates of submarine melting from multibeam sonar (Sutherland et al., 2019) and near-glacier surveying by autonomous kayak Jackson et al., (2019) reveal that ambient melt rates may be 100× higher than expected from standard plume-melt theory—likely due to a combination of the horizontal velocity field (Slater et al., 2018) and errors in the empirical coefficients that are critically embedded in the melt parameterizations. Though the magnitude of ambient melt at Greenlandic glaciers has yet to be directly measured, these studies suggest that both submarine melt regimes (discharge-driven and ambient melt) are critical to the total terminus ablation. The growing discrepancy between melt theory and observations highlights a need for new observations at the ice-ocean boundary to develop an updated, generalizable theory for submarine melting.

The intertwined dynamics of melting and subglacial discharge might play an important role in understanding where and how submarine melting can effect calving. Subglacial plumes can reach the surface—if the grounding line is relatively shallow, discharge is sufficiently large, and/or if fjord stratification is weak—and can be visible as a vigorous, sediment-laden plume in satellite images (Fried et al., 2015; Jackson et al., 2017; Mankoff et al., 2016). While lower discharge plumes may not rise as high in the water column, the impact of buoyant plumes on terminus melt can be large even for small discharge plumes (Carroll et al., 2016), particularly if sufficient melting near the grounding line generates an overhanging geometry that is favorable to calving via sloughing (Fried et al., 2015; Fried et al., 2019; Slater et al., 2017). In fact, submarine melt and subaerial calving of overlying ice in the vicinity of subglacial conduits are the dominant mechanisms driving seasonal terminus change for thin, well-grounded outlet glaciers in west Greenland (Chauché et al., 2014; Fried et al., 2018; Luckman et al., 2015), and possibly around the ice sheet. This causes thin glaciers to form local terminus embayments in the vicinity of subglacial conduits and often visible surface sediment plumes (Fried et al., 2018). Thicker glaciers likely also experience submarine melt and terminus undercutting near subglacial conduits, but the thick ice possibly insulates against downward surface crevasse propagation, and as a result, the seasonal retreat pattern is more uniform across the glacier width (Fried et al., 2018).

5.3. Atmospheric Controls on Outlet Glaciers

The net ice sheet surface mass balance is primarily the result of an imbalance between winter snowfall accumulation and summer surface melt. Although Greenland air temperatures have been increasing since the mid-20th century (Trusel et al., 2018), mean summer temperatures across the GrIS became positive in the mid-1990s (Mernild et al., 2011; van den Broeke & Lenaerts, 2014). In response to this combined natural and anthropogenic atmospheric warming, GrIS surface melt has increased substantially (Fettweis et al., 2017; Noël et al., 2017; van den Broeke et al., 2016), resulting in a decreasing trend in SMB of 10.2 Gt yr⁻¹ during 1991–2015 (van den Broeke et al., 2016). However, because the atmospheric state can change dramatically over annual and shorter timescale and because Greenland SMB is highly sensitive to atmospheric conditions, variations in SMB are significant (Box, 2013). For example, the long-term trends in atmospheric warming and particularly strong GBI combined in 2012, resulting in GrIS meltwater runoff that was unprecedented within at least the last 350 years (Trusel et al., 2018).

Both long- and short-term variations in SMB can have appreciable impacts on ice flow. Just like their land-terminating counterparts, outlet glaciers are susceptible to surface climate changes that impact surface

slopes: Surface melt causes surface elevation lowering that is enhanced at lower elevations, where temperatures are warmer thus steepening the outlet glacier surface (Felikson et al., 2017; Noël et al., 2016). This can create a positive feedback that enhances ice flow into warmer, low-elevation regions and further exacerbates differences in melt and slope. Changes in outlet glacier surface slopes from along-glacier surface melt are not well investigated, although rates of surface melting at the termini of some outlet glaciers exceed 1 m/year water-equivalent (Noël et al., 2016). The influence of surface melt on surface slope is the primary means by which climate influences ice dynamics in earth system models, not necessarily because it has the largest influence on dynamics, but because its effects on ice flow are well understood.

