GLACIOLOGY

Repeat warming in Greenland

Greenland's glaciers have lost significant amounts of ice over the past decade. Rediscovered historical images of the ice margin show a record of southeast Greenland's response to the last major warming event in the 1930s.

Benjamin E. Smith

The past decade has been a warm one for southeast Greenland, at the expense of outlet glaciers. Both ocean and air temperatures have been unusually warm, causing the fronts of more than a dozen glaciers to retreat significantly upstream. These changes have had a substantial impact on sea level; the frontal retreat has led to accelerations in ice flow and temporarily doubled the total discharge of Greenland ice into the ocean[1,2]. The retreat may foreshadow Greenland's future response to a warming climate. Alternatively, the warm twenty-first century could have found the Greenland Ice Sheet particularly vulnerable, and continued warming may produce a more muted response. The ice sheet's response to past warming events is an important clue to Greenland's long-term sensitivity, but large-scale studies of ice-sheet behaviour are largely limited to the satellite era, from the 1970s onwards[3,4]. Writing in *Nature Geoscience*, Bjørk and colleagues[5] combine rediscovered historical aerial photographs and satellite records, to track glacier-front responses to climate variations from the 1930s to the present.

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Figure 1 | The Heinkel hydroplane after returning from a surveying mission during Knud Rasmussen's expedition to Greenland. Bjørk *et al.*[5] use rediscovered aerial photographs from the 1930s expedition to compare historical changes in glacier fronts in southeast Greenland with those of the present day.

The study mixes glaciological research with a splash of Indiana Jones, using a data set that includes a trove of air photos recently rediscovered in a citadel outside Copenhagen. These photos were collected during a 1932–1933 expedition led by the Danish explorer Knud Rasmussen, but, with a few exceptions, were classified as secret and effectively lost to science. These photos document glacier conditions at the start of a previous warming event that was comparable in magnitude to the present one for southeast Greenland. This warm period persisted from the late 1930s to the early 1960s, and featured anomalously warm temperatures of both air and ocean.

Using digital tools for photogrammetry, Bjørk *et al.*[5] compared the 1933 photos with more recent records, including British, US and Danish air photos, unclassified cold-war US satellite images and modern satellite images. The result is an 80-year record of the waxing and waning of southeast Greenland glaciers. The images reveal almost constant change, with less than 2% of the glacier fronts remaining stationary over the study period. The vast majority of glaciers have retreated since the first observations, with significant periods of retreat in both the 1930s and the 2000s. The cooler 1960s and 1970s produced widespread readvance, but most of these gains have been reversed in the past few years.

The aerial images permit comparisons between the responses of individual outlet glaciers that terminate on land and those terminating in the ocean. In the 1930s, land-terminating glaciers retreated almost as fast as ocean-terminating ones. In contrast, changes in land-terminating glaciers during the 2000s were much smaller than the extensive retreat observed for ocean-terminating glaciers. One explanation is the initial state of the ice sheet. At the start of the 1930s warming, land-terminating glacier fronts were at considerably lower elevations than they were at the start of the 2000s. During the 1930s and 1940s, the fronts retreated to higher elevations, effectively making them less vulnerable to the warm temperatures in the 2000s.

In contrast, ocean-terminating glacier fronts retreated significantly during both warm periods. Unlike the shift to higher elevations of glaciers terminating on land, the retreat of ocean-terminating glaciers in the 1930s did not provide protection against later warming. It is important to distinguish between the responses of land- and ocean-terminating glaciers, because it is the frontal retreat of ocean-terminating glaciers that can strongly modulate the discharge of ice into the ocean on annual timescales[6,7]. This distinction is key to assess the future vulnerability of the ice sheet to warmer oceans and the resulting sea-level rise.

Even including the rediscovered data, the record of glacier response in southeast Greenland is both short and sparse compared with the long- and short-term response timescales of the glaciers. For example, between observations taken in 1933 and 1943 — a relatively warm period — a significant minority of the glaciers advanced. This could be attributable to warming that actually initiated in the late 1920s, causing retreat before the first observations in 1933 and then readvance before 1943. Alternatively, longer-term climate variations may be responsible. Detailed, longer records are available for a few glaciers (for example, Helheim Glacier[8]), and future work might help tie these longer records into the larger picture of change for southeast Greenland.

