egusphere-2025-1632

Responses to comments from Referee 2

Analysis of Long-Term Dynamic Changes of Subglacial Lakes in the Recovery Ice Stream, Antarctica

Comments to the Author

Thank you for the work on the subglacial lakes in the Recovery Ice Stream (RIS), Antarctica (https://doi.org/10.5194/egusphere-2025-1632). This work updates the existing inventory of subglacial lakes in the RIS by remapping the lake outlines and identifying more active lakes within the RIS, making a valuable contribution to the community. The writing is clear and easy to understand. I only have one major comment and a few minor ones listed below.

Response:

Many thanks for your positive comments on our manuscript. We would like to express our gratitude for your insightful comments and suggestions, which have been instrumental in enhancing the quality of our manuscript. The manuscript has been revised according to your comments and suggestions. All changes are marked in the revised manuscript, and an item-by-item response to your comments is provided in this document. In the following responses, we have highlighted the reviewers' comments in **"bold text"**, our responses in "non-bold text", and text extracted from the revised manuscript in *"italic text"*.

Major comments

1. The Results and Discussion section is primarily focused on data description, and very little, if any, discussion is present. I would love to read more interpretations from the authors about their data for justification and curiosity. Maybe consider addressing some of the following questions: What is the core reason that some lake outlines need to be updated? Is it because the existing records are inaccurate, or the lake extent naturally changed (due to different water volume, perhaps) over time? L432 might already provide a short answer from the authors, but I would really love to see a more complete elaboration.

Response:

In the revised manuscript, we have added a paragraph that provides a detailed discussion of the reasons behind the changes in previously reported subglacial lake outlines and the identification of new lakes in this study.

(Line 263 in the marked-up manuscript): "... *During the period of our study, we observe changes in the outlines of four previously reported subglacial lakes (Rec1, Rec2, Rec4, and Rec6), suggesting that subglacial lake outlines are dynamically variable, consistent with the* *findings of Siegfried and Fricker (2021). Among these lakes, Rec1 and Rec6 are reclassified as independent lake systems due to their asynchronous variability patterns, indicating that the spatial outlines, activity intensity, and connectivity relationships of these lakes change over time, reflecting the dynamic characteristics of subglacial hydrological environments. In addition, five previously reported lakes show no significant filling or drainage signals during this period, possibly because the subglacial hydrology in these regions is no longer connected or is in a "dormant" state (Wilson et al., 2025). This observation demonstrates the dynamic co-evolution of ice sheets and subglacial hydrological systems (Fricker et al., 2016). In contrast, the 14 newly detected subglacial lakes may be activated from a previously "dormant" state (Fricker et al., 2016), or their detection may be attributed to the higher accuracy and denser track data of ICESat-2. Compared to previous altimetry data, this allows for capturing denser and more precise spatial details (Siegfried and Fricker, 2021), thus revealing hydrological signals that are previously undetectable. ...*"

2. Why did the draining-refilling pattern change significantly after January 2022 (the end of Period III according to Figure 9)? Why did the water stop migrating from the upstream lakes to the downstream lakes?

Response:

Thank you for bring up this important point that we had not considered in the original manuscript. We agree that it is worth further discussion. In the revised manuscript, we have added a paragraph to discuss this issue.

