Reviewer comments are provided in black.
Author responses are provided in blue

Review on "Interannual variability in air temperature and snow drive differences in ice formation and growth" by Arash Rafat and Homa Kheyrollah Pour

Climate change involves many complex processes. For the cryosphere, the timing of the events is a critical concept. The freezing and melting of lake/sea ice alter the energy balance between the atmosphere and the underlying water bodies (lakes or oceans), thereby influencing climate dynamics. One of the most critical practical concerns is that freeze-up timing directly affects the usability of ice roads. This is especially vital for North American Arctic communities, where ice roads serve as lifelines for remote regions in Alaska and Canada.

This manuscript investigates ice formation and growth in a small boreal lake in Canada's Northwest Territories (NWT). The authors conducted *in-situ* observations over three consecutive winter seasons on a single lake. The dataset includes local meteorological parameters such as wind speed, air temperature, and turbulent and radiative heat fluxes. A platform was installed on the lake to collect high-resolution snow and ice temperature measurements using a novel, cost-effective automated device (SIMBA).

These observations, combined with long-term meteorological data from weather stations, were used in a statistical model to calculate ice thickness employing an exponential function of snowfall as input.

The manuscript investigates local variability in climate and weather, particularly ice formation and growth, with a focus on ice freeze-up dates (FUD) and the evolution of snow and ice cover. The authors argue that the derived relationships between air temperature, snow depth, and ice thickness can be used to predict the minimum ice thickness required for ice road construction, aiding in the effective management of construction activities.

The topic of this manuscript is highly relevant to the scope of *TC*. The observations were made without flaws, and the configuration of the SIMBA platform is solid and well-justified. The statistical model is conventional yet robust, and the data analysis is convincing. However, I have some concerns and comments regarding certain aspects of the content, which I hope the authors will address through a proper revision before the manuscript's final acceptance.

Major comments

1. The manuscript's overall structure could be improved for better clarity. a) I don't see a clear chapter on the "Results". The presentation of data and results was somehow mixed. I suggest restructuring the entire manuscript. For example, a chapter entitled "results" that contains partial Chapter 4 and Chapters 5 and 6 may yield better clarity of the manuscript; b) I am not sure why Chapter 8 is needed, especially after the conclusions have been made. I suggest this chapter can be placed before the conclusion, e.g., Discussions.

   We thank this Reviewer for this comment and have revised the manuscript to now include clear results and discussion sections. Chapter 8 now forms part of the discussion section as recommended.

2. Based on the study's objective, as stated in the abstract and final chapter of this manuscript, the discovery of robust relationships between air temperatures, snow cover, and ice thickness is intended to assess the feasibility of ice road construction and support effective construction management, which I agree. However, this work has been carried out in a tiny lake (1.1 km2). The questions I want to ask: a) How representative are the results of this work? b) Can those derived formulae be applied to obtain FUSs in other parts of the NWT? c) Would it be possible to assess the performance of the formula for the other small lakes in NWT? d) At least a discussion of the general applicability of the formula should be included in this study.

   We thank this Reviewer for this comment and acknowledge a similar comment by Reviewer 1. For a) the results of this work are highly representative for many regions of the NWT which are scattered with thousands of small (*e.gs*. < 5 km^2) and shallow lakes (*e.gs*. <10 m) which are commonly used for transportation, recreation, and cultural activities. For b), the applied formulae can be used to approximate the FUD for other parts of the NWT and more broadly, Northern Canada; however, some caution should be applied. FUDs depend highly on lake volume and as such, we don't not recommend applying these equations for large and deep lakes. Instead, these equations can be useful for lakes with similar properties to Landing Lake. Some examples may include typical thermokarst lakes formed in shallow ground ice settings which are widespread across circumpolar regions and have relatively shallow depth (*e.g.* <10 m; West and Plug, 2008; Bouchard et al. 2016).

   For ice road construction, accurate ice thickness prediction would be top of mind, as construction activities would necessitate a minimum ice thickness to be reached prior to snow clearing for the ice road. For this purpose, appropriate parameter ranges would need to be applied and developed for different regions where snowfall, air temperatures, and a few measurements of ice thickness are available. The former two measurements would be used to derive parameters a and b while the later used to derive α. Here, we develop these parameter ranges for one region (Yellowknife), but relationships could be developed for any region where appropriate data exists.

