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Topographic modulation of outlet glaciers in Greenland: a review

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Abstract

Bed topography is a critical parameter for determining the modern-day and future dynamics of ice sheets and their outlet glaciers. This is because the topography controls the state of stress for glaciers. At glacier termini, topography can influence the timing of terminus retreat by controlling access to warm ocean waters and/or by influencing the ability of a glacier terminus to retreat over bed bumps (moraines). Inland from the terminus, the topography can also influence where glacier retreat and thinning can stabilize. In part, this is because of knickpoints in bed topography created through glacial erosion that may influence the extent to which thinning can diffuse inland for an individual glacier and thus, the timing and magnitude of long-term mass loss. Here we provide a review of the current literature on these topics. While much of the reviewed literature assumes that topography is stable on relevant timescales to humans, new research suggests that topography may change much faster than previously thought and this further complicates our ability to project future outlet glacier change.

1. Introduction

The Greenland Ice Sheet (GrIS) is presently the largest contributor of added mass to rising sea levels (10.9 mm; 22.3%), recently surpassing alpine glaciers and ice caps (7.5 mm; 15.4%), the Antarctic Ice Sheet (6.4 mm; 13.1%) and land water storage (7.2 mm; 14.8%) (IPCC, 2021). For comparison, sea level rise due to thermal expansion accounts for 16.7 mm (34.4%) (IPCC, 2021). For Greenland, most of the mass loss is concentrated around the periphery of the ice sheet (Velicogna and others, 2020) due to the low elevations found in these regions (Pritchard and others, 2009; Shepherd and others, 2020), which promotes large negative surface mass balance (Fettweis and others, 2020), abundant supraglacial melt that promotes fast flow at the ice sheet bed (Andrews and others, 2014; Nienow and others, 2017), and the presence of nearly 300 fast-flowing outlet glaciers that act as conveyor belts draining ice from the interior toward the coast (Joughin and others, 2010; Moon and others, 2020). Outlet glaciers are impacted by numerous processes including external climate triggers (surface mass balance and oceanographic heat transfer), which in turn impact the boundary conditions of glaciers (Nick and others, 2009; Howat and others, 2010; Straneo and Heimbach, 2013; Catania and others, 2020). Externally, topography of the ice sheet bed influences surface elevation and ice thickness gradients and thus exerts a first-order control on ice dynamics. This means that while outlet glaciers remain acutely sensitive to climate change (ocean and atmosphere), the magnitude of dynamic adjustment that they make in response to climate perturbations is to a large degree controlled by topography. This idea has been suggested previously by Pfeffer (2007) and forms the premise of this brief review paper.

Our review of the current understanding of how topography controls GrIS mass loss focuses on outlet glacier dynamic response, which exhibits heterogeneity between individual glacier catchments in ice thickness (Csatho and others, 2014), velocity (Moon and others, 2020), and terminus change (Murray and others, 2015; Catania and others, 2018). We first discuss early theories underlying our understanding of irreversible glacier retreat related to topography and how modern observations and modeling of subglacial topography may be used to explain the observed heterogeneous response of the GrIS outlet glaciers to recent climate change. We then discuss the role of topography in modulating the ability, timing and amount of terminus retreat of marine-terminating outlet glaciers as well as how topography far inland from the terminus influences the amount of mass loss resulting from a terminus perturbation. Finally, we will explore the commonly held assumption that topographic change with time is slow and not necessary to include in ice sheet models. We end with an outlook on future research priorities aimed at improving our understanding of topographic influence on the GrIS.

2. How topography controls ice sheet change

The bed topography of ice sheets is deeper in the interior than at the periphery of the ice sheet owing to lithospheric loading that depresses the crust where the overlying weight of ice is greatest (Fig. 1). As a result, Earth's remaining ice sheets both have basal topography that is largely characterized as retrograde - sloped inward to the ice sheet interior from the margins.

