Response to Reviewer 1:

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

The manuscript presents an empirical model for lake ice formation and growth based on three-year field observations at Landing Lake, Canada. While the methodology demonstrates potential for winter road management and climate change monitoring, several critical issues require clarification to strengthen scientific rigor and practical applicability. Specific recommendations are organized as follows:

Specific comments:

1. Line 61: Correct "Xinjing" to "Xinjiang"

   This spelling error has been corrected.

2. Lines 39-71: Condense discussions on ice phenology studies.

   We thank the Reviewer for this suggestion. We have correspondingly condensed the discussion on ice phenology as follows:

   Phenological changes in lake ice covers have been explored across many northern, high-latitude regions and strongly relate to weather conditions (Huang et al., 2019; Latifovic and Pouliot, 2007; Leppäranta et al., 2017). There is coherence amongst most published literature that lakes across the northern hemisphere are experiencing earlier break-up dates (BUDs), with some exceptions depending on time periods analysed, significance levels attributed to trends, and specific regions. Trends of earlier BUDs have been observed in Canada between 1961-1990 (Duguay et al.,2006) in Sweden between 1870-2010 (Hallerbäck et al., 2022; L'Abée-Lund et al., 2021), Poland (1961-2010; Choiński et al., 2015), Lake Baikal (1869-1996; Todd & Mackay, 2003), and in the Laurentian Great Lakes Region (1975–2004, Jensen et al. 2007). Meta-analysed conducted by Newton and Mullan (2021) and studies derived from the Global Lake and River Ice Phenology (GLRIP) Dataset produced by Benson et al. (2002) spread mostly across North America and northern Europe show similar results.

   Trends in freeze-up dates (FUDs) have shown much greater spatial variability, as ice formation depends strongly on local topography, lake morphology, and lake heat storage (Leppäranta, 2015).Regional trends in FUDs are often masked out, under-represented, or are not available, particularily in meta-analyses where a majority of lake may show later FUDs (e.gs. Sharma et al., 2021; Basu et al., 2024). Within meta-analyses, definitions used for delineating FUDs, and methods of observation of ice formation vary in space and with time creating a challenge for drawing accruate conclusions (Catchpole and Moodie, 1974; Wynne, 2000), as does the length of available data record (Benson et al., 2012; Supplementary Material; Sharma et al., 2021; Supplementary Material). Notable examples of lakes with earlier observed trends in FUDs in Finnish Lapland (1930s-1960s; Korhonen, 2006), Xinjiang (2001-2018; Cai et al., 2020), eastern Canada (1961-1990) and the Great Lakes-St. Lawrence regions (1951-1980) (Duguay et al., 2006), Kazakistan and Tajikistan (2002-2022; Hou et al., 2022), Lativa (1945-2002; Apsīte et al. 2014), Poland (1960-1989; Girjatowicz et al., 2022), Sweden (1913-2014; Hallerbäck et al., 2022), and in the Qinghai-Tibetian Plateau (2002-2021; Sun et al., 2023; 2000-2011; Yao et al., 2016). Trends of earlier FUDs in the last 30 years are of particular interest as they largely contrast findings presented in Newton and Mullan (2021) and Sharma et al. (2021) who argue synchronicity in later freeze-up dates.

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3. Lines 72-77: Expand on the disadvantages of conventional techniques (manual observations and numerical modeling) compared to the FRS system to emphasize research significance. (1) Manual measurements: Labor-intensive with discontinuous temporal coverage. (2) Numerical models: Computationally demanding.

   This is a welcomed suggestion. We have added the following text to describe the disadvantages of conventional techniques while expanding on how the FRS addresses these disadvantages.

   Conventionally, high frequency manual measurements of ice thicknesses and snow depths are constrained by finances, labour, site-access, and ice safety and often result in discontinuous datasets. Numerical modelling provides a continuous alternative to frequent in-situ measurements; however, models may be computationally constrained and still require frequent in-situ observations for appropriate calibration. The use of a Floating Research Station addresses these limitations through offering a cost-effective method to measure ice thicknesses and snow depths at high frequencies, without safety constraints, and can provide the necessary in-situ data to calibrate numerical models.

