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Responses to comments from Referee 1

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

Comments to the Author

This study uses satellite-observed changes in ice surface elevation to infer subglacial hydraulic activity in the RIS region. It addresses a topic of considerable scientific interest and importance and provides a detailed analysis based on a substantial dataset. The methods are thoroughly described, and the results are presented with substantial detail. However, the manuscript lacks a discussion of the broader implications of the findings. Please see my detailed comments 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. I appreciate the substantial dataset the authors have analyzed and presented in this manuscript. Given the richness of the data, it is especially important to present the findings in a way that is clear and accessible to readers. I recommend highlighting the key takeaway message at the beginning of each subsection or paragraph in the Results section to help guide the reader through the analysis.

Response:

Thanks for the suggestion. We have added key summaries at the beginning of each subsection in the "Results and Discussions" section to highlight the key findings of that subsection.

(Line 229 in the marked-up manuscript): "... *In this subsection, we delineate the outlines of active subglacial lakes in the study area based on elevation change results during the ICESat-2 mission period. Among the nine previously reported subglacial lakes, four remains active during this period, while five show no significant filling or drainage signals. In addition, 14 newly detected subglacial lakes are identified. A detailed description of these three categories of subglacial lakes is provided below. ...*"

(Line 276): "... *In this subsection, we reveal the cyclical filling-draining patterns of all active* *subglacial lakes in the study area using multi-source altimeter data from 2003 to 2023. Based on their spatial distribution, these lakes are categorized into lower trough, upper trough, and upstream of bedrock trough groups for detailed analysis. ...*"

(Line 397): "... *The results reveal significant spatial heterogeneity within individual lakes, with maximum elevation changes consistently occurring in central areas and minimal changes in peripheral regions. ...*"

(Line 442): "... *Based on hydraulic network simulation, we analyzed the relationship between filling and drainage for active subglacial lakes located along the primary drainage pathways. It is indicated that effective hydraulic connectivity can be established between subglacial lakes in the RIS, exhibiting upstream-downstream hydrological connections during different observation periods. ...*"

2. Section 4 is titled "Results and Discussions"; however, in my view, it primarily presents the study's findings with minimal discussion or interpretation of their broader implications. I commend the authors for the significant amount of work invested in this analysis and for the thorough presentation of the results. That said, for a scientific manuscript, it is important to move beyond simply describing findings to interpreting their meaning and situating them within the broader scientific context. For example, what are the implications of discovering a connected subglacial lakes network in a region with significant ice mass loss potential? Could this connectivity influence ice dynamics or impact sea-level rise projections? Additionally, could the methodology presented in this study be applied to other regions of Antarctica? If so, what challenges might arise in extending this approach to different glaciological or observational contexts? These are merely examples intended to encourage the authors to consider the broader scientific context of their work—there is no need to focus on these specific points.

Response:

Thanks for your insightful suggestion. We have expanded Section 4's discussion to include implications of subglacial connectivity for ice dynamics, basal melting, and mass balance of ice sheet.

(Line 519): "... *Through long-term observations from 2003 to 2023, a persistently active subglacial hydrological system is identified in the RIS region, indicating well-established hydrological connectivity beneath the ice. Drainage processes influence ice dynamics by modulating basal friction, thereby potentially promoting ice-flow acceleration (Diez et al., 2018; Wilson et al., 2025). In addition, the drainage regime in the RIS region is characterized by long-term, sustained water transport rather than episodic outburst floods. This slow but persistent subglacial drainage may be more effective in enhancing basal melting of the ice shelf (Gourmelen et al., 2025). When subglacial freshwater discharges into the ocean from the grounding zone, it has the potential to generate buoyancy-driven plumes that draw warmer deep ocean water toward the base of the ice shelf, thereby intensifying basal melt rates (Gourmelen et al., 2025). This effect is particularly pronounced in RIS, where the zone is deeply situated below sea level and terminates in a floating ice shelf, making the system more susceptible to thermal erosion by warmer water and further destabilizing the ice shelf (Golledge et al., 2017). Moreover, model projections suggest that a significant portion of future ice loss in East Antarctica may originate from the RIS region, with the timing and magnitude of retreat in this area determining East Antarctica's overall contribution to future sea-level rise (Golledge et al., 2017). However, current ice sheet mass loss projections do not systematically account for the influence of sub-*

glacial drainage processes (Wilson et al., 2025), while the subglacial discharge significantly contributes to ice shelf basal melting, ice stream acceleration, and ice thinning (Gourmelen et al., 2025). Therefore, the well-connected subglacial lake system and sustained drainage behavior in the RIS region may take on heightened importance. . . ."

