Response to reviewer 1:

Thank you for your valuable comments, we have incorporated them to improve our revised manuscript.

Line 27-28: The reason why this is the case should be clarified to the reader. How does a decline in manual meteorological observations pose a challenge to LIT retrieval?

We thank the reviewer for pointing out the need to clarify the connection between the decline in manual meteorological observations and challenges in LIT retrieval. We have revised the sentence to explicitly explain that reduced meteorological observation networks limit the availability of forcing data required for ice growth models and decrease the availability of in situ observations for retrieval validation. The revised sentence is in line 27 – 29:

The decline in manual meteorological observation networks is posing increasing challenges to LIT retrieval by limiting the availability of meteorological forcing data required for ice growth models and reducing in situ observations needed for retrieval validation (Vincent et al., 2012).

Line 28-30: This is not necessarily true. LIT is difficult to retrieve using remote sensing technologies and only recently through altimetry (Beckers et al, 2017; Mangilli et al., 2022; 2024) have methods developed closer to operational algorithms. Arguably early work on bedfast ice using SAR reveals information on approximate thickness but not true quantitative retrievals. It would be truer to state that there is an interest in the use of remote sensing technologies as a solution to the current issues with monitoring LIT. To amend this a note stating the large body of work using InSAR would be good. The decision to cite Duguay et al., 2015, instead of a list of key papers from the use of InSAR (Lines 65-82) could reinforce this statement.

We thank the reviewer for this valuable clarification. We agree that the previous statement overstated the current capability and operational maturity of remote sensing-based LIT retrieval. We will revise the sentence to clarify that remote sensing technologies represent an emerging solution to overcome limitations associated with declining ground-based monitoring networks, rather than the dominant approach for quantitative LIT retrieval. We will also expand the discussion to acknowledge previous InSAR-based studies and recent advances in satellite altimetry approaches for LIT retrieval. We have revised line 30-34 as below:

As a result, there has been increasing interest in the use of remote sensing technologies as a potential solution for addressing the limitations of traditional LIT monitoring networks. Previous studies have demonstrated the potential of Synthetic Aperture Radar (SAR) for estimating lake ice growth and thickness variations indirectly (Duguay and Lafleur, 2003; Wegmüller et al., 2010; Duguay et al., 2015), while recent advances in satellite altimetry have enabled progress toward operational LIT retrieval approaches (Beckers et al., 2017; Mangilli et al., 2022, 2024).

Line 31-32: This should be more specific, and SAR is a poor example. It would be better to use radar altimeters as an example here.

We thank the reviewer for this helpful suggestion. We agree that the previous statement was too general and that SAR alone was not the most representative example of active remote sensing techniques for LIT retrieval. We will revise the sentence to provide a more specific description of active microwave approaches by including radar altimeters, which estimate ice thickness from surface elevation measurements, while also acknowledging SAR-based methods that use interferometric phase information for monitoring ice growth and thickness variations. We will revise line 35 – 37 as below:

Active microwave remote sensing technologies have shown significant potential for LIT retrieval, including radar altimeters that estimate ice thickness from surface elevation measurements and SAR-based approaches that exploit interferometric phase information to monitor ice growth and thickness variations (Murfitt and Duguay, 2021).

Line 45-47: Why? What is it about radar systems that make this interaction useful for determining LIT? As of this point in the manuscript the main conclusion is that roughness is what drives the backscatter response from lake ice. How does this interaction translate into the retrieval of LIT?

We thank the reviewer for pointing out the need to better explain the relationship between ice-water interface scattering and LIT retrieval. We agree that the original statement did not sufficiently clarify how the backscatter response from the ice-water interface can provide information on ice thickness. We will revise the text to explain that the LIT retrieval mechanism is not directly based on the magnitude of the backscatter response, but rather on the location of the interferometric phase center. Since microwave signals can penetrate freshwater ice, the phase center of interferometric radar measurements can be located near the dominant scattering interface (i.e., the ice-water interface), allowing the retrieved elevation information to be related to ice thickness. We have revised line 51-53:

Overall, the dominant source of radar returns from freshwater ice has been observed to originate from the roughness of the ice-water interface; microwave penetration through freshwater ice causes the interferometric phase center to be located near the dominant scattering interface which provide height information at the ice-water interface (Gunn et al., 2018).