4. The study focuses on freeze-up, ice-onset, and ice growth. However, the capability of the FRS system to monitor the complete ice thickness cycle (including break-up and melt processes) remains unclear.

   We thank the Reviewer for this inquiry. The Floating Research Station (FRS) was first installed in October 2022 and has since successfully monitored ice thicknesses evolution throughout the year, including during the melt and break-up periods. While this study focuses especially on freeze-up, ice on-set, and ice growth, we acknowledge that a comprehensive analysis for melt processes, and break-up is outside the scope of the present study. However, we have demonstrated the capability of the FRS during the melt and break-up periods in Rafat et al. (2024), where a detailed examination of the FRS during melt and break-up and the recorded ice thicknesses is provided.

   Rafat, A., Kheyrollah Pour, H., Spence, C., and Palmer, M. J. 2024. A field study of lake ice decay. Proceedings of the 27th IAHR Symposium on Ice. Gdańsk, Poland.

5. While the manuscript emphasizes the importance of ice simulation for winter road management under climate change, the empirical model is derived from a small lake (1.07 km^2). Address whether such site-specific relationships can be generalized to larger water bodies or regions with distinct climatic/hydrological conditions.

   This comment is appreciated. To address limitations and applicability of the empirical models, we have added in a small paragraph in the newly created discussion section of the manuscript. This section of text is provided below for your reference.

   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

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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.

We note further that to demonstrate the applicability of the model, we have applied the model to Vee Lake, a lake with similar geometric properties to Landing Lake. Further details are provided in our response to Reviewer Comment 23.

6. Lines 96-101: Add references to support statements about meteorological data requirements.

   We have added references supporting the description of the meteorological data in Yellowknife, Northwest Territories, Canada,

   Spence, C. and Hedstrom, N.: Hydrometeorological data from Baker Creek Research Watershed, Northwest Territories, Canada, Earth Syst. Sci. Data, 10, 1753–1767, https://doi.org/10.5194/essd-10-1753-2018, 2018.

   Environment Canada. Climate Data Online. https://climate.weather.gc.ca/climate_normals/index_e.html, 2025. [April 4, 2025].

7. Section 3.1.1: Clarify MODIS data usage: (1) Specify product version (MOD11A1/MYD11A1?). (2) Justify spatial representativeness: How were pixel quality issues addressed for a 1.07 km² lake under 1 km resolution? (3) Indicate whether day or night data were used.

   1) The MODIS/Aqua Land Surface Temperature/Emissivity Daily L3 Global 1-km SIN Grid product (MYD11A1) was used for reference in this study. 2) We acknowledge the pixel quality challenges associated with a 1.07 km^2 lake and a 1 km^2 grid and potential land inclusions within the pixel. Despite these limitations, the MYD11A1 product was still the optimal choice given the frequency of measurements. As per your suggestion, the MODIS data was compared to optical Sentinel-2 imagery and found good agreement between <0°C surface temperatures and ice appearance on the lake justifying the appropriateness of the selection. 3) Only day-time values were used.

8. Line 167: State the distance between Yellowknife Airport station and Landing Lake.

   The distance (11 km) between the Yellowknife Airport weather station and Landing Lake has been added to this line.

9. Lines 278-288: While agreeing with the 2021 ice-onset (IO) and freeze-up date (FUD) determinations, we recommend utilizing Sentinel-2 imagery for independent validation.

   This is a helpful suggestion. We had previously independently verified the IO and FUD using Sentinel-2 optical imagery which agreed well with these determinations. We had made note of this on L155/156 of the submitted manuscript.

10. Figure 5a: (1) Explain discontinuous T_s curves: Were data gaps caused by cloud masking or quality filtering? (2) Replace connected lines with discrete markers (e.g., circles) for non-continuous MODIS data.

