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Figure 1 | Meltwater drainage across the surface of the Greenland ice sheet. Where meltwater intersects cracks in the ice, it can drain to the bed and affect ice flow.

Climate science

Trapped water affects loss of Greenland ice sheet

Stephen J. Livingstone

An analysis suggests that ice geometry and flow speeds control how meltwater affects the slipperiness of the bed beneath the Greenland ice sheet. Changes in these conditions could therefore influence future ice-mass loss. See p.714

The melting of the vast sheet of ice covering Greenland is one of the largest contributors to global sea-level rise[1]. A key uncertainty in predicting how much of this ice sheet will be lost as a result of future climate change is how the meltwater affects the speed at which the ice flows towards the ocean. Meltwater under ice sheets causes fluctuations in this speed on a timescale of hours to decades[2], but it remains unclear whether this is merely noise, or whether this meltwater actually controls the loss of ice-sheet mass over longer timescales. On page 714, Maier *et al.*[3] report that meltwater moving from the surface to the base of the Greenland ice sheet has caused pronounced and lasting changes in the slipperiness of the bed. The results imply that meltwater can drive large, long-term changes in ice flow speed.

During the summer months, high air temperatures cause melting around the fringes of the Greenland ice sheet, creating an intricate network of beautiful blue lakes and streams on the surface of the ice. When this water encounters cracks in the ice, it can drain to the underlying bed, sometimes through kilometre-thick ice (Fig. 1). Once under the ice sheet, meltwater affects ice flow speed by modifying the slipperiness of the bed — less friction leads to more-rapid movement of the ice. However, the relationship between meltwater and ice speed varies in response to changes in the amount of water that drains to the bed and the capacity of the underlying drainage network to remove this water from under the ice[4,5].

Maier *et al.* used publicly available data sets of Greenland's bed and ice topography and of the surface velocity of the ice, averaged over a period of 20 years, to remove the effect of variability between years. They paired these data

