

## CRYOSPHERE

# Greenland's lurking aquifer

Runoff estimates from the Greenland ice sheet carry uncertainty because the fate of surface melt in permanently snow-covered regions is unconstrained. *In situ* and airborne observations reveal large-scale liquid water storage in buried layers of aged and compacted snow.

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At intermediate elevations along the flanks of the Greenland ice sheet, strong surface melting can occur during summer months. Nevertheless, over the course of a year more snow falls than melts. As snow layers are buried by the accumulating snowfall, they compact and densify. Eventually the snow turns to firn, which can extend up to 100 metres in depth before fully transforming into glacial ice. An important source of uncertainty in determining Greenland's runoff — and how it might change in the future — has been in understanding how much of the melt water from firn-covered regions is partitioned into runoff, and how much is left behind in the ice sheet after infiltrating into underlying firn and refreezing. Writing in *Nature Geoscience*, Forster and colleagues<sup>1</sup> document direct evidence for a massive aquifer in firn that stores melt water year-round beneath the surface of the ice sheet in southern Greenland.

In April 2011, Forster and colleagues mounted a field campaign to traverse part of the southern Greenland ice sheet and drill cores to measure the thicknesses of annually accumulating snow layers. Surprisingly, one of their core holes intersected water-saturated firn 10 metres below the surface (Fig. 1). The springtime air temperatures were well below freezing and the onset of summer melt was still a month away. They had clearly encountered old melt water from a previous summer that had survived one or more winters. Unable to drill through the water-saturated firn, they packed up their drilling equipment and moved a few kilometres away to drill another hole. Again, they found water in the firn — this time at a depth of 25 metres.

The team used radar imaging to search for more water in the subsurface. Moving a ground-based radar system across the area revealed a bright radar reflector, characteristic of a water table surface and nicely matching the water level observed in the two core holes. The reflector was continuous for 25 kilometres, cutting across the undulations of the annual layers while



**Figure 1** | Water draining from a core extracted from 15 metres below the surface of the southern Greenland ice sheet. Researcher Clément Miège is pictured collecting a sample of the water. Forster *et al.*<sup>1</sup> report direct evidence from these drill core observations, as well as from radar imaging, of a perennial and widespread meltwater aquifer in firn below the surface of the southern Greenland ice sheet.

mimicking the surface of the ice sheet above. Further scrutiny of airborne radar collected by the NASA IceBridge mission identified a bright radar reflector in the same area that coincided with that of the ground measurements.

Armed with tens of thousands of kilometres of airborne flight lines over the Greenland ice sheet, Forster and colleagues<sup>1</sup> tracked the top of the subsurface water layer across 843 km of southern Greenland, at depths ranging from 5 to 50 metres. They termed this widespread layer of water-saturated firn the perennial firn aquifer.

The perennial firn aquifer represents a previously undocumented component of the ice sheet's hydrological system, acting as storage for melt water and delaying its removal from the ice sheet. The storage of melt water in firn may be partially responsible for disparities between

simulated mass loss from the Greenland ice sheet from regional climate models, and determinations of mass loss from satellite gravimetry or altimetry measurements<sup>2</sup>. The large mass of liquid water in firn also represents a heat sink that could be playing a role in Greenland's interaction with the climate system. As the intensity of surface melt in Greenland increases and expands upwards to the higher elevations<sup>3</sup> that are covered by firn, liquid water storage may play an expanding role in the ice sheet's future response to changing climate.

Much remains to be determined about the processes leading to the formation and evolution of the perennial firn aquifer in Greenland. Forster *et al.*<sup>1</sup> compare their observations to regional climate model simulations to show that the perennial firn aquifer is generally associated with regions in southern Greenland that have high

snowfall and heavy melt. However, there is no apparent threshold in precipitation for dictating whether the aquifer forms or not. Also, airborne radar might not always return clear reflections from water if very thick ice layers lie above it in the firn, leaving open the possibility that water lurks below the surface in areas not yet identified. Indeed, previous observations have suggested liquid water present at a depth of more than 10 metres below subfreezing firn in at least one location in western Greenland<sup>4</sup>.

The capacity of melt water to travel through many metres of cold snow and firn has long been known<sup>5–7</sup>. The processes involved are strongly heterogeneous, arising from subtle variability in firn structure. Water tends to collect into pipes within the firn that direct flow vertically, or alternatively water can stair-step downwards along imperfections in ice layers<sup>8</sup>. Water can also be routed by capillary suction effects governed by differences in the size of firn grains<sup>9</sup>.

However, numerical models that estimate runoff from the ice sheet operate at a much coarser resolution, with computational cells many kilometres across, and infiltration and retention processes are assumed to balance over time and space. Explicit treatment of local inhomogeneous processes may be required to model the development of and water transport through the perennial firn aquifer through time. Unfortunately, the physics governing inhomogeneous interactions between water and subfreezing firn are not well known, so incorporating these processes into deterministic models will be challenging.

The discovery by Forster and colleagues<sup>1</sup> of a large melt water aquifer in firn has uncovered a fundamental, but previously overlooked, component of meltwater runoff processes in Greenland. With a key part of Greenland's hydrology lurking within reach, much remains to be learned from

*in situ* measurements in Greenland's poorly explored interior flanks. □

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