Comment on tc-2022-193
Response to Referee #2

Referee comment on “Mapping snow depth over lake ice in Canada’s sub-arctic using ground-penetrating radar” by Alicia Pouw et al., Cryosphere Discussion, https://doi.org/10.5194/tc-2022-193, 2022

The manuscript "Mapping snow depth over lake ice in Canada's sub-arctic using ground-penetrating radar" presents a study that takes a commonly used method (GPR) and applies it to snow on lake ice. The study is able to cover great distances with high spatial resolution of observations and compare GPR depth estimates to manual depth measurements with a Magnaprobe. The GPR method resulted in an estimated RMSE of 1.58 cm with a mean bias of -0.01 cm during the early season, and RMSE of 2.86 cm and bias of 0.41 cm later in the season.

Overall, the authors produce a very nice dataset that can be used for modeling efforts and potentially remote sensing validation. However, I do not see anything that justifies this study to be at the level of a "Research Article" in The Cryosphere. Again, this is a great dataset but a more robust analysis of data would need to be presented to be a research article, in my opinion. As it is I think it a great "data paper" or potentially a "technical note" type of manuscript. Unfortunately, The Cryosphere does not publish these types of papers so I recommend either submitting to another journal pretty much as is, or providing further quantitative analysis to bump it up to being a full research article. The variograms are a great start, but I think more information on the spatial variability of the snow on lake ice could be good to include. This could include for example: directional variograms to investigate isotropy, variability or depth as a function of distance to shore or distance to islands, does topography of the shore or presence of trees impact anything. I think that the authors started to go down this route with Figure 9 but it needs to continue for more statistical quantifications, in my opinion.

One reason further analysis would be necessary is because the authors did not develop any new tools advance any of the methods to collect the data. Further minor comments are listed below by line number.

We are thankful to the reviewer, and we appreciate their suggestions and valuable comments. Below, we provide the answers to the comments and questions raised by the reviewer. For convenience, comments from this Reviewer are provided in black text. Responses to each comment are provided in blue text.

General:

We do appreciate the reviewer’s comments and suggestions. However, we do not fully agree with the comment related to the lack of introducing a new tool to advance any of the methods to collect the snow depth data on lake ice. This research article presents an automated approach to derive spatial shallow snow depth observations over lake ice using GPR, which, from our knowledge, has not previously been done and constantly reported that GPR is not able to retrieve lake snow depth and distribution. This research article provides a new inside of how GPR can retrieve even shallow snow depth on lake ice using a fully automated approach. Although GPR is commonly utilized for snow on land, this does not highlight the ability to discern shallow snow depths more specifically over lakes with lack of ice elevation. It has also been used on lake ice to derive the thickness of the ice, however the snow has always been ignored or cleared before the measurements. In addition, the shallower snow depths are difficult to derive due to the direct wave conflicting with the snow-ice interface, however, we present a method that the GPR is capable of decerning that. Additionally, the GPR acquisitions are fully post-processed in MATLAB and does not require use of any additional software. This includes the signal processing and the TWT picking algorithm. This decreases the required time for post-processing radargrams and using manual or semi-automatic picking algorithms that have been commonly used for GPR data in the past.

Current methods available for observing snow depth over lake ice, as outlined in the manuscript, include a ruler and notebook with a GPS – which requires a lot of unnecessary time recording each observation individually, or an automated snow depth probe, which while great for validation, is not the most appropriate option for covering the lake spatially in a timely manner. The method presented within this manuscript is successful in producing 1) a fully automated post-processing workflow for all data processing/ analysis steps, 2) is successful with shallow lake snow and 3) can collect large spatial data sets in a limited time.

Here, we modified the revised version of the manuscript as suggested, including the difference in snow depth and density maps from early season to late winter season, as well as the discussion on variability/depth as a function of distance to shore. We have added an additional figure (Figure 11) to explore the snow depth and density changes from early winter season and late winter season on Landing Lake. Additionally, we have added the following text to the results (Section 4.4: Early versus late winter season):

Lines 301-309: "In comparing the difference in snow depth and snow density over the winter season, Figure 11 shows IDW 1-m snow depth maps and snow density maps (created using the in situ observations). The snow density from early season to late winter season increased between 10 to 80 kg/m^3, while the snow depth increased in areas by 18 to 28 cm. There were no surveyed areas on the lake that experienced a decrease in snow density or depth based on the two field sampling dates. Areas with a shallower snowpack in December 2021 saw the largest increase in snow depth by March 2022 ($R^2 = 0.57$), which agrees with the decrease in snow depth variability noted in Figure 9. Additionally, the largest increase in density from early to late winter season occurred closest to the shoreline. More densification occurred on areas that were less dense than areas that had a higher density in December 2021 by March 2022 ($R^2 = 0.59$). In exploring the change in snowpack over the winter season, we found no spatial relationship between changes in the depth and density across the area surveyed on Landing Lake."