Line 48-59: The discussion on radar altimeter methods is quite short despite the promising recent advances in algorithms. The discussion on the method used here should be expanded.

We thank the reviewer for highlighting that the previous discussion of radar altimeterbased LIT retrieval methods was too brief given recent advances in retrieval algorithms. We will expand this section to provide a more detailed explanation of the physical principles and processing approaches used in radar altimetry. We have revised line 63 – 70:

This has led to increased use of radar altimeters for LIT retrieval on satellites such as CryoSat-2, the Jason series, and Sentinel-6 in recent years (Beckers et al., 2017; Li et al., 2022; Mangilli et al., 2024; Zhang et al., 2026). Radar altimeter-based LIT retrieval over freshwater ice exploits the penetration of microwave signals through the ice column and their interaction with multiple scattering interfaces, where the separation between waveform double peaks (or a step-like break, depending on altimetry mode) at the ice surface and the ice-water interface can be converted into ice thickness (Beckers et al., 2017; Mangilli et al., 2024). Recent developments in waveform retracking and peak detection algorithms have improved the identification of these scattering interfaces, enabling more accurate and robust LIT retrieval from radar altimetry observations (Li et al.,2022; Mangilli et al., 2022, 2024).

Line 60-62: It is worth stating here that fully-focuses SAR altimetry has the capacity to have a resolution of 0.5m which exceeds that of imaging SAR. One aspect missing from the discussion here is that imaging SAR can provided gridded data compared to altimetry which is restricted to tracks. I note only one mention of SWOT which is the exception via the KaRIn sensor.

We thank the reviewer for this important clarification. We agree that the previous comparison between SAR interferometry and radar altimetry based solely on spatial resolution was inaccurate, particularly given recent developments in fully focused SAR altimetry that can provide very high along-track resolution. We will revise the text to clarify that the main advantage of imaging SAR interferometry is its ability to provide two-dimensional gridded observations of lake ice conditions, whereas most radar altimeter measurements remain constrained to satellite ground tracks. The KaRIn sensor of SWOT is more closed to a bistatic interferometry instead of radar altimetry. We have revised line 71 – 74:

SAR interferometry has significant potential for LIT retrieval because it provides large-scale gridded imaging at meter-scale spatial resolution. While recent developments in fully focused SAR altimetry can achieve sub-meter along-track resolution, conventional radar altimeter observations remain primarily limited to measurements along satellite ground tracks (Li et al., 2022; Mangilli et al., 2024; Zhang et al., 2026).

Line 180-188: Because of the lack of citations, to confirm this method is developed by the authors and has not been previously used in the literature?

From former studies that used interferometry for lake ice thickness, Wegmuller et al., 2010 that stated that "From those ice thickness values were then calculated using (4) and starting from a reference height corresponding closely to the height of the ice surface." But the methodological approach wasn't yet fully developed. We have clarified this section in the line 204 – 205:

Our method builds upon the approach of Wegmuller et al. (2010) while further improving its robustness by accounting for the elevation difference between the lake water surface and shoreline.

Line 298: The selection of the 99.7th percentile for ice thickness is unclear. There is expected spatial variability in ice thickness, as authors have mentioned, why use the 99.7th percentile for validation when the maximum retrieved value could not be used instead? This may not need to be clarified in text and just a further explanation in response to the comment here.

We used the 99.7th percentile instead of the maximum retrieved value because consideration of remained interferometric noises, speckle effect, and potential outlier pixel values that might overestimate lake ice thickness. Based on observations that the LIT distribution in each lake is normal, we used the 99.7th percentile as the threshold.

Table 3: This chart is oddly set up. Why are observation data separated by CLIMo simulations? It would make more sense to show observation data versus CLIMo results. I believe it is to display it as increasing values, however, it did not hold for ice thickness, so it does not make sense to do it just for snow depths.

