Response to RC1: Spatial characterization of near-surface structure and meltwater runoff conditions across Devon Ice Cap from dual-frequency radar reflectivity

Dear Anonymous Reviewer,

We thank you very much for your review of the manuscript. The comments/suggestions (italicized below) were very helpful and constructive for improving this work. We've addressed each point below with our responses and proposed revisions provided as bulleted text.

Sincerely,
Kristian Chan, on behalf of the co-authors

<u>*General Comments*</u>

Chan et al. investigate the surface coherent return power of reflected radar waves by applying the Radar Statistical Reconnaissance method to multiple ice penetrating radar datasets with different center frequencies over Devon Ice Cap (Canada). The data is used to better characterize the composition of the firn pack (and if the firn pack contains ice layers) of the upper meters over the ice cap, which is important to better understand melting and refreezing processes as well as meltwater infiltration and runoff. The measured reflectivities are compared with modeled reflectivities using a reflectivity model informed by existing information on the firn pack (from ground-based ice penetrating radar data and firn cores). Their results suggest meter-thick ice slabs in certain parts of the ice cap, which permits surface water runoff away from the ice cap.

Overall I find the study by Chan et al. to be informative and very well written. They applied a smart approach to characterize the firnpack with existing multiple airborne radar data sets and other auxiliary data sets (such as firn cores and land-based radar data). Although the methodology is not fundamentally new and many aspects have been already analyzed and built upon previous studies (such as in Rutishauser et al., 2016), I believe that this article deserves to be published in The Cryosphere.

The basis for my decision is that, in my opinion, this is a robust study that is well structured, clearly written, and represents a significant step forward in knowledge on which future studies can build on and which is very useful for the cryosphere community. What I particularly liked is that the authors use existing data sets and put the data into a new context with their method to find out more about the first meters of firn of the Devon Ice Cap. Below I have some comments and questions that I think might help to add clarity and make the article better readable and easier to follow.

<u>*Main Remarks*</u>

Introduction:

The introduction could benefit from a small introduction on the Devon ice cap and why it is a *particularly good place to characterize the firn column. Either in a new paragraph (which I would prefer) or incorporated in one of the existing paragraphs.*

- Thank you for the suggestion. We will add some introductory text on Devon Ice Cap and how percolation/refreezing has made it a good place for characterizing firn heterogeneity.

Figure 1:

(1) It would be a nice addition to have an overview map of the Canadian arctic or Canadian-Greenlandic arctic pointing out the location of the survey area. This would give the reader a much better impression of where the Devon ice cap is located.

- We will add an overview map that indicates the location of the Devon Ice Cap.

(2) I also would suggest finding a better solution with the contour lines and their elevation labels. They appear very chaotic at the ice caps margins, which is rather confusing than helpful information. The same applies to all other figures (also in the supplement; S4) in which the contour lines are shown. Maybe only displaying contour lines only above 600 m would make the plot less overloaded.

- Thank you for the suggestion. We will clean up the contour lines at the ice cap margins by including contour lines above 600 m elevation (or a similar solution).

(3) It would also be good to state what kind of satellite image you are using as a background image.

- This was a Landsat image. We will include this information in the caption as well.

Table 1:

Please explain the symbols in the table caption (e.g., that range resolution is z_0, etc.)

In addition, but very minor: a hline between the two systems would be nice to immediately see which z0 belongs to which system.

- We will redefine the symbols in the caption and add the hline in the table.

Figure 2:

What about the following idea: To give the reader a better understanding of the different depth resolution of the radar systems and which parts of the firn column are affected, one idea would be to somehow draw or indicate the depths that HiCARS & MARFA and MCoRDS3 resolve in Figure 2b.

- Thank you for this suggestion. Resolution depths for HiCARS were initially included but removed from the plot, because they relied on assumptions made about the firn column, such as firn permittivity/density and layer thickness. This was a motivation for including Table 1 in the main text. However, we agree that having this drawn on the figure could be very useful for visualizing the resolution depth. One option would be to add a resolution depth and indicate somewhere, either in the caption or main text, the assumptions used to calculate that depth. We can include this and/or explore options for how to best communicate the depth resolutions of each radar system while trying to make the overall figure as clear as possible to the reader.

