Response Letter

Reviewer comments 1:

Overall comments

This paper effectively utilizes a wide variety of remote sensing datasets and methods to enhance our understanding of the dynamics and surge history of the NKG basin in the Eastern Karakoram. It effectively demonstrates a novel application of Jason-3 altimetry data to measure elevation changes of glaciers and glacial lakes, as well as a new approach for automatically mapping glacier extents and terminus positions using Sentinel-1 SLC images. These methods have potential for widespread application within High Mountain Asia and other glaciated regions, increasing our ability to efficiently monitor glacier change over time.

The authors provide a detailed description of surges in NKG I and NKG V, employing sound methods that are generally well described. However, I believe the uncertainty analysis requires more detail, particularly regarding the uncertainties in the ITS_LIVE glacier velocities used in this study. I recommend that the authors describe these uncertainties more transparently, offering specific uncertainty ranges for each dataset, where possible. Additionally, some sections of the text and certain figures could benefit from modifications to enhance clarity and interpretability. Suggestions for these improvements are provided in the specific comments below.

Once these minor revisions are addressed, I believe this paper will make a valuable contribution to our understanding of glacier surging in the Karakoram and offer important insights into the mechanisms driving glacier dynamic changes in this region.

Response: We sincerely thank the reviewer for the positive and thoughtful comments on our manuscript. We have improved clarity and consistency in the Methods and Results sections as suggested by the Reviewer. The uncertainty estimation has been enhanced to include quantified uncertainties for all datasets and derived results. Inappropriate wording has been corrected. Additional details have been supplemented to the Results and Discussion sections. We believe these revisions will substantially improve the rigor and clarity of our work and sincerely thank you for your constructive feedback and support for the manuscript.

Specific comments are addressed point-by-point in the following context.

Specific comments

Abstract:

1. L10: “Increased occurrence” is a bit ambiguous. Please specify what the increase is relative to, such as whether surging occurrence is higher in this region compared to other glacier regions or whether the occurrence of surging has recently increased.

Response: “Increased occurrence” means that the occurrence of surging in the Karakoram has increased recently. We have changed “increased occurrence” to “occurrence increasing recently”.

2. L11–12: I would not say that observations are particularly limited in this region, as several studies have reported on glacier surging in the Karakoram and HMA. I therefore suggest to change this sentence to “However, more observations are needed to further our understanding of surging dynamics and their underlying mechanisms”.

Response: We have changed this sentence as suggested.

3. L21: Change “and raising its surface elevation by ~ 180 m” to “and raising the glacier surface elevation by ~ 180 m”.

Response: Done.

Introduction:

4. L29–30: Consider revising to: “Frequent glacier surges and slight mass gains over recent decades are defining characteristics of Karakoram glaciers (Farinotti et al., 2020; Bazai et al., 2021), collectively known as the Karakoram Anomaly (Hewitt, 2005; Berthier and Brun, 30 2019; Bolch et al., 2012).”

Response: We have revised the text as suggested to clarify that frequent glacier surges and slight mass gains are defining characteristics of Karakoram glaciers in recent decades.

5. L33: Change “up to 10 to 100 times of the normal (Guo et al., 2022)” to “increase to 10 to 100 times the normal rate (Guo et al., 2022)”. Also consider revising the 10 to 100 times figure to 10–1000 times, a more widely accepted range, as some glaciers have been seen to accelerate well over 100 times above background levels, such as Variegated Glacier in its 1982–83 surge (Kamb et al., 1985).

References

Kamb, B., Raymond, C. F., Harrison, W. D., Engelhardt, H., Echelmeyer, K. A., Humphrey, N., ... & Pfeffer, T. (1985). Glacier surge mechanism: 1982-1983 surge of Variegated Glacier, Alaska. Science, 227(4686), 469–479. https://doi.org/10.1126/science.227.4686.469

Response: The glacier flow velocity during surge/active phase generally experiences a ten- to hundred-fold acceleration. Given that some glaciers have been seen to accelerate over 100 times above background levels, we have changed “up to 10 to 100 times of the normal” to “increasing by 1–2 orders of magnitude”.

6. L46–48: Since you mention “mass-energy balance”, which is based on the idea of the enthalpy balance theory of surging, you should cite this paper by Benn et al. (2019): https://doi.org/10.1017/jog.2019.62.

References

Benn, D. I., Fowler, A. C., Hewitt, I., & Sevestre, H. (2019). A general theory of glacier surges. Journal of Glaciology, 65(253), 701–716. https://doi.org/10.1017/jog.2019.62

Response: We have cited this paper by Benn et al. (2019).

7. L69: Specify which "key variables" you are referring to here.

Response: Key variables here include glacier velocity, surface elevation, terminus position, and glacial lake level. We have revised the text accordingly.

8. L85–86: The coordinates seem to be reversed; they should read "34.823°N, 77.863°E" instead.

Response: Done.