Early research into the impact of ice sheets on retrograde bed slopes under climate warming led to the development of a theory now termed Marine Ice Sheet Instability (MISI) (e.g., Weertman, 1974; Mercer, 1978; Thomas and Bentley, 1978). MISI suggests that glaciers and ice sheets resting on retrograde beds are more susceptible to rapid and irreversible mass loss as the climate warms. This is because the flux of ice through the grounding line increases with bed depth. Thus, ice sheet retreat on retrograde bed slopes results in greater flux of ice and additional retreat. This runaway process is suggested as a possible mechanism that could lead to rapid collapse of the West Antarctic Ice Sheet, with the potential for much faster rates of sea level rise than currently estimated (IPCC, 2021). Early theories regarding MISI laid the groundwork for modeling this process. This includes Schoof (2007), who found that the presence of topographic overdeepenings results in hysteresis in terminus position; termini that sit on retrograde bed slopes have unstable grounding line states and can rapidly retreat given a climate perturbation, while termini that sit on prograde bed slopes are stable and can advance given a climate perturbation.

3. Topography observations for Greenland

While the theory and modeling of MISI demonstrated its importance, there has been little observational evidence of it in part due to the lack of adequately resolved bed topography. Bed topography became more readily resolved with the collection and publication of radar-derived bed topographic data and the use of these data via the production of BedMachine (Figure 1; Morlighem and others, 2011), a data-constrained estimate of the bed elevation for the GrIS. BedMachine uses radar-derived ice thickness, surface velocity and surface mass balance data with the assumption of mass continuity to estimate bed elevation for fast-flowing portions of the ice sheet. This approach is an improvement over kriging because it provides a physically-realistic bed elevation in areas where radar data are unavailable. This technique is focused at the fast-flowing margin of the ice sheet and in the slower-flowing interior, BedMachine relies on kriging to interpolate between radar-derived ice thickness measurements to create a complete map of topography beneath the ice sheet. BedMachine has been improved over time with the addition of fjord bathymetry data (Fenty and others, 2020), providing seamless topography across outlet glacier termini (Morlighem and others, 2023).

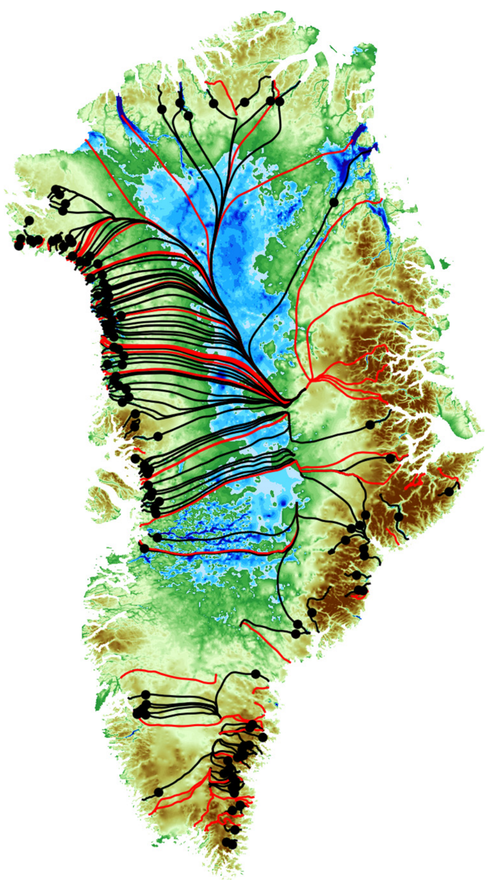

Figure 1. Topography of the Greenland Ice Sheet from BedMachine (Morlighem and others, 2023) showing the location of knickpoints (black dots) and outlet glacier flow lines (black and red lines). Black lines are glaciers with knickpoints, red do not have knickpoints. All data from Felikson and others (2020).

