CLIMATE CHANGE

Warm bath for an ice sheet

Greenland is losing ice through glaciers that flow into deep fjords. New observations highlight the important fjord processes that supply warm ocean waters to the melting glaciers, and thereby affect Greenland's contribution to sea-level rise.

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The Greenland ice sheet contains enough ice to raise sea level by 7 m, and at present contributes about 0.5 mm to global mean sea-level rise each year[1]. The synchronicity across many of Greenland's fjord-terminating glaciers in their retreat, acceleration and thinning indicates that climatic changes are responsible[2]. Ocean warming has been implicated[3], but the circulation and glacier melting within Greenland's fjords — the connection between ocean and ice — is poorly documented. Writing in *Nature Geoscience*, Straneo *et al.*[4] and Rignot *et al.*[5] report observations of fjord waters from East and West Greenland, respectively, and suggest that Greenland's under-studied fjords are a critical regulator of the ice sheet's ongoing change.

Both the snow accumulation that nourishes the Greenland ice sheet and the glacier flow that drains it have been subject to change. Greenland's vast interior is growing slowly through increased snowfall. At the same time, coastal areas are thinning rapidly through increases in surface melting and glacier discharge[6]. The glaciers that flow into Greenland's fjords have accelerated dramatically, and have thinned and retreated more than those that terminate on land[7,8]. These effects are triggered by changes at the glaciers' termini[9,10] — the calving fronts where icebergs are released into the fjords. Why these changes occur is poorly understood, but synchronicity across separate glaciers implies a common climatic cause[2,8]. Atmospheric warming is undoubtedly important, but the changes that are focused on marine-terminating glaciers also indicate an origin within the fjords themselves.

Jakobshavn Isbræ, a large fjord-terminating glacier in West Greenland, accelerated when its floating tongue thinned and disintegrated, removing a significant resistance to flow[9]. The timing of this disintegration was consistent with warming of the ocean outside the fjord[3]. However, documented observations from inside Greenland fjords are rare, not least owing to the notorious prevalence of sea ice and icebergs. The delivery of warm ocean waters

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Figure 1 | A West Greenland fjord. Straneo *et al.*[4] and Rignot *et al.*[5] present observations of Greenland's fjord waters and propose that oceanic melting at the glacier calving fronts has an important role in determining the mass balance of the ice sheet.

to glacier calving fronts, and any cooling that may occur *en route*, is therefore not well understood. The lack of detailed ocean data from glacier calving fronts also prevents an understanding of melting processes; the pattern of melt rates and their size relative to iceberg calving are practically unknown. As a result, we cannot translate observed ocean changes into melt rates or suggest how they might affect the ice sheet.

Straneo and colleagues[4] surveyed Sermilik Fjord, which links Helheim Glacier in East Greenland to the Irminger Sea. Their cruises in July and September 2008 revealed relatively warm deep waters of 3–4° C throughout the fjord. Furthermore, the uppermost 300 m must have been flushed with water from outside the fjord between the two cruises. Measured currents indicate that this could happen in as little as a few days. The findings imply a fjord circulation so vigorous that it cannot be driven solely by meltwater from the glacier. Instead, Straneo and colleagues conclude that the circulation is governed by changes in the temperature and salinity of the shelf sea outside the fjord. Moored instruments left in the fjord for up to eight months show — despite encounters with passing icebergs — that northeasterly winds aligned with the coastline are an important source of such changes in water properties.

Rapid renewal of warm fjord waters implies that Helheim Glacier has a high melt rate that is tightly coupled to the changing water properties of the Irminger Sea[3,4]. The proposed wind-driven circulation may also govern other fjords nearby with a similar coastline orientation. In this way, long-term changes in the winds or ocean properties might synchronously affect all of southeast Greenland. Fjords in other parts of Greenland could be subject to similar dynamics.

Turning to the western side of Greenland, Rignot and colleagues[5] took ocean measurements in August 2008 near four calving fronts distributed over three fjords.

