Final Author's Response

Chris Cox Neil Humphrey Joel Harper

1 Burgess Comment: P5486 L20

Need to mention SMB estimates

1.1 Authors Response

This comment is unclear. We do mention that SMB has recently become the dominant source of mass loss.

2 Burgess Comment P5487 L0-3

Passive voice hard to follow

2.1 Authors Response

Revised

2.2 Changes to manuscript

Original: A significant source of uncertainty in estimates of Greenland mass balance and melt runoff, both remotely sensed and model-based, is the refreezing of surface melt as it infiltrates into the underlying cold snow or firn.

Revised: Refreezing of surface melt water, as it infiltrates into the underlying cold firn, creates a significant source of uncertainty in both remotely sensed and model-based estimates of Greenland mass balance.

3 Burgess Comment: P5487 L18

There are 7 prepositional phrases in this sentence, need to clean up

3.1 Authors Response:

I have attempted to simplify the sentence structure.

3.2 Changes to manuscript

Original: The crux of the difficulty in quantifying the amount of refreezing melt is that infiltration and refreezing in cold firn is highly heterogeneous in space and time.

Revised: The most challenging aspect of quantifying refreezing is that both infiltration and refreezing of melt water in cold firn is highly heterogeneous in space and time.

4 Burgess Comment: P5489 L8-10

Dont understand what you are talking about here

4.1 Authors Response

Edited text to clarify how we are averaging the raw density measurements.

4.2 Changes to manuscript

Original: Field density measurements were averaged on a 0.25 m grid prior to use in this analysis to match the thermal sensor spatial resolution.

Revised: Field density measurements were obtained at variable spacings in order to accurately sample observed firn stratigraphy. Since the thermal sensors were regularly spaced, the density data were averaged and re-sampled on a matching .25m spacing.

5 Burgess Comment: P5489 L2

Best to use variables and identify variables in the text.

5.1 Authors response

The goal of writing out the equation is to rephrase the end of the paragraph above in order to introduce the reader to the mathematics of our approach.

6 Burgess Comment: P5491 L11

Indeed it will break down. Implications? Seems to me that if you know the starting density and the latent heat, then you should know the volume of water that has refrozen and hence you could adjust the density?

6.1 Authors Response

Adjusting the firn density based on the starting density and the water input is possible only if the refreezing is occurring uniformly or if the spatial distribution of the refreezing is known. While our domain avoids several complexities associated with the near surface, infiltration within the domain is actually likely to be more complicated than in the near surface as deeper firn is more likely to experience infiltration characterized by the formation of ice lenses and pipes. Our temperature profile data does give some indication of the location of refreezing events, but the resolution is insufficient to determine exact ice location and thickness. Given that the refreezing is not uniform and the distribution of ice lenses unknown. It is unrealistic to conduct a detailed analysis of density changes in the firn from the data we have. However, some back of the envelope calculations can be performed to get an idea of the magnitudes of density changes. For example, at CP, if the total refreezing quantity is uniformly distributed over the first layer of our domain, the density change is on the order of 20 kg/m^3. At H2, the total refreezing is much higher, but the water is also shown to penetrate much deeper. Distributing the water at H2 over the first 5 meters of the domain results in a density change of about 30 kg/m^3. Both of these are density changes are similar in magnitude to the density variations using in the Monte Carlo trials. We can therefore conclude that density changes may not play a significant role for the majority of the firn pack included in our analysis.

7 Burgess Comment: P5491 L20

Need to state K is conductivity here. And mention how you calculate k here or at least cite the appendix. Im not sure if this is a concern but do we need to worry about how k would change for dry firn, saturated firn or ice. Also what assumptions are we making with respect to this issue?

7.1 Authors Response

Added a short bit to specify K is thermal conductivity. The calculation of K is discussed in the next section of the manuscript: Numerical Implementation. We wait to discuss K in order to keep the theoretical background and numerical implementation separate.

The thermal conductivity of thick sections of saturated firn should not be important because saturated firn is uniformly zero degrees and therefore does not conduct heat due to lack of temperature gradients. We calculate K using the relationship described in the appendix, which has ice as an end member. So, any sections of solid ice in a section of firn are given an appropriate thermal conductivity.

7.2 Changes to manuscript

Original: where $q_{\text{net}}(t)$ is the net heat flux as a function of time and is defined by Fourier's law operating at the boundaries of the profile.

Revised: where $q_{\text{net}}(t)$ is the net heat flux as a function of time and is defined by Fourier's law operating at the boundaries of the profile (K is thermal conductivity).

8 Burgess Comment: P5492 L6

Can you give context? Out of how much melt annually? It seems to me that while this is a cool validation method, in winter you would be more confident of your thermal conductivity since you dont have changing density and liquid water in the mix. Might your summer uncertainties be higher?

8.1 Authors Response:

(We assume this is actually referring to P5493) The uncertainty in each refreezing value, as determined using the Monte Carlo approach, is on the order of +/- 1.5cm w.e. (two standard deviations). So, 1cm of w.e. is used as a method valuation threshold because any refreezing value less than 1 is not significantly different from zero, the expected value of refreezing during the winter. 1 cm w.e. ranges from about 100% of annual melt to about 4% depending on the year and location as calculated by the PDD. Uncertainties are likely to be higher in the winter rather than summer because the densities used are from the previous spring. We will reorder the section so that the Monte Carlo error analysis is first and the winter tests described after. We also added a sentence to clarify the justification for a threshold of 1cm w.e.

8.2 Changes to manuscript

Original With the exception of four sites, all tests resulted in refreezing quantities within 1 cm w.e. of zero.

Revised With the exception of four sites, all tests resulted in refreezing quantities within 1 cm w.e. of zero. Since the two standard deviation uncertainty bounds on all refreezing estimates are on the order of 1.5 cm w.e., these tests confirm the method produces a refreezing value not significantly different from zero in the winter.

9 Burgess Comment: P5492 L7

Is this not contradictory to your previous sentence?

9.1 Authors Response:

(We assume this is actually 5493) No, we mention that there are 4 problematic sites.

10 Burgess Comment: P5492 L16

Increased from what?

10.1 Authors Response:

(We assume this is actually 5493) The densities are an increase of about 200 kg/m^3 at each site. The measured densities in the first meter at these sites are typical of settled snow from the previous winter and are therefore very likely to have substantially increased by the following winter. Edited the text to clarify.

10.2 Changes to manuscript

Original This increase in conductivity implies a plausible increase in firn density in the boundary firn during the melt season. We found that, in all cases, the mismatch can be eliminated when the densities near 1 m depth are increased to around 600 kg/m^3.

Revised This increase in conductivity implies a plausible increase in firn density in the boundary firn during the melt season. Furthermore, the measured densities at these sites are characteristic of the previous winters settled snow and are in sharp contrast to the underlying firn. We found that, in all cases, the mismatch can be eliminated when the densities near 1 m depth are increased by around 200 kg/m^3 to 600 kg/m^3.

11 Burgess Comment: P5494 L25

Analyses

11.1 Authors Response:

Will change in final text.

12 Burgess Comment: P5494 L2

Spell out CP

12.1 Authors Response:

Revised

13 Burgess Comment: P5498

Not fully convinced by your interpretation of H2,H3,H165. Lateral migration of meltwater might occur at one site but this peak is occurring at 3, indicating that water was migrating towards all three sites. Were the holes unfilled and therefore a conveyance for water? Also not convinced that the pdd model is in error. At higher elevations and lower elevations the pdd model makes sense wrt refreezing. Unless the DDF is higher in a band at that elevation, I dont see how that justifies the peak in refreezing. As you say this is a key transition zone, different from areas above or below. Could the thermal conductivity assumptions or something else make your method less effective in these conditions?

13.1 Authors Response:

We provide three possibilities to explain how the refreezing values at sites H165, H2, and H3 can be higher than the relationship between the refreezing values and PDD melt values at: Lateral migration of melt water is occurring at some scale, melt water from the previous melt season is refreezing, or the PDD is under predicting the total melt. It is also possible that some combination of all three explanations is occurring. Regardless, we dont feel there are any characteristics of these sites or region that would increase our uncertainties relative to other sites. These results are instead further evidence for the complex firn hydrology observed in other parts of Greenland.

14 Burgess Comment: P5498

Also given the issues with missing the top 1 meter of firn, in the intro it would be good to prepare the reader for this problem. Fully elucidate the extra difficulties in dealing with the energy balance at the surface and why it was not feasible to deal with that here.

14.1 Authors Response

We agree it would be helpful to foreshadow the problem with the first meter of firn. The introduction has been altered to briefly introduce the issue.

14.2 Changes to manuscript

Original Furthermore, using measured temperatures takes advantage of the diffusive nature of heat conduction which helps reduce the effect of extreme spatial discontinuities inherent to heterogeneous infiltration and refreezing processes. We use a transect of melt season thermal profiles to derive the first in situ measurements of refreezing on the Greenland ice sheet that completely span the percolation zone.

Revised Furthermore, using measured temperatures takes advantage of the diffusive nature of heat conduction which helps reduce the effect of extreme spatial discontinuities inherent to heterogeneous infiltration and refreezing processes. The method is not without its challenges as melting, accumulations, and solar radiation in the near surface make it difficult to account for energy transfers from temperature measurements alone. However, by limiting our domain to firn depths between 1m and 10m, we are able to apply our method to a transect of melt season thermal profiles on the Greenland ice sheet. The result is the first in situ measurements of refreezing on the Greenland ice sheet that completely span the percolation zone.

15 Burgess Comment: Results General

I interpret your tone here as you feel your results arent as good as MAR refreezing. Seems to me your observations are far more reliable than the MAR model and thus discussion on why MAR may be off is entirely valid here (if you have ideas).

15.1 Authors Response

The goal of the MAR comparison is to provide some context within which to interpret our results and not to demonstrate superiority in our results. We realize our method is still new and could use improvement, and it is therefore premature to single out any refreezing values that do not match our own perfectly. In our comparison to the MAR output, we try to find reasonable causes for the large differences between our values and conclude that the differences are not simply due to refreezing in the first meter of firn. We leave it to future studies to confirm our results with similar projects and further diagnose what might be causing the discrepancy.

16 Burgess Comment P5499 L23

This paper covers refreezing but I dont really feel like it shows specifically that ”piping complicates refreezing”. Please clarify.

16.1 Authors Response

Refreezing was originally thought to be a fairly simple problem of determining the cold content and available pore space in the firn. Piping significantly complicates this idealized view because melt water penetrates the firn much deeper than was thought possible and can remain mobile even when residual cold content remains in the firnpack. We discuss these problems in the introduction.

17 Burgess Comment: Figure 2

It would be nice to see the density profiles just so we have a sense of what kind of of firn we are dealing with. Also it would be valuable to state where pore close of might be, not necessarily in the figure, but where appropriate in the paper.

17.1 Authors Response

We have added a density profile to figure 2b. It is unclear that a pore close-off depth exists. Throughout the firn there are layers of relatively impenetrable ice and high porosity low density layers even deep in the firn at the lowest site. This highly heterogeneous structure is one of the reasons firn hydrology is difficult to measure and model.

18 Morris Comment:

Since the mean annual accumulation is said to be of the order of 1 m, the authors are in effect estimating the amount of summer melt water that travels through the winter snow and into snow accumulated during previous years. This is worth doing, as it tells us how far the mass in an accumulation layer (something we can measure) differs from the surface mass balance (something we want to know).

18.1 Authors Response:

It is true that our results could be used to get a general sense of the depth partitioning of melt water refreezing, but our results contribute much more than just that. Our refreezing values are some of the first values obtained for Greenland using in-situ data, and, in addition to providing insights into surface mass balance, they aid in our understanding of melt water infiltration processes.

19 Morris Comment:

The model used is 1-dimensional and based on the assumption that, as far as the energy budget is concerned, the snow can be treated as a medium of density ρ(z), where z is depth. The location of latent heat sources within the layer is not specified, however, so this is a lumped rather than distributed model. Since the temperature sensors move downwards with the snow, a Lagrangian rather than Eulerian approach is implied. All this is perfectly reasonable, but the theory needs to be explained rather more rigorously so that the reader can have confidence in the results.

19.1 Authors Response:

We disagree that our approach is Lagrangian because we do not know the compaction that is occurring in the snowpack. Since the bulk of the snowpack remains below 0, we expect the compaction to be small and the difference between the Lagrangian approach and the Eulerian approach is probably small. However, this is an assumption that we make since we do not have compaction data and we have edited to state our assumption explicitly.

19.2 Changes to manuscript:

Original (5491, L9): This formulation assumes that density (rho) and heat capacity (Cp) do not change over time. This is reasonable because, at most of the sites, the input of melt water is minor compared to the water equivalent of the firn column. This assumption may break down for the lowest sites (H3, H4).