Thanks for the reviewer pointing out this formatting issues. We have revised the chart for better illustrations

Table 3. Snow Depth and Ice Thickness on April 7^{th,} 2015, from In-situ measurements and CLIMo simulations

Lakes & CLIMo simulation	Ice Thickness (cm)	Snow Depth (cm)
Emai	138	19.65
UT9	148	22.75
UT10	140	27.05
UT11	152	22.4
WT	130	24
PK	127	32.05
Lakes Average	139	25
CLIMo 25%	140	20
CLIMo 50%	131	32

Figure 7: The boxplots are very confusing. The results presented in the text are difficult to interpret with the box plots. Primarily because when initially looking at the box plots it appears that the method has done a poor job retrieving ice thickness with mean values being >20 cm less than the CLIMo values. However, re-reading the text does help to clarify a bit the meaning and what should be examined (the red triangles). The recommendation would be to improve the text describing these figures as well as the figures themselves.

Showing the distribution of LIT using boxplots is still important for clarity and transparency, and allows us to present the systematic underestimation of ice thickness in bubbled ice if using mean or median instead of the 99.7th percentile. We have changed the figure caption to improve its clarity to readers in Line 415:

Figure 7. Boxplots for InSAR-derived thickness, CLIMo simulation, and in situ measurements in Ikroavik Lake, Loon Lake, Emaiksoun Lake, West Twin Lake, and East Twin Lake. The red triangles indicate the 99.7th percentile of the InSAR-derived ice thickness distribution, which was used as the representative ice thickness for comparison with CLIMo simulations.

Figure 8: Similar comment to Figure 7. Does not clarify if this is all values or just the 99.7th percentile as specified in the methodology. Why use R2? You are not performing a linear regression. Additionally, the data does

not appear normal, was a normality test performed? Likely a non-parametric correlation coefficient (Spearman's Rho or Kendall's Tau-b) would be better suited.

We have changed the figure caption to improve its clarity to readers, and using spearman correlation coefficient instead.

Figure 8. Scatterplots comparing InSAR-derived lake ice thickness (LIT), represented by the 99.7th percentile of the InSAR-derived thickness distribution, with CLIMo-simulated LIT for each lake under the 25% snow (left) and 50% snow (right) scenarios. The Spearman correlation coefficients (ρ) are shown in each panel. Lakes that are fully frozen to the lake bed are omitted.

Discussion: The results should be placed in the context of existing literature. How does it compare to the results of other studies? Other methods (e.g., altimetry)?

We have revised the discussion section at discussion 4.4 to include more comparisons with existing remote sensing approaches, including radar altimetry-based LIT retrieval methods.

Although the TanDEM-X bistatic InSAR approach investigated here currently exhibits lower quantitative accuracy than recent radar altimetry-based LIT retrievals, it provides a fundamentally different and potentially complementary measurement strategy. In the present study, the mean RMSE is approximately 0.16–0.18 m, whereas recent radar altimetry studies have demonstrated accuracies ranging from approximately 0.03–0.10 m (Mangilli et al., 2022, 2024). Radar altimetry retrieves LIT primarily from the separation of waveform features associated with the snow–ice and ice–water interfaces, with recent retracking algorithms substantially improving the precision of this approach (Mangilli et al., 2022, 2024). In contrast, the TanDEM-X approach estimates the elevation of the dominant interferometric phase center, which is influenced by microwave penetration and scattering within the ice–snow system. Hence, current TanDEM-X immediate interferometry approach is limited due to attenuation or scattering events at bubbled ice layer. However, an important potential advantage of the InSAR approach not only its two-dimensional spatial coverage, using InSAR approach at longer wavelength in future might also have potential to retrieve more acacurate LIT compared to radar altimeter. Where the uncertainty due to the sensitivity of radar altimetry to snow and volume-scattering effects remains an important consideration, that the impact of snow might shift the location of the first echo toward snow surface from the snow-ice interface and lead to overestimation of LIT that is observed in Mangilli et al. (2024). Similarly, volume scattering within bubble-rich freshwater ice may alter the waveform response and complicate identification of the ice–water interface, where its effect haven't been investigated by current Ku-band radar altimetry studies (Li et al., 2023; Mangilli et al., 2022, 2024). These effects motivate further investigation of longer-wavelength bistatic InSAR, for which reduced sensitivity to volume scattering from snow and ice bubble inclusions, and potentially provide a more stable estimate of the dominant ice–water scattering phase center.

