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The Cryosphere Discussions

Interactive comment on "Spatial and temporal variability of snow accumulation for the South-Western Greenland Ice Sheet" *by* Achim Heilig et al.

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This paper investigates spatial variability in accumulation and density between regional scales and point measurements. Three locations in Southwestern Greenland are examined, two in the percolation zone and one at the equilibrium line, and gather observations including density measurements and ground penetrating radar transects. The manuscript attempts to answer four questions: error of internal horizon tracking data from GPR, how well a single point measurement of accumulation represents the larger area, analyzing the inter-annual variability of accumulation over several seasons, is melt and percolation affecting accumulation pattern? The resulting findings are that

there is a 7-8% error on IRH tracking mainly due to density uncertainties which is less than that of other methods like deriving accumulation from airborne radar as well as that point observations at all three sites do represent the average annual accumulation well over larger areas. Additionally, there is some inter-annual consistency for the DYE-2 site, though it was only sampled two years continuously and other sites are inconclusive. The final result is that currently melt is not effecting accumulation patterns.

This is clearly an important study which adds quite a bit of knowledge to our community about the spatial variability accumulation and density in Southwest Greenland. The results that point measurements represent larger areas is very impactful. Overall, the science is sound and credible.

However, my main point of concern is that the manuscript is extremely technical and difficult to follow at some points with concepts that require prior knowledge. It may discourage readers who are not fully comfortable with more in depth details of radar and some of the geostatistical methods. Clarification on several topics, detailed below, is needed for this to become a more readable paper.

Specific Comments: 1) The title is broad and a bit misleading. Three sites are examined in Southwest Greenland, however they are not representative of that entire area (as you state you can look at km wide results from this study). Along with this, the temporal aspect is questionable since there were only two consecutive years compared at Dye-2. The title should be narrowed to better represent what is being shown in the paper – i.e. "Relating regional and point measurements of accumulation in Southwest Greenland"

2) Major Questions (L70-78) – The manuscript attempts to answer quite a few questions (4 stated in the end of the introduction). Question (ii) is your main gap for this study, we do not know how representative point measurements are on a spatial scale and this could be the main focus of the opening since the majority of the paper is about it. In the process, you determine internal reflection horizon error of radar measure-

ments because that is necessary to see how accurate your measurements are, so (i) can be removed. Question 3 is important, though you only have two years of consecutive data at Dye-2 to work with, is this really a main research question of the manuscript or can it just be addressed in the text? Question 4 is unclear, and a sentence follows to attempt to clarify it, however, it should be able to stand on it's own. Are you trying to ask if meltwater percolation effects IRH layers?

3) Depending on the background of the reader, there is a lot of jargon in this article especially in the methods section. The manuscript should be generally self-contained and the reader should not have to dig too deep outside in other literature for concepts that are discussed. Specific topics in the paper that could use more clarification are the radar processing (L99-102), vertical sampling (section 2.2), and variograms/kriging (Section 2.3, Table 3). Even if just a few sentences are added as background that would be helpful, see more specific comments below. Additionally, accumulation and SWE are used interchangeably in the text and figures in the manuscript. Be consistent with your terminology and use one or the other after you define what it is. Using both may confuse the reader if they are not familiar with this area.

In-Line Suggested Changes:

L 11-13 Re-arrange sentence for clarity. "Randomly selected snowpits are . . . occurring with a probability of p = . . ."

L23-24 Can you move the citations to the end of the sentence? The placement interrupts the flow.

L27 Include Enderlin et al, 2014 reference (An improved mass budget for the Greenland ice sheet, https://doi.org/10.1002/2013GL059010) along with van den Broeke.

L28 "(with positive and negative sign)" – what are you referring to here? Needs to be clarified.

L29 "negative trends in SMBs", SMB should not be plural.

L29 "Most of the GrIS, accumulation is dominating factor.. negative trends related to surface melt and runoff" where are these positive and negative trends occurring? Clarify.

L30 Remove "Despite their importance for the GrIS mass balance"

L32 Snowfall can be measured by remote sensing through satellites (i.e. CloudSAT). I.e. Bennartz et al, 2019 (https://doi.org/10.5194/acp-19-8101-2019), etc.

L33 "in concert" use another phrase here, take out "dedicated".

L47 Remove "worked to" and change "link" to "linked".

L52 "Other recent studies at" to "Other recent studies on"

L56-58 "Still, quantification.." This is repeating the same point as earlier in the paragraph (L47) Probably only need to state this once even though it is an important point.

L61-69 This paragraph is a bit disjointed. It begins with surface melt affecting SMB to annual accumulation estimates and observations to validating RCMs to melt impacting firn layers and then stating that there is a gap in how melt impacts temporal changes in accumulation distribution. Needs better flow.

L72 Remove "of altitude".

L70-78 See comments in Major Questions.

L76 Clarify Question (iv) if it is kept here. It should be clear enough on its on that there should not be a "In other words" after.

L89, L83, L94 Remove coordinates and elevations from text and include this in table 1. It is very distracting.

L99-102 Can this small section on radar units be combined with the paragraph above? Or can it be taken out and part of the table with a radar unit column?

L104 Include a sentence or small clause about what and why dewow and bandpass

filters for those who are not spun up about radar terminology.