(Line 496): "... *Examining the spatial patterns in more detail, Fig. 9 shows that during Period III, the system exhibits a relatively consistent "upstream draining - downstream filling" spatial pattern; after January 2022 (the end of Period III), the system's hydrological pattern changes, with overall reduction in drainage and filling amplitudes, and individual event magnitudes generally smaller than during Period III. This systemic transition likely relates to channel erosion mechanisms during drainage events. Siegfried and Fricker (2021) suggested that active subglacial lakes reach drainage thresholds at lower volumes over time, possibly stemming from channel erosion and expansion during drainage processes. In large-scale drainage events, high-volume water flows erode and enlarge subglacial drainage channels (Fricker et al., 2016; Kim et al., 2016). This process improves the water transport efficiency of drainage channels, enabling lakes to generate sufficient water pressure to overcome channel resistance at lower filling volumes, thereby triggering drainage events; correspondingly, the water accumulation needed to reinitiate drainage after emptying also decreases, ultimately resulting in smaller-scale draining-filling cycle patterns. Additionally, subglacial water primarily originates from basal melting (Fricker et al., 2016), and after large-scale drainage in Period III, the time required to reaccumulate substantial water volumes may also limit the scale of subsequent drainage events. After January 2022, the RIS subglacial system's hydrological pattern becomes more complex, generally characterized by drainage in most upstream and midstream subglacial lakes, while the most downstream lakes remain in filling mode. Some lakes show variable draining-filling patterns inconsistent with the overall trend. We hypothesize that this local variability stems from spatial heterogeneity in channel network development; different lakes inherently have different hydraulic gradients, and after experiencing large-scale hydrological activity during Period III, uneven channel erosion intensity leads to varying degrees of drainage threshold reduction among lakes. For lakes experiencing relatively small flow scouring during this period with limited channel cross-section enlargement, their higher thresholds partially persist, thus still requiring greater water accumulation to initiate drainage. Addition-*

ally, differences in basal topography and drainage channel connectivity may further influence individual lake hydrological behavior (Carter et al., 2017; Fricker et al., 2014). Therefore, the pattern shift after Period III likely reflects system readjustment driven by channel erosion, connectivity, and steady supply factors, though process details and regional variations still require higher-resolution observations and model verification in future studies. . . ."

3. Is there any drainage-recharge pattern associated with the geographical distribution of the lakes? In other words, do the lakes have similar patterns within a cluster (lower trough, upper trough, and upstream area) and distinct patterns across clusters? If yes, what does it imply?

Response:

Yes. The lakes within the same cluster do exhibit generally similar filling and drainage patterns; however, there are also individual differences among them. We have added a relevant discussion at the end of Section 4.2.

(Line 384): ". . . *We analyze lakes by clustering them based on their geographic locations and find that some lakes within the same cluster (such as lakes RecN7 and RecN8 in the upper trough region, lakes RecN2 and RecN3 in the lower trough region, and lakes RecN9 and RecN11 in the upstream region) exhibit similar elevation change patterns, indicating a certain degree of regional hydrological consistency. However, lakes within the same region do not change in perfect synchrony, and these differences likely stem from the heterogeneity of basal topography. The hydrological network of the Recovery Ice Stream is strongly controlled by bedrock topography (Fricker et al., 2014), which may lead to different hydrological connectivity pathways even between lakes in close geographic proximity. Therefore, we hypothesize that the hydrological patterns of lakes in the RIS, under the influence of basal topographic features, form a complex hydrological connectivity network, causing lakes to exhibit both a degree of cluster similarity in space while maintaining their unique hydrological characteristics. A more detailed bedrock topography may help to reveal the synchronical pattern of regional draining/filling behavior of lakes, which shall satisfy the mass conservation principle more strictly. . . .*"

Minor comments

1. The authors use the terms "drainage-filling cycle/pattern" and "storage-drainage cycle/pattern" interchangeably. They may need to be unified for clarity. Additionally, I think it is awkward to say "storage event." A rechange event may better describe this dynamic behavior.

Response:

We have standardized our usage throughout the manuscript by consistently using "draining-filling cycle/pattern" instead of alternating between different terms. Additionally, we have replaced "storage event" with "recharge event" as suggested.

2. How did you determine the gap location and width between Rec1-1 and Rec1-2? I ask this because the boundary does not always seem clear to me. For example, data from RGT 0505 (Figure 4c) seems to indicate a wider Rec1-1 section than currently depicted.