Response to Reviewer 2:

Thank you for your valuable comments, we have incorporated them to improve our revised manuscript, specifically the validation between TanDEM-X derived ice thickness and CLIMo simulations.

1. My first impression is that this manuscript may fit better in the scope of the Cold Region Science and Technology (CRST) Journal. Because "TanDEM-X immediate interferometry" is largely a remote sensing technology for EO measurement

We submitted our manuscript to The Cryosphere considering its EGU connection and the use of TanDEM-X developed by an ESA member (DLR). We feel that the manuscript reflects the quantification of a Cryosphere variable using remote sensing observations. The focus of the paper also incorporates thermodynamic modeling of freshwater ice, which The Cryoshpere has extensively published in the past (Li et al., 2023).

2. Once a remote sensing-based LIT product is available, it should ideally be validated against in situ observations. In this study, the retrieved LIT was primarily compared with CLIMo simulations, which may contain systematic errors or biases.

We thank the reviewer for this important comment and agree that contemporaneous in situ observations provide the most rigorous validation for remotely sensed LIT products. We would like to clarify that the primary objective of this study is not to develop an operational LIT product, but rather to investigate the feasibility of using immediate interferometric approaches to derive ice thickness, and the physical relationship between the TanDEM-X interferometric phase center and lake ice thickness using a unique immediate interferometric dataset. As such, this work should be regarded as an exploratory proof-of-concept study.

To strengthen the validation, we have expanded the comparison between CLIMo simulations and available field observations that fell outside the TanDEM-X acquisition extents. In addition to the two lakes originally presented, we will compare CLIMo simulations with in situ ice thickness measurements from six lakes in the study area by Arp et al., 2018. These revision are followed by update in Figure 1, Table 1, Table 3, Figure 7, Figure 8, and Table 5

Also we will note to readers that the comparison between CLIMo and TanDEM-X derived ice thickness only demonstrated that InSAR-based methods show promise in this case study to extract ice thickness, but the RMSE and other metrics does not represents true errors between ground truth and TanDEM-X derived ice thickness.

"It should be noted that the comparison between CLIMo-simulated and TanDEM-X-derived ice thickness demonstrates the potential of the InSAR-based approach to retrieve lake ice thickness in this case study; however, the reported RMSE and other statistical metrics quantify the differences between the two estimates and should not be interpreted as direct measures of the true error of the TanDEM-X-derived ice thickness relative to ground truth."

We also note that CLIMo has been extensively applied and validated for shallow thermokarst lakes in northern Alaska and other and other tundra environments dominated by thermokarst lake development (e.g., Surdu et al., 2014, 2015; Antonova et al., 2016), providing confidence that it captures the regional thermodynamic evolution of lake ice despite the inherent uncertainties.

"Also, CLIMo has been extensively applied and validated for shallow thermokarst lakes in northern Alaska and other tundra environments (e.g., Surdu et al., 2014, 2015; Antonova et al., 2016), supporting its use as a regional-scale representation of lake-ice thermodynamic evolution despite inherent uncertainties in the model inputs and simulations."

3. The treatment of snow is unclear, and the CLIMo snow scenarios are insufficiently justified.

We thank the reviewer for this valuable comment. We did not explicitly include a snow layer in the conceptual workflow because X-band microwave signals are expected to penetrate dry Arctic snow with relatively little attenuation (Gunn et al., 2015). Furthermore, the TanDEM-X retrieval estimates the lake water level using shoreline elevations corrected by the LiDARderived shoreline–water level difference, thereby minimizing the influence of the snow layer on the estimated ice thickness. Any residual influence of snow on the interferometric phase center would contribute primarily to the systematic underestimation discussed in the manuscript and would not affect the agreement between the 99.7th percentile retrieval and the CLIMo simulations shown in the boxplots.