Revised: This formulation assumes that density (rho) and heat capacity (Cp) do not change over time. This is reasonable because, at most of the sites, the input of melt water is minor compared to the water equivalent of the firn column. This assumption may break down for the lowest sites (H3, H4). Densification due to compaction of the firn is also assumed to be minimal within our seasonal timescale.

20 Morris Comment:

The crux point is the argument that horizontal variability can be neglected. I think it is the magnitude of the thermal diffusivity, α, that is important in judging whether the spacing between latent heat sources needs to be taken into account rather than the diffusive nature of heat conduction (p.5488 l.7). The relation between length and time scales, z_0 and t_0, for thermal conduction in homogeneous snow with no internal sources is

$z_0 = (\alpha t_0)^{1/2}$

For $\alpha \approx 4.10^{-6}$ m^2 s^{-}1, $z_0 \approx 1$ m for $t_0 \approx$3 days (c.f. p.5490 l.28). In other words, if the horizontal spacing of pipes is of the order of 1 m, the 1-D model is appropriate for temperature fluctuations with frequency lower than $\approx 4.10^{-6}$ Hz. The authors need to show that fluctuations in surface snow temperature at frequencies higher than this (for example diurnal fluctuations) are damped out by the time they reach the upper boundary of the sub-surface layer. I think it might be possible to demonstrate this using the data that they have, by showing a spectrogram (see, for example Sergionko et al., 2008, Annals of Glaciology 49 p.91) for temperature at the 1 m level, unless the high-frequency electronic noise at $\approx 5.10^{-4}$ Hz complicates the picture too much.

20.1 Authors Response:

We find this comment to be a bit confusing. If we are understanding correctly, the argument is that the time scale of thermal diffusion is important in assessing the legitimacy of the one dimensional approach. We agree with this and provide an analysis of the timescale of diffusion for a melt water pipe (5490 L28). However, Morris is focused on the frequency of the temperature change and suggests we apply her analysis to surface temperature variations. The characteristic frequency of the piping does not need to be investigated with sophisticated analysis because high frequency (narrow spikes in temperature) variations have low energy content while lower frequency variations produce temperature perturbations that spread out on a timescale that is much shorter than our seasonal analysis (per our earlier analysis). It is unclear why we would apply her analysis to surface temperature variations as we use our temperature data to track heat flux at 1m.

21 Morris Comment:

The change in sensible heat over time period t is calculated from the differences between temperatures Tj measured by a vertical string of sensors at the start and end of the period. The question is, whether high frequency variations in latent heat input could mean that the Tj do not give an adequate representation of the temperature profile. The appropriate length scale is the spacing of the sensors (z0 20 cm) and hence t0 3 hours. The temperature profiles shown in the companion paper (Humphrey et al. 2012 JGR doi:10.1029/2011JF002083) show refreezing events on this time scale producing narrow peaks which are only just resolved by the sensors. So this could well be a problem. The answer might be to smooth each Tj over a period of about a day, at the start and finish of the time period, before calculating the change in sensible heat.

21.1 Authors Response:

One of the main benefits of our method is that we do not actually need to capture high frequency temperature fluctuations. Any latent heat released inside our domain, even a very narrow spike that isnt visible in the temperature data initially, will spread out to the other sensors and contribute towards the overall increase in temperatures in the profile. When this heat finally reaches the domain boundaries we are able to account for it since we are tracking heat flux at the boundaries. There is some potential that the ending temperature profile would not have the resolution to detect a narrow spike in temperature that just happened to occur less than a couple of hours before the temperature measurement and was located in between two sensors. However, we chose the end dates for our analysis based, in part, on review of the entire dataset. Any major refreezing event would have been obvious in the temperature profiles measured several hours after the profile chosen for the analysis end date. It is therefore unlikely that any significant refreezing was unaccounted for due to the sensor resolution.

22 Morris Comment:

Finally there is the problem that the thermistor strings were installed in 9 cm boreholes back-filled with fine-grained cold snow. Humphrey et al. consider that the thermistor wires acted as preferential pathways for heat conduction but the boreholes were not preferential pathways for water. Mentioning this, with a little discussion, would help the reader.

22.1 Authors Response:

Our sensor measurements show that after emplacement of the temperature string, the temperatures in the disturbed firn rapidly stabilize to temperatures equal to that of the surrounding snow. Since snow crystal metamorphosis is driven primarily by temperature, the cold snow that was used to backfill the borehole should begin to quickly evolve to a density and structure similar to the surrounding undisturbed firn. Any disturbance to ice layers within the firn caused by drilling would not create a heterogeneity that is significantly different than the inherent heterogeneity in the firn. We have added a short section to describe the method in more detail.

22.2 Changes to manuscript:

Original (5489 L2): Sensor spacing is 0.25 m from 0 to 5.5 m depths and 0.5 m from 5.5 to 10 m depths. The sensors were installed with reference to the surface at time of installation.

Revised: Sensor spacing is 0.25 m from 0 to 5.5 m depths and 0.5 m from 5.5 to 10 m depths. The sensors were installed with reference to the surface at time of installation. After temperature string emplacement, the boreholes were backfilled with fine grained, cold snow, and our temperature measurements show rapid thermal equilibrium with the surrounding undisturbed firnpack (For details see Harper et al. 2011).

Added reference: Harper, J., N. Humphrey, T. Pfeffer, and J. Brown (2011), Firn stratigraphy and temperature to 10 m depth in the percolation zone of western Greenland, 2007-2009, INSTAAR Occasional Paper, (60).

23 Morris Comment:

The authors estimates of refreezing are significantly lower than the levels predicted by the MAR model. They seem to be rather hesitant to suggest that the MAR model may be wrong, but it is surely important to probe into this discrepancy. Do they think the problem lies in their analysis or in MAR? If in MAR, is the meteorological component not predicting surface conditions correctly or is the snow model inadequate? It should be possible to tease this out given their data. For example, one could ask whether the MAR surface temperature series bears any relationship to the observed surface temperature series. And so on.

23.1 Authors Response

The MAR comparison is meant to give our results some context and we assess whether the discrepancy could be due to not including the first meter of firn in our analysis. Beyond that, we leave detailed analysis of local scale MAR outputs to future studies.

24 Morris Comment: P5486 L1

The abstract reads rather more like an introduction than a summary of results and would benefit from a rewrite.

24.1 Authors Response:

Will review.

25 Morris Comment: P5486 L22

Perhaps better to say models suggest something rather than show something?

25.1 Authors Response:

The word 'suggest' implies that the model output is unclear or vague, but the conclusions in the references are fairly clear cut.

26 Morris Comment: P5486 L24

To be precise, remote sensing shows an increase in the area and time period over which melt occurs, not necessarily the amount of melt.

26.1 Authors Response:

Agreed. Reworded.

26.2 Changes to manuscript

Original: Although the increase in melt is clear from the remotely sensed data, the increase in melt water leaving the ice sheet is not as well constrained.

Revised: Increases in the areal and temporal extent of surface melt, evident from remote sensing, support model based increases in surface melting. However, the increase in melt water leaving the ice sheet is not as well constrained.

27 Morris Comment: P5488 L3

Latent heat diffuses in the snow not in the temperature profile.

27.1 Authors Response:

Reworded.

27.2 Changes to manuscript:

Original: Latent heat released during refreezing diffuses into the firn temperature profile as a thermal perturbation that can be quantified using a conservation of energy approach.

Revised: Latent heat released during refreezing diffuses through the firn causing a thermal perturbation in the temperature profile that can be quantified using a conservation of energy approach.

28 Morris Comment: P5490 L3

Better to separate the equation and definition of variables.

28.1 Authors Response:

The goal of writing out the equation is to rephrase the end of the paragraph above in order to introduce the reader to the mathematics of our approach.

29 Morris Comment: P5490 L27

Useful to state the values of the parameters

29.1 Authors Response:

For 1m pipe spacing, any range of realistic values for the parameters will result in a timescale of a few days. We therefore find it unnecessary to give exact values.

30 Morris Comment: P5491 L6

The Lagrangian approach could be made more explicit by using a water equivalent depth variable, say q, to denote position within the layer, rather than z. Equation (1) is not correct if z is depth below the surface.

30.1 Authors Response:

Again, we do not utilize a Lagrangian approach. However, it is true that z should not be depth below the surface. An adjustment has been made to clarify.

30.2 Changes to manuscript:

Original: The change in heat content over the summer melt season can be quantified from the changes in profile temperature (z = depth) using:

Revised: The change in heat content over the summer melt season can be quantified from the changes in profile temperature (z = depth from the top of the profiles) using:

31 Morris Comment: P5492 L9

The authors assume that ρ is constant in time, but clearly this is not the case if melt water penetrates the layer. Rather than make the vague comment that this effect is negligible except possibly at H3 and H4, why not state the maximum melt expected (say 0.5 m w.e) and say what proportion this is of the w.e. of the layer? Furthermore, the layer is deeper at the end of the period than at the start so, even without influx of meltwater, the layer will densify. This again needs to be quantified.

31.1 Authors Response:

Densification can be estimated from melt estimates (assuming all the melt water refreezes). However, the spatial distribution of refreezing must be accounted for somehow, otherwise the density at a particular location could be almost anything between the starting density and ice. Our temperature profile data does give some indication of the location of refreezing events, but the resolution is insufficient to determine exact ice location and thickness. Given that the refreezing is not uniform and the distribution of ice lenses unknown. It is unrealistic to conduct a detailed analysis of density changes in the firn from the data we have. However, some back of the envelope calculations can be performed to get an idea of the magnitudes of density changes. For example, at CP, if the total refreezing quantity is uniformly distributed over the first layer of our domain, the density change is on the order of 20 kgm^{-3}. At H2, the total refreezing is much higher, but the water is also shown to penetrate much deeper. Distributing the water at H2 over the first 5 meters of the domain results in a density change of about 30 kgm^{-3}. Both of these are density changes are similar in magnitude to the density variations using in the Monte Carlo trials. We can therefore conclude that density changes may not play a significant role for the majority of the firn pack included in our analysis. Densification due to compaction is addressed in an earlier comment.

32 Morris Comment: P5492 L18

The authors do not define their terminology but I assume dT/dz is meant to be a material derivative. This needs to be made explicit. Again the effect of temporal variation in ρ needs to be quantified.

32.1 Authors Response

Revised to make methods more explicit.

32.2 Changes to manuscript:

Original: The boundary temperature gradients in Eq. (3) are approximated by taking the gradient of the two sensors closest to the 1 and 10 m bounds.

Revised: The boundary temperature gradients (dT/dz) in Eq. (3) are approximated using the temperature gradient of the two sensors closest to the 1 and 10 m bounds. For example, the temperature gradient at the upper boundary is $\frac{(T_{(1.25,t)}-T_{(1,t)})}{0.25}$.

33 Morris Comment: P5491 L20

Integration over time appears to involve smoothing a fairly noisy series of values of dT/dz. The authors need to explain exactly what they have done rather than rely on Figure 2a.

33.1 Authors Response:

Data were not smoothed at any point. Edited to clarify numerical method used.

33.2 Changes to manuscript

Original: Figure 2a shows a time series of net heat flux at site H2. High frequency variations on the order of 0.5?C are a result of random electronic noise in each temperature measurement. Since this noise is random, the integrated flux derived from the gradients is not biased.

Revised: Equation 3 is approximated by numerically integrating net heat flux using the trapezoid rule. Figure 2a shows a time series of net heat flux at site H2. High frequency variations on the order of 0.5 C are a result of random electronic noise in each temperature measurement. Since this noise is random, the integrated flux derived from the gradients is not biased.

34 Morris Comment: P5493 L5

There were 11 sites, 10 of which had winter data. Of these 6 had refreezing less than 1 cm w.e. and 4 greater than 1 cm w.e. So 40% need further explanation? This paragraph could do with a rethink. I would discuss the sensitivity of all estimates (winter and summer) to uncertainty in snow properties.

34.1 Authors Response:

(A similar comment was made in Anonymous Review 1. The response is the same. The revisions are detailed in that review.) Upon reviewing the winter test results, it appears our original discussion on this topic was oversimplified, but the general conclusions are nonetheless the same. Both H1 and H163 show similar refreezing values around -1 cm w.e. corresponding to the December thru April time period. A negative value means that there is less heat as determined by the temperature change than would be expected from the heat lost at the boundaries of the domain. So, the heat lost through the boundaries needs to be increased in order for it to balance with the change in profile temperature. This is accomplished by increasing the boundary density and thereby increasing thermal conductivity. Our uncertainty is on the order of 1.5 cm w.e., so neither H1 or H163 are significantly different from zero. H165, H2, and H3 have winter refreezing values on the order of -2cm w. e. before tuning the boundary density to 600 $kg\, m^{-3}$. These three sites also have unusually low measured densities at the boundary as compared to the rest of the profile, while H1 and H163 do not. So, overall we should have specified that H165, H2, and H3 are the only sites requiring density tuning and they are also the only sites with inconsistently low density values at their boundaries. We have rewritten the paragraph to account for these issues.