In addition to SMB-linked slope changes, the generation and variability of surface melt has importance for multiple processes operating on outlet glaciers including: (1) subglacial discharge, which drives submarine terminus melt, calving, and fjord circulation (discussed above); (2) the spatio-temporal distribution of subglacial water pressures, which influence friction at the ice-bed interface; and (3) changes in ice rheology from release of latent heat due to refreezing of meltwater within voids, like crevasses and moulins, in the ice sheet. These processes influence outlet glacier behavior over a wide range of time and space scales, demonstrating the important role of surface climate forcing on the future evolution of outlet glaciers. There has been considerable work done to build regional GrIS climate models (Fettweis et al., 2017; Noël et al., 2017), and these models are well-validated where observations permit (Vernon et al., 2013). Validation sites are limited, however, and there is currently no way to validate the time-varying discharge of subglacial water that runs off the GrIS into the ocean. Research addressing this question for subglacial runoff in land-terminating areas suggests variable model success in capturing observations (Smith et al., 2017)

Around the GrIS margins, where melt exceeds local storage capacity, the vast majority of surface meltwater is efficiently routed to the ice-bed interface through moulins (Catania & Neumann, 2010; Das et al., 2008; Smith et al., 2017). The spring onset of meltwater flux to the bed raises subglacial water pressure at the ice-bed interface because of limited water storage capacity and decreases friction at the bed, facilitating faster ice flow (Andrews et al., 2014; Iken et al., 2017; Meierbachtol et al., 2013). Such observations are taken from land-terminating parts of the ice sheet using boreholes to suggest that the subglacial drainage system (and thus the water pressure distribution at the bed) is complex and composed of both subglacial conduits that are sensitive to creep closure and unchannelized bed regions that gain efficiency as the melt season progresses (Andrews et al., 2014; Bougamont et al., 2014; Hoffman et al., 2016). Observations suggest that there is good agreement between regionally modeled ice sheet runoff and ice flow speed in outlet glaciers (Moon et al., 2014; Rathmann et al., 2017), but it is not clear if this is a direct relationship because runoff can alter subglacial hydrology as well as enhance upwelling, melt, and retreat at the terminus (Fried et al., 2018); both of which will influence ice flow resistance. A few studies have examined the influence of subglacial conditions on outlet glacier ice flow speeds using surface and/or borehole geophysics, finding that a highly deformable ice layer exists near the base of each glacier, which is interpreted to be temperate pre-Holocene ice that contributes substantially to total ice motion (Hofstede et al., 2018; Lüthi et al., 2002). Further, outlet glaciers are likely to be underlain with subglacial sediments (Christianson et al., 2014; Hofstede et al., 2018; Walter et al., 2014), with complex spatial patterns of basal slipperiness and suggesting that basal conditions for outlet glaciers may vary over small (~100 m) scales. Finally, because glaciers terminate in the ocean with water depths of 10s–100s of meters, high water pressures exist year round and seasonal changes in flow at glacier termini can result in ice thickness changes that are felt far inland (Young et al., 2019).

Although the majority of surface meltwater routes efficiently to moulins (Smith et al., 2017), there is some evidence for meltwater retention within or beneath the ice sheet. If englacial water refreezes, it releases latent heat into the surrounding ice in a process termed cryo-hydrologic warming (Phillips et al., 2010). Indeed, temperature profiles in boreholes reveal warmer englacial temperatures than would be present from heat diffusion and dissipation alone (Harrington et al., 2015; Lüthi et al., 2015). This heat has the ability to soften the ice, which has a temperature-dependent rheology and may be responsible for some of the observed enhanced ice flow in Greenland (Poinar et al., 2016; van der Veen et al., 2011). Where fast speeds reduce the transit time for ice through the ablation zone (where surface melt is generated), however, the potential impact of cryo-hydrologic warming is likely small (Poinar et al., 2016). In addition to ice temperature and water content, ice viscosity is also a function of the effective strain rate. Bondzio et al. (2017) show that sustained Jakobshavn Isbrae acceleration, following the termination of a retreat period, is due to a decrease in ice viscosity by four orders of magnitude. Because of low basal drag for Jakobshavn Isbrae, most of the driving stress is supported by the lateral shear margins (Shapiro et al., 2016; van der Veen et al., 2011), and

