Responses to comments from Referee 1:

Dear Referee,

Thank you very much for reviewing this manuscript. Your professional insights have been constructive for improving the manuscript. We have basically revised and corrected the manuscript according to your suggestions and have responded to each of your comments in detail, including revisions to the textual descriptions, redesign of relevant sections, and updates to the experimental content. In the document, your comments and suggestions are marked in black, while our responses and the revised sections of the paper based on your suggestions are marked in blue.

General comments

The paper presents a novel approach for estimating the bathymetry of supraglacial lakes by integrating ICESat-2 laser altimetry with Sentinel-2 multispectral imagery. The method combines spectral stratification ("Otsu algorithm") and a classical regression model ("Lyzenga model") and is tested on four lakes in Southwest Greenland. The topic is timely and relevant, and the authors' effort to improve bathymetric inversion accuracy is commendable. The results show modest improvements in accuracy compared to the Lyzenga model without spectral stratification, which are encouraging.

However, the manuscript requires substantial revision before it can be considered for publication. In particular, the methodology needs to be presented more clearly and systematically, with sufficient detail to allow reproducibility and critical evaluation. Below are the main concerns that should be addressed.

We sincerely appreciate your thorough and professional review of the manuscript and the valuable comments you have provided. Your recognition of the research content is highly encouraging for us. We have carefully considered all the comments and questions you raised, and in the following responses, we provide detailed explanations and replies to each of them.

Q1: Title and scope:

The current title implies broad applicability across Arctic supraglacial lakes, which is not supported by the limited dataset used in the study. Since the method is only applied to four lakes in Southwest Greenland, the title should be revised to reflect this scope more accurately. Additionally, the discussion should include a thorough assessment of the method's generalizability to supraglacial lakes on other regions of the Greenland Ice Sheet (and other Arctic ice masses), including potential limitations.

A1: Thank you so much for your valuable comments. The study area selected in this work consists of four supraglacial lakes in southwest Greenland, which is not sufficient to represent the entire Greenland Ice Sheet or the broader Arctic region. Therefore, we have revised the title to *'Southwest Greenland supraglacial lake bathymetry derived from ICESat-2 and spectral stratification of satellite imagery'* to achieve better alignment between the title and the content. In addition, we have supplemented the discussion section to further explore the applicability of the proposed method over larger spatial scales.

Q2: Methodological clarity:

Several key components of the methodology are insufficiently described:

- Lyzenga Model: This model is central to the study but is only briefly introduced. A more comprehensive explanation is needed, including its assumptions (e.g., uniform water clarity, bed type, and spectral behavior). Clarifying these assumptions is essential for understanding the model's applicability and limitations.

A2 (1): Thank you so much for your valuable comments. As you pointed out, the Lyzenga model plays an important role in this study, and it is therefore necessary to provide further clarification of the model. The Lyzenga model is derived from the Beer–Lambert law, in which certain parameters are empirically determined, resulting in its final mathematical expression. This model is particularly suitable for bathymetric inversion in relatively shallow waters. By incorporating partial in situ measurements as constraints, the model parameters can be estimated using algorithms such as the Levenberg–Marquardt (LM) method. The Lyzenga model has been successfully applied in clear oceanic waters and inland lakes. Please see the revised contents as follows:

3.2.2 Traditional Lyzenga model

Both Lyzenga multi-band logarithmic linear model (Lyzenga, 1978, 1985) and Philpot RTE models exploit the exponential attenuation of light in water following Beer-Lambert's law, with Philpot's RTE approach providing explicit physical parameterization of bottom reflectance and water column properties that were empirically combined in Lyzenga's earlier formulation. Unlike the purely theoretical RTE approach, which derives water depth only from optical imagery, this method introduces empirical constraints using a limited number of measured depth values to estimate model parameters. In this formulation, the bottom reflectance (A_d) and the diffuse attenuation coefficient function (g) are treated as constants, where $a_0=ln(A_d-R_\infty)/g$， a_1=-1/g. At this stage, the model equation is written as:

$$Z = a_0 + a_1 \left(R_\omega - R_\infty \right) \tag{1}$$

By integrating the spectral reflectance information from multiple bands, the following expression can be obtained:

$$Z = a_0 + a_i \sum_{i=1}^{n} \ln\left[R_\omega(\lambda_i) - R_\infty(\lambda_i) \right] \tag{2}$$

This represents the commonly used Lyzenga model. In this study, ICESat-2 bathymetric points are incorporated to constrain the empirical parameters of the Lyzenga model, and the parameter estimation is performed using the Levenberg–Marquardt (LM) algorithm.

Reference:

[1] Lyzenga, David R. "Passive remote sensing techniques for mapping water depth and bottom features." Applied optics 17.3 (1978): 379-383.

[2] Lyzenga, David R. "Shallow-water bathymetry using combined lidar and passive multispectral scanner data." International journal of remote sensing 6.1 (1985): 115-125.

- Use of ICESat-2 data: The role of ICESat-2 data in the workflow is unclear. The abstract does not mention it, and the main text provides only a brief reference to its use as training data. It is important to specify how the data is used for calibration of the Lyzenga model: Which parameters are calibrated? And is data from both weak and strong ICESat-2 beams considered. Furthermore, it should be clarified whether the photons identified as originating from the bed are used directly as discrete point data, or if this point cloud is processed into a continuous bathymetric surface beforehand (such as through fitting a smooth model).

A2 (2): Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. It is necessary to clarify several points here. In this study, ICESat-2 data were used to calibrate the empirical parameters of the Lyzenga model, with both strong and weak beam tracks utilized. We have supplemented the manuscript with complete ICESat-2 information, including track details, as shown in Table 1 (the corresponding Table 2 in this document is provided in A34). Moreover, ICESat-2 was applied as discrete point data rather than being fitted into a continuous curve. These clarifications have been fully incorporated into the revised manuscript in the sections on ICESat-2 data processing and model construction.

- Otsu Algorithm: The algorithm is mentioned without adequate explanation. While some details are provided in Section 3.2, a clearer and more complete description of how the algorithm is applied to spectral stratification would benefit readers unfamiliar with this technique.

