Meltwater Penetration Through Temperate Ice Layers in the Percolation Zone of the Greenland Ice Sheet

Samira Samimi[1], Shawn J. Marshall[1,2] and Michael MacFerrin[3]

[1] Department of Geography, University of Calgary, Calgary, Alberta, Canada
[2] Environment and Climate Change Canada, Gatineau, Quebec, Canada
[3] Cooperative Institute for Research in Environmental Sciences, University of Colorado, USA

Corresponding author: Samira Samimi (samira.samimi@ucalgary.ca)

Key Points:

- Time-domain reflectometry probes give direct measurements of meltwater infiltration in firn on the Greenland Ice Sheet.
- We document meltwater penetration through ice layers up to 12 cm thick in temperate firn.
- The wetting front and melting front were coincident, indicating thermodynamic controls on meltwater infiltration and retention.

Abstract

Meltwater retention in the firn layer of the Greenland Ice Sheet is has the potential to buffer sea level rise due to ice sheet melt. The capacity of the firn layer to store meltwater is unclear, however, because refrozen ice layers can act as impermeable barriers to meltwater percolation, promoting runoff rather than retention. We present time-domain reflectometry and thermistor data which demonstrates that meltwater successfully penetrates ice layers up to 12 cm thick in the near-surface firn at Dye2, Greenland. Our observations indicate that ice layers within polar firn can become permeable when summer warming and latent heat release from refreezing meltwater raise temperatures to the melting point. This facilitates meltwater retention, and indicates that the depth of penetration of the summer melting front (the 0°C isotherm) represents the primary control on meltwater infiltration in the percolation zone of the Greenland Ice Sheet.

Plain Language Summary

Meltwater that percolates below the surface of the Greenland Ice Sheet is difficult to track; some of it contributes to runoff, mass loss, and sea level rise, but some meltwater refreezes and is retained within the system. Greenland has a large firn area, where multi-year snow that has not yet transitioned to glacial ice has pore space that can retain meltwater. To improve understanding of hydrological and mass balance processes in polar firn, we excavated two firn pits in the Greenland Ice Sheet accumulation area in spring, 2016, and instrumented these pits with thermistors and time-domain reflectometry (TDR) sensors, connected to continuously-recording dataloggers. These sensors allowed us to directly track the coupled thermal and hydrological evolution in the firn through the summer melt season. We recorded nearly identical conditions at each site, with evidence of meltwater infiltration to a depth of between 1.8 m and 2.1 m and a wetting front that was thermally controlled, i.e. coincided with the melting front. This included meltwater penetration through numerous ice layers, including layers up to 12 cm thick. All of this meltwater refroze. Our results indicate that ice layers do not always present an impermeable barrier to meltwater percolation and retention.

1 Introduction

Mass loss from the Greenland Ice Sheet has increased in recent decades due to significant increases in surface melt and runoff (van den Broeke *et al*., 2009; Mouginot *et al*., 2019). One of the challenges in estimating the contribution of the ice sheet to sea level rise is the fact that the surface melting does not always lead to runoff. In the percolation zone, surface meltwater that infiltrates the underlying cold snow or firn can be retained as liquid water (Forster et al., 2014; Koenig et al., 2014) or as refrozen ice (Pfeffer et al., 1991; Pfeffer and Humphrey, 1998; Harper et al., 2012). This reduces summer runoff and ice sheet contributions to sea level rise (Harper et al., 2012; Rennerhalm et al., 2013), and meltwater retention processes may be increasingly important as melting propagates to higher elevations in Greenland in a warming world (Vernon et al., 2013).

Meltwater that percolates and refreezes is difficult to account for in altimetric measurements of surface mass balance, as it is not possible to detect how much meltwater is retained within the system. This is also a source of uncertainty in mass balance models, as processes of meltwater percolation and refreezing occur at fine scales, are spatially heterogeneous, and *in situ* observations are scarce (*e.g*., Harper et al., 2012; van As et al., 2016; Verjans et al., 2019, Vandecrux et al, 2019). This makes it difficult to calibrate and validate models of these processes, particularly on the scale of polar ice caps and ice sheets.