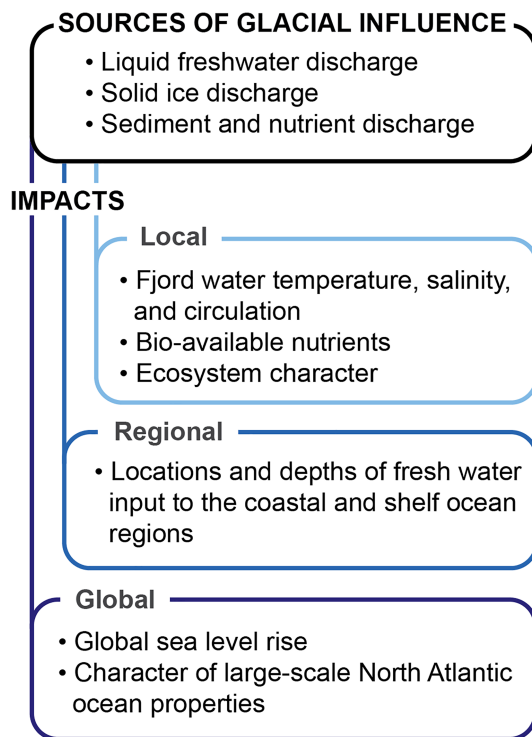


Figure 4. Impacts from GrIS outlet glaciers are felt across a range of spatial scales all of which are key remaining unknowns ripe for future research.

sudden changes in the calving front induce stress perturbations that promote an instantaneous drop in ice viscosity within the shear margins, which further weaken via strain heating (Bondzio et al., 2017). Such observations suggest that ice sheet thermal processes and ice sheet viscosity changes are critical to model to understand changing outlet glaciers.

6. Impacts of a Changing GrIS to the Arctic

While mountain glaciers and ice caps were the largest land ice contributor to sea level rise during the 1990s and 2000s (compared to Greenland and Antarctica), the GrIS began to match and exceed that contribution around 2013 (Chen et al., 2017). The much larger reservoir of potential sea-level rise contained in the GrIS (7.42 ± 0.05 m (Morlighem et al., 2017)), versus mountain glaciers and ice caps (0.32 ± 0.08 m (Farinotti et al., 2019)), gives Greenland the capacity to maintain current (or higher) loss rates much further into the future. This underlies the importance of understanding the mechanisms responsible for mass change in order to improve estimates of the rates of change that are possible. The projected range of future GrIS mass loss across different greenhouse gas emissions scenarios (Vaughan & Comiso, 2014) shows strong overlap over the next several decades, but diverges substantially over the next several centuries (Aschwanden et al., 2019; Clark et al., 2016; Mengel et al., 2016). Projections of future GrIS mass loss under an RCP8.5 forcing (a representative concentration pathway producing 8.5 W/m^2 radiative forcing in 2100 (Vaughan & Comiso, 2014)) suggest that GrIS mass loss could reach up to 33 cm by 2100 (Aschwanden et al., 2019). Between 1972 and 2018, the

ice dynamics contribution to total mass loss was $66 \pm 8\%$ (9.1 mm), and SMB was $34 \pm 8\%$ (4.6 mm) (Mouginot et al., 2019); however, as air temperatures continue to increase, large surface melt events (Nghiem et al., 2012) will occur with increased frequency (Trusel et al., 2018), and SMB losses are expected to increase (Aschwanden et al., 2019; Fyke et al., 2014). Unfortunately, partitioning future mass loss from Greenland is still difficult owing to uncertainties in surface melt processes (Aschwanden et al., 2019; Fürst et al., 2015) and the complexities of interconnected mechanisms described above.

The impacts of GrIS mass loss not only depend on the magnitude of mass loss, but its spatial distribution as well. Local sea-level change experienced in coastal cities is sensitive to the “fingerprints” of mass loss from the ice sheets—the amount of SLR expected across the globe depends on where the mass loss is concentrated (Larour et al., 2017; Mitrovica et al., 2009; Mitrovica et al., 2018). For example, in the United States, Los Angeles will experience greater sea-level rise due to Greenland mass loss than New York, and most U.S. locations are more sensitive to eastern Greenland mass loss than western Greenland mass loss (Larour et al., 2017).

Spatial variations in the delivery of freshwater (and sediments) to the ocean via outlet glaciers also affects ocean dynamics and nutrient fluxes (Figure 4). This freshwater influences ocean stratification and circulation, both locally within fjords and regionally around the continental shelves of Greenland. Freshwater input from glaciers—from subglacial discharge and submarine melting of glaciers and icebergs—can drive a fjord-wide exchange flow (Carroll et al., 2015; Sciacchia et al., 2013), which may impart a positive feedback on future ice mass loss from Greenland by enhancing ocean heat delivery through fjords (de la Guardia et al., 2015). Additionally, these sources of freshwater enter the ocean at depth (often many 100s of meters below the surface) and drive vigorous upwelling of deep waters. Thus, Greenland outlet glaciers impact the ocean both as a source of a freshwater and as a powerful mechanism for vertically redistributing oceanic water masses, pumping heat and salt from the deep ocean to the surface layer (Beaird et al., 2015; Beaird et al., 2018).