   We would like answer c) with applying the empirical relationships for a lake located ~2.5 km from Landing Lake (Vee Lake: 62.55113°N, 114.35578°W). Vee Lake has similar properties as Landing Lake, with a surface area ~0.8 km^2, 5.80 m max depth, 1.58 m average depth. This lake was selected as we have in-situ measurements collected by a SIMBA for the periods of roughly Nov. 8, 2022-Dec. 31, 2022, and Nov. 15, 2024- Dec. 31, 2024 for use in validation of the empirical model. Equations are provided below for reference:

$$CFDD = ae^{bS_T} \tag{5b}$$

$$h_i = \alpha\left(\sqrt{\frac{2k_i}{\rho_i L}}\right)ae^{0.5bS_T} \tag{5c}$$

$$h_i = Ce^{0.5bS_T} \tag{6}$$

   Given the proximity to Landing Lake and the Yellowknife Airport meteorological station, we can apply the same parameters developed from curves of $CFDD\ vs\ S_T$ that were used for Landing Lake in 2022. We have also derived parameter values for Oct.-Dec. 2024 using the Yellowknife Airport weather station and provide a reference Figure (Figure R3) below. For 2024, derived parameters are a=51.52, b=0.037, and C=0.87. An α = 0.48 was selected for application 2024 to account for higher *CFDD* in 2024 as compared to 2023. For 2022, we use α=0.44, a=2.91, b=0.050, and C=0.047 for k_i=2.2 W m^{-1} °C^{-1}, L= 334000 J kg^{-1}, ρ_i=916 kg m^{-3}. These values were identical to those used for Landing Lake in Table 6 for 2022. Results are presented in Figure R4.

Based on this curve, and with higher *CFDD* as compared to 2023, we choose α to 0.48. This is ~10% higher than in α in 2023 to account for the higher *CFDD*. Parameters used can be summarized as follows: In 2022: we use α=0.44, a=2.91, b=0.050, and C=0.047 (Table 6), and for 2024: α=0.48, a=51.52, b=0.037, and C=0.87.

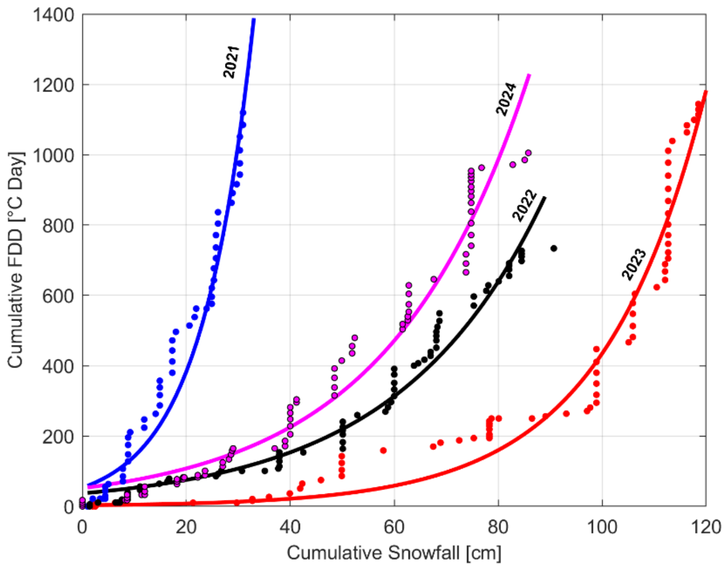

Figure R3: Cumulative freezing degree days (BT=-5°C) versus cumulative snowfall measured at the Yellowknife Airport Meteorological Station between Oct.-Dec. 2021 to 2024.

