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Basal Melting, Roughness and Structural Integrity of Ice Shelves

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Key Points:

- Ice shelves restrict glacier flow but are vulnerable to environmental change
- Basal melting can impact the structural integrity of ice shelves in several ways
- A new study suggests that ice-shelf roughness may provide a measure of the extent to which basal melting has impacted structural integrity

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Abstract Ice shelves restrict outflow from many of the largest glaciers in Antarctica, thus limiting the Antarctic contribution to sea-level rise. However, past ice-shelf collapse events show they are highly vulnerable to surface and basal melting. Collapse of ice shelves in front of glaciers flowing on retrograde slopes could initiate runaway retreat processes. Difficulty in projecting how quickly these could play out makes dynamic ice loss from Antarctica the largest uncertainty in predicting future sea-level rise. Basal melting can impact structural integrity of ice shelves in several ways. Results from analyses of variations in ice-shelf roughness by Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) raise the tantalizing prospect that this may provide a simple quantitative measure of how the structural integrity of an ice shelf has been impacted by basal melting. Applying the method to additional ice shelves would be useful to examine how other factors may contribute to roughness.

Plain Language Summary In many places around Antarctica, and some around Greenland, glaciers flowing on beds that are hundreds of meters below sea level continue out over the sea for some distance, forming "ice shelves". Over the past 40 years, break-up of several ice shelves has been observed and shown to result from melting on their surface and/or at their base. Subsequent increases in the flow speed of glaciers that flowed into them confirmed that ice shelves restrict outflow of glaciers and thus limit their contribution to sea-level rise. Furthermore, changes resulting from removal of ice shelves could lead to runaway retreat of glaciers flowing on beds that get deeper upstream, and lack of knowledge about whether and how quickly this will happen is the largest uncertainty in predicting future sea-level rise. Basal melting weakens ice shelves in several ways. Results from analyses of variations in thickness, or "roughness", of ice shelves by Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) suggest that they may provide a measure of the extent to which basal melting has weakened an ice shelf. Conducting similar analyses on additional ice shelves would help show the extent to which other processes contribute to roughness.

1. Introduction

Ice shelves, extensions of glaciers that float over the ocean, act as buttresses restraining the flow of glaciers feeding into them. They restrict outflow from many of the largest glaciers and ice streams in Antarctica. This concept had been considered theoretically for decades, but its reality was very clearly demonstrated by the collapse of the Larsen B Ice Shelf on the east side of the Antarctic Peninsula in 2002 and the subsequent increase in flow velocity of glaciers that had previously flowed into it (De Angelis & Skvarca, 2003; Scambos et al., 2004). Collapse of ice shelves that larger glaciers flow into leading to acceleration of their flow into the ocean would increase the Antarctic contribution to global sea-level rise.

Many large glaciers in West Antarctica and some covering large parts of East Antarctica flow on beds that increase in depth upstream. For these glaciers, ice thinning resulting from such flow acceleration would force retreat of their grounding lines, where glacier ice starts to float as it flows toward the ocean. This in turn has the potential to initiate runaway retreat through a feedback process called Marine Ice Sheet Instability (MISI; Schoof, 2007; Weertman, 1974).

A further possibility is that sudden ice-shelf collapse could leave tall ice cliffs in which gravitational stress from the mass above water and buoyancy from the submerged part exceeds the yield strength of the ice. Where glacier beds increase in depth upstream, resulting cliff failure would expose even taller cliffs, potentially leading to runaway retreat through a different feedback process called Marine Ice Cliff Instability (MICI; Bassis & Jacobs, 2013; Crawford et al., 2021). There are no examples of MICI having driven substantial retreat during the relatively short period of modern observations of ice-sheet change, but characteristics of iceberg-keel plow marks over an area of past retreat in a part of Pine Island Trough where the seabed increases in depth inshore suggest that the process did operate, at least locally, during retreat following the Last Glacial Maximum (Wise et al., 2017). Some studies have concluded that under certain conditions MISI and MICI will not necessarily cause runaway retreat of glaciers on retrograde beds (Bassis et al., 2021; Gudmundsson et al., 2012; Sergienko & Wingham, 2021). However, the potential for disintegration of ice shelves to initiate these chains of cause and effect and the difficulty in projecting how quickly they could play out is the reason that dynamic ice loss from Antarctica constitutes the largest uncertainty in predicting future sea-level rise (IPCC, 2021).

2. Past Ice-Shelf Collapse Events

Retreat and collapse of ice shelves on both sides of the Antarctic Peninsula over the past four decades has demonstrated their vulnerability to environmental change (Cook & Vaughan, 2010; Vaughan & Doake, 1996). The main driver of loss of these ice shelves was rapid regional warming in the second half of 20th century, leading to development of surface melt ponds in summer and propagation of meltwater-filled crevasses through the full ice thickness by hydrofracture (Scambos et al., 2000).

