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Interactive comment on "Water Content of Greenland Ice Estimated from Ground Radar and Borehole Measurements" *by* Joel Brown et al.

Joel Brown et al.

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Response to: Interactive comment on "Water Content of Greenland Ice Estimated from Ground Radar and Borehole Measurements" by Joel Brown et al. J. MacGregor (Referee) joseph.a.macgregor@nasa.gov Received and published: 1 November 2016

Author responses are in italics.

Summary

This manuscript describes observations and analysis of the englacial water concentration of the western Greenland Ice Sheet from two types of ground-based radar surveys and well-established methods, with validation at boreholes whose results have been

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described in detail in previous studies. A key finding is that the water content they infer for the temperate layer is consistently higher than that assumed by models that account for such englacial water concentrations, such that this water may have a greater influence on the flow of the ice sheet than is commonly assumed.

Major comments

This manuscript is well structured, coherently argued, well supported and well written. The data and methods are well suited to the questions posed. I find little to fault in this regard and will not belabor those points. While the observational scope of the study is fairly narrow, the broader significance of the results is reasonably established. I do not consider any of comments major.

Minor comments

15-6. While accurate, this final sentence of the abstract ought to be expanded upon in a manner consistent with both the Discussion and Conclusions sections.

We have expanded on this in the Abstract.

2/13-14: These two sentences appear redundant in the otherwise excellent Introduction section.

We have removed the sentence "The layer's full spatial extent can never be measured and must be addressed by modelling."

3/5: Is the common-source point multi-offset survey also what's called a "walkaway" survey? If so, less of a mouthful.

We agree that "common-source point multi-offset survey" is a mouthful, yet it is also quite accurate. Indeed, "walkaway" survey or "single moveout" survey also describe the survey setup, but they are subject to misinterpretation. Since

(1) it is our goal to clearly distinguish this survey from a CMP survey, (2) the survey setup, although not novel, is not strictly common in glaciology, and (3) it is our intention to be as clear as possible, we choose to use the most accurate description of the survey setup. We have not replaced "common-source point multi-offset survey" with another term.

4/20-29: This paragraph regarding the pros and cons of this particularly survey design seems better suited to section 2.2.

We have moved the paragraph as suggested by the referee.

5/9-10: This sentence is surprisingly circumspect about the possibility that this reflection is due to the large englacial temperature gradient at this depth. Given the apparent coincidence between the cold–temperature transition and this reflection in Figure 3c (would be nice to also show the borehole sandwich in Figure 2), it is plausible, although the physical mechanism that generates this reflection is somewhat unclear (large increase in permittivity/conductivity/both?).

This sentence is purposefully circumspect. We agree that it is possible that the temperate gradient at this boundary could coincide with a large change in permittivity or conductivity. However, without direct evidence of a large permittivity or conductivity change across this boundary from other direct measurements or from a full multi-offset survey that spans the transect, we choose not to imply that this boundary is observable in our radar profiles. Thus, we stress that this reflection is only used as a starting guess for our two-layer ray-based inversion. Optimally, a full multi-offset profile would be a better method for interpreting the water content along the profile. Unfortunately, we could not conduct a full multi-offset profile due to logistical constraints on our field campaign.

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7/15-16: Not sure exactly what is meant by “grain-scale” water in cold ice. Grain-scale water bodies? Certainly liquid veins can be present even in cold ice, e.g., Dash et al. [2006, Reviews of Modern Physics, 78, doi:10.1103/RevModPhys.78.695]. This statement appears to be contradicted by later statements at the beginning of section 4.2.

We have clarified the term “grain-scale” water to include a reference to previous work (see next comment) which discusses microscopic water systems (water inclusions that exist at the intersection of individual ice crystals) which are known to be present in temperate ice but are not present in ice with temperatures below the pressure melting point of ice.

8/10: Gusmeroli et al. [2010, JGR, 115, doi:10.1029/2009JF001539] is also relevant here.

We have added the reference here. We have also added e.g. to the beginning of the list of references here to indicate that the list is not exhaustive.

8/20: Jacobel et al. [2014, Annals of Glaciology, 55(67), doi:10.3189/AoG67A004] used low-frequency common-offset ground-based radar to study basal crevasse morphology near the grounding zone of the Siple Coast, so this statement does not seem strictly correct to me.