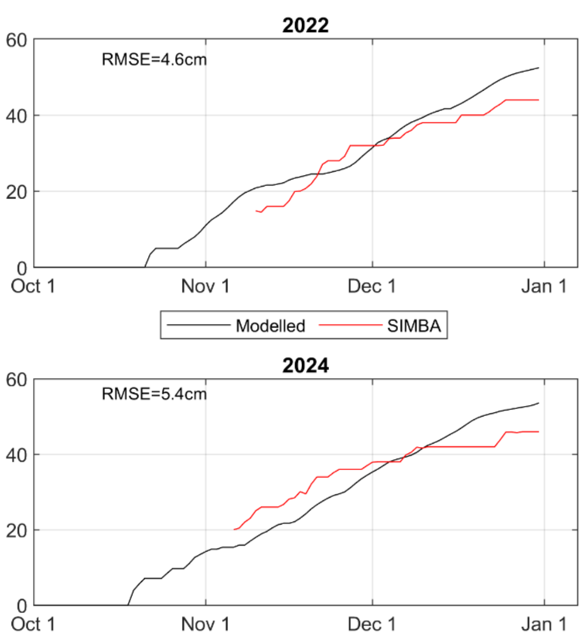

Figure R4: Application of empirical models to a small (~0.8 km^2) and shallow (5.80 m max depth, 1.58 m average depth) lake located ~2.5 km from Landing Lake for 2022 and 2024. Modelled ice thicknesses are compared with in-situ measurements collected by a SIMBA installed in Vee Lake.

Results show good ice thickness simulation accuracies (RMSE<= 5.4 cm). FUDs in 2022 for Vee Lake are uncertain as the SIMBA is installed after ice is thick enough to walk. However, based on Sentinel 2 optical imagery, FUDs for Vee Lake are thought to be within a few days following Oct.22 2022 (but no confirmed date), and between Oct. 22-23 in 2024. Modelled FUDs were Oct. 22, 2022, and Oct. 18, 2024, putting the approximate error in FUDs at 0-5 days. This accuracy would be deemed appropriate as a first-order approximation.

Following comment d), we have added in a small discussion on the applicability of this approach and some limitations of the model to the new discussion section of the paper. We hope that the presented analysis adequately answers your concerns. This discussion is presented below:

The presented empirical models demonstrate an effective means of simulating total ice and snow ice thicknesses in Landing Lake using snowfall and air temperatures recorded from the Yellowknife Airport weather station, located 11 km south of Landing Lake. Relationships between $CFDD$ and S_T (Fig. 8) can be considered as regional relationships which can be applied to other Yellowknife-area small lakes with similar lake depths (e.g. < 5 m) and surface areas (e.g. < 5 km^2) for first order estimates of ice thicknesses. Further, the same methodology can be applied for establishing values of α γ, b, C, D_1, D_2, and D_3 in other regions of the Northwest Territories if measurements of snowfall, air temperatures, and a few measurements of ice thickness are available. This analysis is not intended for use in large and deep lakes whose latency effects during freeze-up would require unique treatment. Multi-year monitoring in other regions of the Northwest Territories can aid in establishing regional curves such as those presented in Fig. 8 for determining inter-annual and regional variability in model parameters.

References:

Bouchard, F., MacDonald, L. A., Turner, K.W., Thienpont, J.R., Medeiros, A.S., Biskaborn, B.K., Korosi, J., Hall, R.I., Pienitz, R. and Wolfe, B.B. 2017. Paleolimnology of thermokarst lakes: a window into permafrost landscape evolution. Arctic Science. 3(2): 91-117. https://doi.org/10.1139/as-2016-0022

West, J.J. and Plug, L.J. 2008. Time-dependent morphology of thaw lakes and taliks in deep and shallow ground ice. Journal of Geophysical Research Earth Surface, 113, F01009

3. I have problems understanding the presentation of figures and tables. Many captions are currently insufficient for readers to easily grasp the key information. I recommend revising them accordingly (see my detailed comments below).

   Thanks for the Reviewer's comment. We have expanded on and clarified as suggested in your detailed comments.

4. Authors investigated several snow parameters: date of the first snowfall (S_{ON}), the cumulative snowfall (S_T), the peak hourly snowfall rate in a given day in each month (S_p), and the number of snowfall days (S_d). Please explain a bit more about S_p. Based on the definition, I understand the

other parameters are one number for each winter season. However, S_p has multiple numbers for each winter, right?