A2 (3): Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have added further explanation of the Otsu algorithm in the manuscript to make its role in spectral stratification easier to understand. Please see the revised contents as follows:

This study applied a spectral stratification method based on the Otsu algorithm, which automatically determines the optimal threshold without requiring user-defined parameters. The algorithm adaptively selects the threshold according to the statistical distribution of pixel intensities in the image histogram by maximizing the between-class variance and minimizing the within-class variance (Otsu, 1975). By utilizing the penetration characteristics and reflectance differences of water across various spectral bands, multispectral images of water were stratified into four layers: near-infrared band, red band, blue band, and green band.

Reference:

[3] Otsu, Nobuyuki. "A threshold selection method from gray-level histograms." Automatica 11.285-296 (1975): 23-27.

- Training strategy: The manuscript does not specify whether the model is trained individually for each lake or whether data from all lakes are pooled to form a single training dataset. Clarifying this point is essential for evaluating the robustness and scalability of the approach. The authors note (L291) that the method is constrained by the limited availability of ICESat-2 data for training. However, if ICESat-2 data from, say, hundreds of lakes are pooled, the volume of training data could be significantly increased. Conversely, if the model is trained separately for each lake, its applicability would be restricted to lakes directly intersected by an ICESat-2 track, limiting its broader utility.

A2 (4): Thank you so much for your valuable comments; your suggestion provided us with a fresh perspective. The model used in this study is trained separately for each lake. Admittedly, as you noted, if a large number of ICESat-2 datasets (e.g., hundreds of tracks) were used for training, the model's stability would undoubtedly improve. In this study, we chose to build models individually for each lake because the spectral characteristics of the water bodies (i.e., the relationship between water depth and reflectance) vary across different lakes. By dividing the optical imagery into zones based on spectral penetration differences and constraining model parameters with a subset of in situ bathymetry data, we aim to achieve higher inversion accuracy for each lake. Moreover, this spectral-stratified zonal inversion approach is transferable and expandable, and expanding the model's transferability and applicability will be an important focus of our future work.

Q3: Comparison with other methods:

The manuscript would benefit from a broader comparison with recent approaches, such as those proposed by Datta et al (2021) and Melling et al. (2024). Including validation metrics from these methods – applied to the same four lakes – would help contextualize the contribution of the present study and highlight its strengths and limitations relatively to existing techniques. At present, the two models compared in the manuscript – the classical Lyzenga model and the spectral stratified variant – are closely related and yield relatively similar performance. A comparison with more distinct methodologies would provide a more meaningful benchmark and significantly enhance the scientific value of the study.

A3: Thank you so much for your valuable comments. We supplemented the analysis with the radiative transfer equation (RTE) model proposed by Philpot (1987) to perform bathymetric inversion and accuracy validation for the four lakes, following the approach adopted by Lutz et al. (2024). Corresponding contents have been made in the manuscript as follows:

3.2.1 Radiative transfer equation model

The RTE model for bathymetry inversion was proposed by Philpot (1987). It is derived based on Beer-Lambert's law and has been widely applied in oceans and lakes. Its expression is shown in Equation (3) (originally Equation (2) in the manuscript):

$$Z = g^{-1}\left[\ln\left(A_d - R_\infty\right) - \ln\left(R_\omega - R_\infty\right)\right] \tag{3}$$

Where R_ω is the water surface reflectance; A_d is the bottom reflectance; g is a function of the diffuse attenuation coefficients for upward and downward radiance; R_∞ is the reflectance of infinitely deep water; and Z is the water depth.

In Philpot's RTE equation, the parameter determination follows previous studies. Specifically, Ad is calculated from averaging the reflectance values within a 30 m radius around each lake (Moussavi et al., 2020). However, ideal optically deep waters are typically absent within the GrIS region, making it difficult to obtain the reflectance values of spectral bands at infinite water depth. Therefore, following the approach of Melling et al. (2024), this study references the deep-water reflectance values of corresponding bands derived from multiple other Sentinel-2 scenes as substitutes. The values of g are typically adjusted to match the specific wavelengths observed by different satellite missions. The RTE equation is constructed using the reflectance of the green band due to its extended depth range and consistent depth-reflectance relationship up to approximately 10 m, following the approach of Lutz et al. (2024). Accordingly, the corresponding g value for the green band is 0.1413, as determined by Williamson et al. (2018) for Sentinel-2.

References:

[4] Philpot, William D. "Radiative transfer in stratified waters: a single-scattering approximation for irradiance." Applied Optics 26.19 (1987): 4123-4132.

[5] Moussavi, Mahsa, et al. "Antarctic supraglacial lake detection using Landsat 8 and Sentinel-2 imagery: towards continental generation of lake volumes." Remote Sensing 12.1 (2020): 134.

[6] Melling, Laura, et al. "Evaluation of satellite methods for estimating supraglacial lake depth in southwest Greenland." The Cryosphere 18.2 (2024): 543-558.

[7] Lutz, Katrina, et al. "Assessing supraglacial lake depth using ICESat-2, Sentinel-2, TanDEM-X, and in situ sonar measurements over Northeast and Southwest Greenland." The Cryosphere 18.11 (2024): 5431-5449.

[8] Williamson, Andrew G., et al. "Dual-satellite (Sentinel-2 and Landsat 8) remote sensing of supraglacial lakes in Greenland." The Cryosphere 12.9 (2018): 3045-3065.

Q4: Evaluation and visualization:

The evaluation of the method relies solely on scatter plots comparing estimated water depths with ArcticDEM-derived values. While informative, this approach would benefit from being complemented by spatial difference maps to visualize where discrepancies occur. Such maps could reveal whether both models struggle in the same regions and under what conditions, offering insights into potential sources of error and guiding future improvements.

