CLIMATE CHANGE

Greenland Rumbles Louder as Glaciers Accelerate

Flow rates of many large glaciers in Greenland and Antarctica have accelerated recently. Greenland earthquakes produced from glacier motion and calving have also increased dramatically.

Ian Joughin

Ice sheets are often assumed to respond slowly to climate change, with dynamic response times measured in centuries to millennia. On page 1756 of this issue, however, Ekström *et al.* (*1*) describe a dramatic increase in glacial seismicity over the past several years, which coincides with the acceleration of many of Greenland's major outlet glaciers (*2–4*). The rapidity of these changes counters the view of a sluggishly responding ice sheet and indicates that outlet glacier dynamics can respond swiftly to climate change with consequent increases in sea level. Over the past decade alone, glacier acceleration has increased Greenland's contribution to sea-level rise by more than 0.3 mm $year^{-1}$ (*2*).

Using teleseismic data from 1999 and 2000, Ekström *et al.* (*5*) previously identified earthquakes associated with glacial flow—"glacialquakes." Their more-recent observations cover more than a decade (1993 to 2005) and reveal a seasonal signal, with summer seismicity nearly five times greater than in winter. They also found a modest increase in seismicity in the late 1990s that was followed by a rapid increase from 2002 onwards, with 2005 producing nearly as many events as the combined total for 1993 through 1996.

The glacialquake magnitudes range from 4.6 to 5.1, yielding products of the displaced mass and slip of 0.1×10^{14} to 2.0×10^{14} kg m. This means that the Hellheim Glacier's 26 glacialquakes each resulted from roughly 0.16 to 3.7 m of slip if the displacement occurred along the full 14-km length of its fast-moving trunk, which has a mass of $\sim 6.1 \times 10^{13}$ kg (*6*) and flows at a rate of ~20 m day^{-1}. This finding suggests that the glacialquakes make up only a small fraction of glacial motion.

The glacialquakes all originated on fast-moving (>2 km $year^{-1}$) glaciers, with Greenland's three largest glaciers—Kangerdlugssuaq, Jakobshavn Isbrae, and Helheim—accounting for 72% of the events. Few glacialquakes were detected from Antarctica (*5*), possibly because the larger spatial extents of Antarctic ice streams produce slower events, with periods well beyond the 150-s detection threshold. For example, much of the Whillans Ice Stream moves primarily during twice-daily 0.5-m slip events lasting several minutes, with mass-slip products of roughly 3×10^{15} kg m (*7*).

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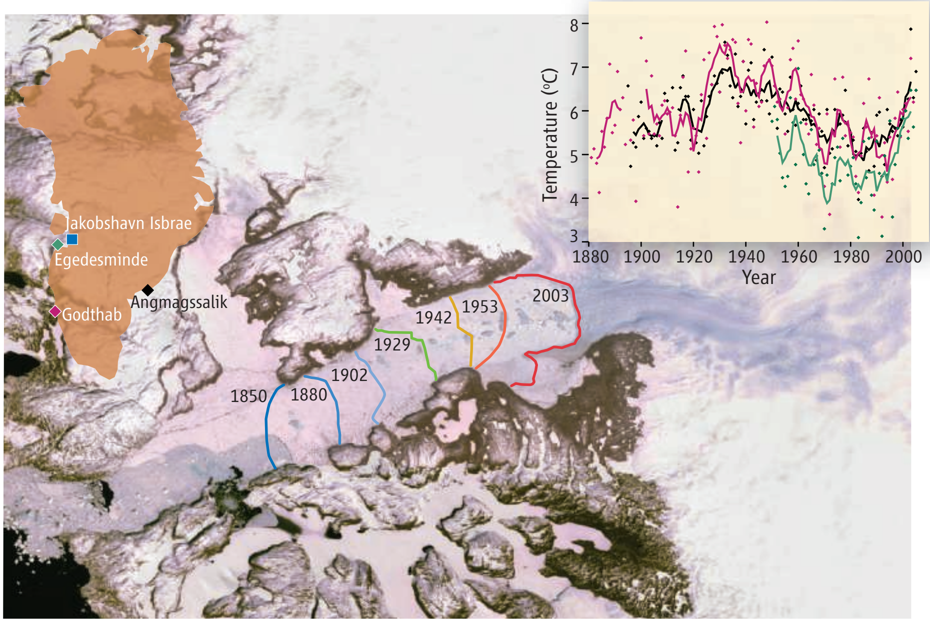

On the move. Retreat of Jakobshavn Isbrae since the Little Ice Age (*10*) marked by colored lines at different yearly intervals. **(Inset graph)** Summer (June, July, and August) temperatures (points) at several coastal stations shown in the silhouette map (*9*, *11*). The solid lines are 5-year averages; color indicates measurement station.

The Kangerdlugssuaq, Jakobshavn Isbrae, and Helheim glaciers all accelerated by more than 50% over the period of increased seismicity, as have many of Greenland's smaller glaciers (*2–4*). The cause, seasonality, and the relation of the glacialquakes to these recent accelerations are not yet clear. Ekström *et al.* note that the drainage of summer melt to the bed through moulins (glacial conduits) may enhance lubrication at the bed to produce slip events. Other explanations may relate to the seasonal variation in calving, which for Jakobshavn Isbrae demonstrates an annual variability similar to that of the glacialquakes (*8*). Large calving events alone might yield mass displacements sufficient to produce glacialquakes. Alternatively, changes in glacier geometry after a calving event introduce a force imbalance, which may yield a slip event as a new force balance is established. Finally, the glacialquakes may be produced by stick-slip events that occur in the normal course of glacier sliding, with only brief (hours) periods of stick required to build enough elastic strain to produce detectable (magnitude >4.6) slip events.

