Firn matters: Changing runoff from Arctic Ice caps and Greenland

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Glaciers are made up of 4 types of material: snow, firn, glacier ice, and liquid water. They may also contain rock and soil material eroded from the glacier bed, blown onto the glacier surface by the wind, or deposited onto the glacier by mass movement processes operating on the valley walls surrounding the glacier.

**Snow and firn**

Snow is deposited directly onto the glacier from the atmosphere as snowfall, or by avalanching from valley walls. Over time it is compacted and transformed to firn as increasing amounts of snow accumulate on the glacier surface. Firn is snow that is being compacted under the weight of overlying snow and on its way to becoming glacier ice. Firn forms from snow that falls on sections of a glacier that are high enough and/or cold enough that the snow does not melt away completely during the summer. The surviving snow becomes denser over time as more snow accumulates on top of it and compresses it to form firn and, eventually, glacier ice. Freezing of meltwater that is generated at the glacier surface and then percolates down into underlying colder snow and firn produces ice layers or ice slabs within the snow and firn (MacFerrin et al., 2019).

**Glacier ice**

Ice slabs form over multiple years by infilling the space between pre-existing ice layers and can be 3-5m thick. They prevent vertical percolation of meltwater into the firn and promote downslope runoff over the upper surfaces of the buried ice layers. Under a warming climate, ice slab formation occurs at progressively higher elevations as surface melting extends up-glacier over time. In Greenland, ice slabs typically form over multiple years where water freezes between pre-existing ice layers, causing them to thicken over time. In Greenland, areas where ice slabs form have annual snow accumulation rates of <522 +/- 32mm water equivalent per year. In areas with higher snow accumulation rates, they are replaced by firn aquifers (i.e. layers of firn in which much of the pore volume is filled by meltwater rather than air). Refreezing of water within cold firn increases its mean density and releases latent heat of freezing that will, over time, cause the firn to warm up.
**Accumulation area and ablation area**

Glacier surfaces are commonly classified into two zones – an accumulation area at high elevations where annual snowfall exceeds annual melting, and an ablation area at low elevations where each winter’s snowpack is totally removed by melting in the following summer. These zones are separated by an equilibrium line along which the annual accumulation of snow (which occurs mainly in winter) is exactly balanced by the annual melting of snow during the summer. In the accumulation area of an ice cap or glacier, firn is continually buried by the accumulation of new snow (which eventually turns into firn and glacier ice). The firn forms a distinctive layer that separates glacier ice at depth from the seasonal snowpack that forms at the surface in winter.

Firn can be exposed at the surface in summer if melting removes the previous winter’s snowpack. Firn is denser and less porous than the winter snowpack, but less dense and more porous than glacier ice. It has a layered structure in which there is significant vertical variability in grain size, porosity, permeability, and ice and water content. In parts of Greenland, the firn layer may exceed 100m in thickness, below which it is replaced by glacier ice (Humphrey et al., 2012.).

**Liquid water**

Firn layers that form where there is appreciable surface melting in summer may absorb percolating water. This will either freeze within the firn to form interstitial ice or be stored as a liquid. Freezing releases latent heat that acts to warm the firn, while, if liquid water is present, the firn layer functions as a large-scale aquifer below the ice cap surface (Harper, 2014). Water storage in such an aquifer may delay the release of seasonal meltwater from a glacier or ice cap. This can affect the seasonal timing and magnitude of runoff in proglacial river systems, and the amount of water transferred from glaciers to the ocean. This has obvious implications for the relationship between glacier melt rates and rates of regional and global sea level change.

The area occupied by firn aquifers and the volume of water they contain may change significantly over time. Water storage in firn extends to higher elevations in periods of unusual summer warmth and is restricted to lower elevations in cooler periods. Radar surveys in southern Greenland have identified a water layer at ~ 5.5 m depth which can be traced over a horizontal distance of > 842 km. This is a perennial aquifer that delays the transfer of water from the ice sheet to the ocean. Water storage in the aquifer mediates the relationship between the rate of surface melting that is driven by climate warming, and the rate of sea level rise (Harper et al., 2012). Slow freezing of the water in the aquifer releases latent heat that acts to warm the surrounding firn.

The total volumes of liquid water in store within Arctic ice caps and the Greenland Ice Sheet may be large enough to appreciably change global mean sea level if returned to the ocean. One estimate suggests that there could be as much as 140 +/- 20 Gigatons of liquid water stored within the Greenland Ice Sheet – enough to raise global mean sea level by 0.4 mm. Put another way, this stored water has the effect of somewhat delaying and/or damping the response of global mean sea level to ice sheet melting (Forster et al, 2014. Koenig et al., 2014).

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