35 Morris Comment: P5493 L23

The authors really need to explain the numerics behind the calculation of heat flux. Do they remove the noise before calculating the gradient?

35.1 Authors Response:

The details of the calculation of heat flux are now included in response to a previous comment. Noise is not removed before calculation, but the impact of the noise is assessed in the Monte Carlo error analysis. I made a slight edit to clarify where we differentiate data with noise in it.

35.2 Changes to manuscript:

Original: Since our method differentiates discrete data when the heat flux is calculated, we assume that the largest errors stem from amplification of data noise by differentiation.

Revised: Since our method differentiates discrete data when the heat flux is calculated (numerical approximation of Equation 2), we assume that the largest errors stem from amplification of data noise by differentiation.

36 Morris Comment: P5494 L5

What about systematic errors?

36.1 Author's Response:

Systematic errors from sources such as sensor calibration or drift can not be quantified by the Monte Carlo analysis above, and indeed, remain as an uncorrectable potential error in our calculated refreezing values

37 Morris Comment: P5494 L19

corresponding to is not the right verb here.

37.1 Authors Response:

The temporal domain over which we apply our method varies between sites, but the concept has been surprisingly difficult to describe in a simple manner. I made some minor edits to try and clarify the sentence.

37.2 Changes to manuscript:

Original: Unfortunately, data quality problems prevented all refreezing quantities from corresponding to exactly the same time period (see Table 1).

Revised: Unfortunately, data quality problems at some of the sites reduced the time period over which our method could be applied (see Table 1 column 4).

38 Morris Comment: P5494 L25

analyses

38.1 Author's Response:

Will fix.

39 Morris Comment: P5496 L20

Why are sites T2 and T1 colder than their neighbors?

39.1 Authors Response

Our analysis of the near surface temperatures is mostly qualitative due to the uncertainties in temperature readings resulting from surface exposure and solar radiation. Figure 4 shows that in 2008, most sites had near surface temperatures close to zero and therefore lack significant cold content that would initiate refreezing. However, near surface temperatures at sites T1 and T2 in 2008 show colder temperature throughout the melt season. This may simply be a due the higher elevations of these sites.

40 Morris Comment: P5499 L23

It seems rather odd to say piping significantly complicates things after arguing a 1-D model is adequate.

40.1 Authors Response:

We argue that piping does introduce significant complexity not accounted for in either snow models or parameterizations currently used. Both models and parameterizations assume melt water moves through the firn in a uniform manner when it is actually heterogeneous. However, despite this heterogeneity, a one dimensional approach is nonetheless appropriate because the major structures associated with piping, ice lenses, are in the vertical dimension. Although the process is termed piping, the vertical pipes themselves have less of an impact on the dominant temperature structure of the firn pack compared to both the ice lenses and vertical heat conduction from the surface. I have made some changes to the conclusion to better summarize our position.

40.2 Changes to manuscript:

Original: The calculated refreezing quantities reveal a transition from complete refreezing of melt water at higher elevations to eventual runoff of melt water near an elevation of around 1500m, up to 40km inland from the ELA. Even where complete refreezing does occur, a significant portion of the overall refreezing takes place at depths greater than 1 m. This may be a result of piping of melt water to much greater depths than would otherwise occur by uniform infiltration. Since heterogeneous infiltration is not currently accounted for in snow hydrological models, these in situ refreezing values provide an important source of snow/firn model validation. Our results show that piping of melt water significantly complicates the relationship between total refreezing and simplified theoretical approaches to predicting refreezing capacity. Thermal profiling for the lower accumulation zone can be used to both quantify melt refreezing, as well as help to locate important zones such as the runoff limit.

Revised: The calculated refreezing quantities reveal a transition from complete refreezing of melt water at higher elevations to eventual runoff of melt water near an elevation of around 1500m, up to 40km inland from the ELA. Even where complete refreezing does occur, a significant portion of the overall refreezing takes place at depths greater than 1 m. This may be a result of piping of melt water to much greater depths than would otherwise occur by uniform infiltration. Since heterogeneous infiltration is not currently accounted for in either snow hydrological models or simple theoretical parameterization, these in situ refreezing values provide an important source of snow/firn model validation. Finally, our results also give some indication that lateral movement of infiltrated meltwater, in some cases from prior melt seasons, may be significant in this region of Greenland, complicating the classic understanding of percolation zone processes.

41 Morris Comment: P5500 L25

with our?

41.1 Authors Response:

Rephrased to make sentence less confusing.

41.2 Changes to manuscript:

Original: We have used these density based K values, that are internally consistent without temperature data, in our modeling of the summer melt/refreezing calculations.

Revised: We utilize equation A1 in our refreezing analysis to calculate thermal conductivity values from averaged field density measurements.

42 Morris Comment: Fig 2a

Why the sudden drop in early July?

42.1 Author's Response:

Q (grey region, panel A) is the total heat gained by the profile due to heat conducted through the domain boundaries at 1m and 10m depths. It is calculated by the integrating the time series of net heat flux (qnet). The drop in qnet mid June is associated with a refreezing event near the 1m boundary that sharply elevated the temperature near the boundary creating a strongly negative net heat flux for a short period of time. In other words, the temperature at 1.25m depth became much warmer than the temperature at 1m and heat was conducted upward out of the method domain. Added a sentence to the caption to clarify.

42.2 Changes to manuscript:

Original: (a) Net heat flux through the top and bottom of the domain (see panel b) from 1 June 2008 to 1 August 2008 at site H2. Q is the integral of the time series (see Eq. 2).

Revised: (a) Net heat flux through the top and bottom of the method domain (see panel b) from 1 June 2008 to 1 August 2008 at site H2. Q is the integral of the time series (see Eq. 2). The sharp drop in qnet mid June is the result of a refreezing event within the domain near the 1m boundary. Refreezing increased the temperature gradient at the boundary and heat was conducted out of the domain (negative qnet).

43 Morris Comment: Fig 3

Different line styles could be used for 2007 and 2008.

43.1 Authors response:

The figure will be edited to make the different lines more distinct using separate colors.

44 Anonymous 1 Comment: Title

Icesheet or Ice Sheet?

44.1 Authors Response:

Will change

45 Anonymous 1 Comment: P5490 L22

When I look at Table 1 I see a factor 10 difference between both T1 profiles, with the difference larger than the SD given for both sites. That suggests to me a large difference. What measurement error are you referring to resulting in both T1 profiles to give the same refreezing estimates?

45.1 Authors Response:

The standard deviations determined from the Monte Carlo error analysis are on the order of of 0.5 cm w.e. across all sites. We give an uncertainty of plus or minus two standard deviations. So while there is a factor of 10 difference between the two T1-08 values, both are within the uncertainty range of each other and are nearly zero.

46 Anonymous 1 Comment: P5491 L1

What time scale of decay results from a distance of 10 m between pipes?

46.1 Author's Response:

Obviously, the further apart the pipe spacing is, the longer it will take the heat to spread laterally and a one dimensional approach becomes less reasonable. However, we argue, based on Brown et al. that the spacing is much less than 10m.

47 Anonymous 1 Comment: L19

When printed the left brackets in this equation became right brackets in my copy.

47.1 Authors Response:

Strange, this hasnt seemed to be a problem for others.

48 Anonymous 1 Comment: P5492 L10

What region and domain do the words this region and this domain refer to?

48.1 Authors Response

Those words refer to the section of firn where we apply our analysis, between 1m and 10m depths. Edited to clarify and will make sure language throughout the manuscript is consistent.

48.2 Changes to manuscript:

Original (5492 L4-12): The method is applied to firn depths ranging from 1 to 10m, and we therefore ignore the data from the upper 4 sensors. This domain is deep enough to remain unexposed, as melting, sastrugi migration and accumulation lead to significant variations in the surface elevation. Furthermore, the influence of solar radiation is greatly reduced below about a half meter. Refreezing that occurs above or below the domain remains unaccounted for by this analysis, but, as is shown below, we estimate this region captures a majority of total refreezing. Heat content in this domain is assumed to change only from conduction across the region boundaries, and advection of heat energy in the form of the phase change of refreezing percolating melt water.

Revised: The method is applied to firn depths ranging from 1 to 10m, and we therefore ignore the data from the upper 4 sensors. We refer to this subsection of the firnpack as our analysis domain. This domain is deep enough to remain unexposed, as melting, sastrugi migration and accumulation lead to significant variations in the surface elevation. Furthermore, the influence of solar radiation is greatly reduced below about a half meter. Refreezing that occurs above or below the domain remains unaccounted for by this analysis, but, as is shown below, we estimate it captures a majority of total refreezing. Heat content in this domain is assumed to change only from conduction across the region boundaries, and advection of heat energy in the form of the phase change of refreezing percolating melt water.

49 Anonymous 1 Comment: P5493 L6-19

I find it surprising that H163 does not show the problem with the density at 1 m depth, although H163 is located between H1/H165 and H2. Can you please comment on that?

49.1 Authors Response

Upon reviewing the winter test results, it appears our original discussion on this topic was oversimplified, but the general conclusions are nonetheless the same. Both H1 and H163 show similar refreezing values around -1 cm w.e. corresponding to the December thru April time period. A negative value means that there is less heat as determined by the temperature change than would be expected from the heat lost at the boundaries of the domain. So, the heat lost through the boundaries needs to be increased in order for it to balance with the change in profile temperature. This is accomplished by increasing the boundary density and thereby increasing thermal conductivity. Our uncertainty is on the order of 1.5 cm w.e., so neither H1 or H163 are significantly different from zero. H165, H2, and H3 have winter refreezing values on the order of -2cm w. e. before tuning the boundary density to 600 kgm^{-3}. These three sites also have unusually low measured densities at the boundary as compared to the rest of the profile, while H1 and H163 do not. So, overall we should have specified that H165, H2, and H3 are the only sites requiring density tuning and they are also the only sites with inconsistently low density values at their boundaries. We have rewritten the paragraph to account for these issues.

49.2 Changes to manuscript:

Original (5493 L5-19): With the exception of four sites, all tests resulted in refreezing quantities within 1 cm w.e. of zero.

At sites H1, H165, H2 and H3, tests showed that the method produced unlikely refreezing quantities somewhat greater than 1 cm w.e., indicative of a mismatch between the change in the firn internal temperature structure and the flow of heat across the boundaries. The most important parameter in this balance (other than refreezing which is assumed to be zero) is the firn conductivity at the boundary. This is based on our measured firn densities of the previous summer. A small increase in the thermal conductivity in the near surface firn eliminates the mismatch in our energy balance. This increase in conductivity implies a plausible increase in firn density in the boundary firn during the melt season. We found that, in all cases, the mismatch can be eliminated when the densities near 1 m depth are increased to around 600 kg m?3. It should be noted that although the above discussion is somewhat speculative, this same density change applied during the melt season has minimal effect on our calculated refreezing quantities as the melt season temperature gradient near 1 m is often near zero.

Revised: (Partially taken from comment in Burgess Review) With the exception of three sites, all tests resulted in refreezing quantities within 1 cm w.e. of zero. Since the two standard deviation uncertainty bounds on all refreezing estimates are on the order of 1.5 cm w.e., these tests confirm the method produces a refreezing value not significantly different from zero in the winter.

At sites H165, H2 and H3, tests showed that the method produced refreezing quantities on the order of -2 cm w.e., indicative of a mismatch between the change in the firn internal temperature structure and the flow of heat across the boundaries. In the winter, a negative refreezing value results from the temperature profile losing more heat than would be expected given the calculated heat flux through the domain boundaries. The integrated heat flux needs to be higher in order to balance the profile temperature change. The most important parameter in this balance is the firn conductivity at the boundary, and we find that a small increase in conductivity at the upper boundary eliminates the energy imbalance. This increase in conductivity implies a plausible increase in firn density in the boundary firn during the melt season. Furthermore, the measured densities at these sites are characteristic of the previous winters settled snow and are in sharp contrast to the underlying firn. We found that, in all cases, the mismatch can be eliminated when the densities near 1 m depth are increased by around 200 $kg\,m^{-3}$ to 600 kgm^{-3}. It should be noted that although the above discussion is somewhat speculative, this same density change applied during the melt season has minimal effect on our calculated refreezing quantities as the melt season temperature gradient near 1 m is often near zero.

50 Anonymous 1 Comment: P5493 L24

Please rephrase. The sentence is unclear.

50.1 Authors Response:

Slight rewording and combined two paragraphs.

50.2 Changes to manuscript:

Original: Since our method differentiates discrete data when the heat flux is calculated, we assume that the largest errors stem from amplification of data noise by differentiation. In addition, we investigate the other large potential error produced by errors in our density profiles.