The extent to which meltwater retention in firn can buffer mass loss and sea-level rise is also unclear. Greenland's firn zone covers more than 80% of the ice sheet, but refrozen near-surface ice layers can act as impermeable barriers, redirecting meltwater percolation into runoff (Machguth et al., 2016; Noel et al., 2017; MacFerrin et al., 2019). In the percolation zone, firn densification associated with warming and refreezing is also leading to a loss of available pore space, imposing further limits on meltwater storage capacity as melting progresses inland (Vandecrux et al., 2019). These processes increase the ratio of meltwater runoff to retention. Hence, models of meltwater infiltration also need to account for ice-layer and firn-densification processes. These represent significant uncertainties in projections of the Greenland ice sheet's response to climate warming.

To examine meltwater infiltration and refreezing processes in the Greenland ice sheet percolation zone, we instrumented two firn pits with arrays of thermistors and time-domain reflectometry (TDR) sensors in order to track the coupled thermal and hydrological evolution of near-surface snow and firn through a summer melt season. The TDR sensors provide continuous measurements of dielectric permittivity, a proxy for liquid water content in the snow and firn. This manuscript presents these *in situ* observations and their implications for meltwater retention in firn. The experiment builds on Humphrey et al. (2012), who used thermistor arrays to track the thermal signature of meltwater infiltration in firn, which is apparent through the latent heat release when meltwater refreezes. Through the addition of TDR probes, we directly trace meltwater flow in the near-surface snow and firn. A similar experimental setup in the Canadian Rocky Mountains successfully demonstrated the ability to track meltwater percolation, refreezing, and snow-water content in a supraglacial snowpack using TDR probes (Samimi and Marshall, 2017). The implementation in Greenland extends the earlier experiments to polar firn, where liquid water content is lower and meltwater refreezing is more significant.

2 Methods

Measurements were established in May, 2016 in the near-surface firn at 66˚28′39″N, 46˚17′5″W, near Dye 2 station on the southwestern flank of the Greenland Ice Sheet. The study sites were at an elevation of 2120 m, representing the upper part of the percolation zone in southern Greenland (Harper et al., 2012). During our 2016 field campaign, colleagues from Ludwig Maximilian University, Munich, also investigated meltwater percolation at one of our study sites, using upwards-penetrating radar (Heilig et al., 2009; Mitterer et al., 2011) installed at a depth of ~4 m below the surface (Heilig et al., 2018). This provides a complementary dataset concerning the depth of meltwater penetration in summer, 2016.

Firn pits were excavated to depths of 2.2 and 5.3 m at two sites 650 m apart. Snow and firn density were measured at 10-cm intervals in the firn pits, using a 100-cm^3 box cutter. The 2015-2016 seasonal snowpack had a depth of ~0.9 m and was free of ice layers. The underlying firn was made up of a mixture of ice layers and porous firn, with the ice layers taking the form of discrete or continuous horizontal bands. Several ice layers were more than 10-cm thick. Figure 1 presents the ice-layer stratigraphy at each site, based on analysis of shallow firn cores drilled adjacent to the firn pits.

A chainsaw was used to cut through the thick ice layers and below about 2 m depth, where the firn became too dense for a shovel. The north-facing vertical face of each firn pit was instrumented with 8 thermistors and 8 time-domain reflectometry (TDR) probes to monitor snow water content. TDR measures bulk dielectric permittivity, ε_b, an excellent proxy for liquid water content in snow and firn (Denoth, 1984; Techel and Pielmeier, 2011). The relative dielectric permittivity of air, ice, and water are ε_a=1, ε_i ~3.2, and ε_w ~ 80. Because liquid water has such a high value compared to air and ice, the dielectric permittivity of snow increases strongly with liquid water content. Dielectric permittivity also increases with snow density, but water content is the main control on variations in ε_b (Stein et al., 1997; Schneebeli et al., 1998).

Installation depths for the thermistors and TDRs are indicated in Figure 1 and Table S1. Sensor spacing was irregular in order to concentrate observations near the surface as well as immediately above and below thick ice layers, to test whether these acted as impermeable barriers to water flow. The thermistors and TDR probes were wired to Campbell Scientific CR1000 dataloggers and data were recorded each 30 minutes from May 11 to September 30, 2016, capturing the complete melt season. Sensors were inserted horizontally into undisturbed snow and firn, with the probes extending 0.3 m into the wall of the firn pit. Pits were filled in with snow after the sensors were installed, several weeks in advance of the summer melt season.