A4: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. Relying solely on scatter plots of error distribution to evaluate the accuracy of the two bathymetric inversion models may not be sufficient. Therefore, this manuscript has been supplemented with spatial maps of bathymetric errors for the four lakes under study — not only for the two models in the original manuscript, but also for the newly added Philpot RTE model — along with a more in-depth analysis of the sources of error, as shown in Figure 1 (corresponding to Figure 6 in the original manuscript)

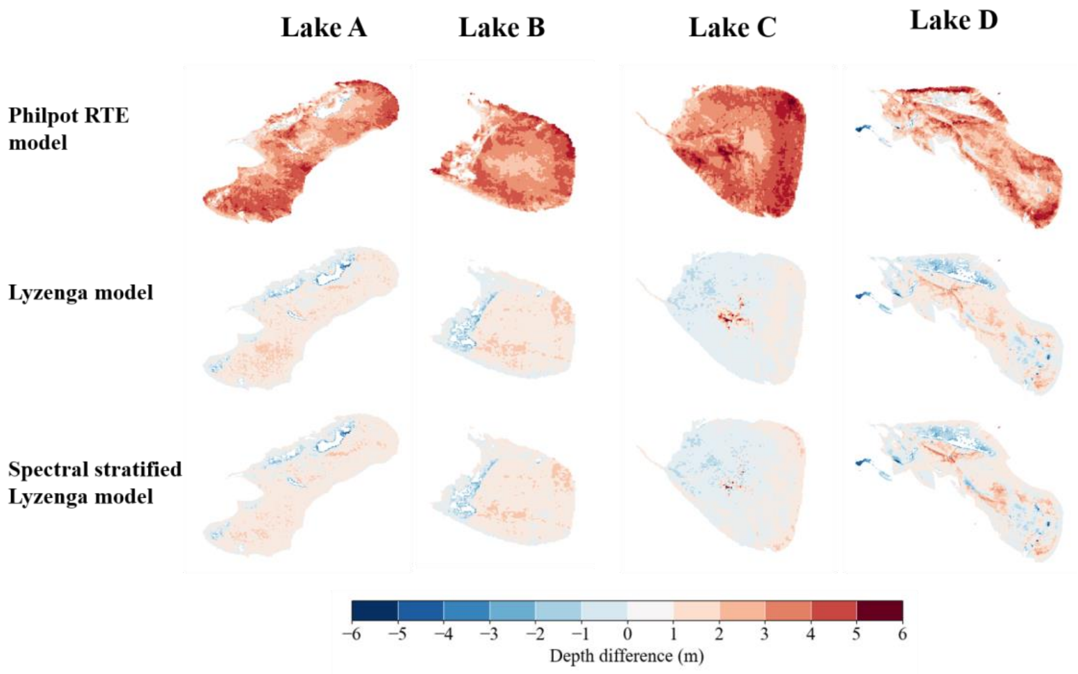

Figure1. Differences between the water results derived from the three SDB models and those obtained from ArcticDEM. Red areas indicate overestimation, while blue areas indicate underestimation.

Summary

In summary, the manuscript addresses an important topic and presents a promising approach. However, substantial revisions are needed to improve clarity, methodological transparency, and contextualization. I encourage the authors to restructure the presentation of the method, provide more detailed descriptions of key components, and expand the discussion to include broader applicability and comparative analysis.

Your comment is constructive for improving the manuscript and makes it more scientifically sound and rigorous. Based on your suggestion, combined with our own understanding, we will comprehensively revise the descriptions of methods, discussions, and related sections.

Specific comments

Q5: L16 + L84: The manuscript states that the four lakes are "representative," but it is unclear what they are representative of. Are they meant to reflect characteristics of all supraglacial lakes across the Greenland Ice Sheet? Please clarify the criteria used for selecting these lakes and substantiate the claim of representativeness.

A5: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. The selected lakes are four relatively large and morphologically intact lakes on the southeast GrIS. These lakes provide favorable conditions for acquiring subaqueous bathymetric points from ICESat-2 and are suitable for applying the method presented in this manuscript. Therefore, they can be considered representative. The corresponding parts in the manuscript have been updated accordingly as follows:

To validate the effectiveness of the proposed method, we apply it to four large and morphologically intact lakes on the southeast Greenland Ice Sheet (GrIS), using time-stamped ArcticDEM (Arctic Digital Elevation Model) strips as reference data.

Q6: L13: In the abstract, the Otsu algorithm is referred to as the "maximum between-class variance method," but the paper does not explain what this entails or how the algorithm functions. A clear description should be added to the methods section.

A6: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have added a more detailed description of the Otsu method in the main text to help readers better understand it. The corresponding revisions in the manuscript are presented earlier in A2 (3).

Q7: L22: The introduction would benefit from a more detailed explanation of the role of supraglacial lakes in glacier dynamics, particularly their potential to rapidly route meltwater to the glacier bed during drainage events.

A7: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have added relevant descriptions of glacier dynamics in the introduction. The revised paragraph is as follows:

These changes in water volume within Arctic SGLs are closely linked to ice sheet dynamics through a critical mechanism: when lake depth and volume reach sufficient thresholds, rapid drainage events can deliver massive amounts of meltwater to the glacier bed, triggering basal lubrication and ice acceleration (Das et al., 2008; Stevens et al., 2015). Observations demonstrate this volume-dependent control on glacier dynamics: a drainage event at Store Glacier transferred 4.8 million m^3 of water to the bed within 5 hours, accelerating ice flow from 2.0 to 5.3 m/day (Chudley et al., 2019), while cascading drainage across lake networks has produced 50-100% velocity increases over distances exceeding 80 km (Christoffersen et al., 2018). Therefore, accurate quantification of lake depth and volume is essential for understanding ice sheet response to climate warming and predicting future sea level contributions.

References:

[9] Das, Sarah B., et al. "Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage." Science 320.5877 (2008): 778-781.

[10] Stevens, Laura A., et al. "Greenland supraglacial lake drainages triggered by hydrologically induced basal slip." Nature 522.7554 (2015): 73-76.

[11] Chudley, Thomas R., et al. "Supraglacial lake drainage at a fast-flowing Greenlandic outlet glacier." Proceedings of the National Academy of Sciences 116.51 (2019): 25468-25477.

[12] Christoffersen, Poul, et al. "Cascading lake drainage on the Greenland Ice Sheet triggered by tensile shock and fracture." Nature Communications 9.1 (2018): 1064.

