Comment on tc-2022-193
Response to Community Comment #1

Community 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

Snow accumulation on lake ice can have a significant impact on the evolution of the ice cover, particularly as wind-driven forces can cause significant spatial variation in the distribution of snow on the ice cover. This is more pronounced in areas of low snowfall, where there are surface conditions of both bare ice and snow crossings, which are critical to the overall heat content of the lake ice. It is currently difficult to quantify precisely the spatial distribution of snow thickness, and shallow snow cover is also a dominant natural phenomenon in many mid-latitude regions. This technique allows rapid access to snow depths over large areas of lake ice as opposed to traditional manual measurements and fixed-point automated observations. It is a valuable tool for estimating and analysing the thermal balance of the ice surface over the entire lake ice and for gaining a clearer understanding of the physical processes involved in snow redistribution.

We are thankful to the valuable comments and questions towards the manuscript. We have responded to all comments to improve the manuscript. Below, we provide the answers to the comments and questions raised. For convenience, the community comments are provided in black text. Responses to each comments/questions are provided in blue text.

Some questions are as follows:

- The rolling of snowmobile and sled compacts the snow, can the reduction in depth and the increase in density be completely offset? This is because in the case of the study where the snow is deeper, the compaction does not act evenly across the snow layer resulting in an uneven increase in overall density. Would it be better if in the future the snowmobiles were to "push" the sleds instead of "pulling" them, or would it be better if they were to be carried by drones?

  Thank you for your question. In our revised manuscript we have added more discussion on the compaction of the snow caused by the sled. We looked at the crossover locations and compared the difference in TWT for the initial pass compared to the second, and found an average difference of 0.02 ± 0.31 ns. This aligns with the uncertainty of the TWT picks (~0.3 ns). In exploring the difference in TWT instead of a function of snow depth or density, we can assume the change in one parameter is compensated for by a change in the other, which agrees with McGrath et al. (2019). Additionally, in looking at the sensitivity in deriving snow depth with density, there is minimal impact on the GPR-derived snow depth with a change in density based on density observations recorded in the field.

  In the future, to further confirm this is the case, mounting the GPR on the front of the skidoo, hovering right on the snow surface would avoid compaction caused from the snowmobile and sled that the GPR sits in. The problem of having a gap between the radar and the snow surface is detecting the air-snow and snow-ice interface within a short time window could present challenges. This would be more achievable in a deeper snowpack, however, would be challenging in shallow lake snow due to the reflections that would be caused from the air-snow interface, and the interference it would cause in decerning the snow-ice interface (due to the vertical imaging resolution) even with removal of the direct wave.

Lines 377-392: “The analysis showed that no correction is required for compaction caused by the GPR sled. In considering the crossover locations (n = 533) on each of the lakes, we assessed the difference in TWT between the initial pass and the second pass and found that the average TWT difference was 0.02 ± 0.31 ns. Given the average velocity of 0.26 m/ns for the four lakes, and applying the one-quarter wavelength Rayleigh criterion, the uncertainty of the TWT picks is approximately three samples (~0.3 ns). Therefore, the average TWT difference at crossover locations is within our uncertainty estimates of the TWT picks. In further exploring the change in TWT from the initial pass to the second, 56 % of the observations show the TWT for the second crossover to be larger than the initial. We found that shallower snow depths (or smaller TWTs) resulted in a decrease in travel time for the second pass, while deeper snow depths (or larger TWTs) showed an increase for the second pass for both early ($R^2 = 0.30$, $p < 0.05$) and late winter season ($R^2 = 0.46$, $p < 0.05$). However, these trends do not show dependency on the total snow depth accumulated throughout the winter season, as the average crossover differences of the data collections for early and late seasons (shallow and deep snow depths) are unbiased. Overall, although there is a change in density on the sled track ($\overline{\rho}$sled = 340 ± 20 kg/m3) compared to the density of the fresh snow (Table 2), the effects of a decrease in depth and increase in density under compaction from the snowmachine are naturally compensated and were confirmed with the crossover location TWT differences. The snow depth was measured at 1.5 cm less on average by using the density of the sled track for depth estimation rather than fresh snow density. Therefore, the effect on GPR derived snow depth is minimal because minimal snow mass was lost.”

