Response to reviewer 2

In situ measurements of meltwater flow through snow and firn in the accumulation zone of the SW Greenland Ice Sheet

Nicole Clerx, Horst Machguth, Andrew Tedstone, Nicolas Jullien, Nander Wever, Rolf Weingartner, Ole Roessler

Dear Reviewer,

We would like to thank you for your thorough and constructive review of our paper, and the suggestions of how to improve its quality. Below, we respond point by point to all comments, and state how we plan to incorporate them in a revised version of the paper. The responses (normal font style) to the reviewer's comments are written directly into the reviews (displayed in italic font style).

Nicole Clerx,

Fribourg, June 21, 2022

1 General comments

1. My general feeling about this paper is that I was very excited about the science that was done, but the paper did not provide adequate discussion (1) about why the results were what they were; (2) about the broader implications of the research; and (3) about assumptions and uncertainties.

Thanks a lot for your enthusiasm about our study (we are excited about the science too!). We agree that the discussion could be improved, so will make sure it is further refined and expanded in the revised version of the manuscript.

An example is that the theoretical, modeled lateral flow rates were 3 orders of magnitude less than the observed lateral flow rates. This is a very large discrepancy, but the discussion section does not include discussion of why this large discrepancy might exist. I encourage the authors to work on the discussion section to add more discussion of how their results corroborate or challenge our current understanding of firn meltwater hydrology. It might be useful to provide a simple, qualitative description of how these flow processes operate on different spatial scales based on the results. To add to the implications, can your results add any perspective to our understanding of the fate of firn meltwater; e.g. on longer time scales, what percent of meltwater is running off? Can your results be extrapolated to non-ice slab regions, or are they spatially limited?

We agree that the discrepancy in calculated and observed flow rates for lateral flow result in significantly different estimates. Similarly, permeability values resulting from having used various methods yield very different results. We will investigate further, and provide a better discussion of how our results fit into the current understanding of meltwater flow and firn hydrology.

Thanks for the suggestion of adding more on the implications of our observations regarding meltwater runoff, we will add more discussion on what our measurements could mean for the overall contribution of runoff to the (surface) mass balance of the Greenland ice sheet.

The paper does not include uncertainty or error analysis, which I would like to see in a field study like this. I realize it can be difficult to quantify uncertainty in work like this, but even a short section qualitatively describing the uncertainties would improve the paper. For example, does permeability change during percolation with ROSA? How will that affect your quantitative results?

We agree that this is indeed missing in the current version of the paper. We will include a (better) description and quantification of the uncertainty ranges related to the various measurements in the revised manuscript.

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2. A central assumption around your analyses is that the flow is Darcian. It may be the case that this is a valid assumption, but I think it would be appropriate to include justification. Is preferential flow in fingers/pipes Darcian? Would you calculate a different hydraulic conductivity if you conder Richard's Equation vs. Darcy's law? Is there a point at which you expect your Darcian assumption to break down? Your abstract says that for the ROSA experiments, "flow predominantly occurring through preferential flow fingers". Is there a difference in the conductivity between the preferential flow fingers and the matrix-flow instances? Do your calculated hydraulic conductivities (Equation 7 and line 198) represent a bulk' conductivity (that might represent conductivity for matrix flow) or the conductivity in the preferential flow pipes?

Darcy's law is generally assumed valid as long as flow is linear and laminar (non-turbulent), i.e. having a Reynold's number Re of <1, where the Reynold's number is defined as:

$$Re = \frac{\rho u L}{\mu}$$

with ρ is the fluid density [kg m^{-3}], u is the flow speed, L is a characteristic linear dimension [m] and μ is the dynamic viscosity of the fluid [Pa·s]. Darcian flow rates are almost never exceeded in granular materials (Freeze and Cherry, 1979).

We will better specify the underlying assumptions related to the applicaton of Darcy's law and why/whether we think these are valid, and also discuss the differences in hydraulic conductivity values between matrix- and preferential flow in more detail.

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3. A structural comment: Consider adding a bit of text at the end of the intro describing the structure of the paper, i.e. outlining, to clarify that there are two distinct but related experiments. You mentioned in the introduction that there were two field seasons/two experiments, but as I read section 4 I kept wondering about the other experiment.