A Monte Carlo approach is used to estimate how these errors contribute to overall method uncertainty.

Revised Since our method differentiates discrete data when the heat flux is calculated, we assume that the largest errors stem from amplification of data noise by differentiation. Additionally, uncertainties in our profile density measurements create the potential for error as the values are utilized to calculate thermal conductivities and are direct inputs into equation 1. A Monte Carlo approach is used to estimate how these errors contribute to overall method uncertainty.

51 Anonymous 1 Comment: P5494 L4

I assume you apply this method to all sites and that the values presented in Table 1 and figure 3 are these averages?

51.1 Authors Response:

Correct, the calculated refreezing values for each site are an average of the Monte Carlo trials and the error bars shown in figure 3 plus or minus two standard deviations.

52 Anonymous 1 Comment: P5494 L25

Why did you use such a simple method to estimate melt? Given the availble data (from CP) it should be possible to use a bit more sophisticated method where short wave radiation is included as well (Giessen and Oerlemans, TC, 2010) or even calculate a full energy balance along the transect line. The latter method also would include a bit more information about the surface properties.

52.1 Authors Response:

The purpose of the PDD melt estimate is to provide a general reference against which to compare our refreezing values. So higher precision melt estimates are not necessarily needed and may be difficult to achieve as well. The uncertainties associated with extrapolating all meteorological data from CP to each site combined with assumptions about surface properties may result in little improvement in precision.

53 Anonymous 1 Comment: P5496 L14

The temperature above 0C is rather large. Is this mainly due to the sensor on the surface? Perhaps better to not use that sensor when calculating the average temperature of a 0.75 cm layer. How does ablation and wind scour affect the snow temperature?

53.1 Authors Response:

Some of the sensors in the near surface (<1m depth) do show positive temperatures, although it is difficult to determine exactly where the surface is located at any given moment as the measured temperature could be the result of some penetration of solar energy through a thin snow layer. Regardless, the goal is to get a *qualitative* sense of the near surface, not to directly utilize the absolute values. Ablation and wind scour will have some impact on the temperatures within our analysis domain, but we track all changes in heat flux so ablation and wind scour will not be problematic unless the entire upper meter of firn is removed (not evident in temperature data).

54 Anonymous 1 Comment: P5496 L17-20

You discuss the discrepancies with MAR only from the perspective of your method. How much refreezing does MAR have if you exclude the upper 1 m, as you do in your method? And how well does MAR represent your observed temperature profiles?

54.1 Authors Response:

While some of the MAR outputs are easily attainable via the MAR Explorer website, localized temperature and small scale refreezing time series are not available. We are therefore unable to make a detailed comparison between the two methods and leave that analysis for future studies.

55 Anonymous 1 Comment: P5497 L1

What difference are you referring to here? Difference with PDD method or MAR?

55.1 Authors Response

That is correct, I made a slight change to clarify.

55.2 Changes to manuscript:

Original: The cumulative effect could drive the increasing difference in values at sites H3 and H4.

Revised: The cumulative effect could drive the increasing difference between our values and MAR sites H3 and H4.

56 Anonymous 1 Comment: P5497 L20:

When is refreezing capacity minimal, can you quantify how much additional refreezing is possible for the sites plotted in figure 4.

56.1 Authors Response:

Refreezing capacity is a function of both available pore space and the cold content of the firn. Refreezing capacity reaches zero when there is no available space for infiltrating melt water and/or when firn temperatures reach zero degrees. With enough data both pore space and cold content could be quantified, but that number would represent a maximum refreezing capacity that would only be achieved if the melt water infiltrated in a uniform manner. Unfortunately, surface variations due to ablation and accumulations, combined with potential influences on the near surface temperature sensors from solar radiation prevent us from being able to quantify the cold content there. Figure 4 is not meant to be a quantitative analysis, but should instead be interpreted qualitatively as has refreezing capacity vs no refreezing capacity.

57 Anonymous 1 Comment: P5497 L26

This is not obvious. For 2008 sites T1a and T2 have much more cold content left, but much less differences between melt and refreezing. This needs more discussion.

57.1 Authors Response

At sites H1, T1-08, and T2-08, the estimated melt is small enough that we do not have the resolution to make any conclusions about the relationship between melt and refreezing at these sites. We admit that this was not mentioned in our original discussion and the paragraph has been rewritten.

57.2 Changes to manuscript

Original (P5497 L23 P5498 L7): At most sites higher than around H165, the refreezing quantities lie within or slightly below the PDD melt range, implying that a significant fraction melt water is infiltrating deep within the firn and that there is sufficient refreezing capacity in this region to capture most of it. The highest site, CP, has more cold content in the upper 1 m of firn (Fig. 4a) than most of the other sites. This could lead to more refreezing in the near surface and may explain why the total refreezing value is significantly below the PDD melt range. Refreezing quantities at sites T1 and T2 overlap with the PDD melt range in both 2007 and 2008 despite the substantial change in total melting between the two years. This shows that the firn has some ability to at least temporarily buffer large changes in melt as the refreezing capacity in this region was not completely eliminated during the 2007 season, or it was able to sufficiently recover during over the 2007/08 winter.

For sites above H165, all melt produced at the surface appears to refreeze in the upper 10 m of the firn column.

Revised: In 2007, the refreezing quantities lie within or slightly below the PDD melt range, implying that a significant fraction melt water (> 50% in most cases) is infiltrating deep within the firn and that there is sufficient refreezing capacity in this region to capture most of it. The highest site, CP, has more cold content in the upper 1 m of firn (Fig. 4a) than most of the other sites. This could lead to more refreezing in the near surface and may explain why the total refreezing value is significantly below the PDD melt range. Refreezing quantities at sites T1 and T2 overlap with the PDD melt range in both 2007 and 2008 despite the substantial change in total melting between the two years. This shows that the firn has some ability to at least temporarily buffer large changes in melt as the refreezing capacity in this region was not completely eliminated during the 2007 season, or it was able to sufficiently recover during over the 2007/08 winter.

For all sites above H165, there is no significant difference between estimated melt and refreezing values indicating that all melt produced at the surface appears to refreeze in the upper 10 m of the firn column.

58 Anonymous 1 Comment: P5498 L4

Remove during

58.1 Authors Response

Change to over.

59 Anonymous 1 Comment: P5498 L15

Bit confusing here: H3 is below H2, and is included in the explanation given above this line. Should this be 163? If not, then you have to explain more/better why H3 is included here.

59.1 Authors Response

H165, H2, and H3 all have refreezing values that are greater than the estimated melt at that site. H3 is also the first site to have a refreezing value that decreases rather than increases with a decrease in elevation.

60 Anonymous 1 Comment: P5498 L19

I dont think it is very likely that at this location liquid water is present at the end of winter. See Kuipers Munneke et al., GRL 2014 about the relation between melt, precipitation and the presence of liquid water at the end of winter.

60.1 Author's Response:

One of the plots in Kuipers Munneke did give some indication of the presence of end of winter liquid water in the location of our transect.

61 Anonymous 1 Comment: P5498 L23

Van den Broeke et al., GRL, (2010) also showed that DDF change over the Greenland ice sheet, based on regional climate model output.

62 Anonymous 1 Comment: Appendix

What values for Kice and rhoice are used?

62.1 Authors Response

Density ice = 915 kgm^{-3}, K ice = 2.2 $Wm^{-1}K^{-1}$

63 Anonymous 1 Comment: References

Forster et al. was published in 2014, not 2013

63.1 Authors Response

Will fix

64 Anonymous 1 Comment: Table

Explain Ave Ref and SD in caption and refer to figure 1 for locations sites. Also explain over what period Ave Ref is determined.

64.1 Authors Response

Will edit column headings from Ave Ref to Ref. and explain the table with a more detailed caption.

64.2 Changes to manuscript:

Revised Caption: Summary of temperature profile data and refreezing results. Refreezing (Ref) is the average value of refreezing from the Monte Carlo trials. SD is the standard deviation of the trials. The method is applied to each site over the time period shown in Dates for Refreezing Calc.

65 Anonymous 1 Comment: Figure 2

Add line explanation to the legend. Mark lines for 2007 and 2008. Add tickmarks. Refer in the caption that the values are given in Table 1.

65.1 Authors Response

Will add.

66 Anonymous 1 Comment: Figure 4

Add depth of sensors over which is averaged. Remove in between but and all. Well visible refreezing events in 4b T1a and T2. Please discuss in the text.

66.1 Authors Response

Will change.

67 Anonymous 2 Comment:

The major comment regards the presentation of the results. Basically, the whole manuscript is based on one figure (Figure 3), presenting the obtained annual refreezing values, as well as the comparison with other values. With only this sole figure presenting the core results, the reader is left with the feeling that there is more data to be presented. What about time series of refreezing (when and at what depth) or vertical temperature profiles? Moreover, the comparison with the PDD approach and MAR simulation is weak, both in the figure and the text. In the figure, there is low agreement between the methods and in the text these differences are not well discussed. The results and discussion section are written in a style that suggests that the PDD and MAR method are likely correct, attributing the differences to uncertanties in the here described method. I find it more likely that the opposite is true.

Compared with the MAR model the differences are large; i) there is a 50-500% overestimation of refreezing at all locations and ii) there is no clear relation between decreasing elevation and increasing refreezing. These results suggest that the MAR model is not able to correctly simulate the refreezing of surface melt water in this region of the Greenland ice sheet. These differences are likely related to the physical parameterization in MAR and/or the horizontal resolution of 25 km. The authors should look into the MAR data to find possible reasons for this mismatch. Another possibility could be to look into a similar model, for example RACMO (Ettema et al., 2009 (GRL)).

For the PDD method, scaled temperatures from the highest site CP are used. By doing so, it is assumed that the climate at all locations is similar to this point, apart from its elevation. However, it is highly likely that the albedo change on lower elevation is larger than at CP, thereby influencing the energy balance and subsequently the temperature and melt amount. This should be discussed in more detail and -if possible- corrected for.

Next to the annual refreezing values, it would be very interesting to show when and at what depth liquid water refreezes. A time series of refreezing would greatly in- crease the impact of the manuscript. Figure 2a shows a time series of the amount of energy available for refreezing, if those are available, why are they not shown in the heat is added, i.e. where melt water is refreezing.

67.1 Authors Response:

We agree that another figure would be beneficial. Figure 5 addresses some of the concerns discussed above. It is difficult to present a time series of refreezing events in a compact way, but we have tried to show how the profiles evolve through the melt season along the transect and in some cases where the refreezing is taking place.

It was not our intent to make any conclusions regarding the accuracy of one method with respect to another. Although we present original data, our major goal in this paper is to develop a method for analyzing this and similar data to get better estimates of melt water refreezing. We compare with other methods mainly to provide some context within which to interpret our results. We realize our method is still new and could use improvement, and it is therefore premature to single out any refreezing values that do not match our own perfectly, especially since there is such a large spatial difference in the scale of the region defined our method and by remotely sensed methods. In our comparison to the MAR output, we try to find reasonable causes for the large differences between our values and we look at the largest potential error in our method and conclude that the differences are not likely just due to refreezing in the first meter of firn. We leave it to future studies to confirm our results with similar projects and further diagnose what might be causing the discrepancy.

Regarding the PDD, as stated above, the purpose of the PDD melt estimate is to provide a general reference against which to compare our refreezing values. So higher precision melt estimates derived from assumptions about surface properties are not necessarily needed and may be difficult to achieve as well.

68 Anonymous 2 Comment:

Personally, I have a preference to list multiple literature references at the end of a sentence chronologically.

68.1 Authors Response:

Will review.

69 Anonymous 2 Comment:

Throughout the manuscript, different units for accumulation and refreezing amounts are used ([m] snow accumulation and [cm] refreezing). It would add clarity to the manuscript if all mass fluxes are given in the same unit, preferably mm w.e. (water equivalent).

69.1 Author's Response:

Will review and correct for consistency.

70 Anonymous 2 Comment: Title

"Ice Sheet"

70.1 Author's Response:

Will change

71 Anonymous 2 Comment: P5488 L26

Is this statement outdated with the recent high-melt summers of 2010 and 2012?

71.1 Authors Response:

The definition of the percolation zone is undergoing a bit of an evolution. Paterson et al. defined the dividing line between the percolation zone and the wet snow zone as the point at which the summer melt has saturated the current years firn pack. However, it is now evident that both infiltration and temperature fields are more complex than previously believed with melt water penetrating deeper and staying liquid longer. At the lowest site H4, temperatures deeper than about 3m remain fairly cold for a majority of the melt season, while higher sites H3 and H2 are actually warmer by comparison. This is probably due to less melt water infiltration at the lower site due to less pore space. Without data it is unclear whether the entire firn pack became isothermally zero degrees at any sites in the high melt summers of 2010, 2012, but it is likely it did not.