While BedMachine provides improvements to bed topographic estimates, the terminal regions of outlet glaciers remain poorly resolved because radar-derived ice thickness is more difficult to obtain in these wet, crevassed and deep regions. Further complicating improvements to outlet glacier topographic measurements is the fact that there are nearly 300 outlet glaciers, each with their own unique characteristics, making data collection onerous. The topography that shapes outlet glaciers partially arises because glaciers are natural erosive agents (Kessler and others, 2008; Koppes and Montgomery, 2009; Love and others, 2016) capable of delivering large amounts of sediment to their termini where it often becomes visible as sediment plumes at the fjord surface (McGrath and others, 2010; Hudson and others, 2014). Glacier erosion is likely to be largest where ice is moving fastest and where there is efficient removal of sediment via an active subglacial system (Hallet and others, 1996; Cowton and others, 2012; Love and others, 2016; Brinkerhoff and others, 2017). Supraglacial water delivery to the bed downstream of the equilibrium line provides a steady water supply in summers, possibly explaining the much deeper beds observed in these locations (Fig. 2). In addition to erosion, because many outlet glaciers approach floatation toward their margins, sediment may preferentially deposit close to the terminus creating a moraine (sometimes called a sill in the literature), which also shapes the topography at termini (Figure 2; Batchelor and others, 2018). Comparisons of BedMachine to radar-derived topography in outlet glaciers reveals that there may be a systematic offset of the bed elevation between the two but that the radar-derived bed slopes are well-preserved in BedMachine (Morlighem and others, 2017; Catania and others, 2018; Narkevic and Anton, 2023). In addition, BedMachine is unrealistically smooth at small scales making it less useful for examining subglacial water routing and the influence of small-scale bed features on dynamics (MacKie and others, 2021). Stochastic modeling of bed topography has emerged as an additional technique to simulate the most realistic bed topography using the statistics of the bed elevation uncertainty to drive the scope of simulations (e.g., Goff and Jordan, 1988; MacKie and others, 2020, 2021).

3.1 Topographic controls on retreat and inland thinning

Much of the dynamic mass loss for the GrIS is thought to have initiated by warm ocean temperatures and sufficient supraglacial melt to drive enhanced melt of the ice marginal region. This has been demonstrated as a consequence of 20th century ocean and atmospheric warming (Holland and others, 2008; Murray and others, 2010; Straneo and Heimbach, 2013; Trusel and others, 2018; Wood and others, 2021). However, while the overwhelming majority of GrIS outlet glaciers have experienced retreat (King and others, 2020), acceleration (Moon and others, 2012) and thinning (Smith and others, 2020), there is heterogeneity in the dynamic response of glaciers to climate (Csatho and others, 2014; Catania and others, 2018; Hill and others, 2018; Moon

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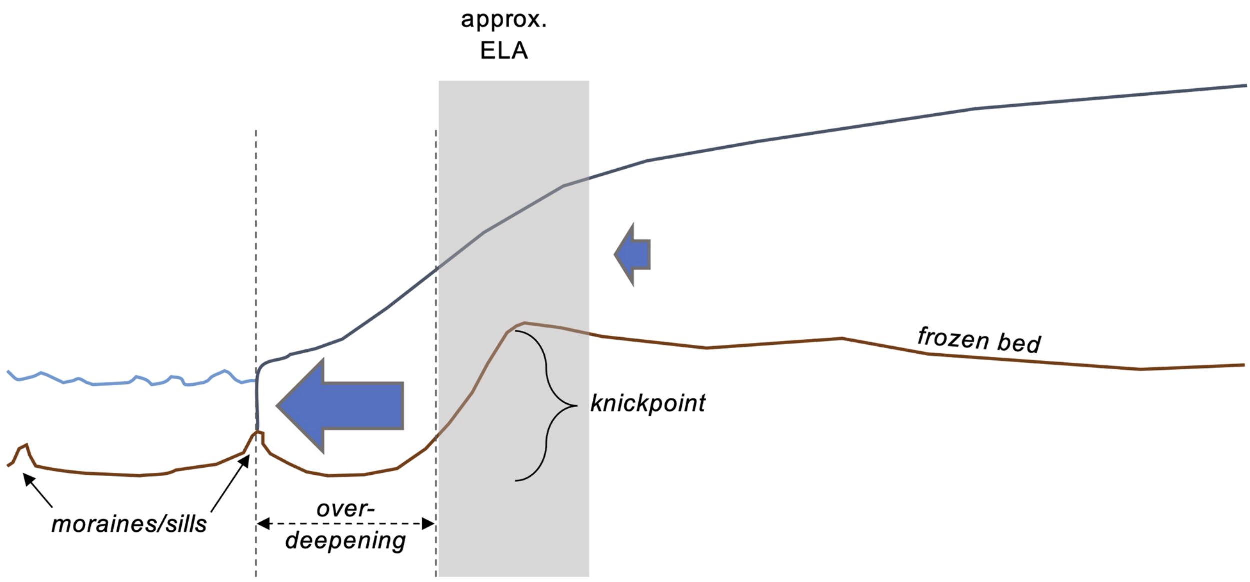