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The discontinuous T_s curve in Figure 5a was the result of both cloud masking and quality filtering of the MODIS/Aqua Land Surface Temperature/Emissivity Daily L3 Global 1-km SIN Grid product (MYD11A1). As suggested, we have replaced the previously connected curve in Figure 5a with only the discrete, MODIS-derived T_s.

11. Definition inconsistency: Ice-onset (IO) and freeze-up dates (FUD) are defined as horizontal lake-wide phenomena (Line 18), yet 2022–2023 determinations rely on vertical SIMBA temperature profiles.

We appreciate the comment and here we are providing further clarity. In 2021, ice-onset and FUDs were defined according to MYD11A1 surface temperatures and Sentinel 2 optical imagery since SIMBA measurements were not available during freeze-up. This had resulted in IO and FUD being defined horizontally as noted by the Reviewer's comment. In 2022 and 2023, SIMBA was used to determine when the surface, at the location of the FRS, had frozen. The IO and FUD were not defined vertically by a threshold ice thickness (e.g. > 3cm), but rather by the appearance of ice on the surface measured by the SIMBA. To rectify differences between 2021 and 2022/2023, we note that the FRS was deployed within the deepest part of Landing Lake and is commonly one of the last locations to freeze. The ice front in Landing Lake progresses from the southern, shallower 'arms' and from the shoreline and continues northward towards the FRS- we describe this progression on L30-35. As such, if ice is identified at the surface near the FRS, it is highly likely that most of the lake is frozen over, thereby additionally satisfying the 'horizontal' criterion implicitly. We hope this satisfies this Reviewer's inquiry.

12. Figure 6: Include time-series plots of SIMBA-recorded vertical thermal profiles to illustrate water column stratification dynamics.

We thank the Reviewer for this suggestion. From investigating select temperature profiles measured by the SIMBA in 2022 and 2023 we noted that: 1) no significant thermal stratification occurs during the open-water season (before FUD) as the lake depth at the FRS is only ~3 m deep and the water well-mixed. Only minor stratification occurs in the upper 6 cm of the lake during the cooling period immediate before IO. 2) Once an ice cover is present, inverse stratification occurs as heat stored in sediments is released over the winter as is typical during the winter periods for shallow lakes. To demonstrate these dynamics, two references figures (Figure R1 and R2) were prepared and provided in response to the Reviewer's comment. While we agree that the SIMBA-recorded temperature profiles may be of interest to some readers, based on the analysis, we have decided not to include an additional subplot for SIMBA time series of thermal profiles within Figure 6.

13. Table 4: Small lakes exhibit low thermal inertia, leading to rapid air temperature responses (11- and 3-day freeze-up durations in 2022–2023). However, the stable water temperature (T_w) in 2022 contradicts this pattern. Analyze potential causes: (1) Assess vertical stratification using mixed-layer depth calculations. (2) Evaluate whether the lake remained fully mixed.

We thank the Reviewer for this comment. The Reviewer is correct in stating that small lakes have low thermal inertia, as was observed in this study; however, we would like to note that T_w in 2022 does not completely contradict this pattern. The FUD, IO, and the freeze-up durations described in Table 4 are consequences of surface temperatures (T_s) falling below 0°C and not from the mean water temperatures presented in Figure 6. Mean T_w in Figure 6b for 2022 do in fact react quite abruptly to large changes in air temperatures, agreeing with the low thermal inertia statement. On L317 we make note of this change: " $\overline{T_w}$ in 2022 declined beginning October 10 at a mean rate of 1.24°C d^{-1}, or 0.30°C per degree decrease in $\overline{T_a}$." T_w was relatively stable, as the Reviewer describes,

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prior to October 11 at ~6.3°C. However, small perturbations were present in response to cooling. This was evident during cooling of T_a on October 5-6[th] when T_a decreased from ~3.3°C to 0.65°C and mean T_w decreased from 6.7°C to 6.3°C. (Figure R1). The effects of cooling T_a were more evident for T_s (Figure 5b) than for T_w (Figure 6b). The consequence of this was a ~ 6 cm layer of stratified water at the surface. Figure R1 below shows this phenomenon in 2022 and Figure R2 for 2023. This surface stratified layer is not to be confused with the friction boundary layer immediately above the water surface. We have identified the water surfaces in each of these figures to help delineate between the two.