Response:

Our current lake outlines are established based on comprehensive analysis of multiple ICESat-2 RGTs. Through observation of these data, it is found that although the two subglacial lakes are geographically close, they exhibit opposite elevation change patterns (as shown in Fig. 4). Based on these distinctly different hydrological behaviors, we classify them as two separate lakes, while recognizing that a transition zone exists between them that is difficult to define precisely. Therefore, we maintain a gap between the lake sections, which represents a conservative approach to avoid incorrectly classifying the transition area as part of either lake. We acknowledge the uncertainty in this outline delineation, particularly in regions where elevation change signals are transitional. Future research will require additional data to further validate and precisely determine the lake outlines. We have added a relevant discussion in Section 4.1.

(Line 248): "… *It is worth noting that the boundary zone between the outlines of these two parts, contains transitional elevation signals that create uncertainty. Therefore, we maintain a gap between the lake sections, which represents a conservative approach to avoid incorrectly classifying the transition area as part of either lake. …*"

3. Please ensure the submitted work adheres to the TC data policy (`https://www.the-cryosphere.net/policies/data_policy.html`). The data availability section does not mention the data generated from the work (e.g., new and updated subglacial lake outlines and elevation change maps for each lake). Please deposit "data that correspond to journal articles in reliable (public) data repositories, assigning digital object identifiers, and properly citing data sets as individual contributions." Additionally, I suggest including visualization(s) (in the main text or as supporting material) that are similar to Figure 3 but encompass all reported lakes. This will enable readers to more easily explore and assess the results.

Response:

Thanks for the suggestion. All the raw data and their corresponding DOIs used in this study are provided in the "Code and data availability" Section of the manuscript. The processed datasets generated using the methods described in this manuscript, such as new and updated subglacial lake outlines, elevation change maps, and the processed results from all raw data sources (ATL06 / ATL11 / ATM / BedMachine), have been deposited at the following link: [`https://zenodo.org/records/15494993?token=eyJhbGciOiJIUzUxMiIsImlhdCI6MTc1ODg2MDM0MSwiZXhwIjoxNzY3MTM5MTk5fQ.eyJpZCI6ImYzNWY2ZjgwLThiNmUtNDg3Zi1iMGJkLTc4MTg4MDVmZDFkOCIsImRhdGEiOnt9LCJyYW5kb20iOiJlYTI1MDBkZGYzOGQ4ZTU3NDgyMWQxZTZiYTUyNzYwZiJ9.3p5UKAEkUWxt84-2e-ca_AF1mA0JgDtrOoUclMuFPr3tm3zQ8j7H7rLLABtktRAwHEGatA9hUmja_316bnNqtg`]. In accordance with the editor's requirements, the link is currently accessible only to the editors and reviewers. Upon acceptance and publication of the manuscript, the link will be made fully open to the public.

In addition, following your suggestion, we have visualized the five previously reported lakes with no observed elevation changes, as well as the 14 newly identified lakes from this study, in a format similar to that of Figure 3. These visualizations have been included in the Supplementary Materials. The Figures S1-S4 placed in the Supplementary Materials are shown below.