Thank you for your inquiry. Parameter S_p represents the peak hourly snowfall rate recorded in each day over a given month and therefore has one value for each month per winter season. Here, the analysis is done from Oct.-Dec. so each season will have 4 values. We present these values in Table 2. For use in the frequency analysis (Figure 4), the maximum S_p value for each season is used. Parameters S_{ON}, S_T, and S_d can represent only one value that is cumulative of the study period (Oct.-Dec.). For instance, S_d can represent that total number of snowfall days between Oct.-Dec. This approach of having one number for each winter was used for the frequency analysis (Figure 4). However, S_d and S_T can also be interpreted for each month to better understand within month weather and climate variability (e.g. Table 1 and Table 2). S_{ON} always has one value as it represents the date of first snowfall for each winter.

The snow measurement was made in the "Yellowknife Airport weather station (1942-2023)". Please write more information about snow observations, e.g., instrumentation, data quality, and possible errors.

Thank you for the inquiry. Snowfall data was collected since 1943 using manually methods and automated methods. Manual methods include measuring the amount of freshly fallen snow on a snowboard- this was the approach used in many Canadian weather stations (see Fischer, 2011). The exact date of when automated methods replaced manual methods is currently unknown; however, appropriate inquiries have been made to ascertain these dates. Automated measurements of snowfall are commonly collected using an SR50 Ultrasonic Snow Depth Sensor. Several challenges have been noted in the past on measuring snowfall/depth using SR50s including penetration of ultrasonic pulses through fresh snowfall layers and reflection by deeper, denser layers (Goodison et al. 1988), and lack of spatial representativeness (Fischer, 2011). Data quality assurance and control is provided by ECCC. Data quality flags are described in ECCC's technical documentation here: https://climate.weather.gc.ca/doc/Technical_Documentation.pdf

Fischer, A. 2011. The Measurement Factors in Estimating Snowfall Derived from Snow Cover Surfaces Using Acoustic Snow Depth Sensors. *Journal of Applied Meteorology and Climatology*, 50(3), 681-699. https://doi.org/10.1175/2010JAMC2408.1

Goodison, B. E., Metcalfe, J. R. and Wilson, R. A. 1988. Development and performance of a Canadian automatic snow depth sensor. WMO Instruments and Observing Methods Rep. 33, 317–320.

If there are good snowfall data, I encourage authors to apply an analytical model to calculate the ice thickness and snow-ice, taking into account the effect of snow. See Lepparanta (1993) for a good example of such an analytical model.

This is a great suggestion. An analytical approach can readily be used to estimate total ice thickness. In this study, we intended to only present a statistical approach based on measured data to estimate ice thicknesses but appreciate the applicability of some analytical or semi-analytical methods. As suggested, we applied Equation (20) from Leppäranta (1993): $H^2 = \frac{2k_i S}{[p_i L\left(1+\frac{\lambda k_i}{k_s}\right)]}$, to measured ice thicknesses and present results here. Applied parameters included p_i=916 kg m^{-3}, k_i= 2.2 W m^{-1} °C^{-1}, k_s= 0.1 W m^{-1} °C^{-1}, and L = 334 000 J kg^{-1}. We note to the reader that λ refers to the ratio of snow depths to ice thicknesses, commonly >0.5. Here, we provide solutions using

Equation (20) using both SIMBA measured values of λ averaged over the season (Figure R5, d, e, and f), and also for optimized values (Figure R5, a, b, and c). Optimized values used λ as a calibration parameter to reduce mean absolute errors between SIMBA measured ice thicknesses and those modelled by Equation (20).

