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Oceanic Low Blows Hitting Ice Sheets Where It Hurts

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Large tidewater outlet glaciers of the Greenland and Antarctic ice sheets exiting from deep subglacial channels exhibit a nearly universal signature of recent increased discharge. This suggests a common cause operating in both hemispheres. Additional heat delivered by subsurface waters melting the bases of these glaciers explains the observations, is evidence that warmer subsurface waters are reaching the Earth's polar latitudes and indicates that the ocean plays a more critical role than the atmosphere in determining near-term glaciological contributions to changes in sea level.

The acceleration and associated thinning and retreat of Pine Island Glacier in West Antarctica in the mid-1990s initiated the emerging awareness of increased activity at the margin of the Antarctic ice sheet *(1)*. Other glaciers discharging directly into the Amundsen Sea were soon discovered to be accelerating and thinning *(2)*. Airborne ice-sounding measurements have identified that these glaciers are deep with bases hundreds of meters below sea level *(3)*. These observations, along with modeling that predicted rapid upstream propagation of thinning, led to a claim that oceanic forcing was at work*(4)*.

Elsewhere around the continent, the Cook Ice Shelf in East Antarctica is fed by ice that is thinning and accelerating at comparable rates *(5)*. This area drains the largest portion of the East Antarctic ice sheet grounded on a submarine bed, making it most like the Amundsen Sea sector of West Antarctica in behavior as well as setting *(6)*.

Nearly half a world away, similar behavior is reported for outlet glaciers draining the southern half of the Greenland ice sheet. On the west coast, the largest outlet glacier, Jakobshavns Isbrae, has been thinning at 15 m a^{-1} since 1997, while on the east coast the major outlets of Kangerdlugssuaq and Helheim Glaciers began thinning in 2003 at rates of 40 m a^{-1} and 25 m a^{-1}, respectively *(7)*. These glaciers also occupy deep submarine channels.

A recent assessment of speed and balance changes around Greenland identifies these three large glaciers as among the most active recently with accelerations up to 210% *(8)*. The activity on Kangerdlugssuaq and Helheim Glaciers has been confirmed by analysis of optical imagery on slightly different time intervals *(9)*. Smaller glaciers along the southeast and southwest Greenland coasts are also accelerating.

Searching for a common cause of the most dramatic changes of the largest outlet glaciers in both Antarctica and Greenland leads one to consider the oceans *(4)*. Melting at the base of a tidewater glacier causes it to accelerate by ungrounding ice reducing basal friction and by reducing the buttressing resistance of any floating ice shelf *(10)*. However, there remain questions of whether this warmer water exists, especially given the absence of any indication of increasing sea surface temperature in high latitudes, and how it accesses the glacier base.

Only about half of the Earth's present radiation imbalance has been detected in rising atmospheric temperatures and the suggestion has been made that the remainder is being stored in the world's oceans *(11)*. Analyzing observations from buoys and ships, Levitus *et al.* demonstrated that the tropical and mid-latitude oceans are warming in recent decades *(12)*. They observed that because regional subsurface warming predated the expression of increased regional sea surface temperatures, the additional heat was being transported below the surface. Most of the warming was limited to the upper 1000 meters, with the single exception of the North Atlantic where deep convection carried increased heat to greater depths.

The warmest water in polar oceans is neither at the surface (where summer melting of sea ice provides a surface layer of fresher water) nor at the bottom (where dense water from winter freezing of sea ice sinks to the ocean floor). In the Amundsen Sea, the relatively warm is concentrated at 600 meters depth *(13)*. However, additional warmth in the ocean arriving from lower latitudes would raise the temperature of this intermediate water a fraction of a degree, hardly enough to initiate a sudden glacier acceleration.

That the deeper tidewater glaciers have proven most vulnerable to recent changes hints that the answer to recent acceleration lies in the manner in which this warmer intermediate depth water can access the deep grounding lines of these glaciers, where the ice first floats free from the bed. These glaciers flow out to the ocean in deep channels with bases well below sea level and short floating ice shelves a few hundred meters thick. Extensive bathymetry data are rare beneath and immediately in front of these glaciers. Jakobshavns Isbrae in Greenland and Pine Island Glacier in Antarctica, the two glaciers with the earliest recorded accelerations, are among the deepest outlets with grounding lines over 1000 meters below sea level. It is likely that the large outlet glaciers such as these eroded deeper basins than smaller adjacent glaciers that have accelerated more recently.

