Comment on tc-2022-193
Response to Referee #1 Round 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

This MS has been revised according to the last round of review comments, and I have no further general comments. However, before considering publication, some details of expression need to be further improved. The following are my comments:

We are thankful to the reviewer for taking the time to review our revisions and provide additional valuable comments for improving the manuscript. Below, we provide the answers to the comments and questions raised by the reviewer with line numbers corresponding to the newly revised manuscript version. For convenience, comments from the reviewer are provided in black text. Responses to each comment are provided in blue text.

1) Abstract: Some main results derived from the observation data, such as the spatial distribution characteristics of snow cover, the relationship between snow cover on lake ice and snow cover on land, should be emphasized in the Abstract. At present, the main conclusions are mainly from the methodology.

Done - The abstract is modified.

Lines 9-29: Ice thickness across lake ice is influenced mainly by the presence of snow and its distribution, which affects the rate of lake ice growth. The distribution of snow depth over lake ice varies due to wind redistribution and snowpack metamorphism, which affect the variability of lake ice thickness. Measuring accurate and consistent snow depth data on lake ice is challenging and sparse to obtain. However, high spatial resolution lake snow depth observations are necessary for the next generation of thermodynamic lake ice models to improve the understanding of how the varying distribution of snow depth influences lake ice formation and growth. This study was conducted using ground-penetrating radar (GPR) acquisitions with ~9 cm sampling resolution along transects totaling ~44 km to map snow depth over four freshwater lakes in Canada's sub-arctic. The lake snow depth derived from GPR TWT resulted in an average relative error of under 10% when compared to in situ observations for the early and late winter season. The accuracy was assessed using 2,430 in situ snow depth observations. The snow depth derived from GPR TWTs for the early winter season was estimated with a root mean square error (RMSE) of 1.6 cm and a mean bias error of 0.01 cm, while the accuracy for the late winter season on a deeper snowpack was estimated with a RMSE of 2.9 cm and a mean bias error of 0.4 cm. The GPR-derived snow depths were interpolated to create 1 m spatial resolution snow depth maps. The findings showed improved lake snow depth retrieval accuracy and introduced a fast and efficient method to obtain high spatial resolution snow depth information. The results suggest that GPR acquisitions can be used to derive lake snow depth, providing a viable alternative to manual snow depth monitoring methods. The findings can lead to an improved understanding of snow and lake ice interactions, which is essential for northern communities' safety and wellbeing and the scientific modelling community.

2) Unit 10 (reference the revised MS with tracked change): "creating variability in the lake ice thickness"-- Snow depth and ice thickness are only physically dependent, but they cannot be

said to be created.

Thank you for this comment. We agree and have reworded to read as:

Lines 10-11: The distribution of snow depth over lake ice varies and due to wind redistribution and snowpack metamorphism, which affect the variability of lake ice thickness.

3) “a root mean square error (RMSE) of 1.58 cm”, as well as the error of snow thickness in the full text, it is enough to retain one decimal place, for centimeter as the unit.

Throughout the manuscript we have adjusted the comparative statistics (R^2, RMSE, MAE, Bias) to one decimal place.

4) Unit 45 “As warming is occurring in Northern Canada”: Whether the precipitation in the study region has a significant change trend?

Thank you for your comment. Precipitation changes have been reported an increase in precipitation with medium confidence due to the limited weather stations located in northern Canada, which is added to the revised version of the manuscript. We also discuss how the type of precipitation, whether it is snow or rain, can impact the formation of lake ice.

Lines 58-68: Snow and lake ice are sensitive to a change in daily air temperature (Rafat et al., 2023). Northern Canada is experiencing warming at twice the global rate, and it is expected that air temperature will continue to increase, along with precipitation (about 10%) in all seasons (Zhang et al., 2019). These changes can significantly impact the surface-atmosphere energy balance which can directly affect snow and lake ice conditions (Brown and Duguay, 2010). As a result of these changes, alterations in snow cover (Brown et al., 2021; Mudryk et al., 2017), snowfall (Vincent et al. 2018), lake ice phenology (timing of ice formation and break-up; Magnuson et al., 2000; Lei et al., 2012; Benson et al., 2011), and ice thickness and composition (Kholoptsev et al., 2021) are being observed. Spatial and temporal observations of lake snow and ice can provide insights to changes in climatic variables. Later freeze up and earlier break-up of ice cover lead to an extended open-season, which can affect lake surface water temperatures (i.e., Woolway et al., 2021), affecting the influencing lake biogeochemical processes (e.g., Adrian et al., 2009; Jeppesen et al., 2014).