3. Causes and Effects of Rapid Basal Melting

However, surface melting is not the only process that threatens ice-shelf stability. Basal melting accounts for about of half of all Antarctic ice shelf mass loss and ice shelves along the coast of West Antarctica facing the Pacific Ocean in the Amundsen and Bellingshausen seas have been thinning over at least the past three decades as a result of rapid basal melting (Adusumilli et al., 2020; Pritchard et al., 2012). This is caused by incursion of relatively warm Circumpolar Deep Water onto the continental shelf and into the ocean cavities beneath the ice shelves (Jacobs et al., 2011; Wåhlin et al., 2021; Figure 1).

In addition to ice thinning, basal melting has further effects that impact the stability of ice shelves. Ice shelves thin seaward, primarily due to creep (longitudinal stretching) within the ice as it flows toward the unconfined ice front (Thomas, 1979). Water enriched with melt at the ice base is buoyant relative to pure seawater and therefore follows the shallowest pathway along the base of an ice shelf to its front. Consequently, water flow is focused along these pathways, leading to more rapid melting and eroding channels that can reach hundreds of meters in height (Le Brocq et al., 2013; Vaughan et al., 2012). Erosion of such channels reduces hydrostatic support to the ice above them, generating flexural stresses that can result in basal crevasses above the channels and surface crevasses along the intervening corridors of ice. Thus basal melting can cause structural weakening of ice shelves (Vaughan et al., 2012).

One further consequence of ice-shelf thinning is that it reduces the thickness of shear margins and the contact area over basal pinning points (Figure 1), thus decreasing lateral and basal drag. This allows faster ice flow and longitudinal stretching, which is likely to lead to an increased incidence of rift development (Arndt et al., 2018; Joughin et al., 2021). Faster ice flow also results in increased damage along shear margins, which further reduces lateral drag leading to another feedback process (Lhermitte et al., 2020).

4. The Most Rapidly Thinning Ice Shelves

The combined consequences of these processes stemming from excessive basal melting are evident in changes in the ice shelves at the fronts of Pine Island and Thwaites glaciers, the two Amundsen Sea glaciers where net ice mass loss is faster than anywhere else in Antarctica. After more than six decades in which there was no overall migration of the Pine Island Glacier ice front, it's northern part stepped back more than 30 km through a succession of large calving events from 2015 to 2020 (Arndt et al., 2018; Joughin et al., 2021; Lhermitte et al., 2020). The current Thwaites Glacier Tongue is pervasively rifted and vestigial compared to the >75 km-long and >40 km-wide tongues that grew and calved through the twentieth century and earliest part of this century, and recent analysis of changes taking place in the Thwaites Eastern Ice Shelf (Figure 1) suggest that it is likely to fully destabilize in the next few decades (Alley et al., 2021; Wild et al., 2022).