Figure 2. Schematic of outlet glacier topography showing retrograde inland topography, the presence of a knickpoint at the location of the equilibrium line altitude (ELA), an overdeepening in the region of fast flow and the presence of moraines (both active and paleo) at the glacier terminus.

and others, 2020) with a small number of glaciers exhibiting stability over this time period. In part, this may be due to the inability for warm ocean waters to access the terminus where fjords are shallow or protected with shallow sills or paleo-moraines downstream of glacier termini (Bartholomaus and others, 2013; Carroll and others, 2016; Batchelor and others, 2019). However, the climate alone is not sufficient to force retreat of every glacier terminus. This was demonstrated by Christian and others (2022) who found that some bed bumps at glacier termini could cause persistent terminus stability even when climate change produces an increased probability of retreat. This is because ice flux reduces as ice flows up to a bed peak, flattening surface slopes and reducing the ability for climate to affect terminus position (Robel and others, 2022). The enhanced stability of glacier termini near the peaks of bed bumps may thus explain why there are a number of persistently stable glaciers despite widespread coincident warming of the ocean and atmosphere around Greenland since the late 1990s.

In addition to controlling the timing of glacier terminus retreat since the 1990s, topography also regulates how much retreat occurs. Using BedMachine data, Catania and others (2018) confirmed that glacier termini retreat from one bed bump to another further inland with retreat that appears insensitive to bed bumps smaller than the seasonal amplitude of the terminus. Carnahan and others (2022) examined this for neighboring glaciers Umiamiko Isbræ and Ingia Isbræ, both of which began to retreat in ~2001. While both glaciers retreated significantly, Umiamiko Isbræ restabilized on the prograde side of a large bed bump in 2010, while Ingia Isbræ has continued to retreat (Zhang and others, 2023). The ongoing retreat of Ingia Isbræ was enabled, in part, because its fjord has flat bed topography, which permits low basal resistance to driving stress for several kilometers upstream of the terminus (Carnahan and others, 2022). The ongoing retreat occurring for many GrIS glaciers in spite of widespread ocean cooling in ~2008 (Wood and others, 2021) suggests that climate alone cannot sustain retreat, and that topography may permit the degree to which a climate trigger will influence future dynamics of individual glaciers.

While we have focused largely on bed topographic controls so far, we note that other variables can exert control on the pace and timing of retreat. In streaming ice, Greenwood and others (2021) found that along-flow bed slope was a poor predictor of retreat style with similar retreats occurring on all types of bed slopes. This suggests that bed topography alone may not be the dominant control to terminus retreat. For the relatively narrow outlet glaciers in Greenland, changes in fjord width also appear to exert control in model studies of glacier retreat (Enderlin and others, 2013; Akesson and others, 2018; Hill and others, 2018). Indeed, model simulations from Akesson and others (2018) show that termini can retreat through fjord embayments even in the presence of bed topographic bumps in the bed. For the GrIS, it has been difficult to ascertain the degree to which changes in fjord width have impacted observed retreat rates because observed variations in width are small compared to variations in bed topography over the relatively short length scale of most retreats (Catania and others, 2018).