An automatic weather station (AWS) configured for surface energy balance monitoring was also installed adjacent to site A. This pit was shared with the upward-looking radar experiments (Heilig et al., 2018). Sensors were left in place through the summer 2016 melt season and we returned to the sites in April 2017 to collect data and excavate the instruments. All data were quality-controlled and any missing data were gap-filled by linear interpolation.

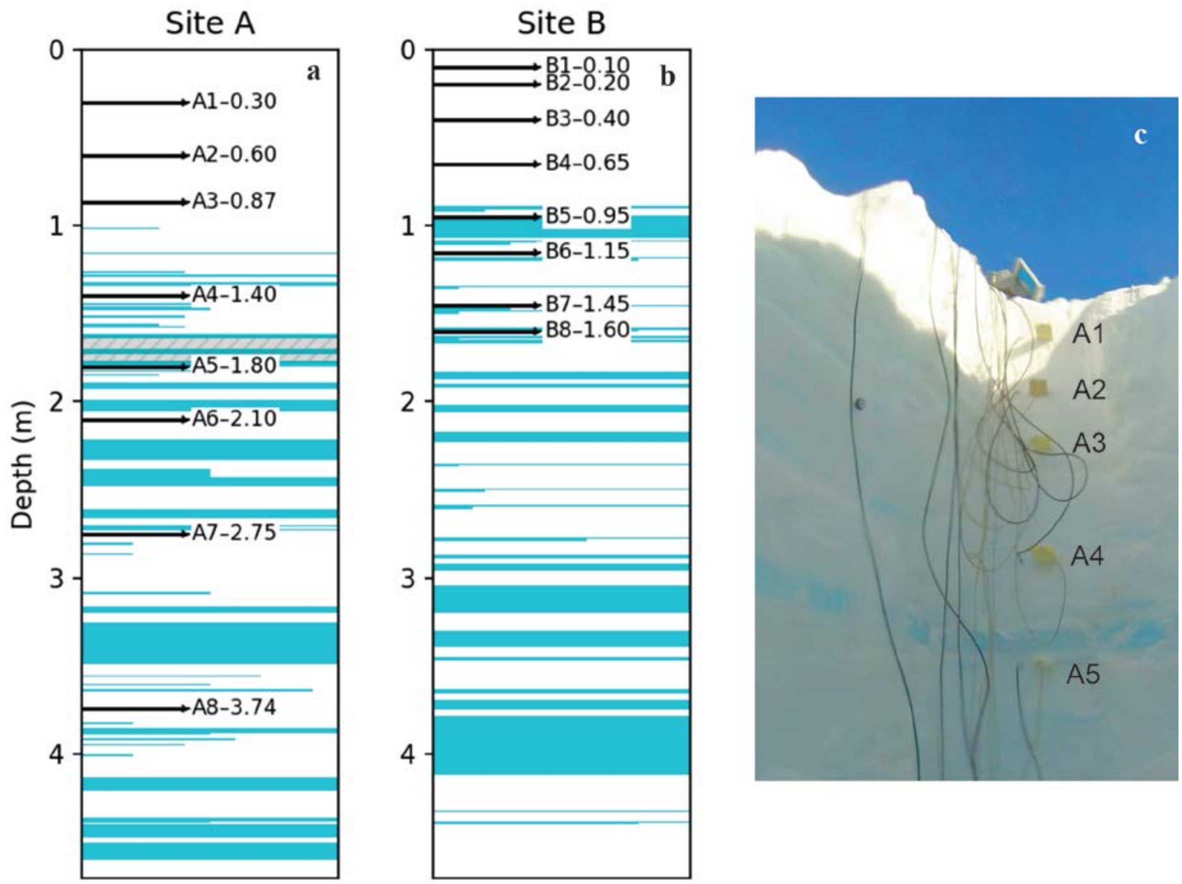

Figure 1. Ice-layer stratigraphy from sites a) A and b) B. Blue colors indicate ice layer location and thickness, and black arrows indicate the locations and depths (in m) of thermistors and TDR probes. The grey hatched zone in (a) highlights an 11-cm thick ice layer just above level A5 (1.68 to 1.79 m), as seen in photograph (c) of the upper ~2 m of pit A, which also shows thermistor/TDR installations A1 to A5. Photograph by Samira Samimi.