The partitioning of mass loss between solid and liquid components is also important, as the timing of iceberg melt is offset from other sources (e.g., peaking in fall rather than summer) and iceberg melt injects freshwater

into the surface of the ocean over much broader regions (Enderlin et al., 2018; Moon et al., 2017). The ratios of solid to liquid freshwater flux vary substantially around the ice sheet (Enderlin et al., 2014; Mougnot et al., 2019), with iceberg freshwater fluxes dominant over all other terms in fjords connected to high discharge outlet glaciers (Enderlin et al., 2016; Moon et al., 2017). At the ice sheet scale, however, liquid freshwater fluxes from GrIS meltwater runoff dominate solid fluxes (~ 1300 to ~ 1170 km³ yr⁻¹) with small liquid fluxes from Greenland's peripheral glaciers and ice caps (~ 920 km³ year⁻¹) and terrestrial runoff (~ 860 km³ year⁻¹) since 2010 (Bamber et al., 2018). Variations in the magnitudes of these freshwater flux components impact the circulation pathways of the freshwater in the Arctic (Böning et al., 2016; Luo et al., 2016), with the capacity to impact deep water formation in the North Atlantic and globally (Böning et al., 2016).

Outlet glaciers are also important for producing and redistributing nutrients to the Arctic ocean (Cape et al., 2018; Hopwood et al., 2018; Kanna et al., 2018; Meire et al., 2015; Meire et al., 2017; Overeem et al., 2017). There are two primary mechanisms at play: (1) direct nutrient input to the grounding line via subglacial discharge that supplies turbid melt water and (2) enhanced nutrient upwelling from the deep ocean due to the input of subglacial discharge at depth. Research at multiple marine-terminating glaciers around Greenland suggests the second mechanism is more important, with upwelling nitrate fluxes that are 10 times larger than discharge fluxes (Cape et al., 2018; Hopwood et al., 2018; Kanna et al., 2018), and direct comparison of fjord productivity near marine-terminating versus land-terminating glaciers confirms the importance of deep water input from marine-terminating glaciers for sustaining high productivity (Meire et al., 2017). In addition, the surface layer in fjord systems is undersaturated in CO₂ due to the input of glacial meltwater, indicating that fjords are strong CO₂ sinks (Meire et al., 2015) and thus important, but overlooked, components of the Arctic carbon cycle. As outlet glaciers continue to retreat into the interior of the GrIS, many will retreat up subglacial beds that rise steeply above sea level behind the present-day terminus (Catania et al., 2018), effectively eliminating their connection to the ocean. This decoupling of glaciers (and their meltwater) from the ocean will have important consequences for the timing and spatial distribution of nutrient delivery and the carbon cycle in the Arctic ocean (Hopwood et al., 2018; Meire et al., 2015).

7. Future Research Needs

At the heart of improved predictions of outlet glacier contributions to sea level and freshwater forcing of neighboring ocean basins is our ability to accurately model outlet glacier dynamic changes and how these changes influence, and are influenced by, climate. In turn, this requires improved understanding of the processes that influence glacier dynamics and concerted effort to link ice sheet models to existing ocean and atmosphere models. Importantly, these links need to be two way because of the intimate interplay of processes at work driving change at the ice sheet margin, and the ability of this change to, in turn, impact the global climate system (Golledge et al., 2019). Thus, future research advances require more observations of critical processes that govern glacier dynamics, better integration of critical processes (e.g., terminus change) in numerical ice flow models based on these observations, and continued development of, and collaboration within, an interdisciplinary and diverse scientific community.