Terminus retreat is thought to precede surface steepening, acceleration and inland thinning of outlet glaciers (Carnahan and others, 2022). Inland thinning of ice is diffusive and leads to slow, long-term mass loss but represents the majority of future committed sea level rise (Price and others, 2011). The amount of inland thinning permitted is also controlled by bed topography (Felikson and others, 2017), with the presence of bed topographic 'knickpoints' - steep reaches where the bed rises from below sea level to above sea level far inland from the glacier terminus (Figures 1, 3; Felikson and others, 2020). These knickpoints also control the degree to which interior ice accelerates in response to thinning and retreat (Williams and others, 2021). The proximity of knickpoints to a glacier's terminus and the steepness of that knickpoint is correlated with regional topographic steepness, which likely steers outlet glacier tributaries to converge enhancing bed erosion (Kessler and others, 2008; Felikson and others, 2020). In regions of steeper terrain, there are steeper, more well-defined knickpoints, while in gentler terrain, there are no knickpoints or much gentler sloped knickpoints (Figures 1, 3; Felikson and others, 2020). Where they are present, knickpoint locations are roughly coincident with the location of the equilibrium line, suggesting that surface meltwater is required to sufficiently lubricate the bed enabling enhanced erosion downstream of knickpoints as opposed to frozen bed conditions upstream of knickpoints (Felikson and others, 2020). When retreat occurs on glaciers without well-defined knickpoints, inland diffusive thinning may be slower, but occurs for much longer than for glaciers with well-defined knickpoints. This suggests that glaciers without

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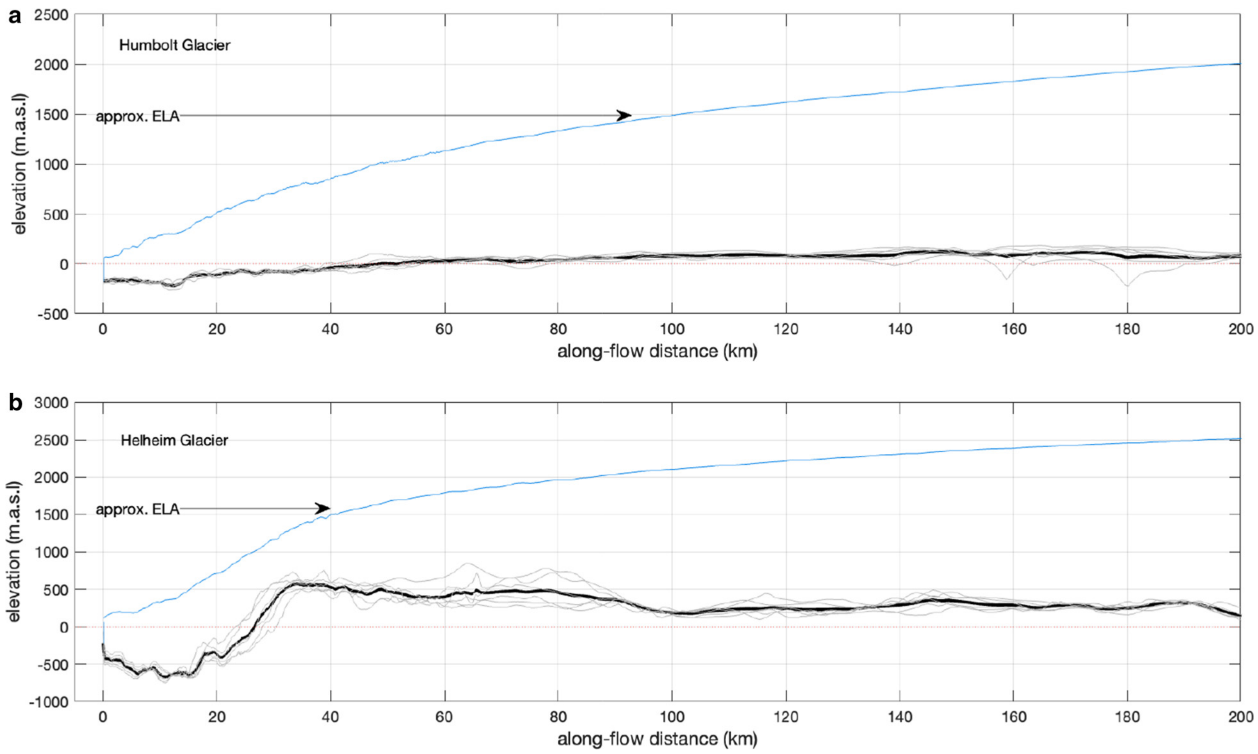