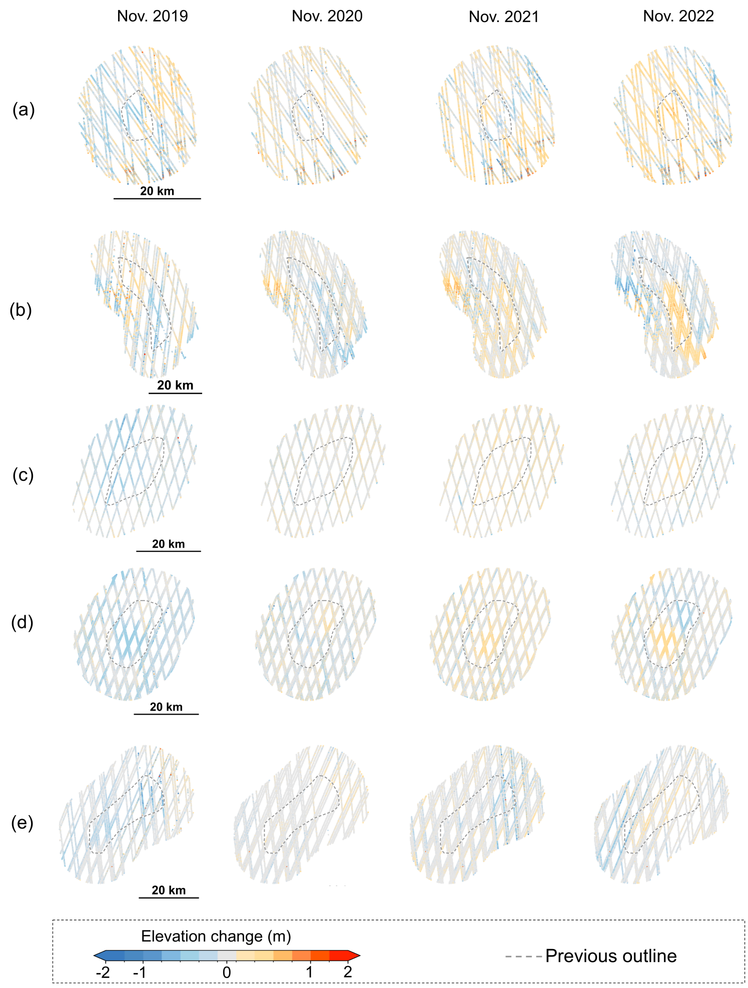

Figure S1: *Previous outlines and annual elevation changes of lakes with no observed elevation changes: (a) Rec3, (b) Rec5, (c) Rec7, (d) Rec8, and (e) Rec9.*

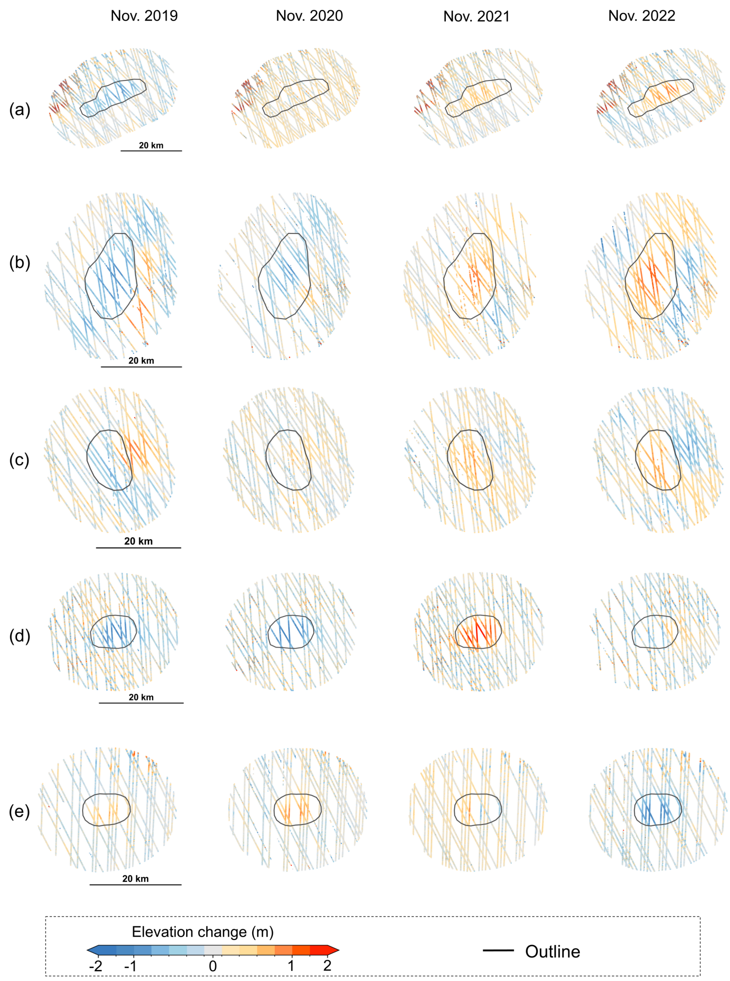

Figure S2: *Outlines and the annual elevation changes of the newly identified lakes (a) RecN1, (b) RecN2, (c) RecN3, (d) RecN4, and (e) RecN5.*