3 Results and Analysis

Figure S1 plots the evolution of air temperature, subsurface snow/firn temperature, and dielectric permittivy in the deep firn pit from May to September, 2016. At the time of sensor installation, near-surface firn was in the process of warming from the winter cold wave. Frequent daily maximum air temperatures above 0°C began in the first week of June, but it took ~two weeks for the snow at 0.3 m to warm to the melting point and for liquid water to be detected at that depth. Diurnal cycles of surface melting continued regularly into mid-August, accompanied by firn warming and meltwater infiltration to a depth of between 1.8 and 2.1 m. The depth of penetration of the wetting front coincided with the melting front (0°C isotherm). Sensors at and below 2.1 m depth remained frozen and dry. The summer melt season ended on August 26, with a return to persistent sub-zero air temperatures after this date.

Figures 2 and 3 examine the two main summer melt periods in each firn pit. The evolution of summer melting, snow/firn temperature, and dielectric permittivity was similar at the two sites, with evidence of thawing- and wetting-front propagation to similar depths. Site B offers more detail on the near-surface snowpack, with sensors at 0.1 and 0.2 m.

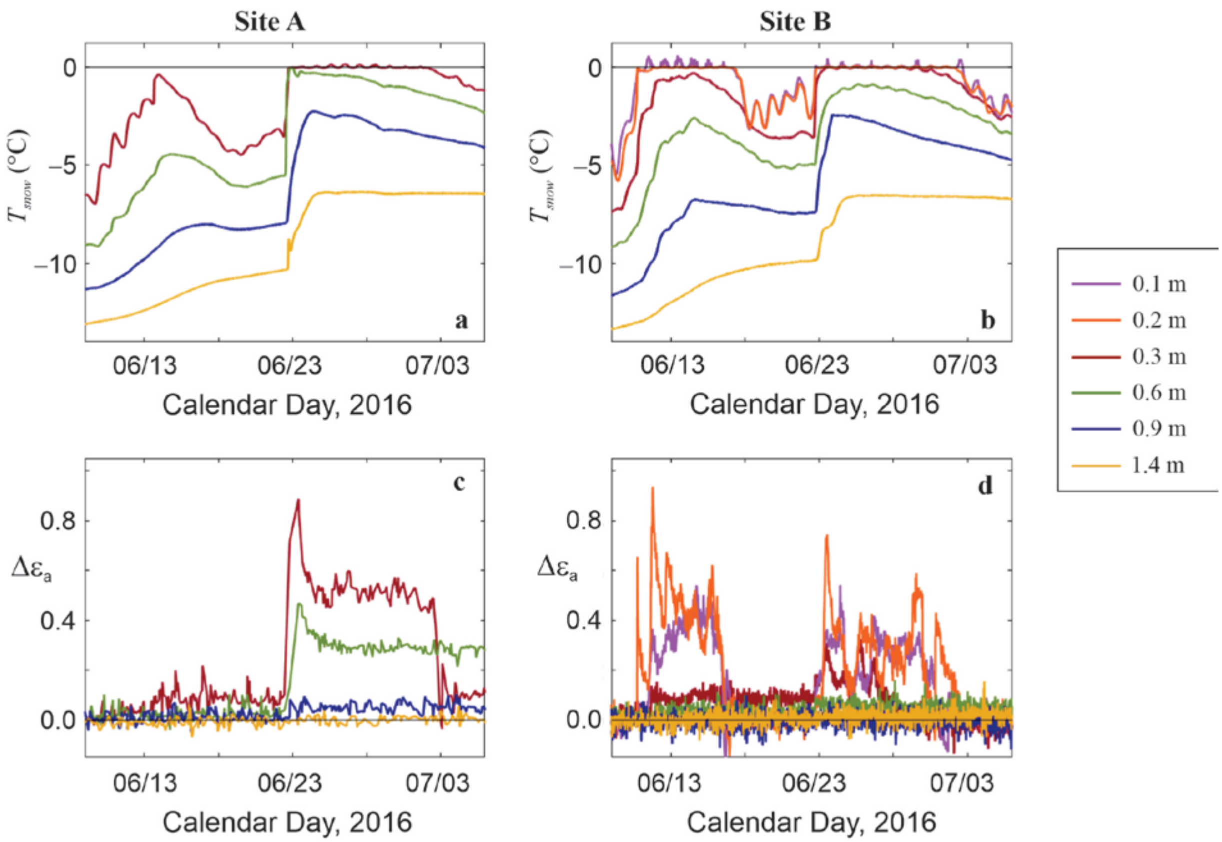

Figure 2. Observed (a,b) snow temperatures and (c,d) dielectric permittivity anomalies in the upper 1.4 m of firn pits A (left) and B (right) from June 9 to July 6, 2016, the onset of summer melt. The legend applies to all plots; values at 0.1 and 0.2 m were only measured at Site B.

Figure 2 presents the subsurface temperature and dielectric permittivity data during the period of melt onset at each site in the upper 1.4 m of each pit. Monitoring depths are not identical at sites A and B, but their nearest analogues are plotted, and are within 0.1 m of each other. The thermistor records from 0.3, 0.6, 0.9 and 1.4 m (Figures 2a,b) indicate the close agreement in snowpack thermal evolution at these two sites. Correlation coefficients for the summer temperature records at these two sites exceed 0.99 at these four depths.

Atmospheric warming in the first two weeks of June drove snowpack warming, with temperate conditions and surface melting evident at site B from June 11-16. The upper 0.2 m of the snowpack reached 0°C (Figure 2b), accompanied by increases in dielectric permittivity of ~0.4 to 0.9 (Figure 2d). Diurnal temperature peaks slightly greater than 0°C for the upper two thermistors are likely due to absorption of solar radiation transmitted through the surface snow. The upper TDR sensor had a relatively constant liquid water content through this period, but the sensor at 0.2 m exhibited diurnal cycles. At and below 0.3 m, the snowpack remained frozen and dry at both sites through this initial phase of melting. Snow at 0.3 m depth at site A came close to the melting point on June 14, reaching –0.3°C before cooling again. Because of this, the summer melt onset was not detected at Site A.