Regarding the CLIMo snow-cover scenarios, we agree our current selection of CLIMo snow scenario is not sufficient. We have incorporated additional in-situ measurements with snow depth to justified our CLIMo snow scenario. Shown in Table 3.

4. How applicable is this methodology in practice? The study uses TanDEM-X data acquired more than a decade ago.

We appreciate the reviewer's comments regarding the practical applicability of the proposed methodology. We have revised the manuscript to clarify that the TanDEM-X pursuit-mode dataset used in this study represents a unique data opportunity rather than an operational observing strategy. TanDEM-X was originally developed for bistatic SAR interferometry, with its primary scientific objectives including the generation of a global digital elevation model, rather than lake ice thickness retrieval (Rizzoli et al., 2017). Consequently, suitable immediate interferometric acquisitions over lake ice are rare, and coordinated field measurements corresponding to these acquisitions are generally unavailable. We have included sentence below:

"TanDEM-X was originally developed for bistatic SAR interferometry, with its primary scientific objectives including the generation of a global digital elevation model, rather than lake ice thickness retrieval (Rizzoli et al., 2017). Therefore, the TanDEM-X observations used in this study represent a valuable dataset of opportunity for investigating lake ice thickness using data acquired for a different scientific purpose."

We therefore emphasize that this work is intended as an exploratory investigation of the physical mechanism linking the interferometric scattering phase center to lake ice thickness, rather than the development of an operational retrieval algorithm. Although TanDEM-X pursuitmode acquisitions are no longer routinely collected, the physical understanding established in this study provides a foundation for future bistatic interferometric missions. In particular, the upcoming ESA Harmony mission, which will acquire passive bistatic observations using the current-era Sentinel-1 C-band signal pulses, offers an exciting opportunity to extend and further develop this retrieval concept for future lake ice thickness studies.

We would also like to emphasize that, although this study is exploratory rather than the development of an operational LIT product, we believe it makes an important scientific contribution to the remote sensing of lake ice. Compared with radar altimetry, which has recently progressed toward operational LIT retrieval algorithms, relatively few studies have investigated the use of InSAR for quantitative lake ice thickness retrieval, despite its considerable potential. In particular, bistatic InSAR offers the capability to provide spatially continuous, high-resolution observations over entire lakes, complementing the track-based measurements of current radar altimeters that are limited in areal coverage and spatial resolution, often only covering large lakes (e.g. Great Slave Lake, Mangilli et al., 2022, Beckers et al., 2017; Li et al., 2023).

Minor Comments:

(a) The structure of the paper can still be improved. Chapter 2 belongs to Data and Methods. Section 5.4 (Future directions) may fit better into the Conclusion chapter

We thank the reviewer for the helpful suggestion. We have revised the manuscript structure accordingly.

(b) Figure 2 needs to be explained in more detail. Also consider drawing frames of these three parts as background in the diagram.

We thank the reviewer for this suggestion. We have revised Figure 2 by improving the graphical layout, adding background frames to distinguish the three major components of the workflow, and expanding the figure caption and corresponding text in the manuscript to provide a more detailed explanation of each processing step.

(c) The third part (3) is not fulfilled in this study; see my major comments 1).

We thank the reviewer for this observation, we have improved our validation parts, mentioned in major comments.

(d) The Discussion is rather subjective; can the authors provide quantitative discussions, e.g., to compare this study with other remote sensing products?

We thank the reviewer for this valuable suggestion. We have revised the Discussion section to include more comparisons with existing remote sensing approaches, including radar altimetry based LIT retrieval methods. We will compare how other studies validated their remote sensing derived ice thickness and RMSE. Described in section 4.4

(e) The quality of some figures can still be improved, e.g., the figure legends and labels are hardly visible in Fig. 7 and Fig. A1.

We thank the reviewer for pointing this out. We have increased the size of the legends and labels to improve its visibility.

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