72 Anonymous 2 Comment: P5491, L1-5

Does this measure differ from site to site? The measurement locations vary from the accumulation zone to the runoff zone, spanning many different percolation and refreezing regimes, potentially leading to different inter-pipe distances.

72.1 Author's Response:

Piping distribution is likely a function of snow structure, total melt, maybe melt intensity and refreezing. The number of pipes probably increases at lower elevations which might actually help with the averaging out of lateral heat differences.

73 Anonymous 2 Comment: P5491 L8

Here the authors assume no change in density over time. However, due to the refreezing of melt water firn density does change. Clarify what the influence of this density change on the eventual calculated refreezing rates is. A constant density approximation may hold for the bottom heat flux, but not for the top one.

73.1 Author's Response

Our temperature profile data does give some indication of the location of refreezing events, but the resolution is insufficient to determine exact ice location and thickness. Given that the refreezing is not uniform and the distribution of ice lenses unknown. It is unrealistic to conduct a detailed analysis of density changes in the firn from the data we have. However, some back of the envelope calculations can be performed to get an idea of the magnitudes of density changes. For example, at CP, if the total refreezing quantity is uniformly distributed over the first layer of our domain, the density change is on the order of 20 kgm^{-3}. At H2, the total refreezing is much higher, but the water is also shown to penetrate much deeper. Distributing the water at H2 over the first 5 meters of the domain results in a density change of about 30 kgm^{-3}. Both of these are density changes are similar in magnitude to the density variations using in the Monte Carlo trials. We can therefore conclude that density changes may not play a significant role for the majority of the firn pack included in our analysis.

74 Anonymous 2 Comment: P5493 L16

Increased from what?

74.1 Author's Response:

Increased from around 300 kgm^{-3}.

75 Anonymous 2 Comment: P5494 L1

Introduce used abbreviations; SD.

75.1 Authors Response:

Will eliminate SD in favor of standard deviation.

76 Anonymous 2 Comment: P5494 L3

A density uncertainty estimate of 20 kg m-3 is very conservative. 50 kg m-3 is more common

76.1 Authors Response:

Although the density uncertainty estimate may be conservative, the uncertainty in final refreezing values are meant to be generous. Each of the final uncertainties is equal to 4 times the standard deviation of the variability generated in the Monte Carlo analysis.

77 Anonymous 2 Comment: P5495 L18

How was it determined that 2007 was a high melt year? Please add a reference. From the MAR results (Figure 3) this is not evident.

77.1 Authors Response

Several modeling studies by Jason Box et al. as well as Ettema et al. 2009 have shown this. It is also somewhat visible in figures in Shepherd et al. 2012. We will review and add the most appropriate reference.

78 Anonymous 2 Comment: P5496 L18

This is a questionable statement. In early summer, the firn pack is quite cold and it is likely that the first summer melt will refreeze in the upper 1 m, thereby warming the firn with latent heat release.

78.1 Authors Response:

We agree that some refreezing will take place in the upper 1m at the beginning of the melt season when the firn is still cold. However, we are trying to show that the temperature sensors in the near surface are fairly warm most of the melt season. I made a small edit to clarify.

78.2 Changes to manuscript

Original: These observations imply that the capacity for refreezing in the upper one meter of firn at these sites is almost zero.

Revised: These observations imply that the capacity for refreezing in the upper one meter of firn at these sites is almost zero for most of the melt season.

79 Anonymous 2 Comment: P5498 L16

The higher values in H2, H165 and H3 would indicate a lot of lateral water flow, too high in my opinion. How does the surrounding topography look, are these measurements taken in a topographical low? It could also mean that the temperature strings work as a preferential flow path themselves.

79.1 Author's Response:

There is some subtle topography in the region that could cause slight microclimates. H2 is at the bottom of a slight depression, however, H165 and H3 are actually on high points. So there is not a clear pattern between topography and total refreezing. We do not feel that the temperature strings themselves create any increased heterogeneity to influence infiltration beyond that which is already inherent in the firn.

80 Anonymous 2 Comment: P5498 L18

From Forster et al., 2013 and Kuipers Munneke et al., 2014 it is unlikely that firn aquifers are present in this region of the Greenland ice sheet.

80.1 Author's Response:

There is likely a range of possible hydrologic features within the percolation zone. Humphrey et al. 2012 calculate that a small amount of water could be liquid for multiple years without the need for an extensive aquifer.

81 Anonymous 2 Comment: P5499 L20-22

This is only true when also vertical profiles are presented. For snow hydrological models it is indeed important to know how much melt water refreezes in the firn pack, but this information needs to be accompanied by vertical profiles that states where and when this liquid water refreezes.

81.1 Author's Response:

This is addressed with the new figure.

82 Anonymous 2 Comment: Figure 2a

What is the physical meaning of the drop in Q in early July?

82.1 Authors Response:

Q (grey region, panel A) is the total heat gained by the profile due to heat conducted through the domain boundaries at 1m and 10m depths. It is calculated by the integrating the time series of net heat flux (qnet). The drop in qnet mid June is associated with a refreezing event near the 1m boundary that sharply elevated the temperature near the boundary creating a strongly negative net heat flux for a short period of time. In other words, the temperature at 1.25m depth became much warmer than the temperature at 1m and heat was conducted upward out of the method domain. Added a sentence to the caption to clarify.

82.2 Changes to manuscript:

Original: (a) Net heat flux through the top and bottom of the domain (see panel b) from 1 June 2008 to 1 August 2008 at site H2. Q is the integral of the time series (see Eq. 2).

Revised: (a) Net heat flux through the top and bottom of the method domain (see panel b) from 1 June 2008 to 1 August 2008 at site H2. Q is the integral of the time series (see Eq. 2). The sharp drop in qnet mid June is the result of a refreezing event within the domain near the 1m boundary. Refreezing increased the temperature gradient at the boundary and heat was conducted out of the domain (negative qnet).

83 Anonymous 2 Comments: Figure 4

Different colours for the different lines would enhance the clarity, especially in A.

83.1 Authors Response

Will change.

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Quantifying meltwater refreezing along a transect of sites on the Greenland ~~Icesheet~~Ice Sheet

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Abstract

On the Greenland ice sheet, a significant quantity of surface melt water refreezes within the firn creating uncertainty in surface mass balance estimates. This refreezing has the potential to buffer seasonal runoff to future increases in melting, but direct measurement of the process remains difficult. We present a method for quantifying refreezing at point locations using in situ firn temperature observations. A time series of sub-hourly firn temperature profiles were collected over the course of two melt seasons from 2007 to 2009 along a transect of 11 sites in the accumulation zone of Greenland. Seasonal changes in temperature profiles combined with heat flux estimates based on high temporal resolution temperature gradients, enable us to isolate the heat released by refreezing using conservation of energy. Our method is verified from winter data when no refreezing takes place, and uncertainty is estimated using a monte carlo technique. Results provide additional evidence of While we limit our method to a subsection of firn between depths of 1m and 10m, our refreezing estimates appear to differ significantly from model based estimates. Furthermore, results indicate a significant amount of refreezing taking takes place at depths greater than 1 m and that runoff begins to occur above the ELA. Near the runoff limit, lateral migration of melt water significantly complicates the relationship between total surface melt and total refreezing.

1 Introduction

The mass balance of the Greenland ice sheet has become increasingly negative over the course of the last decade (Shepherd et al., 2012; Rignot et al., 2011; Vaughan et al., 2014). Recent measurements of outlet glacier discharge indicate that surface mass balance is now the dominant source of mass loss (Enderlin et al., 2014), and regional climate-surface process coupled models show that most of the increases in surface mass loss are due to significant increases in surface melting and runoff beginning in the early 1990s (Ettema et al., 2009). Although the increase in melt is clear from the remotely sensed data, Increases

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in the areal and temporal extent of surface melt, evident from remote sensing, support model based increases in surface melting. However, the increase in melt water leaving the ice sheet is not as well constrained.

A significant source of uncertainty in estimates of Greenland mass balance and melt runoff, both remotely sensed and model-based, is the refreezing of surface melt Refreezing of surface melt water, as it infiltrates into the underlying cold snow or firnfirn, creates a significant source of uncertainty in both remotely sensed and model-based estimates of Greenland mass balance. Modeling studies have estimated that almost half of the melt water generated annually in Greenland refreezes (Ettema et al., 2009). However, the complexity of the infiltration process remains difficult to incorporate into snowpack models and infiltration hydrology is usually modeled as a purely uniform process (Greuell and Konzelmann, 1994; Mernild et al., 2010; Fettweis, 2007; Ettema et al., 2009; Bougamont et al., 2005). There have been some efforts to quantify refreezing using a variety of parameterizations typically based on simple energy balance ideas where refreezing is controlled by the total cold content of the firn (Pfeffer et al., 1991; Pfeffer and Humphrey, 1996; Reeh, 1991; Janssens and Huybrechts, 2000; Oerlemans, 1991) (see Reijmer et al., 2012, for an overview). However, these parameterizations remain largely unverified with in situ data (Reijmer et al., 2012). A limited number of studies have attempted direct quantification of refreezing (Wright et al., 2007) or indirect measurements using density (Parry et al., 2007). However, these techniques are resource intensive, non-continuous, and do not adequately capture the complex three dimensional spatial variability of melt water refreezing.

The crux of the difficulty in quantifying the amount of refreezing melt is that most challenging aspect of quantifying refreezing is that both infiltration and refreezing of melt water in cold firn is highly heterogeneous in space and time. Infiltration is characterized by a complex network of rapidly developing ice lenses and vertical pipe structures (Pfeffer and Humphrey, 1998). Vertical pipe flow can transport water deeper into the firn than uniform infiltration. Recent field observations in the percolation region of the Greenland accumulation zone suggest that melt water is able to penetrate cold firn to depths greater than 10 m and remain mobile throughout the winter (Humphrey et al., 2012; Forster et al., 2014). Piping of melt water into cold firn occurs without warming the entire profile. The water moves down the pipes with only minimal heating of the surrounding firn, making a locally complex temperature field of both cold and near melting temperatures. This deep penetration and heterogeneous heating make rudimentary parameterizations based on Pfeffer et al. (1991) questionable.

Here we demonstrate that temperature measurements in the firn provide an alternative method for investigating and quantifying refreezing. Latent heat released during refreezing diffuses ~~into the firn temperature profile as a thermal perturbation~~ through the firn causing a thermal perturbation in the temperature profile that can be quantified using a conservation of energy approach. Use of thermal data has advantages: installation of thermal sensors is relatively easy with hand held snow drills and thermal measurements and logging is simple and robust. Furthermore, using measured temperatures takes advantage of the diffusive nature of heat conduction which helps reduce the effect of extreme spatial discontinuities inherent to heterogeneous infiltration and refreezing processes. ~~We use a~~ The method is not without its challenges as melting, accumulations, and solar radiation in the near surface make it difficult to account for energy transfers from temperature measurements alone. However, by limiting our domain to firn depths between 1 m and 10 m, we are able to apply our method to a transect of melt season thermal profiles ~~to derive the~~ on the Greenland ice sheet. The result is the first in situ measurements of refreezing on the Greenland ice sheet that completely span the percolation zone.

2 Field measurements

Firn temperature data were collected in 2007, 2008, and 2009 from a transect of 11 sites in southwestern Greenland, about 100 km northeast of Jakobshavn Isbrae (Fig. 1, Fig. 5). All of the sites are within the accumulation zone and annual snow accumulation along the transect is on the order of 1 m (density 0.35 $\mathrm{g\,cm^{-3}}$) (Parry et al., 2007; Benson, 1962; Hanna et al., 2006). In contrast to accumulation, there is a strong gradient in the degree of summer surface melting in this region that is a result of changing elevation and albedo.

This important sub-region of the accumulation zone is known as the percolation zone, and the gradient in melt is reflected in the physical and thermal characteristics of the underlying firn (Cuffey and Paterson, 2010). The highest elevation site (Crawford Point) is near the upper edge of the percolation zone where summer surface melting is rare. In contrast, the lowest elevation site (H4) is within 20 km of the ELA, and enough melting takes place that layers within the firn can become, at times, saturated with water. While extensive refreezing, and thus warming, takes place in the percolation zone, parts of the underlying firn remain subfreezing even at the lowest elevation of H4 (Humphrey et al., 2012).