Following text is added on to the discussion of variability/depth as a function of distance to shore in the manuscript (Section 4.3 Snow depth mapping)

Lines 270-278: "The interpolated GPR-snow depths consistently show an increase in snow depth variability closer to the lake perimeter compared to areas farther from the shoreline and closer to the center of the lake. The snow depth on Finger Lake showed a decrease of ~2 cm per meter as the distance from the perimeter increased, however, this was not observed on the additional lakes. Transect profiles (Figure 8) created over the 1 m resolution snow depth maps show an example of the variability in snow depth across each lake. The spatial correlations of the 1 m resolution snow depths from the GPR transects were estimated using an experimental semi-variogram that was fit using an exponential model (Figure 9). The largest correlation length was observed on Vee Lake (11.25 m) in December 2021, and Landing-M Lake (18.18 m) overall. The correlation length on Landing-D Lake in the early season was measured at ~10 m less than that of the late winter season, while Long Lake showed the smallest distance, at 6.42m over the largest spatial area."

Following text is added on discussion (Section 5: Discussion):

Lines 361-369: "The snow distribution over lake ice is known to be affected by wind and surrounding vegetation (Adams, 1976a). In this study we found weak relationships between the lake snow depth and distance to shoreline perimeter. On Finger Lake where we have more complete coverage of the lake, we found the snow depth to decline ~2 cm per meter from the shoreline to the centre of the lake but found no change on the additional three lakes. We believe this could be due to the lack of data representativeness around the shoreline and the difficulty associated with maneuvering the snowmobile in the deep, lighter snow at slow speeds, or the turbulent winds affecting which shoreline the snow will be distributed along. Winds reported at the Yellowknife weather station reached speeds above the ~14 to 39 km/h threshold required to transport snow (Li and Pomeroy, 1997), however, with the majority of strong winds coming from the northeast and northwest, our lack of data on the southern perimeter on each lake may also affect our findings."

Specific comments:

- 15: 9 cm spatial resolution is the spacing between traces, but after you aggregate the data it is a 1 m raster correct? This is the resolution of the data that should be reported and also incorporates the footprint of observations.

  We thank the reviewer for this comment. We agree with the comment and modified the text in the revised manuscript as follows:

  Lines 143-148: "The average footprint of each collected trace on all four lakes in December was 19 cm, and 30 cm in March on Landing Lake based on the diameter of the first Fresnel zone (Fediuk et al., 2022). In considering the ~9 cm trace spacing to the footprint of each trace, the data results in over 50% overlap. The vertical imaging resolution was estimated at 6.5 cm on average across all four lakes based on the one-quarter wavelength Rayleigh criteria using the 1000 MHz sensor (Kallweit and Wood, 1982), which has a vertical sampling interval of 0.1 ns."

- 115: "was" should be "were"

  This change has been made. Thank you!

- 158: How was the Wong et al. algorithm applied? Matlab? Python? Please specify.

  Thank you, we have added the following text:

Line 181: "All post-processing of the radargrams was conducted in MATLAB."

- 184-190: How much variability occurred over the 6 m. It seems to me that by choosing only values that closely match one would underestimate the magnitude of the error/bias. As it is written, I do not see a justification for this current method and think the authors should use all values within the 6 m range to calculate the comparison metrics.

  Thank you for this comment. The reason we don't use the entirety of the data within the 6 m is because of the variability across the lakes for short distances. For example, the correlation length for long lake shows that the lake variability is on the same scale as the 6 m radius, which agrees with previously published articles on lake snow (Gunn et al., 2021; Sturm and Liston, 2003). In discussing the variability within the 6 m, one standard deviation of the derived snow depths within a 6 m distance is between 2.1 cm to 3.8 cm (Finger = 3.4 cm, Long = 3.8 cm, Vee = 3.2 cm, Landing-D = 3.1 cm, and Landing-M = 2.1 cm).

- 200: what is meant by "closed-off areas"

  Thank you for the comment. The closed-off areas were referring to areas surrounded closely by the perimeter with but not as wide open as the centre of the lake. We have reworded to read as follows:

  Lines 234-235: "The entirety of Finger Lake (area = 0.04 km^2) was traversed on December 9th, where the deepest snow depths were observed along shorelines (max = 24.83 cm), compared to the open stretch of the lake (min = 6.53 cm)."