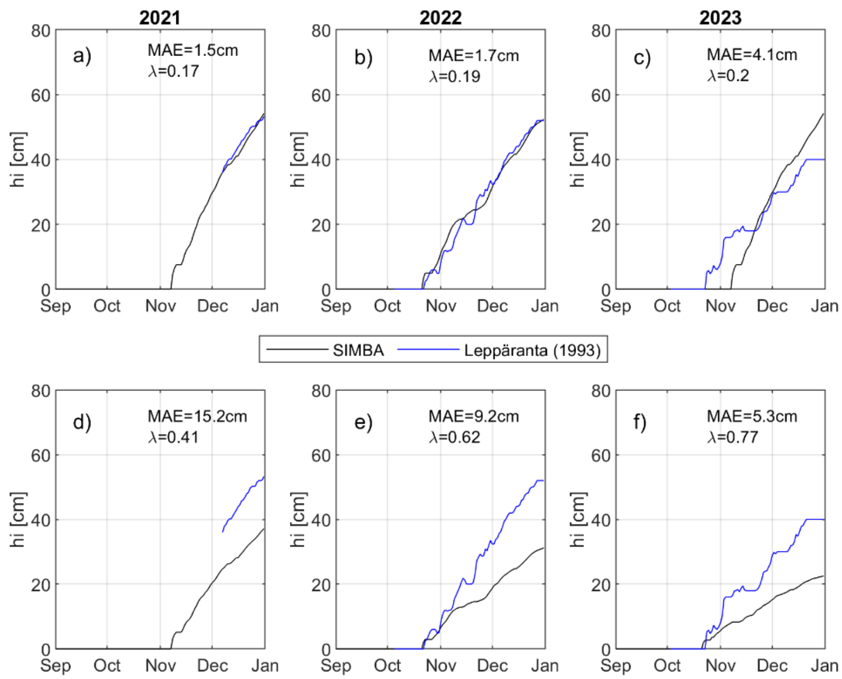

Figure R5: Comparison of SIMBA measured ice thicknesses with an analytical model for ice growth presented in Leppäranta (1993). Plots a, b, and c present results using optimized values of parameter λ, while plots d, e, and f present solutions with average λ calculated using SIMBA measured snow and ice thicknesses.

We observe that errors remain relatively low (less than 5 cm) when λ is calibrated, however, errors increase significantly when using λ measured from field data.

In this study, we chose not to apply an analytical model for snow-ice formation, as we do not present detailed snow density measurement. Without such data, implementing an analytical model would be challenging and would rely heavily on parameter calibration to achieve desired and meaningful results.

Leppäranta M. 1993. A review of analytical models of sea-ice growth. Atmosphere-Ocean, 31(1): 123-138, doi:10.1080/07055900.1993. 9649465.

Detailed comments:

5. Please add a Canada map as a background for Figure 1. I think Photo A can be dropped since Figure 2 shows the details of the SIMBA floating station.

We thank the Reviewer for this helpful suggestion. We explored incorporating a full Canada map as a background for Figure 1 but found that doing so significantly reduced the clarity and spatial detail of the Landing Lake region. Instead, we included a smaller reference map of Canada in the lower left-hand corner of Figure 1 to maintain geographic context.

Regarding Photo A, while we recognize that Figure 2 provides a detailed conceptual overview of the SIMBA Floating Research Station, we believe that Photo A remains valuable as it offers a real-world visual reference of the station's physical setup. In our view, this complements the schematic illustration in Figure 2 and enhances the reader's overall understanding.

6. "Photographs 1, 2, and 3 were taken on October 23, 2023, 105 at 09:00 local time." I don't see any close text to explain those photos. I found at L290, a description "culminating in a FUD of October 23, 2022, 3 days", I would assume this was the explanation of those photos. If so, maybe write: „„at 09:00 local time (see explanation in 5.1), and correct the typo 2022 to 2023. Otherwise, please add text somewhere to explain those photos.

   We thank the Reviewer for noting this. The trail camera photographs in Figure 1 were mainly shown to provide the reader with a perspective few of ice conditions around different sections of the lake during freeze-up. We have extended the caption to describe the intention behind these photographs:

   Figure 1: Site map of Landing Lake, Northwest Territories, including photographs of the Floating Research Station, and perspectives from trail cameras (1, 2, and 3). Photographs 1, 2, and 3 were taken on October 23, 2023, at 09:00 local time and present three perspectives of the lake during the freezing process.

7. Could you edit photo 3 in figure 1 to show a horizontal coastal line?

   We have rotated photo 3 in Figure 1 as per your request so that the coast line is horizontal.

8. It seems to me that the PAR and pressure transducers' data on FRS, as well as turbulent and radiative heat fluxes measurement at the weather station on land nearby, are not used in this study. Please include a brief description of the purpose of these data.

   The primary objective of presenting these measurements was to showcase the full instrumentation setup used at Landing Lake, including the meteorological station on the island and additional sensors on the FRS platform. We acknowledge that not all the collected data were utilized in the present analysis. The turbulent and radiative heat flux data are essential for characterizing the lake's complete annual energy balance. These fluxes are measured at a comprehensive meteorological station located on an island in Landing Lake, while supplementary instrumentation for shortwave radiation measurements is installed on the FRS (Figure 2). Additionally, PAR sensors within the water column are used to estimate light extinction during both the ice-covered and open-water seasons. Although these datasets are not used in this study, they form an integral part of our long-term research framework. Some portions of the data have been published in earlier works (Rafat et al., 2023, 2024; Rafat and Kheyrollah Pour, 2023), and we intend to further explore and publish the remaining datasets in future studies.