Q8: L62: Please clarify how this work differs from the authors' previous study (Lv et al., 2024), which also uses Sentinel-2 and ICESat-2 data to derive bathymetry, seemingly for the same lakes.

A8: Thank you for the thorough review of our study. Our previous work applied the combined active–passive satellite remote sensing approach for bathymetric inversion to supraglacial lakes in Greenland. In this manuscript, we propose an optimization strategy for this method by introducing the concept of spectral stratification and zonal inversion, with a particular emphasis on improving bathymetric inversion accuracy.

Q9: Figure 1: Lakes C and D appear to be intersected by both yellow and red ICESat-2 tracks. Why is data from only one track used? Please clarify.

A9: Thank you so much for your valuable comments. The guiding principle for model construction in this study is to ensure, as far as possible, that the acquisition dates of Sentinel-2 and ICESat-2 data are consistent, to minimize the impact of rapid morphological changes in the lakes. Therefore, the Sentinel-2 and ICESat-2 datasets used in this study are paired on a one-to-one basis.

Q10: L140–143: If the L1C dataset is not used in the analysis, it should be omitted from the text and from the workflow diagram in Figure 2. Only the radiometrically corrected L2A data should be mentioned.

A10: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. It is correct that this study did not use L1C data, and the relevant descriptions have been deleted in the manuscript.

Q11: Figure 2: The workflow diagram could be a valuable aid for understanding the method, but several steps are unclear. For example, what is meant by "water column extraction" (is this the lake area delineation?), and what does "SGLs water-leaving radiance" refer to? The figure and its caption should be revised to ensure the diagram is self-explanatory.

A11: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have improved the diagram to make it clearer. The term "water column extraction" refers to isolating the SGLs water portion. We acknowledge that "SGLs water-leaving radiance" is not a strictly accurate expression; it should be "SGLs water-leaving reflectance," which represents the portion of electromagnetic radiation that penetrates the water column and carries information about the subsurface reflectance. To avoid confusion, we have corrected it to "Water reflectance" in the manuscript. Given that Arctic supraglacial lakes are typically clear and possess strong electromagnetic penetration, the reflectance directly obtained from the imagery essentially corresponds to the water-leaving reflectance, making additional emphasis unnecessary. The revised workflow diagram is as follows:

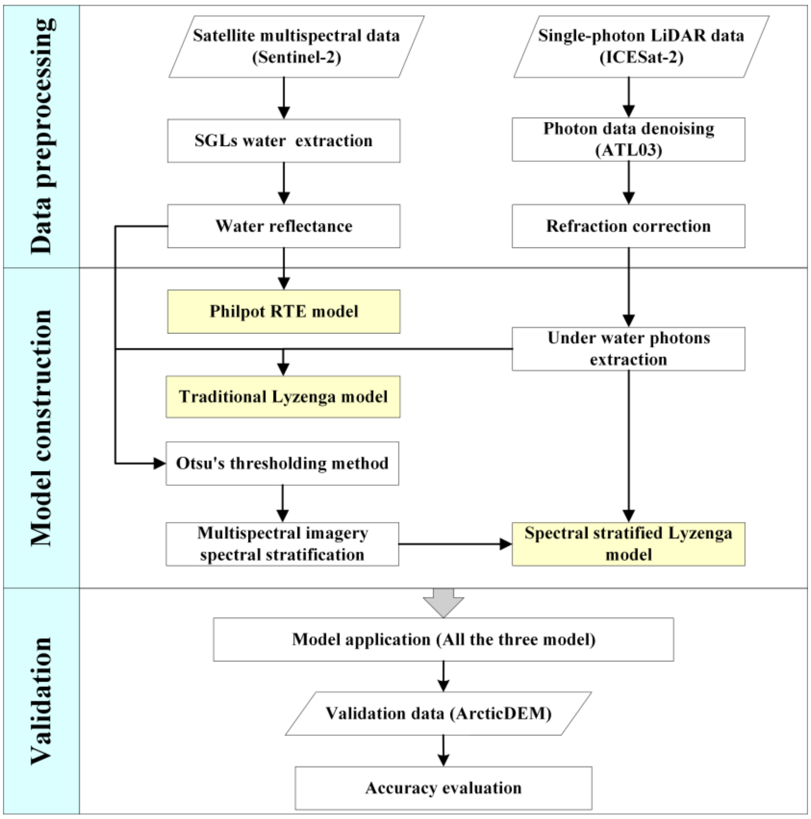

Figure. 2. The workflow of the SDB method.

Q12: L148: Please explain how the ice mask is generated.

A12: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We performed threshold segmentation by combining the global threshold of the grayscale image calculated using NDWIice (different from the NDWI used in the original manuscript; the corresponding experimental procedures have been revised) with manual empirical judgment. The image was divided into water and non-water parts, with the non-water (including ice covering the lake water) portion used as a mask to extract the water body. The revised contents are as follows:

The Sentinel-2 data are divided into L1C and L2A levels. The L1C level data product is a geometric precision correction radiographic product that has not undergone radiometric correction. L2A products are products that undergo radiation correction processing based on L1C. The water column was extracted from multispectral imagery using water-land separation methods, i.e., the Normalized Difference Water Index (*NDWI*), specifically its variant adapted for water extraction in ice–snow covered environments, Eq. (4) (originally Equation 1 in the manuscript) (McFeeters, 1996; Yang et al., 2012)，combined with threshold-based grayscale segmentation.

$$NDWI_{Ice} = \frac{Blue - Red}{Blue + Red} \quad (4)$$

Where *Blue* represents the reflectance at the blue band (corresponding to Sentinel-2 Band 2) and *Red* represents the reflectance at the red band (corresponding to Sentinel-2 Band 4).

The image was divided into water and non-water parts using the $NDWI_{Ice}$, with the non-water portion—including lake ice—applied as a mask to extract the open-water body. As the multispectral imagery contained partially unmelted ice on the lake, this masking process effectively removed ice-covered areas and ensured accuracy during the water column extraction.