The changes we have seen in the Greenland Ice Sheet over the past decade have been the largest in the satellite era. With their pieced-together photographic record, Bjørk *et al.*[5] show that these changes are also large compared with those over much longer eras, such as the 1930s warming period. However, the glacier-front responses are similar in pattern and character to that previous warming event. This indicates that the retreat in the 2000s was a typical response of the ice sheet to warmer air and ocean temperatures, and that future warming events can be expected to have similar consequences. ❐

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CRYOSPHERIC SCIENCE

Vulnerable ice in the Weddell Sea

Of the West Antarctic ice shelves, those in the Amundsen Sea sector have given the most cause for concern. Ocean modelling of the Weddell Sea region, together with a detailed survey of the ice bed morphology, indicates that this region, too, may change soon.

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As a marine ice sheet, the West Antarctic ice sheet rests on ground that is below sea level and has a bed that slopes down, going inland. In the 1970s, concerns about a potential instability of these types of ice sheets were raised — in particular, about the largest one that covers West Antarctica[1,2]. Global-mean sea level could rise by approximately 3.3 m if the entire West Antarctic ice sheet were to disintegrate[3]. So far, indication for accelerating ice loss[4] has mainly been found in the Amundsen embayment at the root of the Antarctic Peninsula. Two papers, published in *Nature Geoscience*[5] and *Nature*[6], indicate that the Weddell Sea sector to the east of the peninsula may soon become susceptible to fast change, too.

An understanding of the current and future development of the West Antarctic ice sheet requires detailed knowledge of the various factors that affect ice sheets. For example, the location of the grounding line — the transition between ice that sits on the bed and ice connected to the sheet but floating on the ocean — plays a key role in the stability of a marine ice sheet, as does the topography of the ice bed[7]. When the grounding line retreats, more ice is discharged from the sheet, because the ice upstream is thicker. This, in turn, leads to further increase of the ice flux into the sea — a positive feedback. Basal melting of the floating part of the ice mass, the ice shelf, plays a particularly important role in this feedback: a warming ocean may change the temperature beneath an ice shelf, leading to enhanced basal melting and, potentially, grounding line retreat. On the other hand, a rough bed topography with small ridges might offer support for a marine ice sheet in retreat, and may thus prevent or delay further disintegration.

Yet before any warm water masses — usually found at intermediate ocean depths between 300 and 700 m — can interact with ice shelves, they must first drain onto the continental shelves. One possible mechanism to push the warm water masses onto the shelves is the momentum transferred between wind and ocean, which drives ocean circulation. A less consolidated cover of sea ice can achieve such a push of warm water onto the shelves.

Over the past few years, glaciologists and oceanographers have been studying these processes, with emphasis on the Amundsen Sea sector, where basal melting, grounding line retreat and accelerating ice flow has been diagnosed[8–10].

Now, Ross *et al.*[5] and Hellmer *et al.*[6] focus their attention on the Filchner-Ronne Ice Shelf in the Weddell Sea sector, which has so far seemed stable. Worryingly, Hellmer and colleagues conclude that, over the course of the twenty-first century, warm pulses of ocean currents are likely to reach this ice shelf and induce basal melt, whereas Ross and colleagues find that beneath the grounded ice streams that feed the

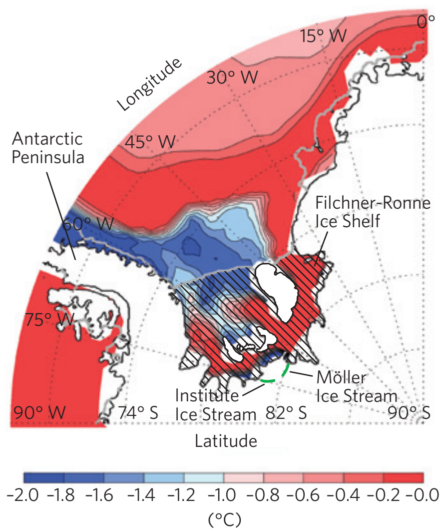

Figure 1 | Warm waters off West Antarctica. In simulations with a coupled ice–ocean model, Hellmer and colleagues[6] show that, later in the twenty-first century, warm ocean currents (red) could reach far beneath the Filchner-Ronne Ice Shelf in the Weddell Sea (hatched), which could lead, in turn, to basal melting. For the Institute and Möller ice streams (green) that feed into the Weddell Sea, Ross and colleagues[5] detected a smooth bed with a relatively steep, retrograde slope — a bed that would offer little resistance to any instability that might arise. The solid grey line behind the coastline (black) indicates the ice-shelf front.