(L116?) Equation 2 - Define beta.

L127 – Could you include the depth of the bulk density that you took from the snow pits?

L129 – Why do you include NASA-SE and EKT? They do provide you with two more range values but they are not relevant for SW Greenland. These sites are not brought up again later for any other analysis so could they be removed?

L133 – "For all three sites", similar to comment above, you are talking about five sites in this section but now only reference three in SW Greenland.

L138 – Is vertical sampling related to the frequency of the radar? If so, state this. Also, what is an example of small scale surface roughness? Are these not wind features?

L149 – Change "picked consistently" to "consistently picked"

L172 – Need an explanation of variograms prior to using it consistently throughout the next section.

L174 – Add a comma after "First"

L175 – Clarify "there are no gaps in accumulation in between", are there no gaps in the radar transmission of the accumulation?

L186 – "Despite the trend removal, anisotropy of the covariance. . .", unclear on what this means?

L187-193 – Using variograms consistently now, the term or concept needs to be explained prior for readers unfamiliar.

L197-198 – Define bs and bn in the sentence before the equation. They are stated but adding in the variables adds another layer of clarification.

L198 – "In the following" – what is this referring to? The following figure(s)?

L199 – Re-arrange this sentence. "Using the recorded radar traces, it is determined whether any randomly located. . ."

L208 – Back to the "Major Questions" point brought up above, the step to assess errors associated with TWT is necessary for your main question (ii) of the paper. This is stated as the first sentence. Is it necessary for this to be a major question in the opening since this is already a part of answering your other question? Clearly, this is a major result and should be discussed (as it is in the paper) but it is not necessarily the focus as the other question(s) are.

L210 – Is "accumulation pattern persistence" the same thing as inter-annual variability? The analysis is how accumulation is changing over space and time.

L211 – The wording of "whether seasonal changes in accumulation due to melt and liquid water percolation have major effects on accumulation pattern" is confusing. How would there be seasonal changes in accumulation due to melt? What is meant by accumulation pattern? How accumulation would change spatially due to melt? Is the question about how meltwater influences thickness of the layer? Please clarify this.

L222-223 – how deep were these snow pits?

L221 – Is it five locations in SW Greenland? The NASA-SE site is in SE Greenland, though the EKT site could be considered to be in SW Greenland.

L247 – Is "8-10m" the scale of the wind generated surface features causing minimums?

L252 – Earlier the "SWE" is referenced as "scaled accumulation", bs.N. (Section 2.3) Can you reference back to this for clarity as the variable?

L293-295 – "which represents not averaging snow depth around the snow pit". This is unclear, why would the area around the snow pit be averaged in?'

L324 – "However. . ." does this refer to KAN-U? Can you combine this with the previous sentence for clarity?

Section 3.3 – Frankly, could take out the KAN-U comparison with such a small area overlapped and not having consecutive years of data, there is no real major conclusions to be drawn here and it is not brought up again in the paper.

L349 – example here to explain the figure is great for clarity.

L363 – Will using a firn core instead of a density pit induce any further uncertainty?

L368 – Can you use a Delta symbol?

L370 – Artifacts in the sense that the GPR data from the winter accumulation was greater than the net accumulation?

L375 – If the ice movement is known from the upGPR site, can it be corrected for?

Section 4 – Conclusions – This very nicely ties up the study concisely and answers the questions put forth in the opening. If some questions are taken out, needs to be revised.

Figures and Tables Comments:

For all figures: make sure if it is a multi-paneled plot, that the (a)/(b)/(c) are either inside or outside of the figures consistently. i.e. figure 4 a is outside the box and b is inside the box.

Table 1 – Move KAN-U April 2017 before Dye-2 May 2017 if table is supposed to be chronological. Include coordinates of sites and elevations in table. Possibly include radar units in table as well?

Figure 1 – Is OK how it is currently, but a little unclear - could take off elevation markings and put a color bar labeling elevations to see if it made the graphic a little less cluttered. Difficult to see the 500m marking near the coast. Not sure if the 1000, 1500m elevations are labelled at all?

Table 2 – See comments from above, take out NASA-SE and EKT if they are not

relevant for the rest of the study. Possible include depth of the pit? For the density ranges, could you use something other than "-" in the range column? It could confuse the reader if they did not scan the text for what the range meant.

Figure 3 – Recommend using colors other than red and green stacked on one another for colorblind purposes. Could use a dashed line or a thicker line of another color.

Figure 4 – Similar comment to above, try a different color than red and green since the lines are close to one another. Could use transparency to see the standard normal distribution behind.

Figure 4/ Figure 5 – Can these be combined into a 3 panel plot since you're talking about the same area?

Table 3 – Never described what the major and minor axis are in the text for variograms. Does the mean prediction error need to be in the table if they are all 0 (expect the first value of 0.01)?

Figure 9 – Need colo rbar for the contour on 9a, difficult to see two locations of upGPR.

Figure 4,6,7,9 – A personal preference is to have coordinates in lat/lon instead of UTM. If the scales do not allow though, especially for an area like Swiss camp, that is fine because it is on a few km scale.

Other comments:

The word "very" is used quite a bit throughout the manuscript as a qualifier and those instances can be removed the majority of the time. Using it does not add to the meaning of the sentences.

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