Following a week of cooler temperatures, surface melting resumed on June 22 at both sites. This was marked by an abrupt subsurface warming, with the upper 0.6 m of snow becoming temperate and wet. Temperatures at 0.3 and 0.6 m at site A increased by 3.5 and 5.4°C over a six-hour period, both reaching 0°C (Figure 2a). The sensor at 0.9 m depth also recorded a warming of 5.5°C, but over 32 hours, with an abrupt step followed by continued warming at a slower rate. Deeper thermistors also registered this step warming, but firn below ~0.6 m depth remained dry, with temperatures below the melting point. In the upper 0.3 m at both sites, conditions remained temperate and wet until July 2, at which point another cooling cycle forced a return to cold, dry conditions.

The summer melt season resumed on July 19, with a sustained period of warm temperatures, melting conditions, and meltwater penetration to depth (Figure 3). This was characterized by a second abrupt warming event in the upper 1.4 m, registered by the top five thermistors at site A and all thermistors at site B (Figures 3a,b). Dielectric permittivities rose sharply at these depths, coincident with temperatures reaching 0°C (Figures 3c,d), although the increase in ε_b was less for the deeper sensors. The upper two sensors at site B, at 0.1 and 0.2 m, experienced more meltwater than underlying sites in either pit, with $\Delta\varepsilon_b$ values greater than 2 (Figure 3d). The abrupt onset of temperate, wet conditions in the upper snow and firn was followed by a more gradual warming below this, recorded at the sensors from 1.8 to 3.7 m depth (Figures S1b and 3a). The wetting front and the 0°C isotherm reached 1.8 m depth by August 12, but firn below this remained sub-zero and dry.

Atmospheric cooling in mid-August caused the near-surface snowpack (upper 0.3 m) to refreeze ($\varepsilon_b \sim \varepsilon_{b0}$), but there was a temperate layer from about 0.6 m to 1.4 m, sandwiched between sub-zero conditions above and below (Figures 3a,b). This was most strongly evident at 0.9 m, where wet-snow conditions persisted until August 22 at both sites. These middle layers of the firn pits were the last to refreeze, as latent heat of refreezing meltwater maintained temperate conditions at these depths for several days before seasonal cooling ensued.