3. The authors estimate lake volume change by multiplying ice surface elevation change by the estimated lake area. While this method can provide a first-order approximation of subglacial water movement and is acceptable for comparing drainage and filling timing, it is known to be an oversimplification (e.g., Stubblefield et al., 2021, `https://doi.org/10.1029/2021GL094658`). More accurate volume estimates require consideration of additional physical processes and ice–water interactions. The limitations of this approach should be explicitly acknowledged in the Discussion section, along with a justification of why it is appropriate for the specific goals and scope of this study.

Response:

Yes, we acknowledge that our approach of multiplying ice surface elevation change by a constant lake area only provides a first-order approximation. We have added the method's limitations and applicability in the Discussion section.

(Line 491): ". . . *In this study, the core purpose of using volume changes is to analyze connectivity between upstream and downstream lakes, rather than pursuing absolute precise volume. As demonstrated by Stubblefield et al. (2021), this simplified estimation based on constant area (due to its failure to account for viscous ice flow effects) leads to underestimation of true volume changes and overestimation of lake extents. The limitations of this method must be acknowledged. . . .*"

Minor comments

1. Line #108: "To maximize measurement accuracy" could be more precisely phrased as "To minimize uncertainty" or "To reduce noise in the data," depending on the intended meaning.

Response:

We have replaced "To maximize measurement accuracy" with "To minimize uncertainty".

(Line 108): ". . . *To minimize uncertainty, we only retained data collected along the nadir track . . .*"

2. Line #124: "with 500 m resolution" would be clearer as "with 500 m horizontal resolution" to specify the dimension being referred to. The same for line #126.

Response:

We have replaced "500 m resolution" with "500 m horizontal resolution".

(Line 125): ". . . *with 500 m horizontal resolution. . . .*"

(Line 127): ". . . *with a horizontal resolution less than 10 m. . . .*"

3. Line #128: Why not obtain bedrock elevation directly from datasets such as Bedmap3 or BedMachine?

Response:

We did obtain the bedrock elevation directly from the BedMachine V3 dataset. The description in the original manuscript was intended to detail the methodology used by BedMachine V3 to generate their bedrock elevation product. To avoid any misunderstanding, we have removed the details regarding the generation of the bedrock elevation product in Bed Machine V3.

(Line 128): "... *The bedrock elevation is obtained from BedMachine V3. ...*"

4. Lines #135 and #151: The basis for selecting the "0.5 m threshold" (line #135) and the "10 km" value (line #151) is unclear.

Response:

The 0.5 m elevation change threshold is a well-applicable empirical threshold, which is widely adopted in Antarctic subglacial lake studies (Fricker et al., 2014; Smith et al., 2017). Particularly in historical studies of our study region, the RIS, active lake detection has also employed this threshold (Fricker et al., 2014), demonstrating that this parameter can effectively capture the elevation change characteristics of active lakes in the study area. The 10 km outward extension distance is also an empirical value in the active subglacial lake studies (Siegfried and Fricker, 2021). We have added an explanation in the revised manuscript regarding the selection of these two value.

(Line 135): "... *A 0.5 m elevation change threshold is an empirical value widely used in Antarctic subglacial lake studies (Fricker et al., 2014; Smith et al., 2017) and previously applied in the RIS (Fricker et al., 2014). Therefore, a 0.5 m threshold is set for the magnitude of elevation change to filter potential active subglacial lake regions. ...*"

(Line 155): "... *This empirical value, commonly adopted in active subglacial lake studies (Siegfried and Fricker, 2021), ensures the lake-induced elevation change signal is fully captured and distinguishable from regional background signals. ...* "

Fricker, H. A., Carter, S. P., Bell, R. E., and Scambos, T.: Active lakes of Recovery Ice Stream, East Antarctica: a bedrock-controlled subglacial hydrological system, Journal of Glaciology, 60, 1015-1030, https://doi.org/10.3189/2014jog14j063, 2014.

Smith, B. E., Gourmelen, N., Huth, A., and Joughin, I.: Connected subglacial lake drainage beneath Thwaites glacier, west Antarctica, The Cryosphere, 11, 451–467, https://doi.org/10.5194/tc-11-451-2017, 2017.

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.

5. Line #148: "elevation changes of subglacial lakes" would be more accurately phrased as "elevation changes of the ice surface above subglacial lakes".