Each site along the transect was instrumented with 32 temperature sensors to a depth of 10(Fig. 2). Sensor spacing is 0.25 m from 0 to 5.5 m depths and 0.5 m from 5.5 to 10 m depths. The sensors were installed with reference to the surface at time of installation. After temperature string emplacement, the boreholes were backfilled with fine grained, cold snow, and our temperature measurements show rapid thermal equilibrium with the surrounding undisturbed firnpack (For details see (Harper et al., 2011) . During the subsequent year or more of data collection, the surface at most sites showed some net snow accumulation of order 0.5 m or less, and seasonal ablation of the same magnitude. Thus, quoted sensor depths are not relative to the actual surface at subsequent times. Site density profiles were obtained from 10 m snow cores extracted during temperature string emplacement (Harper et al., 2012). Field density measurements were averaged on a obtained at variable spacings in order to accurately sample observed firn stratigraphy. Since the thermal sensors were regularly spaced, the density data were averaged and re-sampled on a matching 0.25 m grid prior to use in this analysis to match the thermal sensor spatial resolutionspacing.

Not all sites were instrumented at the same time, for the same period, or with exactly the same sampling interval (Table 1). The higher elevation sites from CP to T1 recorded data in the summer and fall of 2007, while the lower sites from T1 to H4 recorded data from the summer of 2008 to the spring of 2009. Two temperature strings located 20 m apart were installed at site T1 in 2008 to investigate lateral heterogeneity of the temperature field . (See Fig. 5A). Most of the summer data has a 20–30 min sampling interval. However, power requirements limited the sampling interval of the 2008/09 winter data to every 8 h.

3 Method theory

Our approach quantifies refreezing using the change in heat content at each site as measured by the change in the vertical temperature profile over the summer season (Fig. 2). If we assume only vertical temperature gradients (discussed below), the change in the heat content of a section of firn results from the net conduction flux across the top and bottom boundaries plus the advection of latent heat associated with refreezing of infiltration water. Both the change in heat content and the net heat conducted across the boundaries can be estimated from the data. The latent heat released during refreezing is the difference between the total change in heat content and the net heat conducted across the section boundaries.

$$\text{Heat from refreezing} = \text{Change in heat content}(\Delta H) - \text{Net boundary heat conduction}(Q)$$

Where Δ is used here and in the following discussion to indicate change of a variable over the data time period, typically over the summer melt season.

A one dimensional approach requires that horizontal temperature gradients within the firn are negligible when averaged over the summer melt period despite the horizontally heterogeneous nature of melt infiltration. Fortunately, the diffusive nature of heat flow ensures that horizontal gradients in temperature decay rapidly as long as the length scale of the lateral heterogeneity is less than the vertical scale. Furthermore, the gross firn structure, which dominates both thermal and hydrologic properties, is predominantly horizontally layered, and we therefore assume lateral variations in both temperature and infiltration should be stochastically distributed. A random distribution of lateral temperature variations coupled with rapid decay in horizontal temperature gradients implies that the transfer of heat laterally should sum towards zero on a seasonal timescale.

Our assumption that lateral gradients can be ignored is given credence both by analysis of the data from the two adjacent temperature strings located at T1(Fig 5A) and by a theoretical scaling analysis. The two profiles at T1 show occasional, significant differences during melt events that last a few days

~~(see Humphrey et al., 2012)~~ (also see Humphrey et al., 2012) , demonstrating that firn temperatures show some local, lateral variability. However, the calculated refreezing quantities (see Table 1) are within measurement error of each other, indicating that the temperature variations are insignificant when averaged over the summer season. The significance of the lateral variations can be investigated theoretically by using the analytical solution of exponential thermal decay of a line heat source (representing a vertical pipe) in a 3-D homogeneous firn solid (Carslaw and Jaeger, 1986). As an example of this scaling for 1 m pipe spacing, using appropriate parameters for firn, the analytical solution yields a temporal decay scale of 3 days, which also supports our assumption that horizontal gradients decay over the summer season. If the pipe spacing is larger, on the order of 10 m, then our assumption is not valid over the season. We note that the horizontal spacing of observed pipes was typically considerably less that 10 m (Brown et al., 2011). From this we conclude that the lateral temperature variations at each site averages out to a uniform system on seasonal timescales.

The change in heat content over the summer melt season can be quantified from the changes in profile temperature ($z =$ depth from the top of the profiles) using:

$$\Delta H = \int \Delta T(z)\rho(z)C_p(z)\mathrm{d}z \tag{1}$$

This formulation assumes that density (~~rho~~ρ) and heat capacity (C_p) do not change over time. This is reasonable because, at most of the sites, the input of melt water is minor compared to the water equivalent of the firn column. This assumption may break down for the lowest sites (H3, H4). Densification due to compaction of the firn is also assumed to be minimal within our seasonal timescale.

The net heat conducted through the boundaries is:

$$Q = \int q_{\mathrm{net}}(t)\mathrm{d}t \tag{2}$$

where $q_{\text{net}}(t)$ is the net heat flux as a -function of time and is defined by Fourier's law operating at the boundaries of the profile (K is thermal conductivity).

$$q_{\text{net}}(t) = \left(-K\frac{\mathrm{d}T}{\mathrm{d}z}\right)_{\text{Top}} - \left(-K\frac{\mathrm{d}T}{\mathrm{d}z}\right)_{\text{Bottom}} \quad (3)$$

The net heat flux is integrated over the time period corresponding to ΔT in Eq. (1) (see Fig. 2). This time period is typically the summer melt season.

4 Method Implementation

Numerical approximations to Eqs. (1)–(3) are used to calculate refreezing quantities from the observed temperature profile data. We strive to calculate refreezing quantities at each site corresponding to the entire melt season. However, leakage of the water into the data loggers at some of the 2007 sites resulted in sections of unusable data, and we are therefore forced to limit our analysis at some sites to shorter time periods (ie site T1–07, see Table 1).

The method is applied to firn depths ranging from 1 to 10 m, and we therefore ignore the data from the upper 4 sensors. We refer to this subsection of the firnpack as our analysis domain. This domain is deep enough to remain unexposed, as melting, sastrugi migration and accumulation lead to significant variations in the surface elevation. Furthermore, the influence of solar radiation is greatly reduced below about a -half meter. Refreezing that occurs above or below the domain remains unaccounted for by this analysis, but, as is shown below, we estimate ~~this region captures a~~ it captures a majority of total refreezing. Heat content in this domain is assumed to change only from conduction across the region boundaries, and advection of heat energy in the form of the phase change of refreezing percolating melt water. We assume melt water is at 0 °C and has no additional sensible heat. Firn densities are derived from the borehole core data. Heat capacity is considered to be constant at 2097 J kg^{-1} °C^{-1}.

The boundary temperature gradients ($\frac{\mathrm{d}T}{\mathrm{d}z}$) in Eq. -(3) are approximated ~~by taking the~~ using the temperature gradient of the two sensors closest to the 1 and 10 m bounds.

Figure Equation 2 is approximated by numerically integrating net heat flux using the trapezoid rule. Figure 2a shows a time series of net heat flux at site H2. High frequency variations on the order of 0.5 °C are a result of random electronic noise in each temperature measurement. Since this noise is random, the integrated flux derived from the gradients is not biased. Thermal conductivity (K) is calculated as a function of the boundary densities following Schwerdtfeger (1963) (see Appendix).

5 Error Analysis and Testing

We test our approach by applying the method to data Since our method differentiates discrete data when the heat flux is calculated, we assume that the largest errors stem from amplification of data noise by differentiation. Additionally, uncertainties in our profile density measurements create the potential for error as the values are utilized to calculate thermal conductivities and are direct inputs into equation 1. A Monte Carlo approach is used to estimate how these errors contribute to overall method uncertainty. Random perturbations were added to the observed temperatures and densities, and then the refreezing quantity was recalculated for each case. Since the noise in the data is electronic, the distribution of the perturbations is Gaussian with a standard deviation equal to the uncertainties in the observed data. Temperatures showed noise with an uncertainty conservatively estimated to be 0.5 °C and uncertainty in density is estimated to be 20 $\mathrm{kg\,m^{-3}}$. After 1000 Monte Carlo trials, the average and standard deviation of the refreezing is then used to estimate mean refreezing values and corresponding uncertainty.

We test our method using profile temperature data from the winter season. Temperature profiles were chosen from the data in which no surface warming approaching 0 °C occurred and when the quantity of refreezing is assumed to be zero. With no latent heat input, our energy balance should show that the temperature change within the firn is exactly balanced by the heat flow across the boundaries, and errors in the method would show up as spurious melt or refreezing. Multiple tests were performed at all sites except T4 where there is no temperature data outside of the melt season (roughly May–September). In order to verify consistent results, multiple tests were performed with time spans ~~range~~ ranging from 1 to 4 months and include data with different sampling frequencies. With the exception of ~~four~~ three sites, all tests resulted in refreezing quantities within 1 cm w.e. of zero. Since the two standard deviation uncertainty bounds on all refreezing estimates are on the order of 1.5 cm w.e., these tests confirm the method produces a refreezing value not significantly different from zero in the winter.

At sites ~~H1,~~ H165, H2 and H3, tests showed that the method produced ~~unlikely refreezing quantities somewhat greater than 1~~refreezing quantities on the order of -2 cm w.e., indicative of a ~~-~~mismatch between the change in the firn internal temperature structure and the flow of heat across the boundaries. ~~The~~ In the winter, a negative refreezing value results from the temperature profile losing more heat than would be expected given the calculated heat flux through the domain boundaries. The heat flux needs to be higher (more heat loss) in order to balance the profile temperature change. The most important parameter in this balance ~~(other than refreezing which is assumed to be zero) is~~ is the firn conductivity at the boundary~~. This is based on our measured firn densities of the previous summer. A~~ , and we find that a small increase in ~~the thermal conductivity in the near surface firn eliminates the mismatch in our energy balance~~conductivity at the upper boundary eliminates the energy imbalance. This increase in conductivity implies ~~a plausible increase in firn density in~~ that these sites require a corresponding increase in the density of the boundary firn~~during the melt season~~. We found that, in all cases, the mismatch can be eliminated when the densities near 1 m depth are increased ~~to around~~ by around 200 $\mathrm{kg\,m^{-3}}$ to 600 $\mathrm{kg\,m^{-3}}$. This is a reasonable near surface seasonal density change, and furthermore, the near surface measured densities (obtained at the beginning of the melt season) at these sites are unusually low compared to the underlying firn. It should be noted that although the above discussion is somewhat speculative, this same density change applied during the melt season has minimal effect on our calculated refreezing quantities as the melt season temperature gradient near 1 m is often near zero.

~~The analysis of the winter data gives us confidence in the method, however it gives little information on the size of the errors in estimates of refreezing of summer melt. Since~~

our method differentiates discrete data when the heat flux is calculated, we assume that the largest errors stem from amplification of data noise by differentiation. In addition, we investigate the other large potential error produced by errors in our density profiles.

A Monte Carlo approach is used to estimate how these errors contribute to overall method uncertainty. Random perturbations were added to the observed temperatures and densities, and then the refreezing quantity was recalculated for each case. Since the noise in the data is electronic, the distribution of the perturbations is Gaussian with a SD equal to the uncertainties in the observed data. Temperatures showed noise with an uncertainty conservatively estimated to be 0.5and uncertainty in density is estimated to be 20. After 1000 Monte Carlo trials, the average and SD of the refreezing is then used to estimate mean refreezing values and corresponding uncertainty.

6 Results

The calculated quantity of water refreezing between 1 and 10 m depths at each site is plotted in Fig. 3. The error bars on each value are equal to two SDs standard deviations of the variability generated in the Monte Carlo trials. The higher elevation sites show melt results calculated from 2007 temperature data, while the lower elevation sites use data collected from 2008 (Table 1). As might be expected due to increases in melting, refreezing quantities generally increase with decreasing elevation. Sites T2 and T1 have temperature profile data from both 2007 and 2008. In addition, there were 2 temperature profiles available at site T1, placed about 20 m apart. Refreezing values calculated from these two profiles show no significant difference from one another.

The results show a large difference in overall refreezing magnitudes between 2007 and 2008 that reflect the overall melt conditions experienced during each melt season (2007 was a high melt year, see Fettweis et al. (2011)). Unfortunately, data quality problems prevented all refreezing quantities from corresponding to exactly the same time period at some of the sites reduced the time period over which our method could be applied (see Table 1 column 4). With the exception of site T1, refreezing quantities in 2007 correspond to July and August, while all sites in 2008 correspond to June–August. Site T1 in 2007 corresponds to only July. If the T1–07 data also included June, the difference in refreezing trends between 2007 and 2008 would likely have been even more substantial than is shown in Fig. 3.

It is useful to give our results some context by comparing them to two separate and independent ~~analysis~~analyses. First, a simple positive degree-day melt model (PDD), following Hock (2005), is used to calculate a plausible surface melt range at each site (Fig. 3). In Greenland, empirically determined melt factors (DDF) for snow range from 2.5 to 5 mm day^{-1} °C^{-1} (Hock, 2003; Janssens and Huybrechts, 2000; Braithwaite, 1995; Cuffey and Paterson, 2010). Air temperatures at 2 m height from the ~~CP~~ Crawford Point weather station are used as input to the melt model. Prior to calculating the sum of positive degree days, the raw, hourly air temperatures are adjusted for each site using a seasonally variable slope lapse rate given by Hanna et al. (2005). Also, the hourly temperatures are averaged to daily values. The upper and lower bounds correspond to our estimates of maximum and minimum degree day factors. Note that the PDD model only produces melt, it does not deal with refreezing.