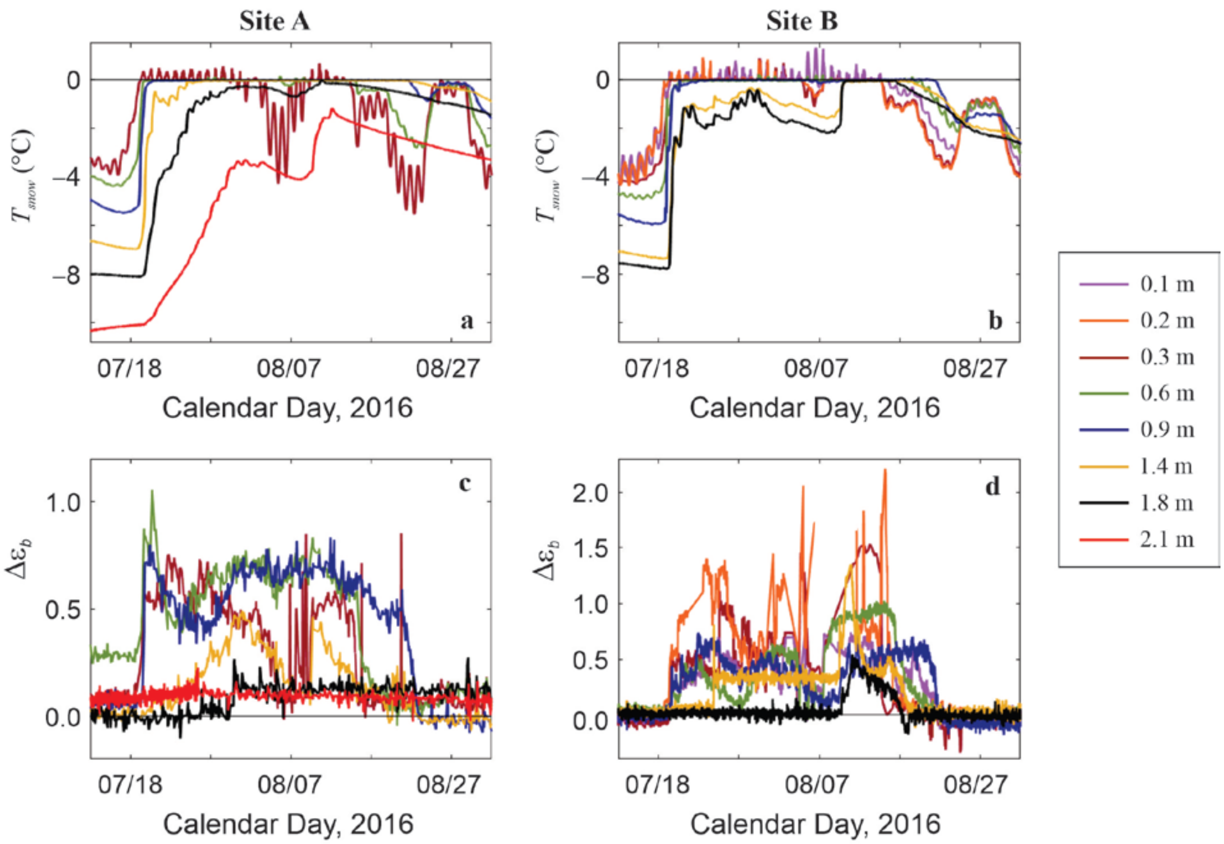

Figure 3. Observed (a,b) snow temperatures and (c,d) dielectric permittivity anomalies in the upper 2.1 m of firn pits A (left side) and B (right side) for the main summer melt season from July 13 to September 1, 2016. The legend applies to all plots; values at 0.1 and 0.2 m were only measured at Site B and 2.1 m is only at site A. Note the different scale in plots (c) and (d).

There is no indication of meltwater percolation below the surface at either site after August 22. Air temperatures above 0°C afrom Aug 23-25 warmed the upper snowpack at both sites, with some lag, but ε_b remained at background levels (Figure 3). This is the only time through the summer when temperate snow conditions were not accompanied by evidence of liquid water. Net energy at the surface was negative at this time and there may have been meltwater refreezing at the surface, above the upper TDR probes. Latent heat generated near the surface may have conductively warmed the underlying snow, but without meltwater infiltration.