The increased seismicity may be directly associated with the glacier accelerations if, for example, they are related to large calving events, which appear to precede acceleration (*4*). Alternatively, the increased incidence of glacialquakes may be a consequence of acceleration if seismicity scales with glacier speed. In either case, the ability to detect these events with teleseismic data provides a powerful new means for monitoring glacial activity. Furthermore, a new network of seismometers around Greenland might allow the detection of events on smaller glaciers, which may produce glacialquakes below the current detection threshold.

Although the reasons for increased incidence of glacialquakes and glacier acceleration are not clear, warming temperatures may be the underlying cause. Greenland undergoes regional warming and cooling (see the figure) on multidecadal times scales, with variability that exceeds global temperature trends (*9*). Summer temperatures from the late 1960s through mid-1990s tended to be cooler than average, which may have promoted glacier stability. For example, after decades of retreat, Jakobshavn Isbrae's calving front maintained its position during this cool period (*8*). Starting in about 1995, mean summer temperatures began to rise at coastal stations (*9*), reaching near-centurial highs. The correspondence between the rapid rise in temperature and the increased glacial activity (*1–4*) suggests that warming has a nearly immediate influence on glacier speeds. Although the duration of the recent warming is too short to determine

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whether it is an anthropogenic effect or natural variability, in either case, the data suggest that modest (~1ºC) changes in temperature can lead to large changes in discharge of glacial ice to the ocean. This sensitivity is not currently represented in ice-sheet models, which largely account for direct melt in response to climate change. Consequently, any further temperature increases may increase Greenland's contribution to sea level much more than anticipated.

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CLIMATE CHANGE

Hitting the Ice Sheets Where It Hurts

In both hemispheres, glacier discharge to the sea has increased markedly in recent years as warm water from intermediate depths is melting the floating ends of glaciers from below, accelerating them.

Robert Bindschadler

Several large tidewater outlet glaciers of the Greenland and Antarctic ice sheets now appear to exhibit a nearly universal signature of recent increased discharge to the ocean. That this increase is occurring in the Northern and Southern hemispheres suggests a common cause. The culprit may be additional heat delivered by subsurface waters melting the submarine bases of these glaciers. This scenario would explain the observations and at the same time provide evidence that warmer subsurface waters are reaching the Earth's polar latitudes. Moreover, it 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, thinning, and retreat of Pine Island Glacier in West Antarctica in the mid-1990s sparked an awareness of increased activity at the margin of the Antarctic ice sheet (*1*, *2*). Other glaciers discharging directly into the Amundsen Sea were soon discovered to be accelerating and thinning (*3*, *4*). Airborne ice-sounding measurements have established that these glaciers are deep, with bases hundreds of meters below sea level (*5*). These observations, along with modeling that predicted rapid upstream propagation of thinning, led to a claim that oceanic forcing was at work (*6*, *7*). Elsewhere around the continent, the Cook Ice Shelf in East Antarctica is fed by ice that is thinning and accelerating at comparable rates (*8*). 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 (*9*).

Nearly half a world away, similar behavior has been 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 $year^{-1}$ since 1997, whereas on the east coast the major outlets of Kangerdlugssuaq and Helheim glaciers began thinning in 2003 at rates of 40 and 25 m $year^{-1}$, respectively (*10*, *11*). These glaciers also occupy deep submarine channels.

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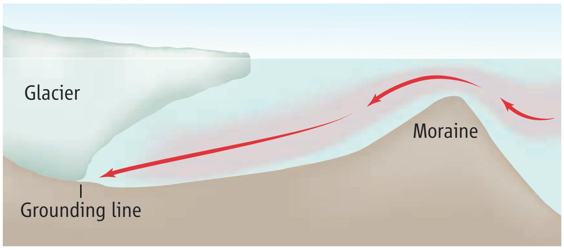

Oceanic low blows. Schematic representing warm intermediate-depth water breaching a submarine sill and sinking in a water cavity beneath the ice shelf to access the grounding line of an outlet glacier.

A recent assessment of changes in speed and mass balance around Greenland identifies these three large glaciers as among the most active recently, with accelerations up to 210% (*12*). The activity on Kangerdlugssuaq and Helheim glaciers has been confirmed by analysis of optical imagery on slightly different time intervals (*13*). Smaller glaciers along the southeast and southwest Greenland coasts are also accelerating (*12*).

Searching for a common cause of the most dramatic changes in the dynamics of the largest outlet glaciers in both Antarctica and Greenland leads one to consider the oceans (*6*, *7*). Melting at the base of a tidewater glacier causes it to accelerate by reducing basal friction and by reducing the buttressing resistance of any floating ice shelf (*14*). 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 comes in contact with the glacier base.

Only about half of Earth's present radiation imbalance has been detected in rising atmospheric temperatures, and it has been suggested that the remainder is being stored in the world's oceans (*15*). Analyzing observations from buoys and ships, Levitus *et al.* demonstrated that the tropical and mid-latitude oceans have been warming in recent decades (*16*). 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 m, 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 warmest water is concentrated at 600-m depth (*17*). 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 in 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