We also compare our results to refreezing quantities output by the regional climate model MAR (Fettweis, 2007; Fettweis et al., 2011; Tedesco et al., 2014) (Fig. 3). MAR has a resolution of 25 km, a time step of 120 s, and has been utilized in numerous studies related to modeling surface mass balance on the Greenland ice sheet (for a list see http://www.cryocity.org/papers.html). MAR utilizes the physically based, one dimensional snowpack model CROCUS to calculate refreezing to a depth of 15 m. MAR based estimates of refreezing quantities were determined for each of our sites by summing the daily average values of refreezing output by MAR over the time periods shown in column 5 of Table 1. Some sites lie within a common grid cell and have identical MAR refreezing values despite their different locations.

The melt range estimated by the PDD is roughly of the same order as our refreezing values, as well as, the MAR refreezing values at the 2007 sites. In contrast, the MAR refreezing values corresponding to the 2008 sites are substantially higher than our values, including some values over 10 times higher (Fig. 3). There is also a significant difference in the data trends. MAR refreezing values do not show any clear difference between 2007 and 2008 or a decreasing amount of total refreezing near the ELA. Differences between our refreezing values and the PDD become more significant at lower elevations. Below H165 the refreezing begins to exceed the estimated melting, peaking at site H2, and below that, the refreezing apparently becomes much less than the melt.

7 Discussion

The large discrepancy between our values and that of MAR may be partly a result of refreezing taking place in the upper one meter of firn. Refreezing in the near surface is not included in our analysis as, unlike the deeper thermistors, the data from thermistors in the first meter are influenced by the effects of ablation, accumulation, and solar radiation, complexities that are outside the scope of our simple energy balance approach. Nonetheless, the near surface data can still be used make qualitative interpretations of the thermal conditions in upper meter of firn, enabling us to investigate the significance of refreezing in the upper meter.

At each site, a daily mean of the average of the temperatures at depths of 0, 0.25, 0.5, and 0.75 m was calculated, and a subset of sites are plotted in Fig. 4 (some sites are omitted for clarity). At all of the sites in 2007 and most of the sites in 2008, warming was sufficient to bring the average temperature in the upper one meter of snow to zero degrees for almost the entire melt season (Fig. 4a). In some cases, the average temperatures are even above the melting point indicating that either the sensors are close enough to the surface to be warmed by radiative heating or even exposed by ablation or wind scour. These observations imply that the capacity for refreezing in the upper one meter of firn at these sites is almost zero for most of the melt season. Consequently, most melt water generated will infiltrate without refreezing until it reaches the deeper, colder firn within our method domain. Sites T2 and T1 in 2008 are the only sites with near surface firn temperatures below zero for a significant part of the melt season. However, the large difference in refreezing values between the two methods (our values vs. MAR) is present at T1, T2 (2008), and the other sites. It is therefore, unlikely that refreezing in the upper one meter of firn is the sole source of the difference in values.

Diurnal melting and refreezing of pooled water at the surface is also unaccounted for using our method. In this situation, refreezing takes place at the surface from radiational cooling without the need for sub-freezing firn temperatures. Several melt-freeze cycles could take place before the water finally infiltrates and/or runs off. The cumulative cumulative effect could drive the increasing difference in values at between our values and MAR sites H3 and H4. However, the significance of this process is highly uncertain since lower elevations, with fully saturated firn also have smaller diurnal temperature changes. Furthermore, there was no evidence of extensive surface water present at any of the sites (Humphrey et al., 2012).

A final possibility is that the large difference is not due to physical parameters. The MAR output is representative of 25 km grid cells that have not been downscaled to each site. Furthermore, climate models are known to have inherent bias (Tedesco et al., 2013) and the 1–3 month time period used may be unreasonably short for assessing MAR results.

It may be more appropriate to interpret our results in relation to the PDD melt estimates, and we give two reasons. First, the temperatures used in the PDD model have been adjusted to elevation and may be better for point measurements than the coarse atmospheric model resolution. Second, a PDD melt model does not capture short duration, minor melt events that are unlikely to infiltrate to within our model domain. PDD melt factors are often calibrated using daily observations of ablation stakes to calculate melt (Hock, 2003; Braithwaite, 1995). This type of observation is more sensitive to significant melt events and may even ignore short duration or diurnal melting. Therefore, the PDD melt range shown in Fig. 3 can be interpreted as the total amount of melt that was likely to penetrate more deeply within the firn. Since the refreezing capacity of the near surface firn is minimal at most sites (Fig. 4), we can therefore utilize the PDD melt range to interpret our results in relation to how much meltwater is infiltrating within the method domain.

At most sites higher than around H165In 2007, the refreezing quantities lie within or slightly below the PDD melt range, implying that a significant fraction melt water significant fraction of melt water (> 50% in most cases) is infiltrating deep within the firn and that there is sufficient refreezing capacity in this region to capture most of it. The highest site, CPCrawford Point, has more cold content in the upper 1 m of firn (Fig. –4a) than most of the other sites. This could lead to more refreezing in the near surface and may explain why the total refreezing value is significantly below the PDD melt range. Refreezing quantities at sites T1 and T2 overlap with the PDD melt range in both 2007 and 2008 despite the substantial change in total melting between the two years. This shows that the firn has some ability to at least temporarily buffer large changes in melt as the refreezing capacity in this region was not completely eliminated during the 2007 season, or it was able to sufficiently recover during over the 2007/08 winter.

For all sites above H165 , (Fig. 5B), there is no significant difference between estimated melt and refreezing values indicating that all melt produced at the surface appears to refreeze in the upper 10 m of the firn column. In contrast, the in situ refreezing in the lower percolation zone, below H165 (Fig. 5C), cannot be simply described as full refreezing of the predicted melt. We interpret our results to indicate two separate processes occurring in the lower percolation zone. At elevations below H2, the refreezing quantities begin to decrease. Additionally, profile temperatures at the lowest site H4 are actually colder than either H3 or H2 (Fig. 5C). This is inconsistent with the expected increased melt at lower elevations and therefore must result from melt water running off rather than refreezing (Humphrey et al., 2012). This region is the location of the runoff limit, where some of the melt water may ultimately leave the ice sheet and contribute to sea-level rise. The zone encompassing H165, H2, and H3 is more difficult to interpret. The refreezing values in this region may be higher than the calculated melt due to lateral migration of meltwater in the firn. It is also plausible that some of the total refreezing quantity is derived from melt water generated during a previous melt seasons remained unfrozen within the firn in a manner described by Forster et al. (2014). Lastly, it is also possible that the PDD melt model significantly under predicts melt in this region. It is interesting to note that Ambach (1988) calculated DDF for the ELA elevation of this transect region in Greenland and found a particularly high DDF, which may indicate that it is not realistic to use a single DDF in this region, but that the DDF should increase with decreasing elevation. Nevertheless, this transitional region is not fully explained by this comparison with the simple PDD model.

8 Conclusions

Firn temperature profiles provide an effective means of estimating in situ quantities of melt water refreezing. Our method treats the firn as a one dimensional system and the heat conducted into and out of the system through time is tracked using temperature measurements. The latent heat released into the system by refreezing is calculated using conservation of energy, and this value is then converted to a water equivalent.

Application of our method is problematic in the upper meter of the snow profile because of radiative heating and cooling and because of unobserved snow accumulation and ablation during the yearly cycle. Any refreezing in this layer represents an unaccounted error in our melt estimates. Nonetheless, testing of the method using winter temperature measurements, when it is assumed that no refreezing is taking place, verified that, in most cases, our method is robust. Four of the sites required slight tuning of the near surface densities, but this is reasonable given expected melt season densification of the firn.

The calculated refreezing quantities reveal a transition from complete refreezing of melt water at higher elevations to eventual runoff of melt water near an elevation of around 1500 m, up to 40 km inland from the ELA. Even where complete refreezing does occur, a significant portion of the overall refreezing takes place at depths greater than 1 m. This may be a result of piping of melt water to much greater depths than would otherwise occur by uniform infiltration. Since heterogeneous infiltration is not currently accounted for in either snow hydrological models or simple theoretical parameterization, these in situ refreezing values provide an important source of snow/firn model validation. ~~Our results show that piping of melt water significantly complicates the relationship between total refreezing and simplified theoretical approaches to predicting refreezing capacity. Thermal profiling for the lower accumulation zone can be used to both quantify melt refreezing, as well as help to locate important zones such as the runoff limit~~Finally, our results also give some indication that lateral movement of infiltrated meltwater, in some cases from prior melt seasons, may be significant in this region of Greenland, complicating the classic understanding of percolation zone processes.

Appendix A:

Typically, snow thermal conductivity (K) is calculated from snow density using an empirically derived relationship (i.e. Sturm et al., 1997; Yen, 1981, and others). However, many empirical formulations are based on measurements from lower density seasonal snow packs and may be less applicable to higher density firn. Instead, we use a theoretical relationship between firn density and thermal conductivity based on modeling the firn as an ice matrix embedded with spherical pockets of air (vapor transport of heat is not included). This idealized geometry enables the analytical calculation of the heat flow through the system. This model was originally determined by Maxwell for electrical conductivity in two phase metal alloys, and was adapted for snow by Schwerdtfeger (1963) (see Carson et al., 2005).

$$K_{\text{eff}} = \frac{2\rho_{\text{firn}}}{3(\rho_{\text{ice}} - \rho_{\text{firn}})} K_{\text{ice}} \quad \text{(A1)}$$

Our dense winter data show the temperature profiles evolving solely via conductive diffusion. The surface temperatures remain below freezing, along with the entire profile. The lack of phase change energy allows us to test the range of K vs. density values against a simple thermal model. A 1-D vertical finite difference thermal diffusion model was run in comparison with the observed data, and a range of conductivity values were compared. This testing revealed that the Maxwell model yielded significantly more accurate firn temperature profiles (as compared to observed) than the Sturm et al. (1997) empirical regression. Furthermore, the Maxwell formulation is quite similar to the relationship found by Calonne et al. (2011) using microtomography on higher density snow. These results may indicate that snow evolves towards a more simplistic geometry as it undergoes densification. We

~~have used these density based K values, that are internally consistent without temperature data, in our modeling of the summer melt/refreezing calculations~~utilize equation A1 in our refreezing analysis to calculate thermal conductivity values from averaged field density measurements.

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Table 1. ~~Temperature~~ Summary of temperature profile data ~~summary~~and refreezing results. Refreezing (Ref) is the average value of refreezing from the Monte Carlo trials. SD is the standard deviation of the trials. The method is applied to each site over the time period shown in *Dates for Refreezing Calc*.