References:

[13] McFeeters, Stuart K. "The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features." International journal of remote sensing 17.7 (1996): 1425-1432.

[14] Yang, Kang, and Laurence C. Smith. "Supraglacial streams on the Greenland Ice Sheet delineated from combined spectral–shape information in high-resolution satellite imagery." IEEE Geoscience and Remote Sensing Letters 10.4 (2012): 801-805.

Q13: L172: The vertical adjustment of ICESat-2 photons is mentioned but not clearly described. Please elaborate on the rationale and procedure for this adjustment.

A13: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have provided a more detailed description of this part in the manuscript. In fact, this step was intended to reduce systematic errors caused by temporal inconsistencies in the dataset. The revised paragraph is as follows:

For details, in this study, the actual lake surface elevation corresponding to the remote sensing imagery was determined based on the location of the ICESat-2 profile intersecting the lake boundary extracted from Sentinel-2 data. The difference between the Sentinel-2 water surface boundary and the water surface photon elevation identified by ICESat-2 was then used to vertically adjust the ICESat-2-derived bathymetry. This adjustment is conceptually similar to the tidal correction applied in ICESat-2 bathymetry in oceanic settings.

Q14: L236: The statement that the lake bed consists of “bedrock” is confusing. Supraglacial lakes typically have ice beds, not bedrock. Moreover, since the ice surface evolves over time, some discrepancies between ArcticDEM and Sentinel-2 data collected 2–4 months apart are likely.

A14: Thank you for raising this important point. We acknowledge that our current manuscript does not provide a sufficiently clear explanation. We have revised the original text accordingly, as follows:

The GrIS is covered by ice, and both the ice surface and supraglacial lakes evolve, making short-term morphological changes unavoidable. However, as noted by Echelmeyer et al. (1991), many large supraglacial lakes remain fixed in space because their surface depressions are dynamically supported by irregularities in the underlying bedrock. This bedrock control limits large-scale spatial shifts within short periods, although minor variations are inevitable. Consequently, some discrepancies between ICESat-2-derived bathymetry and ArcticDEM data collected several months apart are expected. Nevertheless, the overall consistency between the two datasets remains strong, as also demonstrated in the experiment by Melling et al. (2024). These differences fall within an acceptable range and do not compromise the reliability of ArcticDEM as a high-quality reference dataset.

References:

[6] Melling, Laura, et al. "Evaluation of satellite methods for estimating supraglacial lake depth in southwest Greenland." The Cryosphere 18.2 (2024): 543-558.

[15] Echelmeyer, Keith, T. S. Clarke, and Will D. Harrison. "Surficial glaciology of jakobshavns isbræ, West Greenland: Part I. Surface morphology." Journal of Glaciology 37.127 (1991): 368-382.

Q15: Figures 6 & 8: What does the “density” color scale represent? Please clarify in the figure captions.

A15: Thank you so much for your valuable comments. The color bar represents point density, defined as the number of validation points within a given Euclidean neighborhood radius. The corresponding description in the manuscript has been revised in the corresponding figure captions.

Q16: Figure 7: Consider adding ICESat-2 track lines and difference maps comparing both models to ArcticDEM, as well as a direct comparison between the two models.

A16: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We appreciate your suggestion. After considering the revised experimental content and the overall structure of the manuscript, we believe that the contents described in Figures 7 and 8 (originally L246–L260) are no longer necessary to retain. This is because we have supplemented spatial error maps for all lake model inversion results relative to ArcticDEM, and all results have been quantitatively evaluated for accuracy. These additions fully cover the information previously presented in those figures.

Q17: L255–258: The claim regarding discrepancies between models should be supported with visual evidence—such as a plot—to allow readers to assess this directly.

A17: Thank you for your suggestion. We no longer retain this section, as the updated figures and analyses already provide comprehensive visual and quantitative comparisons of all model inversion results with ArcticDEM, making the previous description redundant.

Technical comments

Q18: Figure captions: The figure texts (e.g., Figs 3, 5, 6, 9) are repetitive and should be written more concisely. Where appropriate, captions should be revised to ensure that they are self-contained and provide sufficient context for stand-alone interpretation.

A18: Thank you for your suggestion. We have revised the figure texts as suggested, making them more concise and clearer, and ensuring better consistency with the main text. Taking Figure 3 (originally in the manuscript) as an example, the revised figure and texts are as follows:

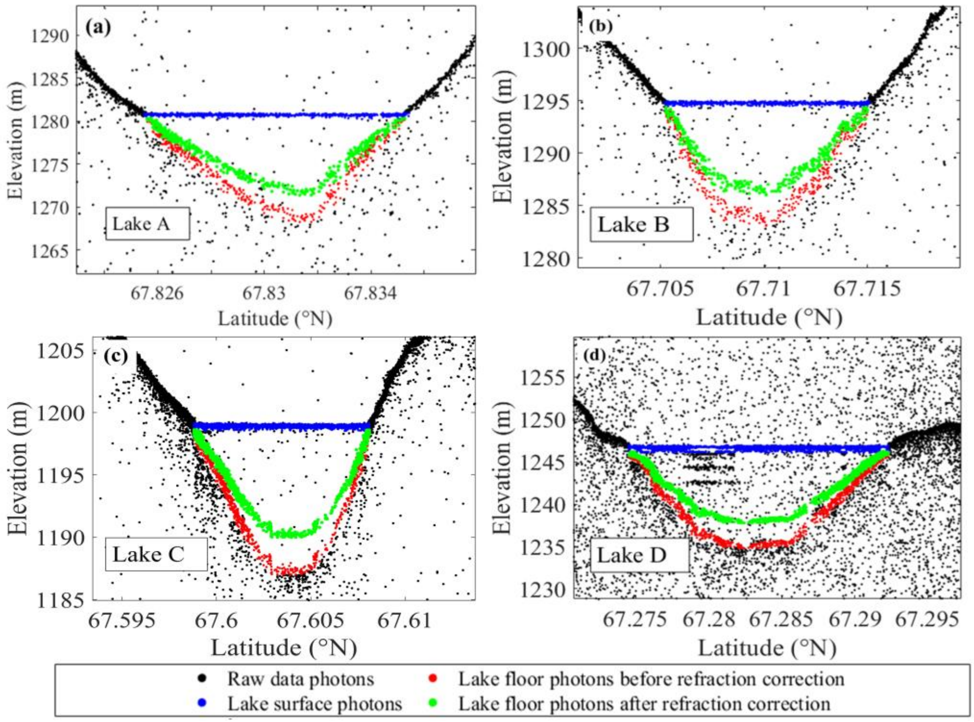

Figure. 3 Extraction and correction of ICESat-2 bathymetry photons for four lakes. (a) Data track for Lake A (b), Data track for Lake B (c), Data track for Lake C (d), Data track for Lake D.