Lines 35-44: While snowfall can accelerate the onset of lake freeze-up, once the ice has formed, the accumulation of snow hinders the ice growth in the water column (Adams, 1976a). Snow present on top of lake ice acts as an insulative barrier due to its lower thermal conductivity compared to ice. This process slows the growth rate of congelation ice (or black ice; Brown and Duguay, 2010; Leppäranta, 2015) and affects the heat released from the water column to the atmosphere. However, snow on lake ice can also impact the timing of melt and the ice-free season. The albedo of the snow surface reflects incoming solar radiation and can lead to a longer ice-on season (Jensen et al., 2007; Brown and Duguay, 2011; Robinson et al., 2021). Moreover, snow can produce ice growth as snow ice (or white ice), if the snow on the ice surface encounters water, forming slush, and refreezes (Leppäranta, 1983). This process can occur through the upwelling of water through leads, precipitation falling as rain, or heavy snow causing the depression of ice below the water level.

5) Unit 85 “when the distance between measuring locations is kept relatively small (<10 m)”--How did you get this “10 m”? In fact, the snow probe is very suitable for field observation in the range of hundreds of meters.

Thank you for this comment. We did not mean that the magnaprobe is not suitable for observations on the scale of hundreds of meters. In referencing less than 10 m, we are referring to the increased efficiency and ease to data collection when the sampling resolution is smaller. The efficiency in data collection using the magnaprobe decreases as the sampling area increases, even if the sampling resolution is increased. We have slightly adjusted the wording as follows:

Line 93-96: An advantage of using a magnaprobe is the increase in speed with which a depth and position measurement can be obtained compared to measuring with a traditional ruler and writing down the results. The highest boost in snow depth measurement efficiency occurs when the distance between measuring locations is kept relatively small.

6) The unit of wind speed is preferably m/s.

We have converted wind speeds to m/s instead of km/h.

Line 138-142: The most predominant winds in December and November came from the east (~27%) and had an average wind speed of 2.5 m/s, with the strongest winds coming from the northeast (~15%) reaching 9 m/s. Throughout January to March, the strongest winds came from the northwest (~22%) reaching 10 m/s, but frequent winds came from the northeast in January (~ 22%), northwest in February (~26%) and northeast, east, and northwest in march (~21%) travelling at 3 m/s on average, while very little winds were recorded from the south (~6%) between October to March.

Line 412-415: Winds reported at the Yellowknife weather station reached speeds above the ~4 to 11 m/s 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.

7) Caption of Figure: you miss the panel a.

Thank you for noticing this missing detail. We have now added reference to the figure panel.

Line 149-152: Figure 1: This study focuses on (a) four lakes located north of Yellowknife, NWT, Canada, (b) Landing Lake, Finger Lake, Vee Lake, and Long Lake, shown on different scales depicting the area data collection took place (shaded colour). (c) The location of the GPR transects (Left) and in situ snow depth and density measurements (Right) on Vee Lake. (Background imagery: ESRI 2022, Landcover source: CCRS and NRCan, 2020)

8) Unit 230 “Landing-D = 190 kg/m3”--How is the density of snow obtained? When the snow is thick, whether the texture of snow is considered and the density of snow is measured at each sub-layer?

During data collection we obtained the bulk density of the snowpack at 6 to 10 locations per lake. Unfortunately at the time we did not excavate a snow pit and use the density cutters or obtain the stratigraphy. Therefore, our observations are just based of an average bulk density for each lake. We have added more information in section 3.2 on how density observations were obtained:

Lines 192-195: For each lake, the bulk snow density was sampled at 6 to 10 locations through measuring the specific snow volume and weight of the vertical snow profile using a 5 cm diameter snow tube and an electronic scale with a 1 g accuracy. The bulk snow densities measured on each lake were averaged (Table 2) and used as a guide in determining the appropriate density to use for deriving the snow depth.