In this context, a key characteristic of tidewater glaciers is that they erode overdeepened troughs ending with a shallower terminal moraine at the site of their maximum glacial cycle extent. In warmer climates, they retreat from this advanced position and often maintain an ice shelf in the overdeepened cavity *(Figure)*. This moraine, or sill, is a barrier that prevents deeper water seaward of the sill from reaching the deep grounding line. Once breeched, however, the warm, salty water will sink in the cold, fresh water behind the sill and reach ice at the grounding line. Increased pressure at these greater depths lowers the melting point of this ice, increasing the melting efficiency of the warmer water. Rapid melting results. This process has been modeled for the observed sill geometry in front of and beneath Pine Island Glacier *(14)*.

Surface meltwater cannot explain this common behavior. Penetration of surface meltwater to the glacial bed in Greenland can lead to seasonal flow acceleration *(15)*, but the annually averaged increase in speed is only a few percent. In the case of Helheim Glacier, the relative intensities of warm summers were not associated with the observed changes in glacier speed *(16)*. And surface melting is uncommon for any of the Antarctic glaciers cited here.

Outlet glacier acceleration will probably continue. As sea ice growth and decay diminishes, warmer waters will reach shallower depths and access shallower tidewater glaciers as well as move northward along Greenland's coasts. This will lead to increasing discharge of grounded ice and accelerating sea level rise. Increased discharge could encourage longer ice shelves, helping to protect the grounding lines, but this has not been observed as ice shelves have failed to grow in front of accelerating glaciers and retreat is exceeding historical bounds. Retreating glaciers lengthen the distance warmer water must travel from any sill to the grounding line and eventually tidewater glaciers retreat to beds above sea level. This might limit the retreat in Greenland but will save neither West Antarctica, nor the equally large subglacial basin in East Antarctica where submarine beds extend to the center of the ice sheet.

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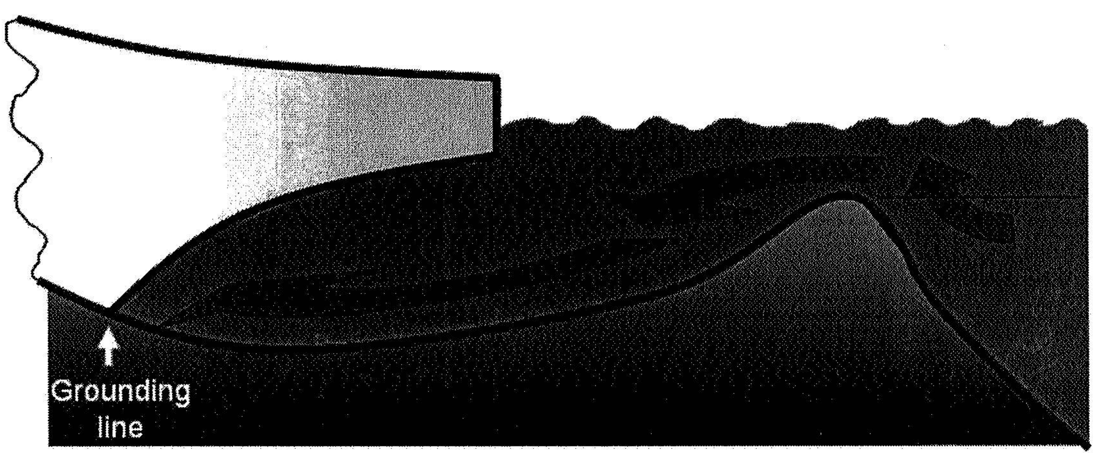

Caption: Schematic representing warm intermediate depth water breeching submarine sill and sinking in water cavity beneath ice shelf to access the grounding line of outlet glacier.

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The recent acceleration, thinning and retreat of large outlet glaciers in both Antarctica and Greenland is altering the mass balance of these two large ice sheets and increasing their contribution to rising sea level. In this short Perspective solicited by *Science* for a special March 24th issue on sea level change, I argue that the cause of these bi-hemispheric changes is that warmer water has gained access to the undersides of these glaciers where they come afloat from the continent. This process is particularly effective at accelerating glaciers because the beds of the large outlet glaciers are well below sea level (1000 meters or more) but "guarded" downstream by a shallow moraine formed when the glacier was more advanced. Once warmer water can breach this moraine, it sinks in the colder, fresh water behind the moraine and reaches the submarine front of the glacier. The pressure melting effect lowers the melting point of this deep ice allowing the warmer water to melt ice at rates of many tens of meters per year. This melting reduces the frictional hold of the bed on the ice, allowing the ice to accelerate in agreement with the observations. Hansen has discussed the likelihood that approximately half of the Earth's radiation imbalance is manifesting in warmer ocean waters and Levitus *et al.* have seen warming in ocean temperature measurements at mid and low latitudes. The behavior of these outlet glaciers indicates this ocean warmth is reaching polar waters. The prognosis is for a continuation of this process, more negative ice sheet mass balances and increased rates of sea level rise.