Q19: L10 & L31: An important reason for the limited use of airborne LiDAR and shipborne sonar in supraglacial lake (SGL) bathymetry is the rapid temporal variability in lake depth. This should be explicitly mentioned alongside the logistical and environmental challenges.

A19: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript and added clarifications to more fully and clearly explain the limitations of using airborne LiDAR and shipborne sonar for bathymetry in supraglacial lakes. The revised content is as follows:

Accurate lake depth measurements are essential for reliable volume estimation, yet traditional bathymetry methods (e.g., airborne LiDAR and shipborne sonar) face significant challenges and high costs in the harsh Arctic environment, and are also inadequate for capturing the rapid temporal variability in lake depth.

Q20: L11: Clarify here the nature of the data, i.e. specify that ICESat-2 provides photon-counting laser altimetry and Sentinel-2 offers multispectral optical imagery.

A20: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly.

Q21: L26: Revise to "SGLs are formed *in* surface depressions" for grammatical accuracy.

A21: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly.

Q22: L37: References should be placed immediately after the respective models are introduced to improve readability and attribution.

A22: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly.

Q23: L41: "Precise measurement data" is vague. Specify the type of measurements (e.g., lake surface elevation, lake bed depth).

A23: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly; the term measurement data specifically refers to the water depth data.

Q24: L43–L56: This section is overly broad, focusing on global shallow water bathymetry. It should be shortened and refocused on SGL-specific applications. Conversely, the discussion of prior SGL bathymetry methods could be expanded to better distinguish the proposed approach.

A24: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have reorganized this section to more clearly highlight the bathymetry methods specific to SGLs and to expand the comparison with other related approaches. Corresponding revisions have been made in the manuscript as follows:

In recent years, the launch of the spaceborne single-photon altimetry satellite ICESat-2 (Ice, Cloud, and Land Elevation Satellite-2) has partially mitigated challenges in obtaining precise water depth measurement data (Albright and Glennie, 2020; Li et al., 2023). Numerous studies have integrated multispectral technology with ICESat-2 to conduct bathymetric detection and inversion, leveraging both passive and active remote sensing methods. These studies have yielded significant results, primarily in island reef areas. For the bathymetry inversion in island reef areas. Cao et al. (2016) developed a high-precision bathymetry model for Ganquan Island in the South China Sea by using laser satellite data and optical imagery. This approach leverages active and passive remote sensing techniques, tailored to the specific characteristics and requirements of shallow water bathymetry. Ma et al. (2020) used ICESat-2 data and Sentinel-2 data to retrieve the bathymetry information of the Xisha Islands and Aklin Island in the South China Sea. Chu et al. (2023) considered the penetration limit bathymetry in different bands of multispectral imagery and proposed an SDB method based on spectral stratification, which was successfully applied to the long line reefs in the Nansha area of China and Buck Island in the United States Virgin Islands, improving the inversion accuracy to a certain extent. For the bathymetry inversion in polar lakes, Lin et al. (2012) used multibeam bathymetric data and Landsat TM data to invert the bathymetry of lakes in the Arctic Alaska Coastal Plain. Pope et al. (2016) also utilized the Landsat satellites with the OLI sensor, applying both the Philpot radiative transfer equation (RTE) model and a semi-empirical model based on partial in situ measurements to estimate the water volume of SGLs in western GrIS. The results were evaluated and validated using satellite stereo-derived elevation data. Similarly, Moussavi et al. (2016) also utilized the stereoscopic imaging capability of Worldview-2 data to estimate and validate the bathymetry of SGLs of the GrIS, achieving high accuracy. Williamson et al. (2018) applied this RTE-based approach to Sentinel-2 multispectral imagery. Through the synergistic use of

Sentinel-2 and Landsat 8 satellites, they identified numerous drained lakes, providing algorithmic support for water depth and volume estimation. Melling et al. (2024) used Sentinel-2 data to construct RTE for different bands and validated them with toICESat-2 and ArcticDEM (Arctic Digital Elevation Model) data. Based on a rigorous adherence to physical principles, they evaluated the applicability of the RTE model to SGLs. Fricker et al. (2021) utilized ICESat-2 data to estimate the meltwater depth of the Antarctic ice sheet (AIS) and Greenland, providing a reference for the GrIS and AIS lake water depth inversion. Datta and Wouters (2021) proposed the Watta algorithm, which automatically calculates SGLs bathymetry and detects potential ice layers along tracks of the ICESat-2, focusing on the drainage situation of arctic lakes by utilizing ICESat-2 data and multispectral data. Lv et al. (2024) used the Stumpf model, combined with ICESat-2 and Sentinel-2 imagery, to invert the bathymetry of some SGLs on the GrIS from 2019 to 2023. Lutz et al. (2024) integrated ICESat-2 altimetry, in situ sonar measurements, and the RTE to establish four depth estimation methods, validated against TanDEM-X elevation models, providing a systematic methodological comparison for supraglacial lake depth and volume estimation in GrIS. Feng et al. (2025) integrated ICESat-2 and Sentinel-2 data using a multi-layer perceptron neural network for depth inversion, achieving volumetric evolution monitoring of SGLs throughout the 2022 melt season in southwestern GrIS.

References:

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Q25: L58: Add “to” in “validated them to ICESat-2”

A25: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly.

Q26: L65: Given the multiple examples cited, it is inaccurate to state that the method has “rarely” been applied to SGLs. Please revise accordingly.