Figure 3:

(1) I think the figure could be better arranged if, for example, (a) and (b) were in a row and (c) below. Then the subfigures would be bigger and the whole figure would take probably less space in the document at the same time. The same could be done with Figure 4.

- Agreed, we will rearrange the subplots in Figures 3 and 4 as suggested.

(2) Shouldn't the label of the colorbar be "dB" instead of "db"?

- Yes, we will make this correction.

(3) I would suggest a different color scale, preferably linear rather than divergent. This is because in the HiCARS display, for example, the transition from -10 to -15 dB is shown as a weak color change, while from -20 to -25 dB there is a strong color change (yellow to blue). Therefore, I would suggest a linear graded color scale to better interpret the changes in dB based on a color scale across the different data sets.

- We chose the current color scale, because it is a colorblind-friendly option and broadly captures the changes of Pc across all the surveys and their relation to the zone boundaries. However, we will try to use a linear scale if it can better represent these data while maintaining consistency across the surveys.

Figure 4:

Caption: define again that interquartile ranges is IQR and P_c surface coherent power (as in Fig. 3).

- We will redefine these in the caption.

Discussion:

I have a question regarding the ice slab thicknesses in Zone II. In Line 336 you state that the HiCARS/MARFA system captures the entire thickness of the ice slabs. Maybe I have missed it, but why is that the case and how do you know that the ice slabs along these radar profiles are not thicker than the range resolution of the system?

My next question is very similar and refers to the average ice slab thicknesses. You calculated a *mean ice slab thickness based on the range resolution of the two different radar (groups). Wouldn't it be rather a minimum average ice slab thickness? Because since you are only analyzing the surface return within the limits of the range resolution of the radar system, you cannot estimate if the ice slab continues with depth and is thicker, right?*

For me it seems that based on the surface GPR data it is assumed that the ice slabs in this region are not thicker as what is for example shown in Figure 2b. However, it might nevertheless be possible that thicker ice slabs might be present along the airborne radar profiles where no surface radar data exists. I think this should be clarified and also mentioned in the uncertainty section.

- Thank you for the comments and suggestions. On Devon Ice Cap, the Zone II/III boundary represents the transition from a region with firn to one without firn, which is also validated by the Landsat imagery (Fig. 5). This spatial boundary also represents where the maximum ice slab thickness is obtained over Devon Ice Cap, because ice slabs grow in thickness from higher to lower elevations (e.g., MacFerrin et al., 2019) but shouldn't exist beyond the Zone II/III boundary due to the lack of firn. In other words, the Zone II/III boundary constrains the maximum ice slab thickness on Devon Ice Cap. In addition, we believe that our derived ice slab thickness represents an average range of values for Devon Ice Cap. If ice slabs are thicker than the range resolution of HiCARS/MARFA in Zone II, we would expect a change in the pattern of Pc, particularly near the Zone II/III boundary. However, it remains fairly consistent throughout and thus also consistent with the interpretation that HiCARS/MARFA observes a 4-layer medium in Zone II. However, we do acknowledge in other regions, particularly in Greenland, ice slabs can certainly be thicker than the range resolution of both radar systems. In that case, the average ice slab thickness derived via this method could represent a minimum average, depending on the location of the firn line and how Pc behaves near this boundary. We will add some text to discuss the uncertainties/limitations of the approach, as suggested.

  MacFerrin, M., Machguth, H., As, D. V., Charalampidis, C., Stevens, C. M., Heilig, A., ... & Abdalati, W. (2019). Rapid expansion of Greenland's low-permeability ice slabs. *Nature*, *573*(7774), 403-407.

Figure 5:

Here now appears a reference to the background satellite image, but the coordinates are missing. Again, I would prefer to get rid of the contour lines and labels below a certain depth.

