The Neglected Middle Child - Snow, Firn, and Water Storage in the Ice Sheet Percolation Zone

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Bright radar reflections within the firn are typically interpreted as the top of a local water table, and that all pore space below this depth to the firn-ice transition is saturated with water. We use an enthalpy formulation of the 1-D conservation of energy equation to show that this interpretation is not always valid, especially in the percolation zone. Our model suggests that under certain conditions, layers of water-saturated firn can persist between layers of cold, dry firn. Two key requirements for a thermally layered percolation zone are relatively high accumulation (to increase downward advection) and relatively high – but not too high – surface melt in the summer (to slow the refreezing of meltwater).

We use conservation of enthalpy because it allows us to track both the temperature and water content. A key assumption is that the effective vertical diffusivity of water is much smaller than the diffusivity of heat. Figure 1 shows the layered structure for an extreme high accumulation rate site (7m/yr), such as found in British Columbia. The left side of the figure shows the firn column when there is less surface melt: all surface meltwater refreezes and the entire firn column is below the freezing point. The right side of the figure shows the firn column when there is higher surface melt: the firn is all temperate with layered variations in enthalpy corresponding to differing amounts of water storage.

We present model results for a range of surface conditions, including those found in WAIS, supporting four key conclusions:

1. Enthalpy transport between winter and summer layers is limited by the ability of the cold ice to conduct heat away from the warm wet layers, slowly freezing the water. Therefore, even a temperate firn column, variations in the amount of liquid water can persist.

2. Differing densification rates for cold and warm firn suggests two bubble close-off depths. The warm wet firn reaches bubble close off higher in the column than the cold dry firn. Because densification reduces the ability of warm firn to hold water, the water becomes concentrated at the upper boundary of the warm layer where it meets the overlying colder (less dense) layer. This process likely results in the bright radar reflector we observe.

3. Finally, our model shows that daily random noise superimposed on a steady state seasonal surface enthalpy results in structure in the enthalpy profile much deeper than 10 meters for both cold and temperate ice. *This has implications for inferring past surface temperatures from*

borehole temperatures in cold sites and for inferring firn water storage from radar for temperate sites.

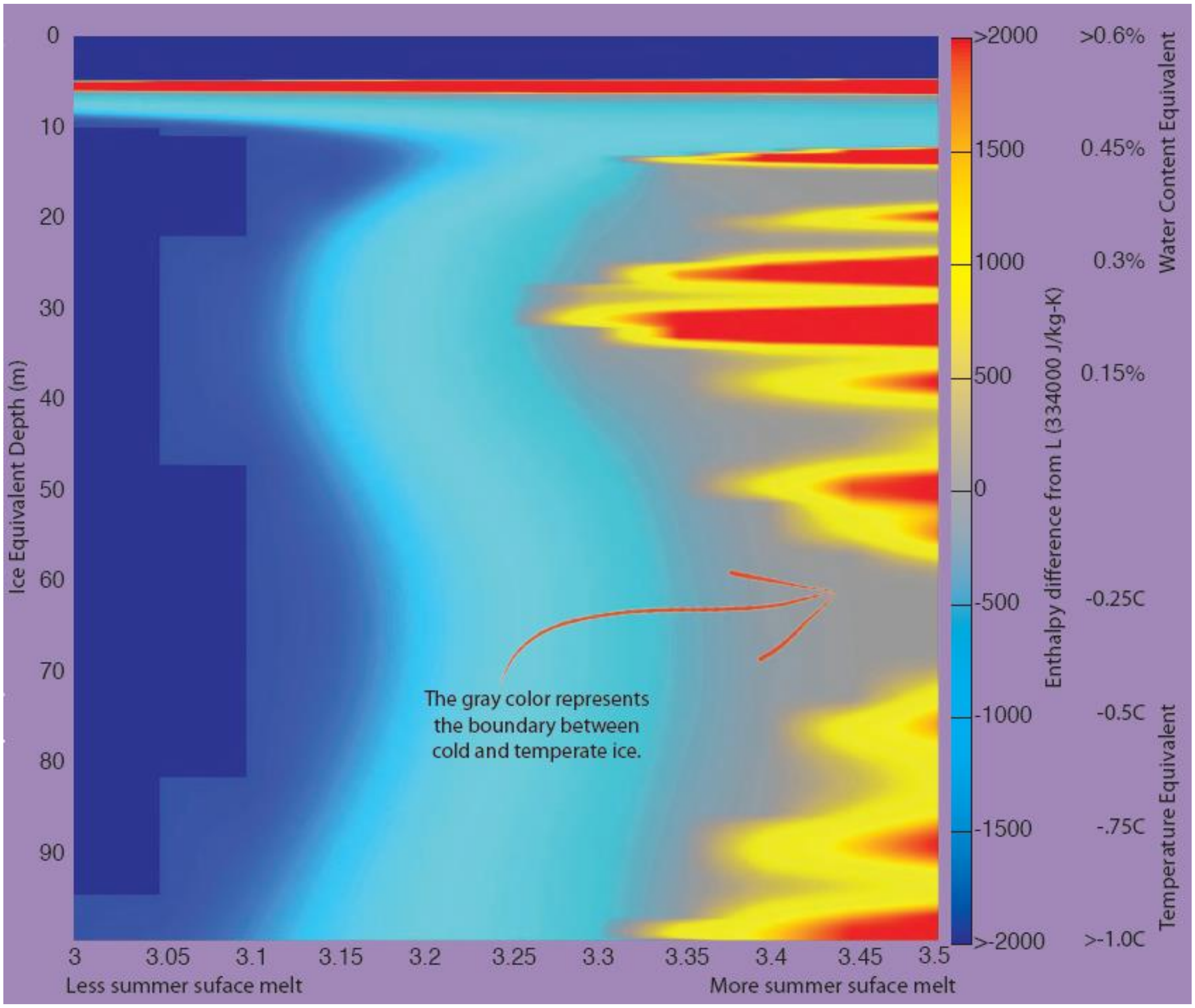

Figure 1: Enthalpy as a function of depth for the top 100m for a site with 7m/yr accumulation. An enthalpy difference of zero is equal to ice at $0^{o}C$ without any liquid water present. The x-axis is a proxy for the surface melt. All model runs are steady state and use the same surface data (including noise) with daily timesteps.