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

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 snow cover on lake ice is of great significance for the growth and decay of lake ice, lake climatology, limnological hydrology, and lake ecology. It is a positive work to develop a new technology based on the ground penetrating radar to quickly obtain the snow depth over large lake-ice areas. Based on the observation system, the authors carried out observation experiments in four lakes in the Canadian sub-Arctic region, proving the applicability and application value of the observation method, especially proving that the observation ability for the shallow snow layer over the ice surface. Thus, it is a method worth popularizing. The obtained data of large-scale snow observation can be further applied to the numerical simulation of lake ice and limnological hydrological processes, to evaluate the impact of snow and lake ice layers on the ecological environment of frozen lakes, and to evaluate the satellite remote sensing products of snow over the lakes. The paper is well written and structured, the method description is appropriate, the data analysis is basically sufficient, and the conclusion is clear, so it is a research work worth publishing in the TC. However, there are still some problems in the current expressions. It is mainly about the physical analysis of some data statistics results, and the impact of destruction of snowmobile track for natural snow surface on the observation data. Therefore, I recommend that the paper can be considered for publication only after a few minor revisions.

We are thankful to the reviewer, and we appreciate their suggestions and valuable comments for improving the manuscript. We have addressed or responded to all comments to improve the quality of this manuscript. 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:

- Some statistical results based on observation data lack the analysis of potential physical mechanisms, for example, the difference of snow depth, density, relevant length in various lakes.

  Thank you for this comment. 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, where these measurements are collected. Additionally, we have added the following text to the results (Section 4.4: Early vs. late winter season). Additionally, we have added additional discussion on the relevant lengths for each lake which are discussed in more depth in coming comments.

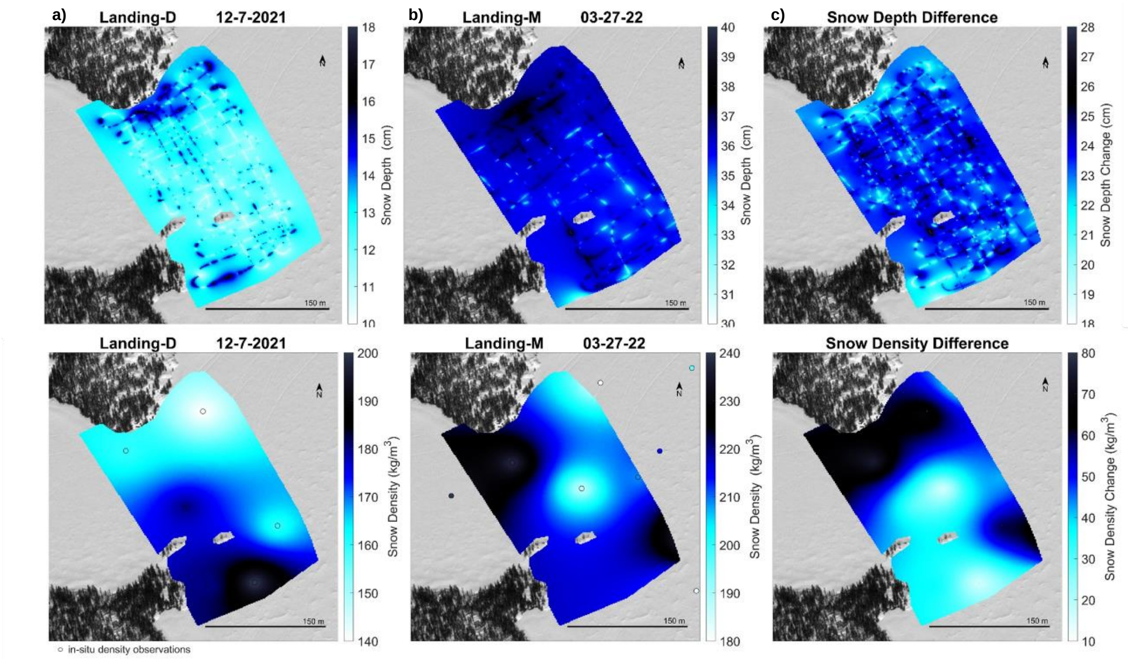

Figure 11: Maps of Landing Lake snow depth (top) and density (bottom) in (a) December, (b) March, and (c) the difference between the two were created using IDWs of the GPR-derived snow depth and the in situ snow density observations.