Figure 3. Subglacial and surface topography along flowlines of two GrIS glaciers. Grey lines show smoothed bed topography along six individual flowlines for each glacier, black line shows the mean of all six flowlines. Blue shows ice surface topography. All topography data from (Felikson and others, 2020). Sea level is indicated at zero elevation with a red dotted line. The approximate equilibrium line elevation is ~1500 m (Noël and others, 2019) and is indicated for each glacier. (a) Humbolt Glacier showing an overdeepened bed near the terminus but no presence of a strong knickpoint detected. (b) Helheim Glacier showing a strongly overdeepened bed topography near the terminus and a steep knickpoint at ~35 km where inland thinning would be limited according to Felikson and others (2020).

knickpoints may represent bottlenecks of mass loss; where ongoing long-term mass loss can continue well after the retreat has occurred.

Given the importance of bed topography, and our knowledge that glaciers are effective at erosion, it seems logical then to suspect that topography can co-evolve with glacier dynamics. Indeed, this was proposed to explain the 'tidewater glacier cycle' (Meier and Post, 1987; Nick and others, 2007), which is a long-term cycle of slow terminus advance and rapid retreat initially described as typical of Alaskan tidewater glaciers. The importance of coupling sediment to ice dynamics was demonstrated by Brinkerhoff and others (2017) who showed that the tidewater glacier cycle could be reproduced within a steady climate simply through interactions between ice flow, glacier erosion and sediment transport. Glacier erosion is also responsible for the creation of overdeepenings (Patton and others, 2016), which then feedback onto the ice dynamics including the rate of terminus retreat (Robel and others, 2022) and the ice flux (Hooke, 1991; Creyts and others, 2013). Differences in glacier bed erosion rates are also likely responsible for the formation of knickpoints (Kessler and others, 2008; Felikson and others, 2020), which suggests that long-term erosion may be responsible for the heterogeneous dynamic response in inland thinning of the ice sheet that is observed today.

4. Future research priorities

While the role of topography in controlling outlet glacier dynamics is of clear importance, our ability to actually observe subglacial topography with reasonable accuracy is quite recent. For the GrIS, considerable data acquisition occurred through CReSIS (Gogineni and others, 2001, 2014), NASA's Operation IceBridge (Studinger and others, 2010; MacGregor and others, 2021) and Oceans, Melting, Greenland Missions (Fenty and others, 2020), which provided significant improvements in the spatial resolution and coverage of bed topography in Greenland. Despite the significant funding and effort that went to securing these data, we still lack adequate topographic data for many outlet glacier terminal regions in Greenland. Thick, warm, wet and steep-walled ice conditions here pose unique challenges for airborne radar data collection. Some progress is being made to counter these challenges using unmanned aircraft, which can house lower frequency radar systems than are typically used, permitting deeper penetration (Arnold and others, 2018). Additional dedicated funding is needed to fully map these parts of the ice sheet, perhaps focusing on those glaciers that are most susceptible to initiating large changes in mass loss.