9) Figure 7: From the data in the figure, the error is different with different snow depth, and the thin snow corresponds to a relatively large error. This should be taken seriously.

We agree and in the manuscript we have addressed there is a threshold and the accuracy of the snow depth derived from the GPR-TWT decreases with thin snow with this method. The thinner snow depths (< 10 cm) are difficult to discern due to the imaging resolution associated with the 1000 MHz GPR sensor, as well as the associated errors in picking the travel times (~ 0.3 ns). We have added the following lines within the results and discussion sections in the revised manuscript to ensure that the limitation is clearly highlighted.

Lines 292-293: The snow depth derived from the GPR-TWT was consistently overestimated when compared to in situ observation for shallower snowpacks (<10 cm) across all four lakes.

Lines 418-424: This study revealed a limitation in deriving snow depths below 7cm using the 1000 MHz sensor, identifying a threshold. This finding is consistent with previous studies (Pfaffhuber et al., 2017), and as such, the in situ observations below 7 cm were excluded from the validation analysis. During the March 2022 campaign, seldomly snow depth was observed below 25 cm, meaning the vertical imaging resolution of 6.5 cm for the 1000 MHz sensor did not limit our data acquisition.

10) Unit 295 "The snow depth on Finger Lake showed a decrease of ~2 cm per meter as the distance from the perimeter"-- Whether the correlation length of snow depth will also change with the distance from the shoreline?

We found that the variability in snow depth is larger closer to the shoreline than further away on all four surveyed lakes. This would allow us to suspect the correlation lengths to be smaller closer to the shoreline than further away, however we do not quantify it as there was no significant trend shown across the lakes with snow depth and distances to shoreline.

Lines 302-304: 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.

11) Unit 365 "which suggests that minimal overflow"-- I don't understand the overflow here.

Thank you for this comment. The text has been modified in the revised version of the manuscript:

Lines 364-372: The timing and amount of snowfall influences the composition, thickness, and phenology of lake ice. Increased snow accumulation in early season and on thin lake ice that has reduced buoyancy will create leads and cause overflow (the upwelling of water from the water column), which increases the likelihood of snow ice growth. Thin and patchy snow ice (0–4 cm) was observed on the lake ice surface during the December and March field campaigns, comprising 0% to 6% of the lake ice composition. Based on observations up until March 2022, minimal amounts of snow ice were found, indicating that there was little overflow that occurred on these four lakes during the winter season prior to the beginning of ice break-up.

12) Unit 515 "however, the impact density variability has on lake ice formation needs to be further investigated"-- I also don't understand this sentence, maybe just remove it.

Thank you for this comment. We have removed the sentence.

13) 6 Conclusion: The expression of this section seems a bit messy, and I suggest further modification.

The conclusion is revised (**Lines 468–494**)

14) "The snow over lake ice has commonly been ignored when deriving lake ice thickness, with best practices for mapping ice thickness suggesting to avoid snow drifts and variable snowpacks, as it will estimate a thicker ice thickness due to the radar travel-time, but in reality, areas of snow drifts are expected to have a shallower ice thickness due to snow insulating the ice thickness and slowing ice growth. Variable snow depths are important areas across the lake to map for monitoring lake ice conditions as the ice thickness is expected to vary spatially. "-- These contents are not the conclusions derived from this study and have been introduced as background knowledge before, so it is suggested to delete these contents.

The paragraph has been deleted.

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

I would like to thank the authors for their response and revisions. The manuscript has greatly improved and the majority of my previous comments have been satisfactorily addressed. However, two of my earlier comments have not been sufficiently addressed and must be in order for the manuscript to be publishable, in my opinion.

We are thankful to the reviewer for taking the time to review the manuscript a second time, and we appreciate their additional feedback. 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.

These are as follows:

1) The authors argue that the work is a novel advancement at implementing a new algorithm.

However, they did not develop the Wong et al. algorithm so I think the contribution is the matlab code. So, in order for this to be considered an advancement I would ask that the authors make this matlab script publicly available through something like CUAHSI Hydroshare or github.