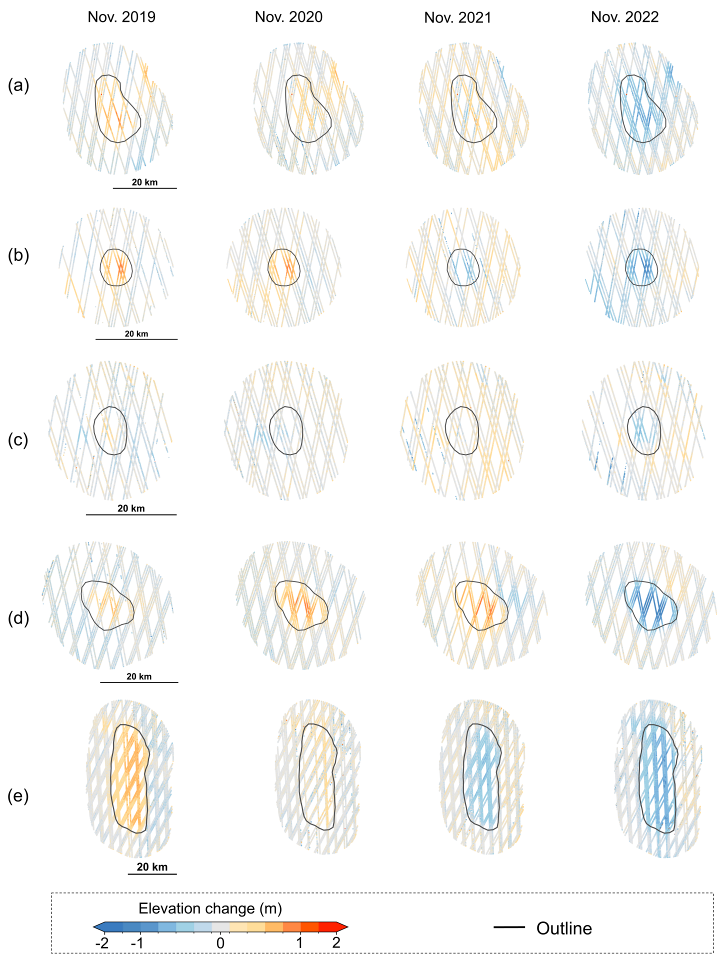

Figure S3: *Outlines and the annual elevation changes of the newly identified lakes (a) RecN6, (b) RecN7, (c) RecN8, (d) RecN9, and (e) RecN10.*