Similarly, additional surveying of fjord topography is needed (Jakobsson and Mayer, 2022), particularly for fjords that are persistently chocked with melange, making the terminus region much more difficult to access via ship (e.g., Helheim Glacier). For glaciers without persistent melange, coordination across nations can crowd-source data collection to happen during periods of time when accessibility is available. Perhaps this means that we make use of even single-beam sounding from fishing and expedition ships working in Greenland. For fjords that have persistent melange, a different approach is needed that allows remote sounding of the sea floor topography. This could occur via including remotely operated vehicles (Jakobsson and Mayer, 2022), using novel remote-sensing techniques that make use of iceberg draft heights (Scheick and others, 2019) and the use of airborne gravity (Boghosian and others, 2015; Tinto and others, 2015). While airborne gravity provides a coarser resolution bed topography estimate compared to multibeam data, it can be done more easily by plane and with complete coverage of the terminal zone (An and others, 2019).

Given the importance of bed topography, particularly at the ice-ocean boundary, we must next understand the pace at which topographic change is possible. Glaciologists largely assume stable bed topography over time assuming that bed erosion and deposition rates are small compared to terminus change rates (Koppes and Montgomery, 2009). Yet, sedimentation has been observed to be critical to understanding the stability state of glacier termini (Alley and others, 2003, 2007). Indeed, glacier advance has been shown to be uniquely dependent on sediments infilling into bed lows in front of the advancing terminus (Nick and others, 2007). Further, sedimentation rates at Alaskan glaciers were recently measured to be on the order of several meters per year (Eidam and others, 2020), which is larger than the vertical motion of the solid Earth following deglaciation, now considered an important stabilizing feedback on ice loss (Barletta and others, 2018). Despite its clear importance, sedimentation is either entirely missing from sea level projecting models of ice sheets (Aschwanden and others, 2019) or is modeled without clear knowledge of the types and rates of processes that contribute to moraine building (Brinkerhoff and others, 2017). While there has been extensive research on glacial landforms from past glaciations, most of these studies are not able to produce a precise depiction of the coincident ice dynamics at the time of deposition. Thus, we lack a set of governing equations that describe how to couple ice and sediment dynamics in a way that is consistent with observations. We thus recommend new observations of sedimentation rates that can be paired with observed glacier dynamics so that we can build equations that describe moraine-building and erosion of overdeepenings that are consistent with observations.

Finally, there is a remaining need to consider outlet glacier dynamics holistically because there are multiple processes (both internal and external to the ice sheet) that impact dynamics making it difficult to tease apart cause and effect of glacier change. Poorly constrained boundary conditions for outlet glaciers exacerbates this (Malles and others, 2023). New observations must therefore be coupled to focused modeling of ice sheet outlet glaciers to discern the processes that are most important for accurately estimating future sea level.

5. Conclusions

Ice sheet mass loss has direct implications to sea level rise for coastal communities who rely on accurate forecasts of sea level across a wide range of time scales (Larour and others, 2017; Ultee and others). To address this need, there have been increased efforts to coordinate and improve model predictions of ice sheets over the last decade (Nowicki and others, 2016; Seroussi and others, 2020). Capturing historical GrIS mass change in model simulations remains a challenge (Aschwanden and others, 2021), which is due to a range of uncertainties including the lack of understanding of processes that control ice sheet mass loss. Such uncertainties make accurate model prediction of sea level challenging. For example, recent modeled future mass loss of the GrIS suggests that it will contribute somewhere between 5–33 cm to sea level by 2100 (Aschwanden and others, 2019). Meanwhile, the most recent IPCC report for the first time included a 'low-likelihood, high-impact storyline' suggesting that sea level could be 0.5 m or more higher than anticipated by 2100 from 'deeply uncertain processes related to ice sheet instability' (IPCC, 2021). Such a large range in future sea level means the difference between a coastal city that remains largely untouched by sea level rise versus one that becomes submerged. The research community has the responsibility to improve ice sheet uncertainties. Within the focus of this review, we argue for improved radar-data coverage over the more difficult to access terminal regions of outlet glaciers that will improve the mass conserving bed solution. We also argue for observations of the role of sedimentation/erosion for sculpting and changing bed topography over time. To a first order we need a better understanding of the rates of topographic change that are possible and what controls such rates.

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