The authors obtained snow depth data with a large spatial coverage and also assessed the accuracy of the data. Consideration could be given to discussing this in the context of climatic background and terrain features to improve the potential application of the data. For example, is the variability in snow depth influenced by the wind speed and direction prior to measurement? Is the greater depth of snow on the banks due to the barrier effect of vegetation or bank slopes?

Thank you for these comments. We did add more analysis related to the snow depth distribution into the revised manuscript, where we considered the distance to the shoreline and discuss the micro-topographic snow features. We have also added an additional figure (Figure 11), looking at the difference in snow depth and density between the December 2021 and March 2022 field campaign.

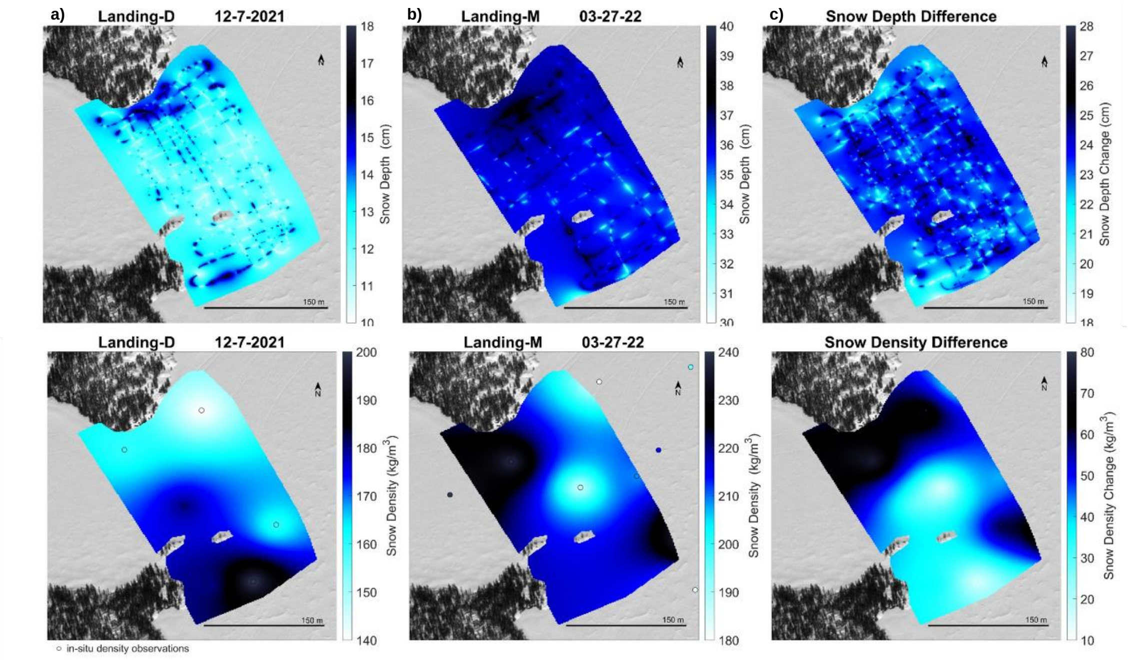

Figure 11: Maps of Landing Lake snow depth (top) and density (bottom) in (a) December, (b) March and (c) the difference between the two were created using IDWs of the GPR-derived snow depth and the in situ snow density observations.

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 by the correlation lengths. 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.”