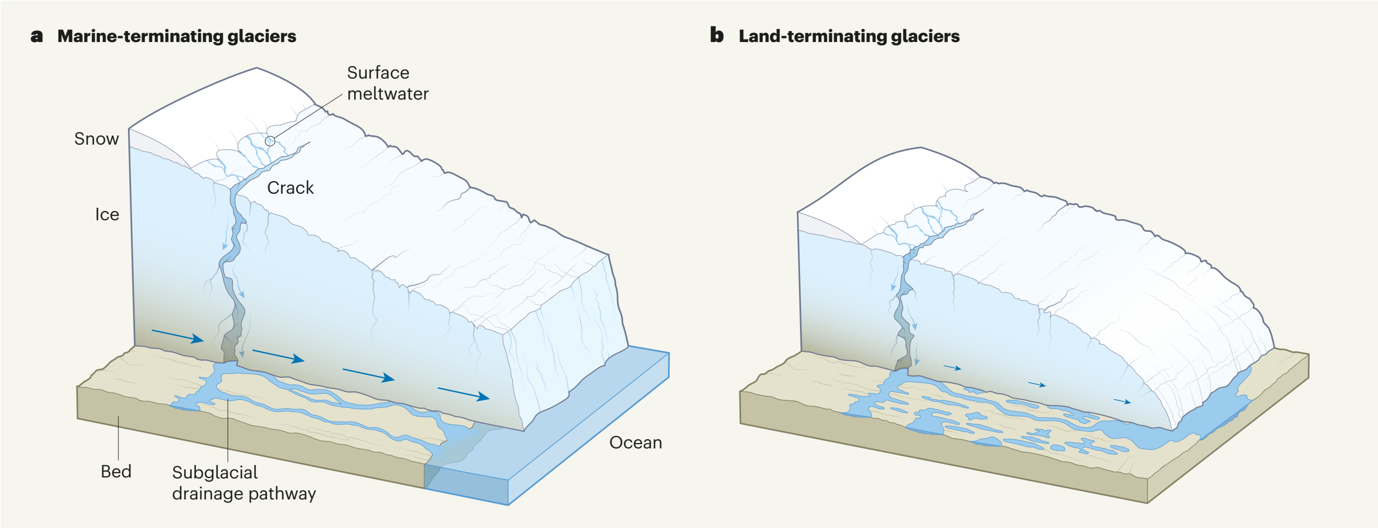

Figure 2 | Mechanisms of meltwater drainage for different glacier types. Maier *et al.*[3] found that, where meltwater drains through cracks in the Greenland ice sheet, the bed below is less slippery in the north of the country than it is in the south. They also noticed that glaciers typically flow into the ocean in the north, whereas most terminate on land in the south. **a**, The 'marine-terminating' glaciers are steeper and faster flowing (shown by blue arrows) than are the land-terminating glaciers, with the authors' research suggesting that this results in drainage pathways that can efficiently capture and evacuate meltwater from their surroundings. **b**, By contrast, land-terminating glaciers are associated with shallower slopes and slower ice flow speeds, leading to trapped water being less easily evacuated, and a more slippery bed.

with a numerical ice-sheet model to calculate the friction of the bed and the ice velocity at the base of the sheet for the whole of west Greenland. This is an inverse problem, because it involves starting with the responses (the ice geometry and surface velocity) and calculating the causes (the bed friction and basal velocity). The authors then fitted these data to a relationship between basal-ice velocity and friction that is thought to be typical of ice sliding over a bed composed of rock. By using inland regions unaffected by summer melting as a control, they were able to determine whether regions of the bed influenced by surface meltwater were more or less slippery than expected.

Their results show a remarkable pattern, in which surface-meltwater drainage in north Greenland produces a bed that is less slippery than regions with no underlying meltwater, whereas the bed in south Greenland is 20–40% more slippery than these control regions. So why does this pattern arise?

Maier *et al.* noticed that, in north Greenland, glaciers typically flow into the ocean. These 'marine-terminating' glaciers are steeper and faster flowing than are glaciers in the south, which should result in drainage pathways beneath the ice that can more effectively capture water from their surroundings and squirt it out into the ocean (Fig. 2a). By contrast, glacier catchments to the south mostly terminate on land, resulting in shallower ice slopes and lower ice flow speeds. These physical characteristics cause more-sluggish water flow that can less easily capture and evacuate water from the bed, resulting in more water storage and a more slippery bed than that associated with inland portions of marine-terminating glaciers to the north (Fig. 2b).

As the Greenland ice sheet recedes owing to rising air and ocean temperatures, the proportion of ice in contact with the ocean will decrease[6]. Maier *et al.* predict that, as glacier catchments become land terminating — flattening the slopes and slowing the flow of ice — they will become more slippery inland, owing to the increase in water storage. This shift to a more slippery bed would initiate a subsequent acceleration of the land-terminating margin, lowering the ice surface to elevations at which the air is warmer and will more readily melt the ice. By incorporating these findings into numerical models, glaciologists will be able to make improved predictions of how the Greenland ice sheet will evolve in the future, and thus estimate its contribution to sea-level rise.

Maier and colleagues' discovery is notable because it suggests that meltwater can have a large, long-term impact on ice-sheet geometry and evolution. It also indicates that variations in ice flow speed in response to surface-melt supply[7] that were previously observed over multiple years might have a secondary effect on bed slipperiness and subglacial drainage efficiency relative to glacier characteristics such as ice-surface slope and ice flow speed. Nevertheless, the bed under ice sheets is one of the most challenging environments to observe on Earth, and we still know very little about how meltwater is organized in this realm, and how it evolves over time. Some aspects of the bed, such as sediment, groundwater and geothermal heat flux, are particularly poorly constrained, and might also turn out to be crucial. Despite this, the mechanism that Maier *et al.* invoke to explain the observed pattern in slipperiness offers a simple explanation that is consistent with current theory.

The authors' findings will inspire future work to test this mechanism using observations of how slipperiness and water storage are changing beneath glaciers in a range of settings affected by surface melt: those in other parts of Greenland, steeper alpine glaciers and glaciers that have undergone a transition from being marine terminating to land terminating, for example. In Antarctica, melt events are largely limited to ice shelves and occur more sporadically than in Greenland. But as warming increases in the future, melt-driven changes in bed slipperiness could become relevant there, too.

Finally, ice sheets wax and wane on glacial timescales, and even longer. As the ice geometry changes, fast-flowing corridors of ice appear and disappear, and the area of the ice sheet affected by surface melt varies. Maier and colleagues' study acts as a starting point for making predictions about long-term alterations in bed friction and ice flow speeds under these conditions.

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