Meltwater successfully percolated through several ice layers in the upper meter of firn at both sites. There were no ice layers in the winter snowpack, representing the upper ~0.9 m, but the underlying firn contained several discrete ice layers, some thin (1 mm to 2 cm), and others substantial. This included an 11-cm thick ice layer from 1.68 to 1.79 m depth at Site A and a 12-cm thick ice layer from 0.95 to 1.07 m depth at site B (Figure 1). In total over the upper 1.8 m, we measured 22 cm of ice in 11 discrete layers at site A and 19 cm of ice in 9 discrete layers at site B. Meltwater effectively penetrated through all of these ice layers, although not until temperatures reached the melting point at these depths. This implies that ice layers became permeable when they transitioned to a temperate state.

4 Discussion

The thermistor and TDR data give a consistent account of the thermal evolution and meltwater infiltration at Dye 2 site in summer, 2016. The melting front, characterized by 0°C conditions and evidence of liquid water, penetrated to a depth of between 1.8 and 2.1 m. Below this, temperatures remained less than 0°C, there were no abrupt warming events, and dielectric permittivities did not rise above their background levels. This is consistent with observations from the upward-looking radar at site A, which also indicate only shallow penetration of the wetting front into the firn in summer 2016 (Heilig et al., 2018).

To our knowledge, these data represent the first direct observations of meltwater penetration through ice layers in the Greenland percolation zone. This result implies thermodynamic controls on the depth of meltwater infiltration, rather than impermeability limits imposed by ice layers. We were not present in the summer melt season to directly observe this, but it may be that ice layers become soft or slushy. Overall, the depth of the melting front (the 0°C isotherm) appears to have been the main barrier to deep penetration of meltwater during summer 2016.

Whether ice layers can be altered to become permeable depends on the thermal energy available for warming the firn and maintaining temperate conditions. Warming occurs through a combination of thermal conduction, driven by summer atmospheric warming, latent heat release from meltwater refreezing, and advective heat transfer associated with meltwater penetration into sub-zero snow. These mechanisms are very clear in the thermistor data, with gradual temperature shifts in response to atmospheric warming and cooling trends punctuated by three abrupt warming events, reaching progressively deeper into the snow and firn (Figures 2 and 3). The latter are too rapid to be due to thermal conduction, so must be associated with meltwater advection and refreezing. Meltwater penetration to depth appears to follow a stepped process, facilitated by latent heat release.

Ultrasonic depth gauges installed adjacent to each firn pit recorded a total ablation of ~0.35 m over the summer. This was partially offset by several periods of snowfall, with a total summer accumulation of about 0.25 m. Most of the measured surface lowering occurred from July 18 to August 10, in line with the main melt season (Figure 3). Based on our density measurements, we estimate a total summer melt of 160 mm w.e. All of this meltwater likely refroze within the upper 1.8 m of the snow and firn, with an associated latent heat release of 5.3×10^7 J m^{-2}. Distributed over the 1.8-m snow/firn column with an average density of 480 kg m^{-3}, this energy would warm the firn by 14.8°C. This indicates that latent heat release was sufficient to drive the warming to temperate conditions over 1.8 m depth, although conductive heat flux also played an important role in the early melt season.

The observations provide new insight into meltwater percolation and refreezing processes in the percolation zone of the Greenland Ice Sheet. In particular, we present clear evidence of meltwater penetration through ice layers and thermodynamic controls on meltwater percolation depth. Ice layers appear to become permeable when warmed to 0°C, which would promote meltwater retention in firn. We saw no evidence of meltwater penetration through frozen (sub-zero) ice layers; these are likely to present impermeable barriers, as is commonly assumed (*e.g.*, Machguth et al., 2016; Noël et al., 2017; MacFerrin et al., 2019). As such, ice layers may still present an effective barrier to meltwater percolation where they are extensive (with a high thermal inertia) or when there is insufficient thermal energy to thaw such layers. Where there are thick ice slabs, such as in the lower percolation zone (MacFerrin et al., 2019; Vandecrux et al., 2019), high quantities of seasonal meltwater can provide large amounts of latent heat to thaw near-surface snow, firn, and ice layers, but there must be sufficient pore space where meltwater can refreeze. Impermeable ice layers close to the surface would limit this process. In addition, refreezing will desist once near-surface snow and firn are temperate, eliminating latent heat as a mechanism for firn warming. Thick near-surface ice slabs are therefore less likely to reach a temperate, permeable state, especially when insufficient snow and firn are present above them to store substantial quantities of meltwater.