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."

- The author said that snowmobile and sled rolling will increase the snow density and reduce the snow depth to a certain extent. The two impacts can offset each other, so their impacts are not significant. My suggestion here is whether you can further analyze the difference of the impact on thick and thin snow layers, on new and old snow layers, as well as on the snow accumulated in early December and the snow accumulated in late winter.

We appreciate your comment. We did revise the manuscript to discuss the crossover locations. We included discussion on the impact on thick and thin snow layers (or in terms of TWT – smaller and larger TWT) and for early and late winter snow accumulation. Following text is added to the revised manuscript:

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 ($\bar{\rho}$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.”

- This study presents observation data obtained from one winter. Although the data spatial coverage is relatively large, there is still a lack of data representativeness. Therefore, it is suggested to increase the discussion of data representativeness obtained from the observed winter. How does the snow accumulation on land compare with previous years? What is the difference of the atmospheric precipitation, temperature and other parameters in the winter of the observation related to the climatology? etc. Through such comparison, the application value of observation data can be enhanced.

Thank you for this comment. To further improve the data representativeness, we have added the following lines to the revised manuscript:

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.

In December 2021 and March 2022, the lakes consistently showed a shallower snowpack on average (Table 3) than snow on the ground (Figure 2) reported at the nearby Yellowknife weather station. The lakes measured at an average of 24 % to 29 % less snow than measured over land in December 2021, and 15 % less in March 2022. Thus, assuming snow depths measured on land as an input to lake ice models will overestimate lake snow depth by a seasonally dependent factor and impact the modeled ice thickness (Kheyrollah Pour et al., 2017)."

Special comments:

- Line 15 "~9 cm spatial resolution along transects" 9-cm is the sampling resolution, not the data resolution, because you have not considered the footprint of observation. Therefore, it is recommended to further analyze the observation footprint of single observation.

  We thank the reviewer for this comment. We agree with the comment and modified the text in the revised manuscript from "spatial resolution" to "sampling resolution" when referencing the GPR trace spacing. In addition, we added the following text to the revised manuscript in the methodology (Section 3.1: GPR data acquisition)

  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."

- Introduction: The application of observation data of snow over the lake ice cannot only focus on the developing of lake ice numerical model, but also be applied to lake ice phenology (e.g., Lei et al., 2012), lake ecology and other fields. The description of research background should be more comprehensive in the introduction.

Ref.: Lei R, Leppäranta M, Cheng B, et al. Changes in ice-season characteristics of a European Arctic lake from 1964 to 2008. Climatic change, 2012, 115(3-4): 725-739.

We thank the reviewer for this comment and the additional reference provided. The description of research background has been expanded on in the introduction for the revised manuscript as suggested.

Lines 34-59: "A challenge to measuring lake snow is the inconsistent snow thickness across the lake. Snow redistributed by wind commonly deposits on the leeward side of topographic features. Snow accumulation on lake ice surrounding these features (i.e., pressure ridges) leads to the formation of snowdrifts. Additionally, snow dunes will form in areas of turbulent winds on relatively level ice surfaces (Liston et al., 2018). The formation of snowdrifts and snow dunes creates a heterogenous snow thickness across the ice surface. The uneven snow depth distribution leads to spatial variability in the lake ice thickness due to the increase in heat transfer through the snow for areas of shallow snow (assuming a constant thermal conductivity). Micro-topographic snow features impact the ice mass balance and must be considered when evaluating local and regional energy balances and fluxes (Sturm et al., 2002).

Snow and lake ice are sensitive to a change in daily air temperature (Rafat et al., 2022). As warming is occurring in Northern Canada at twice the global rate and is expected to continue to increase (Zhang et al., 2019), a change in the surface-atmosphere energy balance will directly affect snow and lake ice conditions (Brown and Duguay, 2010). Within the changing climate, a change in snow cover (Brown et al., 2021; Mudryk et al., 2017), 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 be indicators to changes in climatic variables. Later freeze up and earlier break-up of ice cover leads to an extended open-season and can influence the lake surface water temperatures (i.e., Woolway et al., 2021), affecting the lake biogeochemical processes (e.g., Adrian et al., 2009; Jeppesen et al., 2014). Additionally, northern communities rely on lake ice for cultural and recreational use, and as a source of transportation through ice roads (Knoll et al., 2019). Ice roads allow travel to neighbouring communities and alternative access to goods and supplies (instead of transport via airplane). With warming projected to increase, it can be expected that the safety of ice roads and operational duration will be affected (Stephenson et al., 2011; Mullan et al., 2021). As the presence of snow over lake ice directly affects ice thickness, measuring snow depth on lake ice is crucial for lake modelling and ice thickness estimation on a regional scale. Previous studies by Kheyrollah Pour et al (2017) show that accurate snow depth observations over lake ice can significantly improve the thermodynamic lake ice models.