- We will include coordinates and clean up the contour lines as previously mentioned.

Supplement

Figure S4: Please mention once more in the caption that P_c is coherent specular and P_n incoherent/scattered. I'm sure many readers don't, but I often have the problem that I forget the *abbreviations in the text while reading and then have to look for them again in the text when they appear in a figure.*

- Agreed, especially since this is a supplemental figure. We will define Pc and Pn in the caption.

<u>*Line-item Comments*</u>

L 84-86: I think that Operation Ice Bridge should be mentioned here as well in addition to the University of Kansas. Moreover, I would suggest using the acronym MCoRDS3 instead of just MCoRDS throughout the document.

- We will mention Operation Ice Bridge here and change MCoRDS to MCoRDS3 throughout the manuscript.

L 99-101: With respect to the factors affecting permittivity, I think that temperature and the anisotropy due to the orientation of the ice crystal fabric should also be mentioned (although COF may not be so important in the firn column). In that sense you could additionally cite for example Fujita et al. (2000):

"Fujita, S.,T. Matsuoka,T. Ishida,K. Matsuoka, and S. Mae (2000), A summary of the complex dielectric permittivity of ice in the megahertz range and its applications for radar sounding of polar ice sheets, in Physics of Ice Core Records, edited by T. Hondoh, pp. 185–212, Hokkaido Univ. Press, Hokkaido, Japan. "

- Agreed, we will include temperature and ice crystal fabric as factors affecting permittivity, citing Fujita et al., 2000.

L 128 (and L177-178): You mention that "[...] surface roughness is not the main contributor to surface scattering over DIC (Rutishauser et al., 2016).". It would be interesting to mention in one sentence why this is not the case. Especially because this assumption is important for the interpretation of the results.

- Thank you for this comment. We agree that this is an important assumption for interpreting the results. Rutishauser et al., 2016 showed that the incoherent power is mainly governed by volume scattering from the ice layers as opposed to surface roughness.

  Looking at Figure 3 of Rutishauser et al., 2016, the majority of the laser-derived roughness values are concentrated at σ_h = 0.05 m. Propagating this value into Eq. 2 of this manuscript, specifically the exponential part of the equation representing the effects of surface roughness, we find that this contributes 0.07 dB to the coherent power (Pc). On the other hand, the effects of r^2 vary on the order of tens of dB (Figures 3 and S5). Moreover, the σ_h values from laser altimetry in Rutishauser et al., 2016 were derived using a baseline of 171.5 m. We expect the surface roughness at the wavelength-scale of interest (λ = 5 m) to be much smaller, because the surface roughness scales with the baseline length scale of interest (Shepard et al., 2001). Thus, the 0.07 dB surface roughness contribution to Pc already represents a highly conservative value. We can incorporate this calculation into the manuscript as well.

L 137-139: Here you state that: "Previous applications of the RSR method have empirically shown that an aircraft roll of 2 to 3° allows for a stable coherent radar return." Is there a reference for this?

- There is no reference for this at the moment. However, we will include this analysis and make it available, either here or elsewhere with a reference.

L 141: The airborne radar data in your study is also "ground-penetrating". From what I understood you refer to land-based or surface radar in this section. Therefore I would suggest making clear that all radar surveys are ground penetrating and some are airborne and this one is land-based/surface radar data.

- Thank you for pointing this out. We will clarify the terminology here to distinguish between land-based/surface radar and airborne ice-penetrating radar.

L 248-252: I am not sure if I missed it, but is the difference between the old and refined Zones shown somewhere? If not, I think it should be (maybe in the Supplement). I guess the old Zones are those displayed in Rutishauser et al. (2016) in Figures 1a and 2?

- That is correct. The old zone boundaries are those in Figure 2 of Rutishauser et al., 2016 but currently not shown in this work. We will include the old and new zone boundaries in the Supplement section.

L 252-254: Here you refer to the Discussion Section but I think it would be also good to refer to Figure 5.

- We will update this to point to Figure 5.