The summer evolution of snow-water content is consistent with propagation of a wetting front that tracks the 0°C isotherm in the snow and firn, rather than episodic drainage through preferential flow. We conclude this based on the near-simultaneous arrival of the wetting front at our two sites, and its progressive propagation to depth over the course of the melt season. The measurements only represent two points, however, and preferential flow paths or ‘piping’ may well be the dominant mechanism of meltwater infiltration in firn (Humphrey et al., 2012; Wever et al., 2016). We also cannot rule out meltwater penetration to depths greater than 2 m at other locations in the Dye 2 region in summer 2016. Spatial variability is a large challenge in understanding and modelling firn hydrology and meltwater retention in Greenland. Our measurements nevertheless provide helpful insights to modelling efforts of meltwater infiltration into firn (*e.g.*, Wever et al., 2016; Steger et al., 2017), in particular the observation that ice layers do not always act as impermeable barriers to flow. Additional measurements like those reported here, especially during melt seasons of variable intensity, could help to track meltwater penetration into firn in the lower percolation zone and other sectors of Greenland.

Uncertainties

Sensor depths are reported as constant values in this manuscript, but actual depths changed over the course of the study, in association with fresh snowfall and surface ablation. All instruments at site A were deep enough to avoid melt-out. However, ablation from July 18 to August 10 was sufficient to expose the uppermost (0.1 m) sensors at site B, and inspection of the data is consistent with melt-out at this level on August 5. A ~0.15 m snow event from August 10 to 12 buried the melted-out sensors and they give sensible signals again after this point.

With our study setup, there is a risk that water flows or percolates more easily into the disturbed area of the firn pits, but we see no evidence of this. The thermal and hydrological evolution appear to be natural, are virtually identical at the two sites, and only extend to a limited depth in the pits with each abrupt event. As the pits were excavated to below the lower-most sensors, free-flowing water in the disturbed areas would be expected to propagate deeper. The low rates of meltwater production and low-sloping environment at Dye 2 are more conducive to vertical infiltration than lateral flows, and the data are consistent with that expectation. We are therefore confident that the thermodynamic and hydrological signals reflect vertical meltwater infiltration from above, without influence from the disturbed snow in the firn pit.

5 Conclusions

The thermistor, TDR, and AWS data provide a consistent and detailed account of the coupled thermodynamic and hydrological processes governing meltwater percolation and refreezing at Dye 2. This dataset presents an excellent opportunity to constrain the effective thermal and hydraulic conductivities of polar snow and firn, to help constrain models of firn hydrology. Modelling of the joint thermal and hydrological evolution of the near-surface firn will be examined in follow-up work. Additional measurements are needed to test and confirm the inferred processes at other locations in Greenland's percolation zone.

Measurements from the two sites 650 m apart are exceptionally coherent, and indicate that meltwater at Dye 2 percolated to a depth of about 2 m in summer 2016. The wetting front and the melting front were coincident at the two sites, implying thermodynamic controls on meltwater infiltration. Meltwater penetrated through ice layers up to 12 cm thick, but there is no evidence of meltwater infiltration through ice layers until firn temperatures reached 0°C. We hypothesize that melting conditions may have turned the ice layers into more permeable, slush-like horizons. The depth of the 0°C isotherm, rather than the presence of ice layers, governed firn permeability and meltwater penetration depth at our sites. This observation is a significant advancement in understanding meltwater infiltration and retention in polar firn. For an ice layer to become permeable, sufficient latent heat release is needed in the overlying firn and snow, which depends on the available pore space, cold content, and meltwater supply. Ice slabs that are thick or close to the surface may be difficult to thaw, as heat transfer will be dramatically reduced once firn is temperate or saturated. Models of this process can help to project whether meltwater is likely to infiltrate vertically or be redirected laterally, contributing to ice sheet runoff.

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