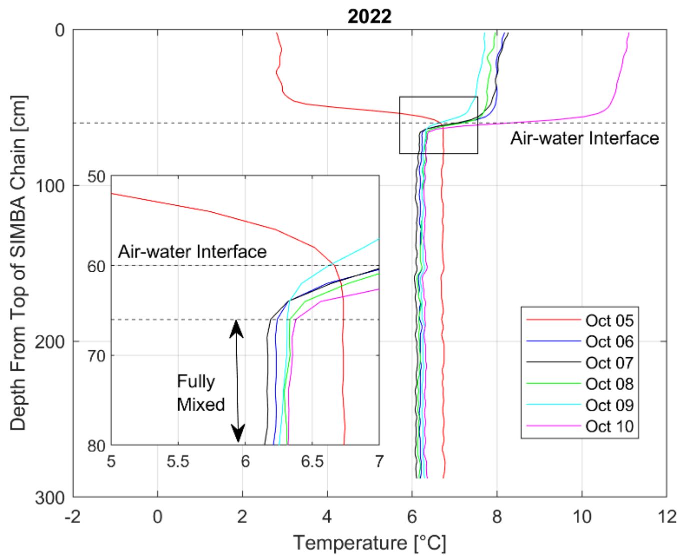

Figure R1: Stratification dynamics in response to cooling air temperatures prior to ice-onset in 2022

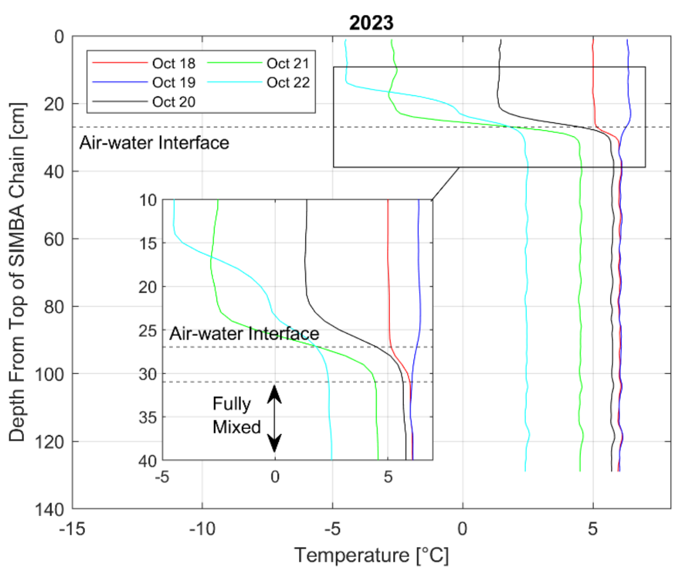

Figure R2: Stratification dynamics in response to cooling air temperatures prior to ice-onset in 2023

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As is evident in Figures R1 and R2, only a weak stratified layer forms on the surface. Deeper waters remain fully fixed. Stable, inverse stratification forms after the FUDs in both years and remains this way for the remaining study period.

14. Figure 7a: Explain the abrupt snow depth reduction on 7 November 2023 (25 cm → < 10 cm). Was this due to melting, compaction, or sensor artifacts?

The reduction in snow depths beginning on November 7th, 2023, was largely from wind scour and redistribution. A significant amount of fresh snowfall (9 cm) had fallen on November 6th corresponding to the large peak in snow depths on November 7th over Landing Lake. Although visually the reduction appears quite abrupt, the timescale over this large reduction in snow depths from 22.7 cm to 8.8 cm is 7 days over which significant wind gusts up to 13.6 m s^{-1} (November 9th, 18:15) were recorded. It is therefore likely that much of the freshly fallen snow was redistributed to elsewhere on the lake, away from the FRS. From Figure 12b, it is also evident that ~1 cm of snow-ice had formed during this period which would corresponding aid to reducing the snow depth. Note that Figure 12 in the original manuscript had a mislabeled legend. The dashed lines represent snow depths and solid lines snow-ice thicknesses. This correction has been made in the revised manuscript.