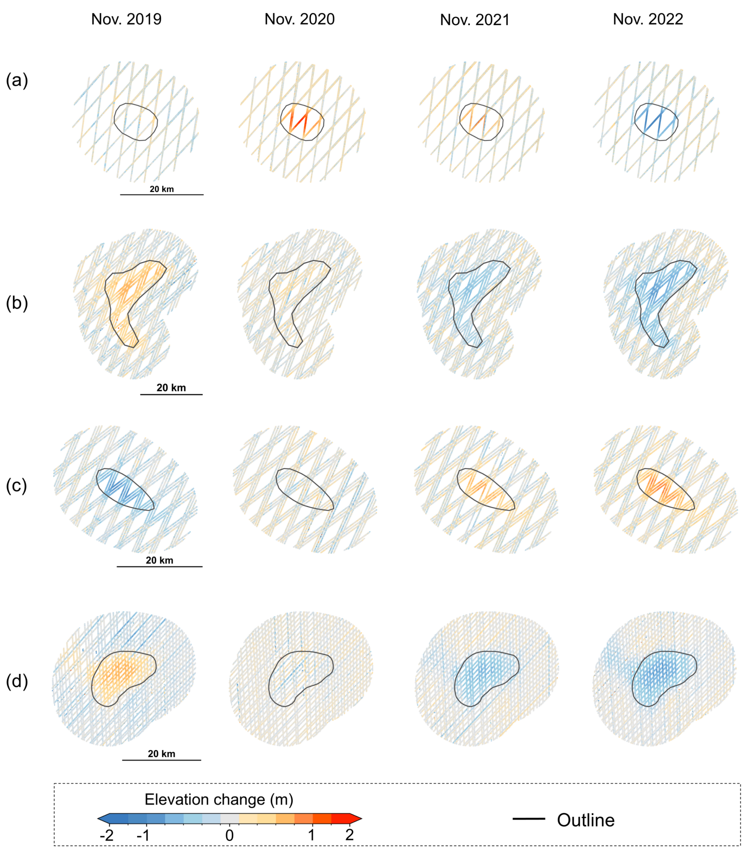

Figure S4: *Outlines and the annual elevation changes of the newly identified lakes (a) RecN11, (b) RecN12, (c) RecN13, and (d) RecN14.*

4. L44: "DEM differencing" is more common than "differencing DEM."

Response:

Thank you for your suggestion. We have corrected the text as suggested.

(Line 44): "... *In response to this situation, the DEM differencing method is often adopted.* ..."

5. L138: What does this slope constraint actually do?

Response:

The "slope constraint" used in our study is primarily designed to minimize errors induced by surface topography. As described by Smith et al. (2009), areas of steeper surface slope are commonly exhibit significant apparent displacement. Additionally, ICESat-2 is not based on exact repeat-track measurements and contains cross-track positioning errors. On sloped surfaces, such horizontal positioning errors directly translate into elevation measurement uncertainties. Although ATL11 data undergoes slope correction, certain uncertainties remain (Liu et al., 2025). Therefore, by applying the slope constraint to filter out these less reliable data regions and improve the reliability of the elevation change signal associated with subglacial hydrological activity. We have added the reason for using slope constraint in the revised manuscript.

(Line 141): "... *Therefore, a slope constraint is used to enhance the reliability of the signal by excluding data from steeply sloping terrain prone to measurement errors (Liu et al., 2025; Smith et al., 2009). ...*"

Smith, B. E., Fricker, H. A., Joughin, I. R., and Tulaczyk, S.: An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008), Journal of Glaciology, 55, 573–595, https://doi.org/10.3189/002214309789470879, 2009.

Liu, J., Tang, D., Cui, X., Chen, L., Xie, H., and Li, P.: An Improved Method for Monitoring Subglacial Lake Activity in Antarctica From ICESat-2, IEEE Transactions on Geoscience and Remote Sensing, 63, 1–14, https://doi.org/10.1109/TGRS.2025.3578437, 2025.

6. Section 3.2.1: I am not sure whether I understand this correctly, but it appears that the reference DEM is created by interpolating only ICESat-2 data. What is the nominal date of this DEM? If it represents elevations from the ICESat-2 era, why does every time series of elevation changes start from 0 in 2004 (Figures 5-7)?

Response:

Following the methodology established by Siegfried and Fricker (2021), we use ICESat-2 mission data from 2018 to 2023 to generate a reference DEM with 100 m spatial resolution, whose nominal date represents the mean topography over the five-year period, and calculate elevation changes for all three satellite missions (ICESat, IceBridge, ICESat-2) relative to our ICESat-2 reference DEM. Then followed Siegfried and Fricker (2018), we subtract the elevation change values at the initial ICESat observation time, Oct 2003, from each time series, normalizing all curves to start from zero. This process aims to highlight relative changes and facilitate direct comparisons of water level variation amplitudes and patterns across different lakes and time periods. We have added a relevant description in the revised manuscript.