The common offset radar used to detect basal crevassing in the Jacobel et al. study were collected in TM mode, meaning the radar were collected with the antennae laid out end-to-end. As they describe in their paper, the antennae beam pattern from TM mode can result in off-nadir reflections that are stronger than nadir reflections. In their study, Jacobel et al. inferred the presence of basal crevasses from these off-nadir reflections. Our common-offset data were collected in TE mode which typically results in the strongest reflections

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occurring from nadir or near nadir. We have not revised the sentence since our methods were not targeted to their detection.

8/21-22: This statement is key to the broader significance of the study and I recommend expanding on it if possible.

We agree that this is key to the broader significance of the study. We expand on this significance in Section 4.2 and again in the last sentence in the conclusion. We are unaware of studies that model the high strain rates implied by the high wetness values for the temperate layer shown in this study, as we state in the manuscript, there is typically a 1We have not expanded further upon this key point.

9/7 and 10/11-12: These statements indirectly include enhanced shearing of basal/temperate ice as part of a set of "sliding processes", which doesn't sound quite right (also at odds with 9/3-4). In my perhaps conventional view, it is simpler to consider sliding processes as those that cause absolute motion of ice at the bed itself, of which I would only include direct sliding over subglacial material or mechanical failure of the latter.

9/7 - We have changed "thus making the distinction between high straining of the temperate layer and other sliding processes ambiguous." To "thus making the distinction between motion due to high straining of the temperate layer and motion due to sliding processes ambiguous." 10/11-12 – We have removed the last line of the manuscript which the referee points out is practically tautological (below).

Section 4.3: This section would be strengthened if it considered the bulk permittivity of ice used by CReSIS for ice thickness determination (3.15). 10/12 would especially be

strengthened in this regard. The sentence about velocity assumptions in 10/11-12 is practically tautological.

We added the information as suggested by the reviewer. However, we would like to point out that the CReSIS provided depth scale for the data use a permittivity of 1 to convert from traveltime to depth. We assume that this is NOT what is used to determine depth of basal reflectors and that a bulk permittivity of 3.15 is used to determine ice thickness. We have removed the last line of the manuscript which the referee points out is practically tautological.

9/30: While the study has elucidated the englacial water concentration of the ice sheet in this region in greater detail, it's a stretch to consider the two-layer model "complex".

We removed the word 'complex' the sentence now reads: "Our integration of ground based-radar data with information collected in boreholes reveals a two-layer, thermo-hydrologic structure of varying thicknesses in the ablation zone of western Greenland."

10/7-8: This statement about the possible influence of an icefall should be moved earlier and shouldn't be first introduced in the Conclusions section.

We respectfully disagree with the reviewer on this point. The provenance of water-filled voids in this section is speculation and does not merit further comment or attention in the manuscript. We have not moved the location of the statement.

Table 2 is somewhat confusing and ought to be reorganized so that upper/lower layers are shown as sub-columns of S3 and S4.

We have reorganized the Table as the reviewer suggested.

Figure 2: Add Figure 3c's borehole sandwich to each panel.

The borehole data has a vertical axis of depth; the panels of Figure 2 have a vertical axis of traveltime. This was done on purpose to show the data before the depth conversion was made. The depth conversion in Figure 3c (as we state in the figure caption) were calculated from the final velocity model shown in Figure 3c. Using the final velocity model to convert the data from TWT to depth in Figure 2 is not appropriate as this data was used in the derivation of the velocity model. We did not add the requested data to the other panels of this figure.

Figure 4: 3-D is tough. I appreciate the effort but had of difficulty interpreting the different radargrams. Perhaps include a legend, a map and the view directions for each panel?

We have added a map view with the relative locations of the three radar transects to this figure.

SI/S3: This section is worth including in the main text.

We have moved this section to the main text as suggested by two reviewers.

Grammar, etc. 1/23: that is tens of metres

3/3 and throughout manuscript: use "ice thickness" instead of "ice depth" when referring to the distance between the ice surface and bed

6/9: This agrees with the 240 m. . .

7/30: constant: same in time; uniform: same in space

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9/9: Ryser

We have made all of the grammar changes suggested by the referee

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