Site	Complete Data Timespan	Data Sample Interval	Dates for Refreezing Calc.	Ref. (cm w.e.)	SD
CP	25 Jun 2007–21 Oct 2007	30 min	30 Jun 2007–1 Sep 2007	2.29	0.9
T4	3 Jul 2007–27 Jan 2008	30 min	5 Jul 2007–24 Aug 2007	7.77	0.44
T3	25 Jun 2007–2 Jan 2008	30 min	28 Jun 2007–1 Sep 2007	10.87	0.46
T2–07	28 Jun 2007–29 Oct 2007	30 min	30 Jun 2007–1 Sep 2007	13.1	0.44
T1–07	28 Jun 2007–22 Dec 2007	30 min	30 Jun 2007–31 Jul 2007	14.93	0.49
T2–08	27 May 2008–16 May 2009	20 min, 8 h Oct–Apr	28 May 2008–1 Sep 2008	0.76	0.51
T1–08a	30 May 2008–16 May 2009	20 min, 8 h Oct–Apr	30 May 2008–1 Sep 2008	0.1	0.63
T1–08b	1 May 2008–16 May 2009	20 min, 8 h Oct–Apr	30 May 2008–1 Sep 2008	1.42	0.58
H1	31 May 2008–15 May 2009	20 min, 8 h Oct–Apr	1 Jun 2008–1 Sep 2008	1.8	0.63
H163	30 May 2008–15 May 2009	20 min, 8 h Oct–Apr	1 Jun 2008–1 Sep 2008	4.42	0.60
H165	30 May 2008–15 May 2009	20 min, 8 h Oct–Apr	1 Jun 2008–1 Sep 2008	5.96	0.53
H2	30 May 2008–15 May 2009	20 min, 8 h Oct–Apr	1 Jun 2008–1 Sep 2008	15.99	0.63
H3	31 May 2008–17 May 2009	20 min, 8 h Oct–Apr	1 Jun 2008–1 Sep 2008	11.44	0.63
H4	31 May 2008–15 May 2009	20 min, 8 h Oct–Apr	1 Jun 2008–1 Sep 2008	4.2	0.73

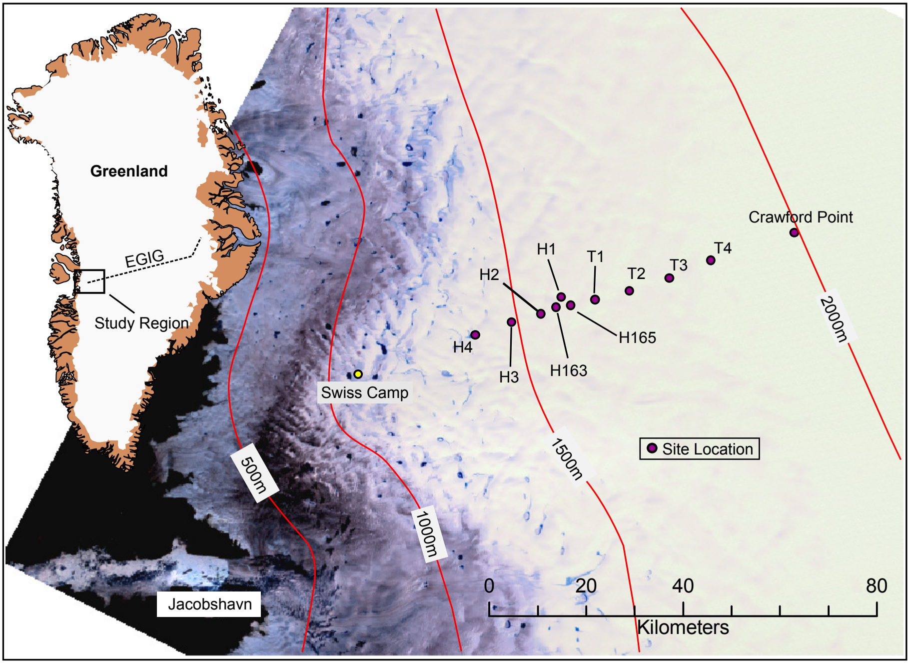

Figure 1. Temperature profile site locations in SW Greenland.

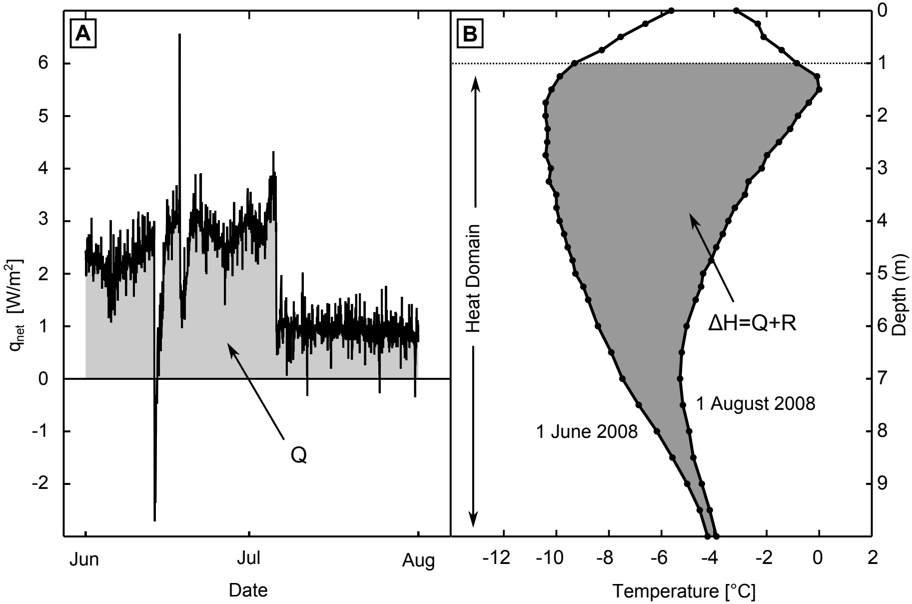

Figure 2. (a) Net heat flux through the top and bottom of the method domain (see panel **b**) from 1 June 2008 to 1 August 2008 at site H2. Q is the integral of the time series (see Eq. 2). The sharp drop in q_{net} mid June is the result of a refreezing event within the domain near the 1 m boundary. Refreezing increased the temperature gradient at the boundary and heat was conducted out of the domain (negative q_{net}). **(b)** Temperature profiles at site H2 on 1 June 2008 and 1 August 2008. The grey area between the profiles (ΔH) is equal to the heat gained through the top and bottom of the domain (Q) and the heat released by refreezing (R). Note that the domain does not extend to the surface. The upper meter of the firn was not included in analysis due to uncertainties caused by accumulations, melting, and solar radiation.

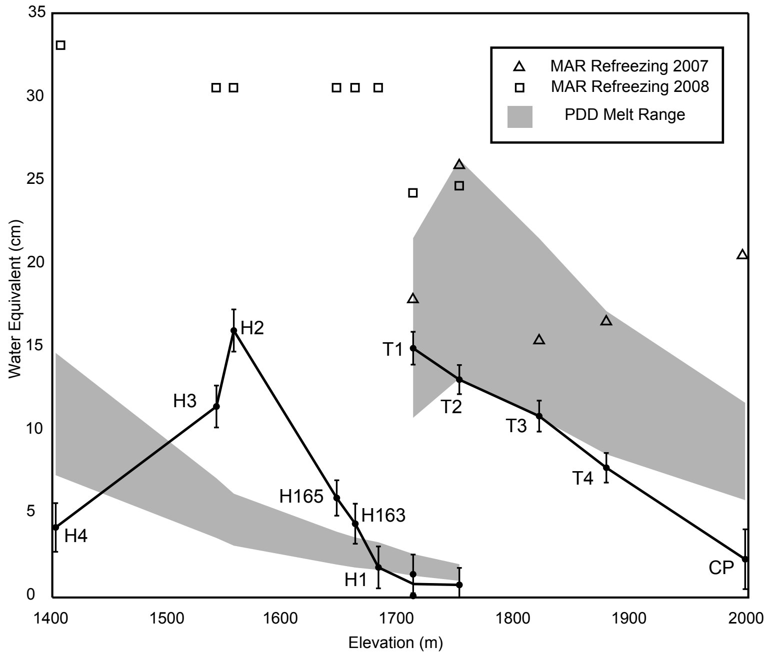

Figure 3. Refreezing quantities at each site with error bars equal to plus and minus two standard deviations. A line connects sites with data from the same melt season (either 2007 or 2008). The grey region is an estimated range of surface melt at each elevation calculated using a positive degree day model. Triangles and Squares are refreezing quantities output by the regional climate model MAR. MAR values are associated with the model grid cell encompassing the site and correspond to the time periods used to calculate refreezing values shown in Table 1.

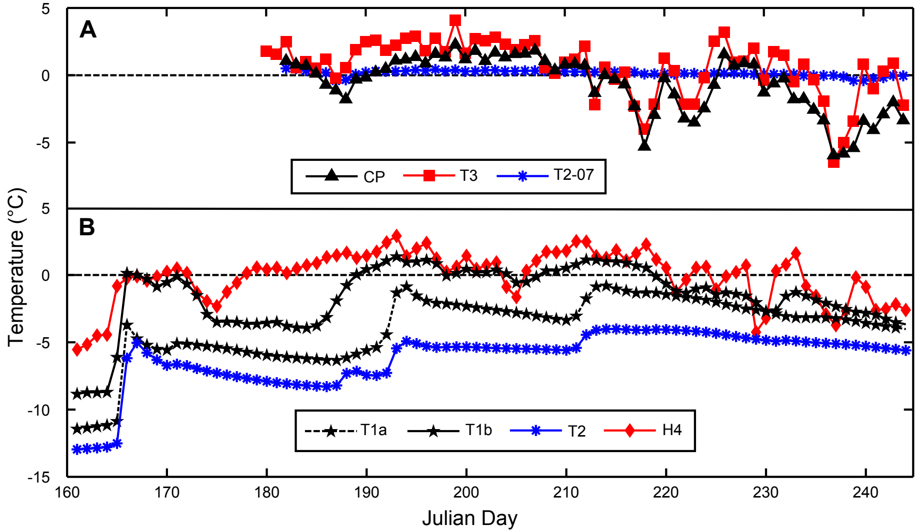

Figure 4. Daily mean values of near surface temperatures at select sites. Some sites are not shown for figure clarity, but in all cases were very similar to the sites that are included. **(a)** 2007 sites. **(b)** 2008 sites. The near surface temperature is calculated as the average of the temperatures output by the upper four thermistors (one meter) in the temperature strings at each site.

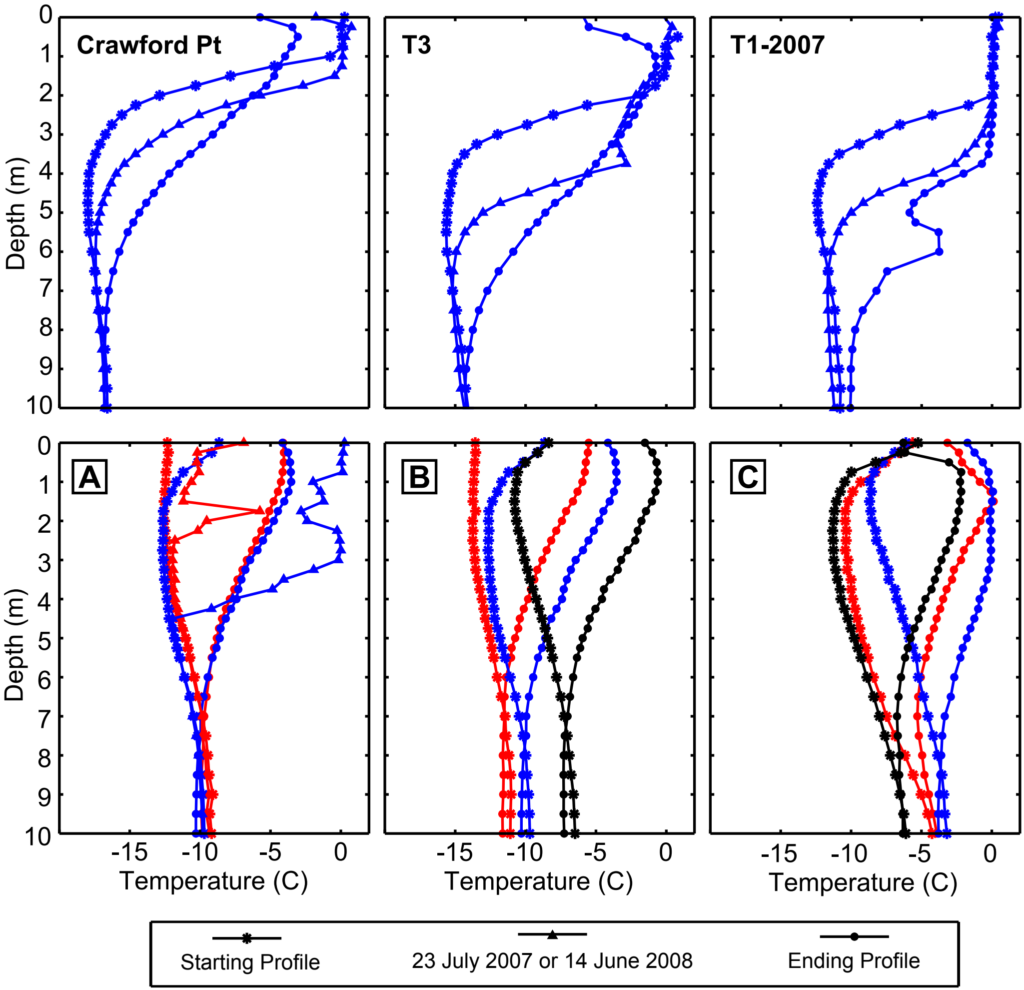
Crawford Pt
T3
T1-2007
A
B
C
Depth (m)
0
1
2
3
4
5
6
7
8
9
10
-15
-10
-5
0
Temperature (C)
Starting Profile
23 July 2007 or 14 June 2008
Ending Profile

Figure 5. Select temperature profiles at various sites showing the evolution of the temperature profile over the melt season. Starting and ending profiles correspond to the starting and ending dates used for the refreezing calculation at each site (See Table 1). Profiles with triangles correspond to 23 July 2007 at 2007 sites and 14 June 2008 at 2008 sites. On these dates, significant refreezing events occurred at most sites along the transect. A: T1-2008 profiles. B: T2-08 (Red), T1-08 (Blue), H163 (Black). C: H2 (Red), H3 (Blue), H4 (Black).