(Line 290): "... *This normalization facilitates comparison of variation patterns across different lakes and time periods. ...*"

Siegfried, M. R. and Fricker, H. A.: Thirteen years of subglacial lake activity in Antarctica from multi-mission satellite altimetry, Annals of Glaciology, 59, 42–55, https://doi.org/10.1017/aog.2017.36, 2018.

Siegfried, M. R. and Fricker, H. A.: Illuminating Active Subglacial Lake Processes With ICESat-2 Laser Altimetry, Geophysical Research Letters, 48, https://doi.org/10.1029/2020gl091089, 2021.

7. Equation 1: How did you determine the values of p? I know they are "based on the minimum distance from the elevation measurement points to the lake outline," but I suppose you did a certain conversion or normalization for p, correct?

Response:

Yes, the raw distances undergo normalization to obtain the weights used in Equation 1. We first calculate the minimum distance from each ICESat-2 measurement point to the lake outline using a point-to-polygon distance algorithm. The inside and outside point groups are normalized separately so that the sum of weights within each group equals to 1.

(Line 190): "... p_i, p_j *correspond to the weights, which are assigned based on the minimum* *distance from the elevation measurement points to the lake outline, and are normalized to sum to 1 for the interior and exterior points separately. ...*"

8. Figure 3: Are all panels at the same scale?

Response:

Thank you for this important observation. We have updated Figure 3 and added scale bars to each panel to clearly indicate the spatial scale of each lake.

(Above Line 235)

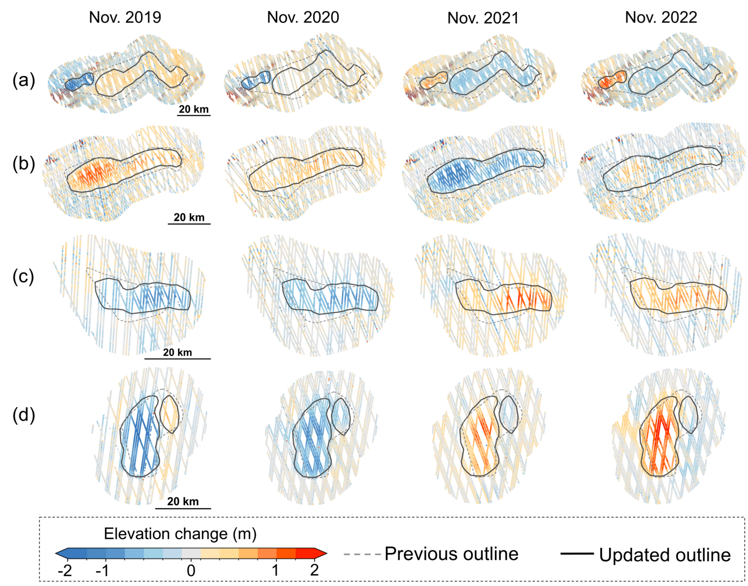

Figure 3: *Updated outlines and the annual elevation changes of lakes (a) Rec1, (b) Rec2, (c) Rec4, and (d) Rec6.*

9. Figure 4 b-d: might need a clearer way to tell readers that only the cyan line (elevation change range) follows the axis to the right. I realized this after multiple reads.

Response:

Sorry for the confusion. We have modified the figure caption to clarify that only the cyan line follows the right axis.

(Above Line 255): "... ***Figure 4.*** *Repeat-track analysis results of lake Rec1. (a) The location of three repeat tracks crossing through lake Rec1. (b-d) show the elevation changes of individual cycles along each repeat track, as well as the overall elevation change range (cyan line, right y-axis) for (b) RGT 0063, (c) RGT 0505, and (d) RGT 0947. ...*"

10. Figures 5-7: What are the exact locations of this time series over the subglacial lake area? I ask this because you mentioned that the elevation change is weaker at the edge than at the center of the lake, and in Figure 8 you showed many time series sampled from different locations within one lake.

