

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

C. Cox et al.

chrisrycx@gmail.com

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1 Comment: Title

Icesheet or Ice Sheet?

1.1 Author’s Response:

Will change

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2 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?

2.1 Author's 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.

3 Comment: P5491 L1

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

3.1 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.

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4 Comment: L19

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

4.1 Author's Response:

Strange, this hasn't seemed to be a problem for others.

5 Comment: P5492 L10

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

5.1 Author's 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.

5.2 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,

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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.

6 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?

6.1 Author's 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

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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.

6.2 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

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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 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.

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7 Comment: P5493 L24

Please rephrase. The sentence is unclear.

7.1 Author's Response:

Slight rewording and combined two paragraphs.

7.2 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.

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8 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?

8.1 Author's 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.

9 Comment: P5494 L25

Why did you use such a simple method to estimate melt? Given the available 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.

9.1 Author's 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.

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10 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?

10.1 Author's 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).

11 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?

11.1 Author's 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

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therefore unable to make a detailed comparison between the two methods and leave that analysis for future studies.

12 Comment: P5497 L1

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

12.1 Author's Response

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

12.2 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.

13 Comment: P5497 L20:

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

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13.1 Author's 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”.

14 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.

14.1 Author's 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.

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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.

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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.

15 Comment: P5498 L4

Remove 'during'

15.1 Author's Response

Change to "over".

16 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.

16.1 Author's 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.

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17 P5498 L19

I don't 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.

17.1 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.

18 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.

19 Comment: Appendix

What values for Kice and rhoice are used?

19.1 Author's Response

Density ice = 915 kg m^{-3} , $K_{\text{ice}} = 2.2 \text{ W m}^{-1} \text{ K}^{-1}$

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20 Comment: References

Forster et al. was published in 2014, not 2013

20.1 Author's Response

Will fix

21 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.

21.1 Author's Response

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

21.2 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".

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22 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.

22.1 Author's Response

Will add.

23 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.

23.1 Author's Response

Will change.

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