The Cryosphere
Discussions

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Interactive comment on "Quantifying meltwater refreezing along a transect of sites on the Greenland Icesheet" *by* C. Cox et al.

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1   Comment: P5486 L20

Need to mention SMB estimates

1.1   Author's Response

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

2   Comment P5487 L0-3

Passive voice hard to follow

2.1   Author's 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   Comment: P5487 L18

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

3.1   Author's 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   Comment: P5489 L8-10

Don't understand what you are talking about here

4.1   Author's 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   Comment: P5489 L2

Best to use variables and identify variables in the text.

5.1   Author's 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   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   Author's 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 $\mathrm{kg\,m^{-3}}$. 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 $\mathrm{kg\,m^{-3}}$. 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   Comment: P5491 L20

Need to state K is conductivity here. And mention how you calculate k here or at least cite the appendix. I'm 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   Author's 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 $q_{net}(t)$ 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 $q_{net}(t)$ 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 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 don't have changing density and liquid water in the mix. Might your summer uncertainties be higher?

8.1 Author's 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 Comment: P5492 L7

Is this not contradictory to your previous sentence?

9.1 Author's Response:

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

10 Comment: P5492 L16

Increased from what?

10.1 Author's Response:

(We assume this is actually 5493) The densities are an increase of about 200 $\mathrm{kg\,m^{-3}}$ 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 $\mathrm{kg\,m^{-3}}$.

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 $\mathrm{kg\,m^{-3}}$ to 600 $\mathrm{kg\,m^{-3}}$.

11 Comment: P5494 L25

Analyses

11.1 Author's Response:

Will change in final text.

12 Comment: P5494 L2

Spell out CP

12.1 Author's Response:

Revised

13 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 don't 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 Author's 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 don't 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 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 Author's 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 Comment: Results General

I interpret your tone here as you feel your results aren't 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).

C3102

15.1 Author's 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 Comment P5499 L23

This paper covers refreezing but I don't really feel like it shows specifically that "piping complicates refreezing". Please clarify.

16.1 Author's 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 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 Author's 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.