7.1. Meeting Observational Needs

Spaced-based observations of Earth's glaciers and ice sheets have been acquired at an accelerated pace over the last few decades as new satellite missions are launched (e.g., ICESat and GRACE), existing ones are prolonged (e.g., Landsat, ICESat-2, GRACE-FO, CryoSat-2, Sentinel), and nongovernmental agencies have become involved in polar imaging (e.g., DigitalGlobe). These instruments provide observations of many of the essential variables involved in glacier dynamic changes including surface elevation, terminus position, and surface speed. The timescales of data acquisition have also improved with many observations made at month-to-seasonal frequency, which is necessary to remove observation biases. Surface speeds and elevations are now automatically generated for the entire ice sheet and provided to public databases with regular updates (Fahnestock et al., 2016; Howat, 2017; Howat et al., 2014; Joughin et al., 2010; Rosenau et al., 2015). Care must be taken to ensure long-term continuation of these important observations, particularly for studies that examine the attribution of ice sheet change to anthropogenic and/or natural climate change, as has been done for alpine glaciers worldwide (Marzeion et al., 2014). The extraction of terminus positions from satellite data, on the other hand, remains a manual process performed as needed by individual researchers. Machine learning techniques are beginning to make this task less onerous (Lea, 2018; Mohajerani et al., 2018), although terminus mapping in the often cloudy, ice-congested, and seasonally shadowed conditions may still require semimanual delineation by a well-trained operator, a particularly time-consuming

endeavor. We encourage community collaboration to rapidly make these records available for the satellite data archive and continued efforts focused on automated picking of termini. These data will be valuable for multiple reasons, but importantly by identifying terminus “hot spots” over the satellite era (regions of focused, rapid change), we can focus ice sheet models to produce higher resolution solutions for individual glacier basins and use these estimates to update sea-level predictions.

Important observational gaps also exist in terms of understanding how subglacial processes influence glacier dynamics, noted by the lack of an agreed-upon sliding law (Joughin et al., 2019). While additional in-situ geophysical observations are needed (e.g., drilling, passive and active seismic, etc.), such observations are costly and logistically difficult on heavily crevassed outlet glaciers. Further, while models have rapidly accelerated in development to the point where now they can reproduce the bulk of some of the hard-won observations (Hoffman et al., 2016; Stevens et al., 2018; Werder et al., 2013), many of these observations take place on land-terminating portions of the ice sheet. Evidence from ground-based geophysics on a small number fast-moving outlet glaciers points to a sediment layer on the order of 100 m thick that underlies with highly variable slipperiness (Christianson et al., 2014; Hofstede et al., 2018; Walter et al., 2014). This suggests a need for additional ground-based observations aimed at characterizing the possible range of subglacial conditions that exist under outlet glaciers. Further, since subglacial erosion and deposition contribute to changes in subglacial water pressure (Andrews et al., 2014; Catania & Paola, 2001), and influence glacier stability (Alley et al., 2007; Brinkerhoff et al., 2017; Nick et al., 2007), the rates of these processes need to be measured as well. Additionally, understanding how subglacial drainage evolves over time and how this, in turn, influences outlet glacier velocity is still uncertain and ripe for additional model development. In particular, the redistribution of stresses within an outlet glacier are likely to adjust on a range of time scales in response to changing subglacial conditions. Estimates of glacier stresses minimally require time-evolving observations of surface speed and elevation. Sufficiently highly resolved surface topographic observations are available at least annually (Porter et al., 2018); however, shorter time scale changes may also be relevant (Enderlin, Carrigan, et al., 2018). In addition, it is unclear how basal resistive stresses behave outside of the regions covered with subglacial conduits, arguing for increased spatial resolution in observational data needed for force balance studies.

In addition to its influence on basal properties, surface melt plays a critical role in controlling outlet glacier dynamics through its influence on submarine terminus melt hence possibly the rate of calving. Unfortunately, we currently lack the ability to regularly and uniformly validate subglacial discharge estimates in the submarine environment. Most estimates come from regional climate model evaluations of surface melt-derived runoff with routing via the subglacial drainage system. Partitioning of runoff within a given drainage system introduces errors in runoff estimates, and some meltwater could be stored subglacially or in the surface firn layer (Forster et al., 2014; Rennermalm et al., 2013). Seismic techniques have been proven viable to elucidate patterns in subglacial water movement and storage (Zhan, 2019) as well as subglacial discharge flux through time (Bartholomaeus et al., 2015), and we argue for widespread observations of subglacial tremor in Greenland in order to reduce uncertainty in model-based estimates of subglacial water storage, transport, and discharge.