Improving snow depth observations and retrieving an accurate higher spatial resolution snow depth is essential for hydrological, limnological, and lake ice studies (Lei et al., 2012; Kheyrollah Pour et al., 2017; Marsh et al., 2020; Li et al., 2022)."

- Line 46 "Daily snow depths are reported across Canada using instruments, such as." As you mentioned later, the SnowHydro Magnaprobe is a common method for snow depth measurement. Therefore, it should be introduced in introduction, and its advantages and disadvantages should be described, such as manual operation, which is not conducive to obtaining a wide range of snow depth observation data.

  Thanks for the comment. We have added the text in the revised manuscript introducing the magnaprobe and its advantages and disadvantages as follows:

  Lines 66-77: "Currently, retrieving accurate snow depth observations over lake ice and mapping the spatial distribution and heterogeneity of snow over ice is challenging because of the limited support of point measurements using contemporary methods, such as a ruler and notebook or automatic snow depth probe. An automatic snow depth probe, such as the magnaprobe, is equipped with a metal rod probe that penetrates the snowpack to the ice surface and a sliding basket that sits on the surface of the snow, recording the snow depth and spatial location when manually placed in position (Sturm and Holmgren, 2018). The magnaprobe records the snow depth accuracy with errors ranging from near zero for hard bases to +5 cm. The Wide Area Augmentation System-enabled GPS provides a position accurate to ±2.5 m. The advantages of using a magnaprobe is the increase in speed with which a depth and position measurement can be obtained by a factor of 10 compared to measuring with a traditional ruler probe and writing down the results. The highest boost in snow depth measurement efficiency occurs when the distance between measuring locations is kept relatively small (<10 m). The snow depth probe has been commonly utilized for validation of remote sensing techniques (*i.e.*, McGrath et al., 2019; Walker et al., 2020), however, due to the limited spatial coverage that current methods pose; it is not logistically feasible to measure the snow depth on lake-wide scales."

- Line 83 "It is expected that the wind fetch and shoreline vegetation affect the snow distribution", However, in the later data analysis, the impact of these two factors on different lakes has not been discussed enough.

  We thank the reviewer for this comment. We agree with the comment and expand the discussion of how the wind fetch and shoreline vegetation were found to affect the snow distribution in the revised version of the manuscript as follows. First, we expand on the study area and add the following text (Section 2: Study area):

Lines 111-117: **“**These lakes are part of a turbulent wind field, as the wind direction and speed reported at the Yellowknife weather station vary rapidly. The most predominant winds in December and November came from the east (~27 %) and had an average wind speed of 9 km/h, with the strongest winds coming from the northeast (~15 %) reaching 33 km/h. Throughout January to March, the strongest winds came from the northwest (~22 %) reaching 37 km/h, but frequent winds came from the northeast in January (~22 %), northwest in February (~26 %) and northeast, east, and northwest in march (~21 %) travelling at 11 km/h on average, while very little winds were recorded from the south (~6 %) between October to March.”

The following text is added in the results (Section 4.3: Snow depth mapping):

Lines 270-273: “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.”

The following text is added in the discussion to clarify on the differences between the lakes:

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 $\overline{\mathbf{h}}_{\mathbf{s}}$ = 12.76 cm) to December 14th (Vee Lake $\overline{\mathbf{h}}_{\mathbf{s}}$ = 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.”

- Table 2: Could you explain why the Long Lake has a relative large snow density compared to other lakes?

We believe the relatively large snow density on Long Lake is due to the surface area of the lake compared to the additional other three lakes. The lake has a larger wind fetch due to the shape and the location along to the highway. We have added the following clarification in the discussion of the revised manuscript:

Lines 348-353: “In comparing the spatial snow depth variability across the four lakes, we believe the physical characteristics of Long Lake explain the reduced correlation length in comparison to the three additional lakes. Long Lake has the largest surface area to perimeter ratio and spans ~3 km northwest to southeast. Therefore, Long Lake exhibits the largest wind fetch area compared to the additional three study areas and can explain the higher snow density compared to the other lakes. While on Landing Lake, both the snow depth and density increased over the season, however, to determine the reason for the decrease in snow depth variability from December to March, more frequent sampling dates would have to occur between early and late season.”