15. Equations 5a–5b: Replace ambiguous coefficient symbols (e.g., use β, γ instead of α, a) to avoid confusion.

This is a great suggestion and recognize that these coefficients may be confusing, especially α and a. We have replaced a to be γ but have retained the use of α. We chose to retain α as it is commonly used when discussing *CFDD* models and Stefan's Equation.

Equations 5b, c and 6 now read:

$$FDD = \gamma\, e^{bS_T} \tag{5b}$$

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

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

16. Line 380: Strengthen analysis by presenting SIMBA thermal profile time series

Although we acknowledge that the SIMBA-recorded temperature profiles may be of interest to some readers, as noted in response to Comment 12, we believe that these temperature profiles would not offer additional insight beyond what is already presented in Figure 6. Additionally, we have provided two reference Figures (R1 and R2) in response to this Reviewer's comment which aim to clarify water column stratification dynamics in greater details.

17. Figure 8: Provide model results across BT = 0 to -10°C (not 0 to -5°C) to justify selecting BT = -5°C as optimal. Include sensitivity analysis of BT variations.

Figure 8 provides the optimal results for BT=-5°C while Table 6 provides the optimal parameters. We have provided all model results for BT=0 to -10°C for BUDs, FUDs, and parameters α, a, b, and C in Table A1 which is now incorporated as part of the main text of the paper per your following comment.

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18. Lines 387 vs. 395: Conflicting descriptions of BT experimental ranges ("0 to -5°C" vs. "0 to -10°C").

We thank the Reviewer for point out this discrepancy. We have revised L387 so that the BT experimental ranges are consistent (0°C to -10°C).

19. Lines 379–399: Reorganize logic: Step 1: Present BT sensitivity experiments. Step 2: Identify optimal BT (-5°C). Step 3: Report corresponding α, a, b, c Step 4: Show final model performance (Figure 8).

We agree with this comment that the suggested workplace provides better clarity. We have adopted this logic as suggested in the revised manuscript.

20. Lines 411–417: Improve readability by integrating Table A1 into the main text.

We have now integrated Table A1 into the main text, as recommended by this Reviewer.

21. Lines 399–417: Relocate to the Discussion section to critically evaluate: (1) Model applicability across lake types. (2) Limitations in parameter transferability.

This section has been reworked with many parts of L399-417 relocated to the new discussion section as requested. In response to 1), we have made note within the newly created discussion section that the model should only be applied for lakes with similar geometric properties to Landing Lake, *i.e.* small (e.g. < 5 km^2) and shallow (e.g. <5 m deep). For 2), we also make note that parameters should be established for each region uniquely but once established using data from one or a few lakes in a particular region, the parameters could be used for regional scales.

22. Lines 461-463: The statement is debatable, as freeboard can be estimated using Archimedes' principle.

We agree that this statement may be debated. It is correct that Archimedes' principle can be used and is in fact most commonly used. The use of Archimedes' principle is still challenging in practice due to accurate estimates of snow densities. If accurate measurements are available, then freeboard can be readily estimated. We have softened the language of this statement to reflect that the statement is debatable.

The addition of a freeboard component to the model would likely improve simulation strength but at a cost of increased complexity and uncertainty as the accurate estimation of freeboard could be challenging.

23. While the authors aim to develop a simplified empirical model for ice thickness estimation, the interannual variability of coefficients (α, a, b, c) necessitates field-based calibration, severely limiting practical utility. To strengthen conclusions, I recommend: (1) Comparative studies across lakes to establish parameter ranges. (2) Explicit guidance on minimum data requirements (e.g., duration and type of meteorological/hydrological inputs) for reliable model application in the future.