The ocean influence on the GrIS has recently been a target for accelerated research with three emerging research needs related to ice-ocean interactions. The first need involves understanding the ocean conditions near glacier termini, how they vary in time, and what drives this variability. This involves understanding the drivers of ocean circulation at the fjord scale and fjord-shelf exchange, as well as larger scale ocean processes (the origin of AW and PW, decadal variability, etc.). While there has been considerable progress on this over the last few decades, we critically lack systematic, long-term monitoring of ocean properties around the GrIS (Straneo et al., 2019). This should include observations of heat content and fjord/shelf conditions with an aim to improve understanding of how fjord and shelf properties are related to near-glacier properties and then how those are related to melt rates at glacier termini. In addition, we prioritize velocity data within fjords because these data are critical for understanding fjord-scale processes, measuring freshwater export, and monitoring heat transport. Many groups have conducted difficult and expensive observational campaigns to obtain moored observations in select glacier fjords and around the GrIS (Carroll et al., 2018; Gladish et al., 2015; Gladish et al., 2015; Mortensen et al., 2014; Straneo et al., 2016), but these efforts only began within the past ~10 years and are often not maintained long term, so there remains a limited understanding of the temporal evolution in ocean forcing of the ice sheet. There is significant opportunity for coordinated

ocean-observing platforms as suggested by Straneo et al. (2019) to overcome these observational bottlenecks and provide critical data necessary to address this need.

The second research priority related to ice-ocean interactions involves improved understanding of terminus submarine melt rates and how they relate to ocean conditions near the terminus. There has been rapid advancement in obtaining observations close to glacier termini via autonomous platforms (Jackson et al., 2017; Mankoff et al., 2016), but these have been limited to a few glaciers and do not allow for direct measurements of melting nor validation of modeled melt rates. In addition, the existing near-glacier observations are taken in summer, when glacier termini are easier to access by boats; however, biases in the spatial and/or temporal coverage of observations may limit our understanding of the seasonal evolution of melt processes. Finally, recent studies (Carroll et al., 2016; Slater et al., 2018; Sutherland et al., 2019) suggest that melt rates might be significantly underestimated by the prevalent melt parameterizations (Holland & Jenkins, 1999; Jenkins, 2011; Magorrian & Wells, 2016). Thus, we argue for more observations—near the ocean-ice boundary and across a range of glacier-fjord systems—to obtain a generalized, observationally validated theory that can link terminus melt rates to ocean conditions and subglacial discharge flux.

The third research need for ice-ocean interactions involves improving our understanding of how submarine melt impacts the glacier, including calving. Observations of melt-induced calving primarily come from smaller glaciers that do not have iceberg-congested fjords, biasing our understanding of calving processes to these glaciers. We have no estimates for how important submarine melt is for large-flux, deeply grounded outlet glaciers with persistent, year-round mélange. In particular for these larger glaciers, the importance of submarine melt on the propagation of basal crevasses may be important to determining the calving flux (James et al., 2014; Murray, Selmes, et al., 2015).

A final observational need includes improved estimates of fjord bathymetry and basal topography in terminus regions of outlet glaciers. These data are of fundamental importance to glacier stability, as well as to understanding ocean heat transport to the ice sheets and freshwater exchange with the Arctic Ocean. Despite the rapid acquisition of new observations from projects like oceans-melting-greenland in many fjords (Morlighem et al., 2016), there remain numerous glaciers where topography is poorly constrained, primarily those along Northern Greenland (Morlighem et al., 2017). Many of these fjords, as well as those along SE Greenland, are choked with icebergs year-long, making it difficult to gain ship access close to the glacier termini. Further, radar-based efforts to map the ice sheets are to be commended for the rapid pace at which observations have accelerated; however, the heavily crevassed, meltwater-rich, deep outlet glaciers remain a challenge for radar-energy propagation to the bed. Observations of basal topography for a few key outlet glaciers should be prioritized, possibly through drone, or helicopter support.

7.2. Including Critical Processes in Models

Over the last several years, as the sensitivity of GrIS outlet glaciers to changes in atmospheric and oceanic forcing has become more apparent, there have been tremendous advances in our understanding of critical processes controlling ice dynamics as well as in numerical modeling of glaciers and ice sheets. However, progress in observations and models has largely occurred side-by-side, with a few exceptions where observations for a specific glacier system are sufficiently dense that observation-based numerical modeling of the coupled ice-atmosphere-ocean system can be performed (Bondzio et al., 2017; Seroussi et al., 2014; Todd et al., 2018). As a result, we argue for model development to prioritize the inclusion of data via assimilation techniques (Goldberg et al., 2015; Heimbach et al., 2019) to produce ice sheet projections that are fully consistent with past observations. In part, this remains a challenge because of the lack of observations of changing bed and terminus conditions, but also because of the possibly high dependence of ice dynamics to unmeasured quantities (e.g., small-scale bathymetry or bed characteristics, factors influencing ice rheology). Further, this requires an assurance that data—including processes study results—are findable, accessible, interoperable, and reusable (FAIR) (Wilkinson et al., 2016). This includes efforts to establish and use standard data formats and to create suites of data that are curated to tackle interdisciplinary science questions. Well-designed data access and visualization systems are also invaluable for reducing startup times for new research and researchers, facilitating connections between glaciology and other disciplines and providing tools and information for connecting with stakeholders.