Response:

The elevation changes indicated in Figures 5-7 are the overall hydrological dynamics of each lake through spatial weighted averaging based on Equation 1, while Figure 8 shows elevation changes at individual crossovers within the lakes, revealing spatial variations between different locations within the same lake. To avoid any misunderstanding, we have added explanations for Figures 5–7 in the revised manuscript.

(Line 291): "… *The time series in Figures 5–7 represent the weighted average elevation change across the entire lake area. …*"

11. L267: I do not think we have sufficient evidence to say there is a "continuous rise" due to the huge data gap.

Response:

Thank you for your suggestion. We have revised the inappropriate description.

(Line 302): "… *During Operation IceBridge, lake RecN2 shows particularly significant variations, with elevation dropping sharply by over 10 m between October 2011 and October 2012, and then showing an overall elevation increase of approximately 9 m when measured again in October 2018. …*"

12. L275: Again, it is a bit confusing to say "seamless connection" here since the IceBridge data have lengthy temporal gaps.

Response:

We have revised the inappropriate description.

(Line 309): "… *Additionally, the observations from IceBridge in October 2018 show high consistency with ICESat-2 data from the same period, providing reliable connecting data for elevation changes and further confirming the reliability of the observational data. …*"

13. Figure 8: What do the thick dashed lines show?

Response:

In each panel of Figure 8, the thick black dashed line represents the overall weighted average elevation changes for each lake, which serves to validate the consistency and accuracy of elevation change results computed by the differential DEM method and crossover analysis method, respectively. We have add the relevant description in the revised manuscript.

(Line 409): "… *Additionally, it can be observed from the figure that the thick black dashed lines (weighted average results) show consistent trends with individual crossover curves and are located near the median range of all crossover results. …*"

(Above Line 452): "… *The thick black dashed lines represent the weighted average elevation changes of the lakes calculated using the method in Section 3.2.3. …*"

14. L382: Elevations cannot "reach their trough." I suggest finding an alternative to

characterize the time series. Maybe something like "ice surface elevations decrease until August 2020…?" Also, "maximum elevation change of -2.8 m" seems awkward since the value is negative.

Response:

We have revised the relevant statements.

(Line 435): "… *During this period, the crossover elevations decrease until August 2020, achieving their minimum values, with the largest elevation decrease of 2.8 m observed in the central region of the lake, while the elevation decrease in the peripheral region is relatively small at only 0.6 m, resulting in an elevation difference of over 2 m between the central and peripheral regions. …*"

15. L395-398: This should be put in the method section. To estimate the volume change, you multiply the lake area by what?

Response:

In the revised manuscript, we have added an explanation of the volume change calculation in the Methods section.

(Line 194): "… *To characterize the draining-filling dynamics of lakes between adjacent observation months, we conduct a quantitative analysis of volume changes for each lake. Assuming the subglacial lake outlines remain constant, we estimate the volume changes of each subglacial lake using the following approach:*

$$\Delta V = A \times \Delta h, \quad (2)$$

where ΔV is the volume change, A is the lake area calculated based on the lake outline, and Δh is the weighted average elevation change derived from altimetry data. …"

16. L437-438: "Most newly discovered lakes gradually show active trends during the Operation IceBridge and ICESat-2 periods…" I am not sure if it is legitimate to say this; after all, the altimetry method requires the lake to be active to be detected.

Response:

We have revised the inappropriate description.

(Line 543): "… *Most of the newly detected lakes are identified mainly due to their activity during the Operation IceBridge and ICESat-2 periods. …*"

17. L442: Is it always true over time? (see the second bullet point in the major comment)

Response:

We have revised the inappropriate description.

(Line 548): "… *It is suggested that an effective hydrological connection can be established between the subglacial lakes in RIS. …*"