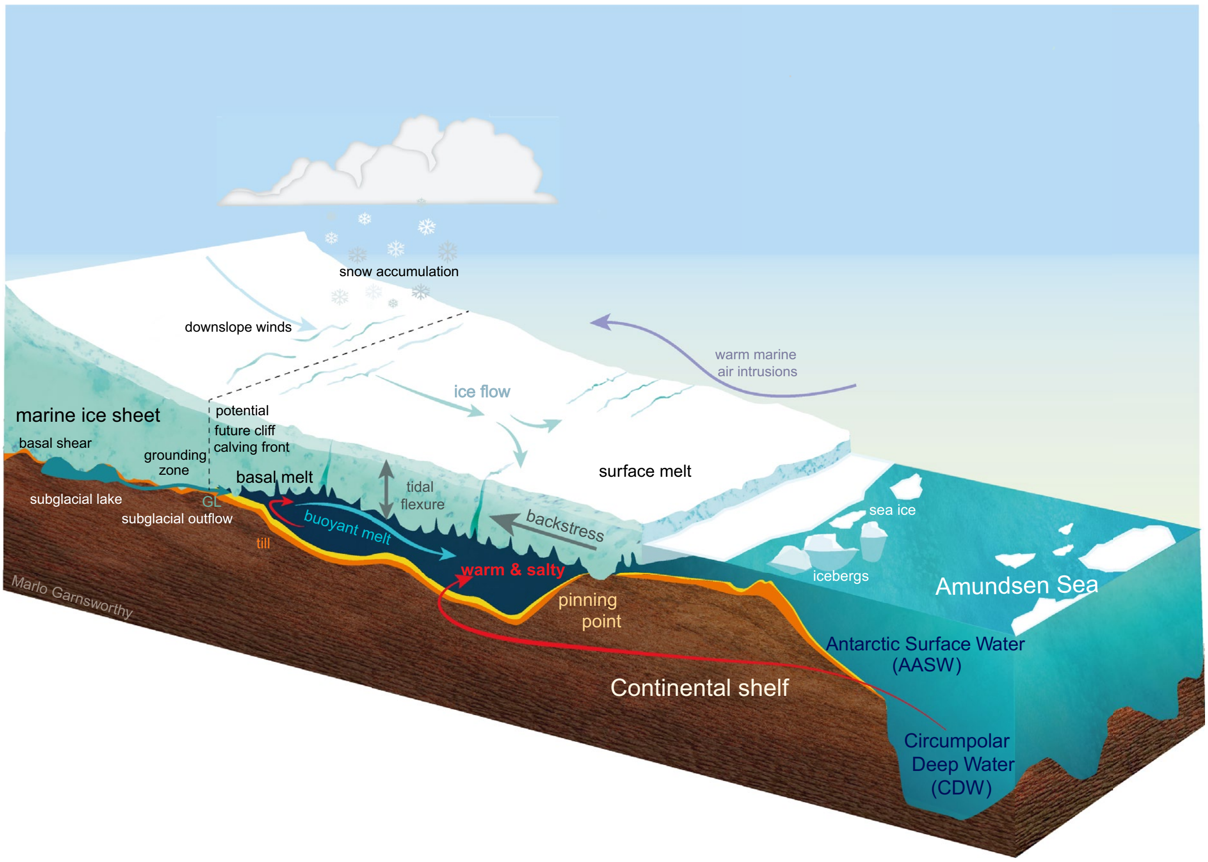

Figure 1. Schematic view and section through Thwaites Glacier Eastern Ice Shelf, illustrating how it extends from the glacier to a pinning point and various processes, including ice flow, inflow of relatively warm Circumpolar Deep Water, basal and surface melting, flow of buoyant melt-enriched water along the ice base, and backstress from the ice contact with the pinning point that helps stabilize the ice shelf. GL = grounding line. Orange seabed layer represents subglacially deposited sediments and yellow seabed layer represents sediments deposited in and seaward of the ice shelf cavity.

5. A Way of Measuring Impact on Structural Integrity?

It is clear that excessive basal melting can make ice shelves more vulnerable to collapse in a variety of ways. Some processes involved in the ultimate collapse of ice shelves (e.g., crevasse and rift propagation) are non-linear, and therefore the precise timing of collapse is essentially unpredictable. In order to provide some forewarning of when basal melting is driving an ice shelf into a highly vulnerable state though, it would be useful to have a simple quantitative measure of how its structural integrity has been impacted. Results from analyses of variations in ice thickness, or "roughness", of ice shelves by Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) raise the tantalizing prospect that this may provide such a measure.

In general, ice shelves have very smooth, flat surfaces over most of their area. However, crevasses, rifts, surface subsidence over basal melt channels and deformation features around pinning points interrupt these smooth surfaces, and because the ice is floating, surface irregularities usually correspond to much larger ones at the ice base.

By analyzing radio-echo sounding (RES) profiles from airborne surveys Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) examined the spectral signature of variations in roughness on seven ice shelves of a range of sizes and in different settings. To their surprise they found no significant peaks in the power spectra, indicating that within the range of spatial frequencies analyzed (a range equivalent to wavelengths from 90 m to 10 km) there are no characteristic widths of features causing roughness. Furthermore, by analyzing profiles with different orientations they showed that these smooth spectral signatures, which follow a power law, are not simply a consequence of profiles intersecting roughness elements at different angles. Their results did, however, reveal large differences in the overall magnitude of roughness between ice shelves, and they showed that this correlates with basal melt rates. From this correlation they speculate that basal melt may be the key control on roughness of ice shelves, and suggest that the fact the power law nature is maintained across a broad spectrum of wavelengths over such a large range of overall roughness levels may indicate a complex interplay between increased basal melt and ice dynamics.

6. Potential for Further Work

In order to confirm that these results are more widely applicable it would be useful to extend the analyses to a larger number of ice shelves, including fringing ones around East Antarctica that include areas where a significant amount of damage unrelated to basal melting has been observed, resulting from deformation in the grounding zone (King et al., 2018). Among the ice shelves that were analyzed, the roughness determined for the Getz Ice Shelf is a little lower than the 95% confidence bound of a linear best fit between roughness and basal melt rate. Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) suggest that this could be due to the small number of tracks analyzed, or to the Getz Ice Shelf's relatively slow flow and the fact that it is constrained by multiple pinning points. A comparative analysis with George VI Ice shelf, which has a similar basal melt rate, is also slow flowing and is pinned between Alexander Island and Palmer Land, Antarctic Peninsula, could provide a useful test of the importance of the latter two factors.

From visual observations of features that cause irregularities within ice shelves there is no doubt that roughness extends to shorter wavelengths than those analyzed. If RES data with higher spatial resolution could be obtained it would be interesting to determine whether or not the power law relationship reported by Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) extends to even shorter wavelengths.

A further interesting way to build on the study by Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) would be compare results from data of different vintages for ice shelves where there are high basal melt rates, to reveal how roughness has changed through time. RES surveys over the Thwaites Eastern Ice Shelf, which has the highest basal melt rates among those analyzed, have been conducted several times since 2004 (Holt et al., 2006; Jordan et al., 2020; Paden et al., 2010) so this would seem to present an ideal opportunity, particularly in view of recent studies that conclude this ice shelf will soon become critically vulnerable (Alley et al., 2021; Wild et al., 2022).

In summary, the findings of Watkins et al. (2021; https://doi.org/10.1029/2021GL094743) are intriguing and provide a basis for further work to test their hypothesis that roughness correlates with basal melt and its potential applications.

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