- 236: Given such low density values, I am not sure that teh Kovacs equation is appropriate. Kovacs was developed for much denser firn. Di Paolo et al. (2018) and Webb et al. (2021) could be good references for a more appropriate equation.

  Thank you for this comment. Within our analysis we use Kovacs et al. (1995) equation to derive the permittivity as we found minimal variability in deriving the relative permittivity using different equations for shallower lake snow. Additionally, Di Paolo et al. (2018) shows in Figure 1 that in comparing 17 different empirical formulas to calculate permittivity, there is not as much variability for lower densities than there is for higher density snowpacks (i.e., 300kg/m^3 to 550 kg/m^3). In addition, with testing different empirical relationships to calculate the permittivity (i.e., Di Paolo et al., 2018; Webb et al., 2021; Stein et al., 1997; Tiuri et al., 1984), there is very slight differences in the dielectric constant, if any at all. Which when further used to derive the snow depth, the largest difference in accuracy from comparing the GPR-derived snow depth to the in situ was found with Webb et al. (2021) with an R^2 =0.61, MAE = 1.08 cm, RMSE = 1.61 cm, Bias = 0.47 cm on average for the four lakes. Within the study we report an R^2 =0.63, MAE = 1.05 cm, RMSE = 1.58 cm, Bias = 0.01 cm using the Kovacs et al. (1995) equation, showing millimetre differences. These results from the Kovacs et al. (1995) method is however identical to using the Tiuri et al. (1984), Robin et al. (1969), Robin (1975), Frolov & Macheeret (1999), and very similar to Stein (1997) equation (R^2 =0.62, MAE = 1.06 cm, RMSE = 1.58 cm, Bias = 0.08 cm). To bring more attention to our decision we have added the following text to the revised manuscript in the methodology (Section 3.3.4):

Lines 201-206: "To determine the wave speed of the radar signal traveling through the snow, the relative permittivity was calculated. There are several empirical equations available for deriving the relative permittivity from snow density. Previous work (i.e., Di Paolo et al., 2018; Webb et al., 2021) found there is significant variability between these equations for larger snow densities, however, based on the snow densities presented within this study, there is minimal variability between equations. Therefore, the Kovacs et al. (1995) equation is used to calculate the relative permittivity."

Lines 393-407: "Lake snow is not well characterized in the various dielectric permittivity models used for wave speed estimation. In this study we found the snow depth retrieval is weakly dependent on the choice of empirical equation used to derive the snow depth from density. Within our analysis we used the Kovacs et al. (1995) equation to derive the permittivity. In addition, we also tested different empirical relationships to calculate the permittivity (i.e., Robin et al., 1969; Robin, 1975; Tiuri et al., 1984; Stein et al., 1997; Frolov and Macheret, 1999, Webb et al., 2021) and found very slight differences in the dielectric constant, if any at all. The results ($\overline{\varepsilon_r}$ = 1.37) from the Kovacs et al. (1995) method are identical to using the Robin et al. (1969), Robin (1975), Tiuri et al. (1984), Frolov and Macheret (1999), and very similar to Stein et al. (1997) equation ($\overline{\varepsilon_r}$ = 1.34), with the largest difference using the Webb et al. (2021) equation ($\overline{\varepsilon_r}$ = 1.29). In exploring the permittivity for the snow densities presented within this study (175 kg/m^3 to 245 kg/m^3), the numerous empirical relationships result in very similar permittivity's for these lower densities and sub-millimetre differences in the snow depth accuracy statistics (not shown). Di Paolo et al. (2018) shows in comparing 19 different empirical formulas to calculate permittivity, there is less variability for lower densities than there is for higher density snowpacks (i.e., 300 kg/m^3 to 550 kg/m^3). Di Polo et al. find that Robin Lake snow has generally been reported to be shallower and less dense than snow types used to parameterize these models. However, based on the agreement among models and the limited representation for a model based on lake snow observations we have sided with the Kovacs et al. (1995) equation."

references:

Di Paolo, F.; Cosciotti, B.; Lauro, S.E.; Mattei, E.; Pettinelli, E. Dry snow permittivity evaluation from density: A critical review. In Proceedings of the 2018 17th International Conference on Ground Penetrating Radar (GPR), Rapperswil, Switzerland, 18–21 June 2018; pp. 1–5

Webb, R.W.; Marziliano, A.; McGrath, D.; Bonnell, R.; Meehan, T.G.; Vuyovich, C.; Marshall, H.-P. In Situ Determination of Dry and Wet Snow Permittivity: Improving Equations for Low Frequency Radar Applications. Remote Sens. 2021, 13, 4617. https://doi.org/10.3390/rs13224617

These comments are meant to be constructive. I think this is an excellent dataset and good work.