- Line 199 “area = 4 ha” ha is not the International Standard Unit.

Done. We have switched to state area as 0.04 km^2. (4 ha). Thank you.

- Figure 5: In fact, there are multiple intersections in the observation transects for all lakes, which means that there should be two observations at these intersections. In order to explain the stability of the observation and retrieval results, it is necessary to compare the repeated observation results obtained from these measurement intersections.

Thanks for the comment. To address this comment, we added the text outlined in the above general comment (**Lines 377-392**).

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/m^3) 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.”

- Lines 222, 225 “Long Lake showed the lowest agreement”, “with Vee Lake being the most accurate”: Corresponding to such measurement difference, some physical explanations are required.

We appreciate the reviewer's comment. We expect the snow depth variability on long lake to vary on a shorter length scale due to the surface area, shape, and location of Long Lake compared to the other three additional lakes, which attributes to the accuracy of the derived-snow depths with using a 6m radius. Similarly, Vee lake has higher agreement most likely due to the deeper snowpack (more accurate to derive deeper snowpack with GPR) and also Vee lake has the largest correlation length, meaning there is less variability in the snow depth within the 6 m radius used to derive the snow depth. To address this further, we have added to the following text in the discussion:

Lines 343-360: "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 observed 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).

In comparing the spatial snow depth variability across the four lakes, we believe the physical characteristics of Long Lake explain the reduced correlation length in comparison to the three additional lakes. Long Lake has the largest surface area to perimeter ratio and spans ~3 km northwest to southeast. Therefore, Long Lake exhibits the largest wind fetch area compared to the additional three study areas and can explain the higher snow density compared to the other lakes. While on Landing Lake, both the snow depth and density increased over the season, however, to determine the reason for the decrease in snow depth variability from December to March, more frequent sampling dates would have to occur between early and late season.

We believe the lower accuracy in GPR-derived snow depths on Long Lake (±11 %) could be attributed to using a radius to compare the derived and in situ snow depths that was approximately the same magnitude as the length scale of snow depth variability. Vee Lake had the highest accuracy (±6 %) in deriving the snow depth and the largest correlation length (~11 m) in December 2021. The greatest accuracy (± 5 %) was found during the late season on Landing-M Lake which also found to have the largest correlation length (~19 m). Therefore, the snow depth variability within 6 m was less on Vee Lake and Landing Lake than on Long Lake. Overall, we may expect the accuracy to increase by improving the spatial location of the in situ snow depth measurements and sampling more frequently within the length scales of each lake."

- relative error = 11.04 %, and other somewhere: For relative errors, it is not necessary to retain two decimal places, because the accuracy of the evaluation cannot reach this level.

  Thank you. We have adjusted the relative error to whole numbers in the revised version of the manuscript, updating Table 4, as well as throughout the results section.

- Line 240 "However, the relative error was improved on Landing-M Lake with a deeper snowpack (5.33 %) than that of Landing-D Lake (8.06 %). During the later season, the GPR could derive the minimum snow depths seen on Landing Lake, as opposed to that in the early season, where" Some further explanation is needed here, not only to give the data results.

  We appreciate the reviewer's comment. The following text is added to the revised manuscript:

  Lines 294-296: "However, the relative error was improved on Landing-M Lake with a deeper snowpack (5 %) than that of Landing-D Lake (8 %). The GPR could derive the minimum snow depths seen on Landing Lake during the later season, as opposed to that in the early season, where the GPR-derived snow depth could not capture the shallowest snow area (4.5 – 10 cm).”

We also mention later in the discussion that a 7cm threshold has to be applied due to the wavelength of the 1000 MHz with the snow (vertical sampling resolution).

Lines 372-376: “Overall, the results of this study showed that a 7 cm threshold exists as a limitation of deriving shallow snow depth from GPR TWT using the 1000 MHz sensor. Showing similar agreement with previous studies (Pfaffhuber et al., 2017), the in situ observations below 7 cm were not considered in 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.”