Response:

Thanks for pointing out the imprecision statement in the original manuscript. In our method, we subtract the surface elevation changes outside the lake from the elevation changes inside the lake to isolate the elevation change signal specifically attributable to subglacial lake activity (filling/draining) by removing background signals from other factors, such as snowfall accumulation and ice flow. Therefore, the final result represents the elevation changes induced by subglacial lake activity. We have revised this sentence to make the expression more accurate.

(Line 152): "… *and obtaining elevation changes induced by subglacial lake activity from 2003 to 2023 using multi-mission altimetry data by differencing elevation changes between inside and outside the lakes. …*"

6. Line #253-254: There appears to be a repeated or redundant statement in this section.

Response:

We have removed the redundant statement about elevation change calculation.

7. Line #391: more elaboration is needed for "the first-order and second-order stream network".

Response:

The analysis utilized the Strahler stream ordering method, classifying the subglacial hydrological network into six distinct orders. Subglacial water flows along these streams, gradually converging from lower order streams to higher order streams, with the flow becoming progressively stronger. In our study, the activity of subglacial lakes located along the highest-order and second-highest-order stream networks are analyzed. We have added more detailed description of the stream network.

(Line 448): "… *Based on the Strahler (Strahler, 1957) method, we classify the hydrological network into six distinct orders. Subglacial water flows along these streams, gradually converging from lower order streams to higher order streams, with the flow becoming progressively stronger. In this study, we focus on the activity of eleven active subglacial lakes (blue areas in Fig. 9(a)) located along highest-order and second-highest-order stream networks. These networks constitute the primary drainage pathways within the system, forming the main trunk channels where subglacial water from extensive upstream catchments converge, resulting in maximized water fluxes. …*"

(Above Line 471):

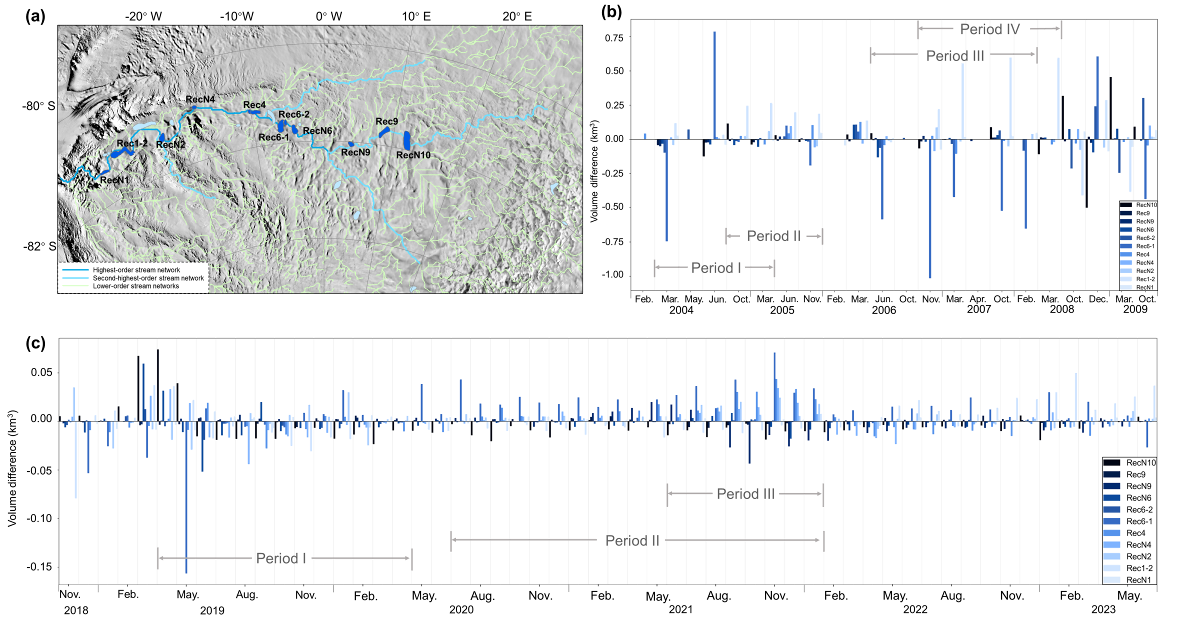

Figure 9: *(a) The simulated distribution of hierarchical hydrological networks in the subglacial hydrological system. (b) and (c) present the histograms of elevation differences between adjacent observation months of eleven lakes along the highest-order and second-highest-order stream networks during ICESat and ICESat-2 missions, respectively.*