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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:

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.

1.1 Author's Response:

We agree that another figure would be beneficial. Figure 5 has been added and addresses some of the concerns discussed above. It is difficult to present a time series of

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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. (Note that figure 5 in the final manuscript will have the appropriate line weights and fonts)

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.

2 Comment:

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

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2.1 Author's Response:

Will review.

3 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).

3.1 Author's Response:

Will review and correct for consistency.

4 Comment: Title

"Ice Sheet"

4.1 Author's Response:

Will change

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5 Comment: P5488 L26

Is this statement outdated with the recent high-melt summers of 2010 and 2012?

5.1 Author's 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 year's 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.

6 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.

6.1 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

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might actually help with the “averaging out” of lateral heat differences.

7 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.

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

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8 Comment: P5493 L16

Increased from what?

8.1 Author's Response:

Increased from around 300 $\mathrm{kg\,m^{-3}}$.

9 Comment: P5494 L1

Introduce used abbreviations; SD.

9.1 Author's Response:

Will eliminate SD in favor of "standard deviation".

10 Comment: P5494 L3

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

10.1 Author's 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

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4 times the standard deviation of the variability generated in the Monte Carlo analysis.

11 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.

11.1 Author's 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.

12 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.

12.1 Author's 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.

12.2 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.

13 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.

13.1 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.

14 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.

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14.1 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.

15 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.

15.1 Author's Response:

This is addressed with the new figure.

16 Comment: Figure 2a

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

16.1 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

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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.

16.2 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).

17 Comments: Figure 4

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

17.1 Author's Response

Will change.