We appreciate the comment by this Reviewer and for the useful criticism. The intention of this study was to establish and present empirical relationships that could be used for simulating ice thicknesses in Landing Lake. While we acknowledge that readers may be interested in variability of the parameters across the Northwest Territories in lakes of varying sizes, this was not the intended purpose of the presented study. We do however now note in the new discussion section that parameter ranges can be established by following a similar analysis in other watersheds or hydroclimatic regions where time series of air temperatures, snowfall, and a few ice thickness measurements are available.

Here we have applied the empirical relationships in Equations 5b, 5c, and 6 for simulation of ice thicknesses in Vee Lake (62.55113°N, 114.35578°W), a lake located ~2.5 km from Landing Lake. This lake was selected as we have collected frequent in-situ measurements using a SIMBA for the periods of roughly Nov. 8, 2022- Dec. 31, 2022, and Nov. 15, 2024- Dec. 31, 2024, which are used for validation. 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. We also present the empirical $CFDD$ vs. S_T curve (Figure R3) for Oct.-Dec. 2024 using the Yellowknife Airport weather station for reference with derived parameters 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 (Table 6). Results are presented in Figure R4.

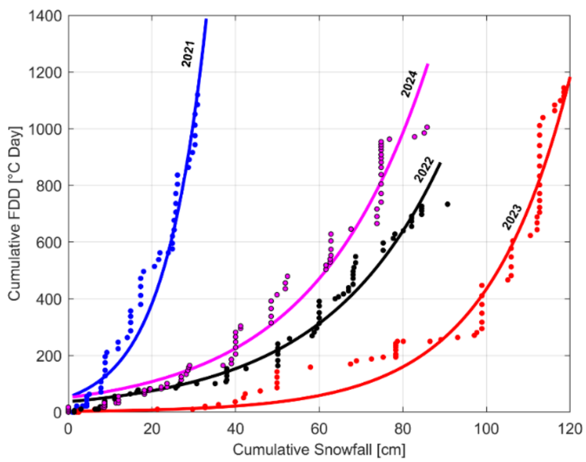

Figure R3: Cumulative freezing degree days (BT=-5°C) versus cumulative snowfall measured at the Yellowknife Airport Meteorological Station between Oct.-Dec. 2021 to 2024.

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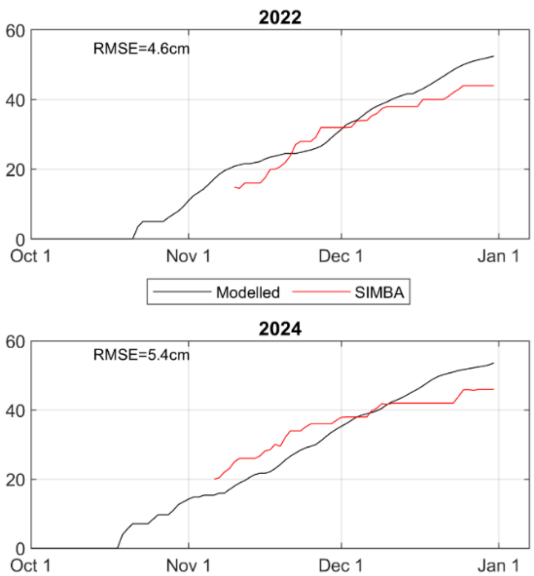

Figure R4: Application of empirical models to a small (~0.8 km^2) and shallow (5.80 m max depth, 1.58 m average depth) lake located ~2.5 km from Landing Lake for 2022 and 2024. Modelled ice thicknesses are compared with in-situ measurements collected by a SIMBA installed in Vee Lake.

Results show good accuracies in simulated ice thicknesses when compared to in-situ SIMBA measurements (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. From this analysis, it appears that three years worth of data proved sufficient to adequately simulate ice thicknesses in a nearby lake.

24. Section 8 (Lines 488–524): Restructure content: (1) Relocate technical discussions (e.g., model assumptions) to the Discussion section. (2) Retain application scenarios and future research directions in Conclusions

We have restructured the manuscript following this, and previous comments by this Reviewer. We greatly appreciate this Reviewer's time in providing critical feedback and suggestions for improvement and believe we have responded to all suggestions and concerns appropriately.