Thank you for this suggestion, we will incorporate this in the revised manuscript.

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4. The slush vs runoff limit finding is mentioned in the abstract, which indicates that it is an important result/outcome of the work. However, the discussion of this is only briefly mentioned at the end seems disparate from the results. I think it would be useful to add a bit more about how this 4 km is calculated and more discussion about the implications, including what additional "essential data" are required.

We agree. We will include references to sources that we used to determine the 4 km distance that meltwater can flow laterally, and discuss under what assumptions this calculation is valid. We will also include a more expansive discussion of the slush- and runoff limit, to link our findings to the more general hydrologic system on the SW Greenland ice sheet as shown in Fig. 1.

2 Specific comments

Line 89: It may be worth specifying what a 'ripe' snowpack is for TC readers not familiar with snow hydrology.

Good idea, we will include some explanation in the revised manuscript. (A 'ripe' snowpack means that it has warmed up to 0°C and now consists of metamorphosed, granular snow crystals that can yield meltwater.)

136: "systematic me asurements of which are required to determine the hydraulic conductivity and water retention capacity of icy firn": this is very vague. Can you specify how they are systematic, and what the parameters are?

The word "systematic" was used since the original version of ROSA only had an analog flow meter, and inflow was manually steered by opening or closing a plastic valve on a jerry can on top of the device. Hence, flow ratae was was hard to control. In the upgraded ROSA the inflow is governed by a digital flow controller, and water is pumped up actively by aquarium pumps to ensure continuous and constant inflow. We will rephrase this sentence.

165ish: I would like a bit more detail about the samples here. What are the dimensions of one sample? Are the firn samples taken from different depths in the pit, or side-by-side extractions, (which would allow you to understand spatial variability, perhaps)? Table 1 could include a column that states the depth interval that the firn came from in the pit.

All samples were roughly 70x70x15 cm in size. The block for the snow experiment originated from a snowpit at ∼1.5 m depth and was made up of older, transformed, relatively coarse-grained snow including layers of depth hoar, alternated with layers of finer-grained wind-blown snow. The firn blocks originated from a 2 m deep quarry close to the laboratory tent at FS4. The samples were extracted side by side, and the depth of their top surface (i.e. the top of the firn layer at the time) was at 1.32 m below the snow surface. We will include this information in the revised manuscript.

170: Can you be more specific about what is on this checklist?

The checklist ensures that all relevant metadata of the experiment and the snow/firn sample are recorded, and is quite extensive. We didn't provide more details on what is on the checklist in the manuscript for readability purposes. Categories on the checklist include i.a. date/times (quarrying/transport of the firn block, start/end of the experiment), firn block properties (dimensions, rough stratigraphy, location of and tools used during quarrying, initial weight), and experiment variables (placement location of the various sensors in the sample during the experiment, flow rate).

201: Is the densification just due to adding mass to the sample, or is there compaction (volume change) too? Also, what is the 'apparent rate of densification'? Is that different than the actual rate?

The densification is only due to the mass increase – no volume change was observed in the course of the individual experiments. We used the term 'apparent rate of densification' to indicate that this is a transient rate that is valid during the experiments. The 'final' density is not simply the densification rate * experiment duration but less, due to outflow after the water supply was stopped.

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203-205: I found the description of steps here a bit hard to follow. I suggest putting the description into past tense and write as a narrative; e.g. the water flow started, went this long, we observed X, then this happened, etc.

OK. We will rephrase this sentence.

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220: Is there a difference between piping and preferential flow? If not just say preferential flow was visible. Also, this is the only instance in the paper in which you use 'piping'; otherwise you use 'fingers', which I think is an interchangeable term. I suggest sticking with a single term.

Thanks for this remark, there is no intended difference between piping and preferential flow through 'fingers'. In the improved manuscript we will stick to one term.

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Figure 5 – I suggest coloring the hydraulic conductivity axis (ticks and label) to be blue (same as the dot color) to be consistent with "density" and "added mass" axes. For clarity, I would remove the date-time portion of the subfigure titles, which will make the figure titles consistent with the naming in Table 1 and 2.