The shift in focus to more realistic boundary processes in numerical ice flow models should result in the development of parameterizations that can be feasibly implemented into large-scale numerical models (i.e., that have reasonable computational demands). This task is challenging for several reasons. First, there is

still debate on how to parameterize important processes like submarine terminus melt, calving, and basal sliding. The recent surge of new observational data around the GrIS has enabled observation-based testing of a number of existing process parameterizations that control glacier flow (Bondzio et al., 2017; Choi et al., 2017; Choi et al., 2018; Enderlin & Bartholomaeus, 2019; Stearns & van der Veen, 2018), but these must be generalized across all glacier systems and validated with observations. Second, improvements in model resolution and nested modeling techniques are beginning to allow full ice sheet models to resolve outlet glaciers (Aschwanden et al., 2016; Aschwanden et al., 2019), but resolution challenges continue. On the oceanic side, connecting ocean processes across a range of scales, from the continental shelf to the turbulent ice-ocean boundary layer, remains an open challenge to the research community. Small-scale plume models (~1 m resolution) can resolve the upwelling plumes at glacier termini; fjord models (~100 m resolution) capture larger circulation patterns between the glacier and shelf ocean, and regional models (~1 km resolution) reveal shelf and subpolar gyre dynamics. Typically, these scales are studied separately, but going forward these various scales must be integrated more effectively in order to model the interaction between the large-scale ocean and the GrIS.

Third, several of the processes important to ice-ocean interactions require coupling to atmospheric parameters, and integration across all of these models is challenging, particularly given the observed sensitivity of the GrIS to atmosphere and ocean change and the substantial uncertainties in future atmospheric and oceanic conditions (Pattyn et al., 2018). This is hard and costly, but remains a necessary step so that ocean models no longer ignore solid ice discharge (Luo et al., 2016), convert solid ice discharge immediately to liquid flux, and/or input all freshwater into the ocean surface (Böning et al., 2016; Gillard et al., 2016) but instead incorporate time-evolving partitioned freshwater fluxes appropriately. Simpler modeling approaches could, and have been, applied to project glacier or changes in glacier boundary conditions over shorter timescales. For example, Bamber et al. (2018) use the relationship between SMB and ice discharge estimates to extrapolate discharge to years without observations. Slater et al. (2019) use relationships between observed terminus change and submarine melt estimates, forced using future atmospheric change scenarios, to predict 21st century GrIS terminus change. Although there is utility in these methods, they are unlikely to yield accurate projections of GrIS mass loss over long time scales since the evolution of the glacier geometry as it recedes will undoubtedly influence its sensitivity to climate change and ice discharge. Thus, despite the difficulties coupling numerical models and uncertainties in these models, they are the most likely to yield accurate mass loss estimates and we recommend that future modeling efforts focus on their continued development.

7.3. Community Coordination and Capacity Building

Solutions to many of the research challenges presented above are within reach, given sustained, coordinated funding. More frequent in-situ observations of deep ocean circulation around the GrIS coupled with long-term observations within multiple glacial fjords would provide much-needed data to test parameterizations of ice-ocean exchanges. Thus, there is significant opportunity for funding agencies to work across internal boundaries and with international partners to facilitate the development and maintenance of such observations. In lieu of large funding schemes for collaborative observational platforms, we urge the dismantling of boundaries that hamper intellectual collaboration. The recent rapid growth of interest in outlet glaciers in Greenland, and ice-ocean interactions in particular, has been matched with rapid expansion of knowledge on processes and information that would have taken the previous generation of glaciologists much longer to acquire in isolation. We argue for an even more expansive community of scientists interested in the GrIS because the inclusion of outside knowledge and experience drives innovation in our field. This includes increasing diversity in our field, expanding international collaborations (including with indigenous knowledge holders and local communities) and integrating across an even wider range of scientific disciplines. These necessary advances can, in part, be accomplished through joint AGU Fall Meeting sessions across typically separated focus groups, special conferences focused on specific problems that remain unresolved at the boundaries of traditional disciplines, greater international cooperation similar to the joint U.S.-U.K. efforts underway at Thwaites Glacier funded through coordinated efforts at NERC and NSF, and a wider range of mechanisms that engage and support new researchers within our community. Achieving these goals will also advance opportunities to explore the impacts of the current rapid reconfiguration of the GrIS in a system science context, where many of today's most exciting discoveries are being made. In addition, because so many of the recent discoveries in ice-ocean exchanges in Greenland have occurred through

teams composed of diverse scientists, we suggest that awards from scientific societies be augmented to recognize the enormous team efforts needed to produce quality observations in many of the far-flung reaches of the poles. AGU could lead such an effort.