Lines 339- 347: “On relatively level ice surfaces and in turbulent wind fields, snow dunes are formed from snow redistributed by wind. The snow depth accumulation over the lakes varied but could be explained by the total snowfall (8 cm) with consideration to wind redistribution and compaction seen between December 7th (Landing-D Lake $\mathbf{\overline{h}_s} = 12.76$ cm) to December 14th (Vee Lake $\mathbf{\overline{h}_s} = 16.06$ cm). During both field campaigns there was evidence of snow dunes present across the lakes. This study explored the distribution of snow over each lake (Figure 9), which showed local-scale variability of snow depths from redistribution of the snow across all the lakes (correlation lengths between 6–19 m). We used semi-variogram analyses to determine the horizontal spacing of the snow dunes and found Long Lake to have the shortest correlation length (6.42 m). On Landing Lake, we saw an increase in correlation length throughout the winter season from ~7 m to ~19 m. The inferred variability length-scales are similarly supported in the literature, reporting correlation lengths from 5 to 20 m (Gunn et al., 2021a; Sturm and Liston, 2003)."

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."

- Line 17-19, "On average, the snow depth derived from GPR TWTs for the early winter season is estimated with a root mean square error (RMSE) of 1.58 cm and a mean bias error of -0.01 cm. For the late winter season on a deeper snowpack, the accuracy is estimated with RMSE of 2.86 cm and a mean bias error of 0.41 cm." Is the increase in mean bias error in the late winter season due to the effect of increased snow depth or the effect of deterioration?

  In comparing the difference in snow depth from March 2022 to December 2021, we found that there was only ever an increase in snow depth between the two dates and believe the increase in mean bias error is due to the effect of increased snow depth.

- Line 34-36, "As warming is occurring in Northern Canada at twice the global rate and is expected to continue to increase (Zhang et al, 2019)…" Has warming had an impact on snowfall? Is there a gradual increase or decrease in the amount of snow in winter?

  We have added to the manuscript to discuss how this years data could compare to previous years. This is done through the following text:

  Lines 320-338: "Lake freeze up for small lakes surrounding Yellowknife generally occurs during October, however, lake freeze up was reported to occur later this year compared to the 2018 to 2020 seasons based on Yellowknife's snowmobile association data. October air temperatures reported at the Yellowknife weather station showed a mean temperature increase of 4.4°C between 2020 (-1.85°C) and 2021 (2.6°C), and a 3.18°C increase when comparing to the 5-year and 10-year October mean air temperatures. Within the 2021 to 2022 water year, ~ 75 cm of snowfall was reported by the Yellowknife weather station, accounting for 46 % of total annual precipitation. In comparing the snowfall to previous years, the 2021 to 2022 water year experienced 20% less snowfall than the 2020 to 2021 water year (~93 cm and 76% of total precipitation). In the past 5 to 10 years, on average, 40 to 45% more snowfall was reported compared to the 2021 to 2022 year. The timing and amount of snowfall will influence the lake ice composition, thickness, and phenology. Larger amounts of snow accumulation on thin, early season lake ice with reduced buoyancy will create leads and cause overflow, which increases the likelihood of snow ice growth. Thin and patchy snow ice (0 – 2 cm) was observed on the lake ice surface during the December and March field campaigns, making up 0% to 6% of the lake ice composition. Based on observations recorded up until March 2022, scarce amounts of snow ice were present, which suggests that minimal overflow occurred throughout the winter season on these four lakes prior to the beginning of ice break up.

- Line 75, "(2) validate the snow-depth retrieval algorithm using in situ observations…" Measuring uncompacted or compacted snow layers?

  Thank you for this question. The snow depth measurements were taken along side the track, so in the uncompacted snow – and that's why we use the uncompacted snow density. Although the depth and density are changing when the sled gets pulled over the snow, with no change in snow mass, the TWT will not be affected as clarified above.

- In addition to the spatial distribution of snow depth, I would like to know if you have also carried out research on the spatial distribution of ice thickness? Or is your technique actually focused on the identification of the snow-ice interface for shallow snow layers and is not actually an optimal technique for the identification of the ice-water interface?

  Thank you again for a great question. We collected snow depth and ice thickness simultaneously using the GPR. The GPR with the 1000 MHz is capable of capturing the snow-ice and ice-water interface simultaneously, and the automated post-processing can pick both interfaces. This will be part of future research we are currently working on.