A26: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have removed this inaccurate statement, and the revised content is as follows:

In this study, we further extend previous methods for retrieving SGLs bathymetry. Inspired by Chu et al. (2023) on offshore islands and reefs, we applied an improved bathymetric inversion approach for SGLs that combines active and passive remote sensing.

References:

[20] Chu, Sensen, et al. "Shallow water bathymetry using remote sensing based on spectral stratification." Haiyang Xuebao 45.1 (2023): 125-137.

Q27: L74: The claim that the method supports predictions of Arctic glacier melt is overstated. The results pertain to four lakes in Southwest Greenland and should be framed accordingly.

A27: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly and have explicitly clarified that the study area is located in southwestern Greenland.

Q28: L80: Remove “in the Arctic”—the location of the Greenland Ice Sheet is well known and does not need reiteration.

A28: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly.

Q29: Figure 1: Lake D is not visible in the main Sentinel-2 background image. Consider adjusting the inset map to focus on Greenland rather than the entire Arctic to improve clarity of the study area.

A29: Thank you so much for your valuable comments. We have revised the manuscript accordingly. The inset map has been replaced with a section of Greenland. In addition, regarding your comment that Lake D is not visible, this is because some lakes, such as Lake D, were in a dry state at the time of imaging. As you noted, the morphology of SGLs changes rapidly, making it difficult to fully display all four lakes on the same background map. The revised inset is shown as Figure 4 (corresponding to Figure 1 in the original manuscript):

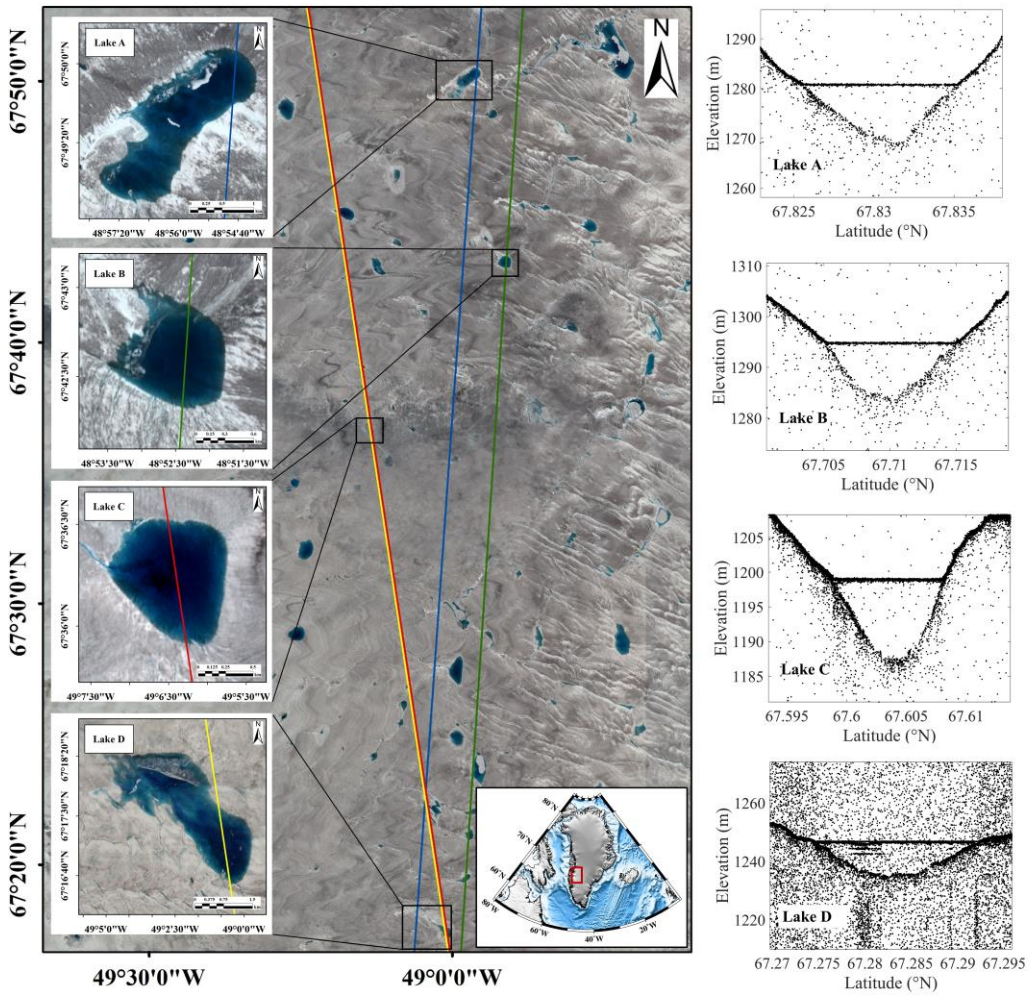

Figure 4 Revised inset map.

Q30: L102 & L114: Provide proper citations for the data sources (e.g., Copernicus Open Access Hub for Sentinel-2, NASA Earthdata for ICESat-2), rather than stating they were "downloaded from the internet."

A30: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly. The revised contents are as follows:

The Sentinel-2 multispectral imagery data were downloaded for free from Copernicus Open Access Hub (https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2).
The ICESat-2 data can be obtained freely from NASA Earthdata (https://search.earthdata.nasa.gov/).

Q31: L109–112: The description of ICESat-2 track geometry is unclear, and several terms are either unclear or possibly misapplied (e.g., orbital spacing). Rewrite this section more concisely and accurately, using standard terminology. Also, specify the ICESat-2 product used (e.g., ATL03), including version number and citation.