Thank you for this comment. We have made revisions to the text to address this concern. Firstly, we have added additional details regarding the availability of the data and code section of the manuscript (**Lines 497-498**), stating that the code is available upon request. All post-processing steps are included within the workflow, including the signal processing, and prepared if and when requested. However, throughout the manuscript we do not claim to develop the Wong et al. algorithm and just state that we adapted the algorithm to make it usable for identifying the snow-ice and ice-water interface using a fully automated processing workflow (**Lines 118-124**). We focus on the derivation of relatively shallow snow depths using signal processing to remove the direct air wave that hides the snow-ice interface. We bring attention to the fact that it is possible to derive the lake snow depth and can be accomplished in a fast and efficient way.

Lines 497-498: All code used for data processing and analysis of this study are available from the corresponding author upon request.

Lines 118-124: We utilize extensive GPR two-way travel-time (TWT) observations and in situ observations of lake snow depth and density to complete the following objectives: (1) To improve the retrieval of lake-specific snow depth observations by applying a fully automated snow processing algorithm, (2) To validate the accuracy of the snow depth retrieval algorithm by comparing it to in situ observations, and (3) To spatially map the distribution of snow depth across lakes.

2) Additionally, I fundamentally disagree with the exclusion of values within the 6 m for comparison to your GPR technique. This implicitly assumes that your GPR processing is correct and is not actually testing your methods. Thus, the current error metrics are biased from the flawed methodology. I think that the authors must use all values within the 6 m window. I think it would be OK to discuss how this is a conservative estimate that could later be improved with a more accurate location for depth, etc. but I also suspect it will be within the 6.5 cm accuracy for the radar frequency as well.

Thank you for this follow-up comment. While we appreciate your perspective, we respectfully disagree. Throughout the manuscript, we explain our rational for using scenario 2 to determine the accuracy of our method for deriving snow depth over lake ice. Including all observations within the 6m radius would lead to an incorrect comparison of one observation to many (inverse distance weighted), when we know that the snow depth can vary on similar length scales across the lake. In our previous response we described how the snow depth variability within the 6m radius ranges from approximately 2 cm to 5 cm (standard deviation of snow depth), which could result in a variability of between 5% to 40% in the estimate when compared to the average snow depth. However, we have addressed this issue in the manuscript by including a section that explains and reports the error for the magnaprobe spatial location (Section 3.2 In situ Observations, **Lines 184-189**). We also suggest future work to improve the accuracy estimate of this method through enhancing the GPS data (Section 5. Discussion, **Lines 401-404**). In response to the reviewer's concern, we have included error metrics on the inclusion of all observations within the 6 m radius and our findings show a negligible increase of only ~1 cm in both the MAE and RMSE (**Lines 284-287**). These results demonstrate that there are minimal differences in the error statistics other than the R^2, which would be due to the variability in snow depths being on the same magnitude of the error in snow depth which, again, is confirmed with the correlation length scales (e.g. long lake correlation length = 6.42m with ~ 3.8cm standard deviation in snow depth at 6m).

Lines 184-189: The spatial accuracy for the magnaprobe GPS receiver with use in the Arctic has been reported as ± 5 to 10 m (Walker et al., 2020), with a 0.01 m depth precision (Sturm and Holmgren, 2018). With known limitations in the Magnaprobe GPS accuracy, we used the RTK GNSS rover to measure the location of 291 magnaprobe measurements spaced out along the sampling transects on three of the four lakes (Landing, Finger, Vee). We found the error from the magnaprobe GPS to be between 1.72 m to 8.43 m, with a mean (± standard deviation) error of 4.44 ± 1 m.

Lines 402-405: The accuracy of this method may be improved by enhancing the spatial location of the in situ snow depth measurements and sampling more frequently within the length scales of each lake. In improving the spatial accuracy of the in situ snow depth observations and the frequency of measurements the accuracy of this method can be further assessed.

We have added additional lines stating the results of using all points within the 6m buffer:

Lines 284-287: Scenario 2 showed strong agreement between the in situ and estimated observations (Figure 7) with R^2 = 0.63, RMSE = 1.6 and MBE = 1.0 cm on average for all lakes. If considering all GPR-derived snow depth observations within the 6m radius there is minimal differences in the validation statistics (RMSE = 2.0 cm, MAE = 2.7 cm, Bias = 0.13 cm), however Scenario 2 is used for further analysis due to the variability in snow depth seen within the 6m radius (2.1 cm to 4.9 cm).