9. Figure 2. Please add "lake water surface or ice surface close to the black inverted triangle symbol.

   The terms "water surface" have been added to Figure 2 where requested.

10. Section 3.3 Heat storage: please explain the physical meaning of negative heat storage in this section. Such values were calculated around L315.

We thank the Reviewer for this inquiry. The heat storage here is calculated as a rate of change of mean lake heat content over a one hour period relative to the previous hour. Therefore, a negative number would indicate a cooling or loss of heat in the lake while a positive value indicated.

11. Figure 3. Please explain the symbol “x”. It is hard to see the yellow color of the triangle.

The ‘x’ in Figure 3 indicates extreme values that were >±2.7 standard deviations away from the mean data. We agree that the yellow triangles are difficult to see and have therefore re-rendered the figure with a new colour, provided below for reference.

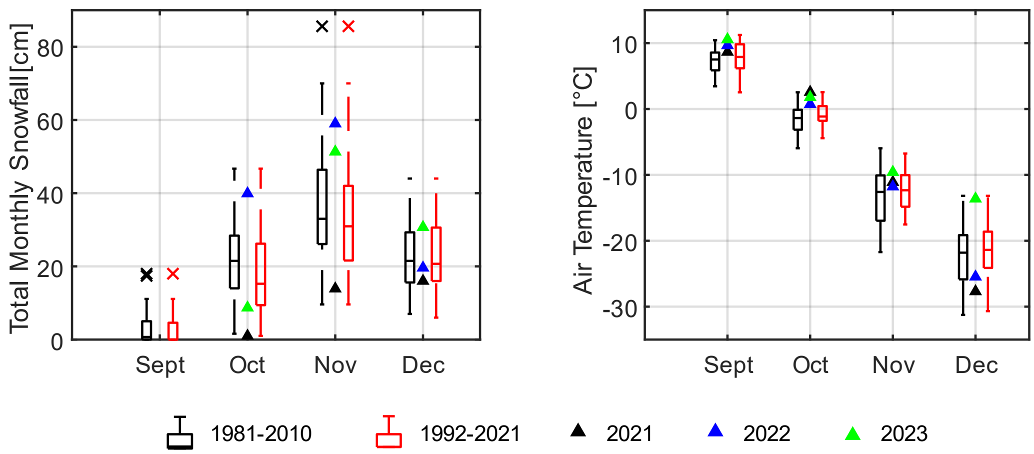

Figure 2: Comparison of a) cumulative monthly snowfall and b) mean daily air temperatures for the September-December period in 2021, 2022, and 2023 against the climate normal (1981-2010) and preceding 30-year record (1992-2021) periods.

12. L219: “The same year saw colder than normal conditions by the end of December with $CFDD$ being 123% of normal”. Please add the number before 123%. Also for those >100% in the following text until L230 if possible.

We have added in the numbers (magnitudes) of snowfall for the percentages as per your recommendation.

13. Table 1. Please explain what those numbers with parentheses (4.1, 10.5). In the Table, I see (Tmin - Tmax),**mean (min, max) monthly cumulative snowfall between 1981-2010 and 1992-2021*.

The bracketed values represent the minimum and maximum daily mean air temperatures in each month. For snowfall, bracketed values represent the minimum and maximum cumulative snowfall values recorded in a given month within the climate normal 1981-2010 and 1992-2021 periods. We see the possible confusion in Table 1 as the dates for the climate normal period “(1981-2010)” are also in parentheses. We have removed parentheses around “(1981-2010)” to avoid this confusion.

14. I would remote “-“ on the 3rd line. Please explain a bit more Sp, see my major comment 4.

“-“ from the third line in Table 2 has been removed as per your request. Sp has been further explained further in the response to major comment 4.

15. Figure 5. Please explain how the surface temperature was measured by SIMBA. Could you add air temperature measurements from the nearby weather station on land for comparison?