Their data allow ocean-based calculations of Greenland glacier melting. Perhaps their most notable finding is the marked variability of ocean properties between fjords sited within 30 km of each other. As a result, derived melt rates vary by a factor of five. For the glaciers Rignot and colleagues studied, ocean melting accounted for between 20% and 75% of frontal ice loss, with the remaining ice loss being through iceberg calving. Observed fjord currents reveal narrow jets near the surface, which could be glacial meltwater flowing away from the ice. Very fine sampling would be required to adequately measure these features.

Rignot and colleagues only observed the top 100 m or so of water, so melt-rate calculations partly rely on a conceptual model of fjord flow[11], rather than directly being based on conservation laws for mass and energy. In the model, the glacier face is melted by a rising plume that is initiated by fresh ice-sheet meltwater emerging from beneath the glacier. The plume incorporates warm fjord water at depth, and the heat of this water melts the glacier. Cooled water is then ejected at the surface[11]. This means that melt rates can be estimated by measuring the temperature decrease between deep and shallow waters near the calving front. However, Rignot and colleagues only sampled the full depth of the water column in one of the three fjords under investigation, Eqip Sermia (Fig. 1); for the others the source of heat for melting is obtained by extrapolation. Observed currents indicate that the fjord circulation is more complex than a simple rising plume, but for Eqip Sermia the results derived from the model agree with direct calculations. Obtaining melt rates from Greenland oceanographic data is a crucial advance, but future studies require fine sampling of the entire fjord cross-section.

The observed variability in water properties in the three adjacent fjords casts doubt on any extrapolation of conclusions drawn from a particular glacier outlet. However, the results from Sermilik Fjord on the east side of Greenland show that shallow waters are most variable[4], so deeper glaciers than those investigated by Rignot and colleagues might experience more uniform warm-water forcing. The Sermilik observations demonstrate that glacial meltwater plumes do not control circulation in the wider fjord, but they are not inconsistent with the existence of plumes or their control of glacier melting[11].

Important questions remain about the dynamics of ocean–glacier interactions. It is unclear how melting at the calving front accelerates Greenland glaciers — most glaciers terminate in a sheer vertical front rather than a floating tongue that can thin and disintegrate. Perhaps faster melting simply drives the ice front backwards, either directly or by undermining it. Undermining could increase iceberg calving or cause the glacier to float[5]. Alternative ocean-led explanations include a weakening of the fjords' mélange of sea ice and icebergs that is thought to resist glacier flow in winter[12].

The possibility remains that ice losses are driven entirely by increases in surface melting imposed by the atmosphere. Increased surface melting could thin the glaciers and cause them to float, increase iceberg calving through ice thinning or fracturing[12], or moderately accelerate glaciers by lubricating their base with meltwater. In an intriguing twist, increased surface melting would raise the flow of meltwater entering fjords from underneath the glacier. As this flow initiates the plumes that melt the glacier faces[11], its increase could raise oceanic melt rates by mixing more of the existing warm fjord water towards the glacier (refs 5, 11 and A. Jenkins, unpublished). In this way, ocean melting could be increased without any change in external ocean properties. None of the intricate processes linking glaciers and the ocean are included in current climate models.

The studies by Straneo and Rignot and their colleagues[4,5] are vital steps towards an understanding of Greenland's ice loss into fjords, but more needs to be learnt before fjord processes and their connections with glacier flow can be modelled to predict the fate of the Greenland ice sheet. Ongoing field studies promise to advance our understanding in this rapidly evolving field. ❐

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EARLY EARTH

Leftover lithosphere

The earliest evolution of our planet is difficult to reconstruct. Ancient rocks in Western Australia show an isotopic signature that links their formation with 4.3-billion-year-old crust.

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During the initial stages of Earth's evolution, the planet cooled and separated into core, mantle and crust. This process was a consequence of the different chemical and mechanical properties of the elements and compounds that went into its formation. A solid outer crust could have formed within ten million years of the formation of the Moon[1], but the precise timing of crustal differentiation and emplacement of basalt or more evolved rock types such as granite is unknown. Writing in *Nature Geoscience*, Tessalina *et al.*[2] report that a roughly 4.3-billion-year-old component of Hadean crust was later reworked into the Dresser Formation (Fig. 1) in Western Australia's Pilbara Craton, indicating that some geochemical fingerprints of primordial lithosphere survived to the Archaean. These venerable remnants could help us to understand