Thanks for these suggestions, we will update the figure accordingly.

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242: What parameters? I think you say in the next paragraph, but as a reader my initial reaction is that this is vague. I suggest reworking the text a bit to avoid this.

OK, this is indeed mentioned in the subsequent paragraph. Text will be rephrased.

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244: This is vague: what is 'shallow'? How deep were the snow pits?

Both the cores and the snow pits reached the top of the ice slab, which was encountered at a maximum of 1.2 m depth. We will clarify this.

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246-249: The method here is vague – can you briefly explain the steel-tape method? Are you implying that you remove snow from the hole after drilling the borehole? Doesn't drilling a borehole inherently remove snow?

The steel-tape method involves chalking the bottom part of a ruler or steel tape that is subsequently lowered into a hole, typically a well, until a certain known depth where the bottom of the tape is below the water table. Upon bringing the tape back to the surface, the wetted part of the chalk indicates the water level. We will include more details on this method in the updated manuscript.

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275: I think it would help clarify the text if your methods above use the same language of 'slush matrix properties' – it took me a moment to realize that your 'slush matrix properties' described in 5.2.1 were just the properties you were describing in 2nd and 3rd paragraphs of section 5.1. Also – it might be useful for you to include a more formal definition of what you mean by slush matrix.

Thanks for this suggestion, we'll include a more formal definition of slush and improve the wording in section 5.2.1.

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Section 5.2.2/6.1.2: The discussion of the large variation (a factor of 10) in observed flow velocities is not adequately discussed. Why is there this large variation? Is it just local storage? Snow pack properties?

Agreed. We think that the main cause for this variation in lateral flow velocity is related to small-scale topography of the ice slab surface over which meltwater flows. We will include this in more detail in the revised version of the manuscript.

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313: Consider adding language like "modeled flow velocities" throughout the text to clearly differentiate between when you are calculating theoretical velocities from an equation and your measurements.

OK, we will use more consistent language to differentiate calculated and measured velocities.

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Figure 12: I am not sure that this figure is needed, or if you want to include it consider adding a meltwater flux calculation from a surface energy balance model.

We think this figure is relevant in the description of the field sites providing as background information on the meteorological conditions responsible for the observed meltwater, but it is true that its placement in this part of the paper is suboptimal. We will move it to the section describing the measurement set-up and -location in the revised manuscript.

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335: Can you be a bit more specific about which measurements are comparable? I.e., are the previous measurements that your data agree with capturing the same process?

Given the variety in age of, and the detail of methodological description in the various papers cited, it is tricky to confidently say to what degree the various measurements are comparable to our data. As far as we are aware, lateral flow velocities through a slush matrix have never been measured. Vertical percolation velocities/firn hydraulic conductivity have been determined before in other studies (i.e. Miller et al. (2018)) although again, either the setting or set-up of the measurements is not always completely analogous. We do agree that comparison of the various values in literature could be better, so we will improve the discussion this section in the revised manuscript.

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340: typo, unsaturated

OK.

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372: vague sentence – what is relatively large? What is 'more generically'?

Agreed, will be clarified. We meant to say that we assume that the firn hydrological properties we measured are representative of 'average' firn characteristics in this region of the Greenland ice sheet, and of firn in similar settings (i.e. relatively flat, in the accumulation zone, limited precipitation).

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395: this seems to be a restatement of earlier, but still no why

Agreed. We will further investigate this matter and provide a better discussion of the differences in permeability values and calculation methods in the updated version of the manuscript.

447: rewrite sentence – incomplete at this point.

OK, we will rewrite this sentence.

References

Freeze, R. and Cherry, J.: Groundwater, Prentice-Hall, Englewood Cliffs, New Jersey, 1979.

Miller, O., Solomon, D. K., Miège, C., Koenig, L., Forster, R., Schmerr, N., Ligtenberg, S. R. M., and Montgomery, L.: Direct Evidence of Meltwater Flow Within a Firn Aquifer in Southeast Greenland, Geophysical Research Letters, 45, 207–215, https://doi.org/10.1002/2017gl075707, 2018.