A31: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly and provided the complete information for ICESat-2 in Table 1 of the original manuscript. The revised content is as follows:

The ICESat-2 satellite orbits at an altitude of approximately 500 km with an inclination of 92°, observing the Earth's surface between latitudes 88°S and 88°N. The platform is equipped with the Advanced Topographic Laser Altimeter System (ATLAS) single-photon lidar and auxiliary system, which determines the distance between the spacecraft and the Earth's surface by measuring the round-trip time of photons (Markus et al., 2017). The ICESat-2/ATLAS laser emits laser pulses with a wavelength of 532 nm and a width of 1.5 ns at a frequency of 10 kHz, forming overlapping light spots along the Earth's surface with a laser footprint spacing of approximately 0.7 m (Magruder et al., 2021). The left and right points of each beam pair are approximately 90 m apart in the cross-track direction and approximately 2.5 km apart in the along-track direction. Paired tracks are approximately 3.3 km apart in the transverse track direction (Neumann et al., 2021). The detailed information of ICESat-2 used in this study is listed in Table 1. The ICESat-2 data can be obtained freely from NASA Earthdata (https://search.earthdata.nasa.gov/). Due to the rapid morphological changes of SGLs, ICESat-2 data were selected as close as possible in time to Sentinel-2 imagery. This study utilized ICESat-2 point data intercepted from Sentinel-2 data as training data, and assumed a lake water depth of 0 m at the edges of the ICESat-2 tracks. We assume that this study assumes that the depth at the intersection of the ICESat-2 track and the lake's land-water boundary is 0 m.

References:

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Q32: L119: Clarify that ArcticDEM strip data were used, not the mosaic. Include a brief explanation of the dataset's origin (e.g., derived from satellite stereophotogrammetry).

A32: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly. The revised contents are as follows:

It is primarily generated using satellite stereophotogrammetry, covering all land areas above 60° north latitude, with a spatial resolution of up to 2 m, and has a significant reference value for topographic research in the Arctic region.

Q33: L121: Melling et al. (2024) is not the correct reference for ArcticDEM. Please cite the Polar Geospatial Center instead.

A33: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have replaced the incorrect reference with the appropriate one:

Porter, Claire, et al. "ArcticDEM-Strips, Version 4.1." Harvard Dataverse https://doi. org/10.7910/DVN/C98DVS (2022).

Q34: L125: Rather than listing acquisition dates in the text, refer to Table 1 for a clearer overview.

A34: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly by providing all the data details in Table 1 (originally) and removing the textual description. The updated Table is shown below:

Table 2. Detailed information of the datasets used in this study, the acquisition dates are highlighted in bold within the dataset names in the format yyyy/mm/dd.

Study area	Datasets	Data filename
Lake A	Sentinel-2	T22WEA_**20200704**T145921
	ICESat-2	ATL03_**20200706**005932_01630805_005_01_gt2l
	ArcticDEM	SETSM_s2s041_WV01_**20200511**_1020010094C9D900_1020010098791800_2m_lsf_seg3_dem
Lake B	Sentinel-2	T22WEA_**20200704**T145921
	ICESat-2	ATL03_**20200706**005932_01630805_005_01_gt3l
	ArcticDEM	SETSM_s2s041_WV01_**20200511**_1020010094C9D900_1020010098791800_2m_lsf_seg3_dem
Lake C	Sentinel-2	T22WEA_**20220717**T150811
	ICESat-2	ATL03_**20220714**010847_03381603_006_02_gt2r
	ArcticDEM	SETSM_s2s041_WV01_**20220420**_10200100C131A200_10200100C42D4300_2m_lsf_seg1_dem
Lake D	Sentinel-2	T22WEV_**20210715**T151911
	ICESat-2	ATL03_**20210715**182907_03381203_006_01_gt2r
	ArcticDEM	SETSM_s2s041_WV02_**20210312**_10300100BB24B100_10300100BBC0A100_2m_lsf_seg1_dem

Q35: Table 1: Remove “Southwest Greenland Ice Sheet” from the table header—it is redundant given the context.

A35: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly; the updated table has already been provided in the previous response.

Q36: L148: Revise to "unmelted ice cover *on the lake*" to avoid confusion with general ice sheet coverage.

A36: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly.

Q37: L169–171: This important note about temporal alignment between ICESat-2 and Sentinel-2 data should be moved earlier in the manuscript, ideally in the data or methodology section.

A37: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly and have moved this note to the data section; the relevant descriptions have already been listed in our previous response.

Q38: L222: Avoid referring to lake surface ice as “ice sheets,” which has a distinct glaciological meaning.

A38: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We apologize for our oversight and have revised the manuscript accordingly, as well as conducted a thorough check of the entire text.

Q39: L263–269: Consider moving this information into a table and referencing it from the main text to improve readability.

A39: Thank you for your suggestion. We have added figures illustrating the model differences and error analyses (Figure 1 in this document) to make the discrepancies among the models more visually intuitive. The supplementary table is provided below, including the Philpot RTE model as well as the two models originally presented in the manuscript.

Table 2. Accuracy evaluation of the three SDB models for the four lakes.

Study area	Philpot RTE model			Lyzenga model			Spectral stratified Lyzenga model		
	R^2	RMSE (m)	MAE (m)	R^2	RMSE (m)	MAE (m)	R^2	RMSE (m)	MAE (m)
Lake A	0.81	2.94	2.78	0.96	0.54	0.43	**0.97**	**0.47**	**0.37**
Lake B	0.85	3.38	3.26	0.94	0.67	0.53	**0.95**	**0.61**	**0.46**
Lake C	0.92	3.73	3.65	0.97	0.54	0.40	**0.97**	**0.50**	**0.40**
Lake D	0.81	1.68	1.41	0.90	0.76	0.57	**0.91**	**0.72**	**0.52**

Q40: L284: The phrase "low temporal resolution" is misleading. Instead, refer to the "sparse temporal coverage" of ArcticDEM data.

A40: Thank you so much for your valuable comments, which have helped make the manuscript more rigorous. We have revised the manuscript accordingly. The revised contents are as follows:

Compared to the sparse temporal coverage of ArcticDEM data, the method of calculating lake volume using bathymetry information obtained by the study approach is more effective and better meets the needs of long-term, accurate monitoring of lake volume.

Finally, we would like to sincerely thank you once again for your professional and thorough review. Your comments have made our manuscript more rigorous. Admittedly, there are still aspects in the revised manuscript that can be improved, and we will continue our efforts to further advance this work.

Best regards.