Surface temperatures in 2022 and 2023 were measured directly by the SIMBA by noting the temperature reading at the identified air-water interface along the SIMBA thermistor chain. We have added in this information to the caption. Measurements of air temperatures from the Yellowknife Airport weather station compare well to those recorded by the SIMBAs at Landing Lake. Please see a comparison below in Figure R6 of daily mean air temperatures. Values are nearly identical except for slight deviations in very cold weather. We have opted not to include the Ta measured from the Airport to Figure 5 as it would make interpretation difficult due to line clutter.

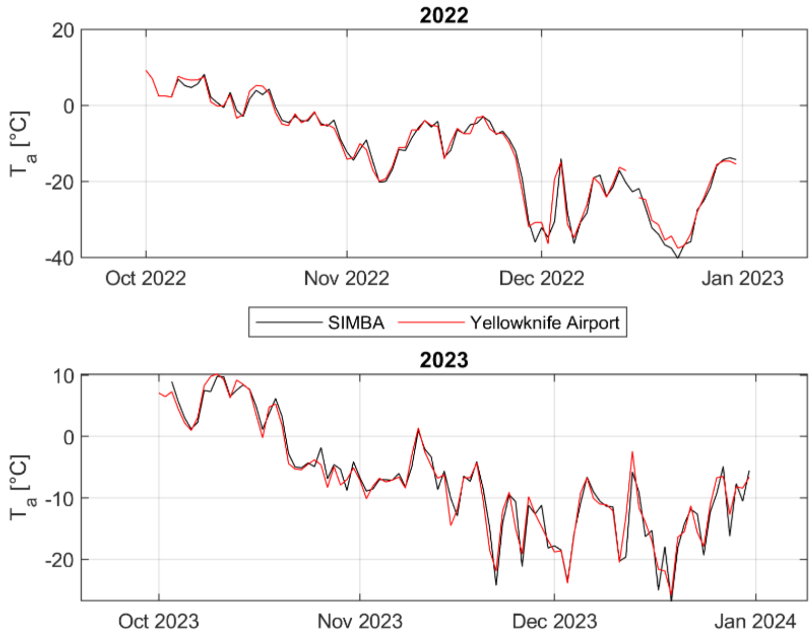

Figure R6: Comparison of daily mean air temperatures measured by the SIMBA and at the Yellowknife Airport weather station located ~11 km away.

16. Table 5. What is "X"? maybe N/A is better?

We agree that "N/A" is clearer. This has been changed.

17. Figure 8. Please explain how those dots (blue, black and red) were obtained.

The dots represent values of $CFDD$ and S_T recorded at the Yellowknife weather station. This has been added to the caption for clarity.

18. Figure 11. Please explain how the observed snow-ice thicknesses were made?

We acknowledge that no clear description was provided in the methods section for how snow-ice was calculated. Rather than inserting how these measurements were made within Figure 11's caption, we chose to add in a description within Section 3.1: Interface detection and manual observations.

Ice thicknesses were calculated as the difference between the identified ice bottom and surfaces, while snow depths calculated as the difference between the snow and ice surfaces. If the ice surface is identified at a position that is higher up the chain than its original position, snow-ice has formed. Therefore, snow-ice thicknesses could be calculated as the difference in these positions.

19. L406: CFDD should b*e CFDD.*

This has been corrected.

20. L79: "inter- and intra- annual variability", maybe good to write "inter-annual and seasonal variability".

We have adopted this phrasing as suggested.

21. "Code and data availability". I am not sure whether the statement the authors made is acceptable to the TC. The data link (https://climate.weather.gc.ca/) is the main page of ECCC. I think the authors should provide the data link that can direct access the air temperatures and snowfall measurements at the Yellowknife Airport weather station between 1942-2023. The lake measurement data sets (weather station, SIMBA) were missing and should be publicly accessible.

We thank the Reviewer for this note.

As recommended, we will provide direct access to the air temperature and snowfall data from the Yellowknife Airport weather station (1942–2023), rather than linking to the general homepage of the ECCC website. We have combined this data into an csv file for ease of use by the public.

We appreciate all the comments provided by this Reviewer and would like to thank the Reviewer for their time in critically assessing the contents of this manuscript.