8. Outlook

As a community, glaciology has moved quite rapidly in the last few decades spurred by outside interest, increased quantity, quality, and access to data, and improved methods for interpreting and reproducing observations with ice flow models. However, we still have not solved the problem of how much sea level will rise, when, and where it will come from. Much work is focused on these goals, and we encourage greater coordination from funding agencies, data providers, and within research communities to make rapid progress on this grand challenge. Observational challenges remain, primarily in the ice-ocean and at the ice-bed interfaces, but these can be overcome with targeted, well-coordinated, long-term monitoring and improved technology for observing bed properties and submarine termini. These efforts should be prioritized by funding agencies. Model development is also making great leaps in resolution and incorporation of processes. That community has come a long way from the Fourth Assessment Report from the IPCC (Lemke et al., 2007), which stated that although observations indicated the importance of dynamical processes in ice sheets, they were not included in ice sheet models because of the lack of consensus on their ability to increase ice sheet loss in a warming climate. Further progress is needed to link ice sheet models to the climate and ocean models that exist outside of our community. This is particularly important for ice-ocean exchanges because of the range of impacts that are associated with a melting GrIS.

Glossary

ice sheet mass balance The difference between ice sheet mass accumulation (e.g., through snowfall) and ablation (e.g., through meltwater runoff and calving). Ice sheet mass balance is usually measured on an annual timescale to capture seasons of accumulation and ablation.

surface mass balance The difference in mass caused only by changes in accumulation and ablation independent of calving and iceberg discharge (which are associated with ice dynamics). Primary contributors to surface mass balance are snowfall and meltwater runoff.

ice dynamics Describes the motion within large bodies of ice, such as glaciers and ice sheets, subject to numerous processes that influence the rheology of ice and the boundary conditions.

calving The process of breaking ice from the end of a marine-terminating glacier or ice shelf, adding broken ice to the ocean, which are then referred to as icebergs (bergy bits and growlers are smaller than icebergs).

grounding line The subglacial location at which the glacier terminus region loses contact with ground beneath it. Sometimes also referred to as a grounding zone. Up-glacier of the grounding line, the glacier is 'grounded' while down-glacier the glacier is floating.

moraine Unstratified and unsorted rock and sediment piles moved into place via sediment deposition, glacier erosion and flow. Moraines can exist in front of, next to, and along interior flowlines of a glacier. Oceanography disciplines use the term sills to describe moraines.

tidewater glacier cycle The idea that tidewater glaciers undergo cycles of dynamic behavior that oscillate between slow advance and rapid retreat, punctuated by periods of stability. This oscillation occurs with little sensitivity to climate forcing.

moulins A tubular chute through which water enters the glacier from the surface. Moulins may be formed by surface meltwater entering a crevasse, with water flow maintaining the channel.

firn As surface snow remains past one year (one melt season) it is compressed, becoming more dense than snow but less dense than glacier ice. This intermediate material is called firn. As firn densifies the pore spaces within it becomes less connected and ice crystal size usually increases.

glacier hypsometry Hypsometry describes the distribution of glacier surface elevation with respect to sea level within an area of interest, with positive values being above sea level and negative values below sea level.

Acronyms

- SMB** Surface Mass Balance
- GrIS** Greenland Ice Sheet
- NAO** North Atlantic Oscillation
- GBI** Greenland Blocking Index
- AMO** Atlantic Multidecadal Oscillation
- AW** Atlantic Water
- PW** Polar Water
- PARCA** Program for Arctic Regional Climate Assessment
- ATM** Airborne Topographic Mapper
- ICESat** Ice, Cloud, and land Elevation Satellite
- GRACE** Gravity Recovery And Climate Experiment
- LIA** Little Ice Age
- RCP** Representative Concentration Pathway
- IPCC** Intergovernmental Programme on Climate Change
- FAIR** Findable, Accessible, Interoperable, and Reusable
- NSF** National Science Foundation
- NERC** Natural Environment Research Council

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