9. L91: It would be useful to also mention mean annual air temperatures in this sentence.

Response: We have added the mean annual air temperature for this area (−2.54 °C).

10. L110: Synthetic aperture radar should not be capitalised.

Response: Thank you for pointing this out. We have revised it.

Methods:

11. L142–143: How did you determine that longer intervals resulted in underestimated velocities rather than shorter intervals overestimating velocities if you did not have independent data to validate the ITS_LIVE velocities? Smaller time intervals in the ITS_LIVE image pair data, such as the interval that you used for this study, can be more noisy and have higher errors. Therefore, it would be important to properly quantify uncertainty estimates for the ITS_LIVE data that you used in this study (see other comment for L262–270 below).

Response: The flow velocity at a specific point on the glacier is calculated as its displacement divided by the time interval (Equation (1)). Due to seasonal or short-term variations in glacier velocity, longer time intervals between image pairs tend to underestimate velocities. In hydraulically controlled surges, which typically last only a few weeks or longer, using extended time intervals could markedly underestimate peak velocities (Fig. R1a).

$$\begin{cases} v_X = \dfrac{d_X}{dt} \\ v_Y = \dfrac{d_Y}{dt} \\ v = \sqrt{{v_X}^2 + {v_Y}^2} \end{cases} \tag{1}$$

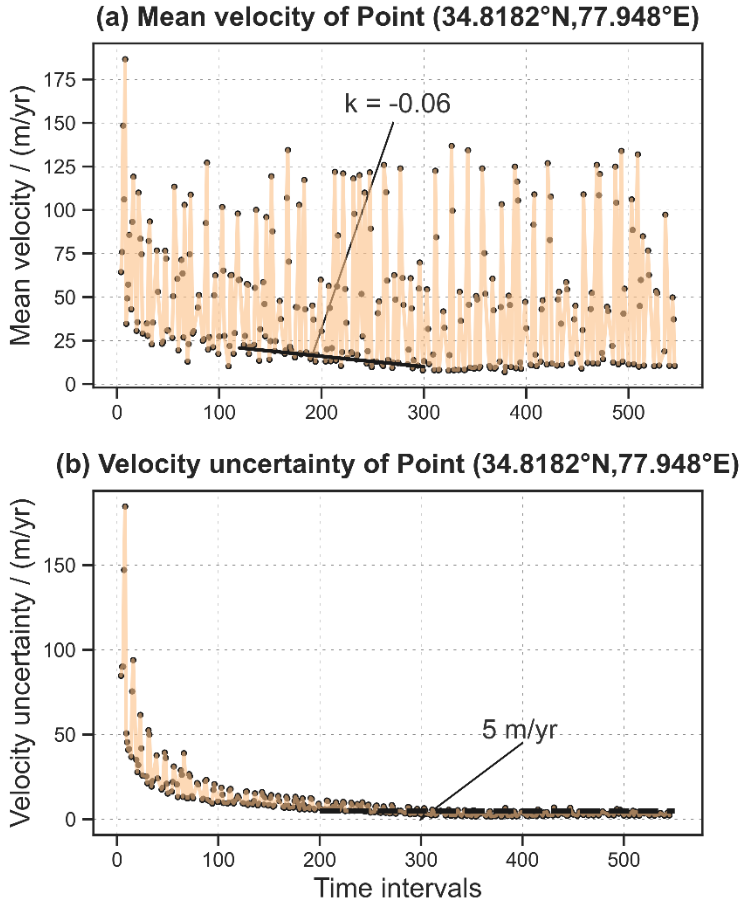

Figure R1: (a) Mean velocity and (b) Velocity uncertainty of Point (34.8182°N, 77.948°E)

Conversely, excessively short time intervals between image pairs may introduce greater noise (Fig. R1b). For example, at Point (34.8182°N, 77.948°E), we analyzed the relationship between image-pair time intervals and derived glacier velocities. We found that very short time intervals lead to substantial velocity uncertainties. However, image pairs with intervals shorter than 6 days account for only 3.5% of all cases, minimizing their overall impact.

To derive accurate peak velocities during surging and reduce uncertainty, we will refine our selection of image-pair time intervals and systematically quantify uncertainties in the ITS_LIVE dataset in subsequent revisions.

12. L145: Change "Give" to "Given".

Response: Done.

13. L153: Specify the resolution of the DEM.

Response: We have added the DEM resolution (1 m) in the text.

14. L156–157: Consider adding this DOI for the Theia data portal, where the Hugonnet et al. (2021) data can be downloaded: https://doi.org/10.6096/13.

Response: We have added the citation for the ASTER DEMs as suggested, and other relevant sections have also been updated accordingly.

15. L189: Small typo: Change "Jaosn-3's" to "Jason-3's"

Response: Done.

16. L262–270: It is good to know that the velocities derived from these different satellites tend to agree well with each other. However, you did not give any estimated uncertainty value (i.e., in m yr^{-1}). The ITS_LIVE dataset provides GeoTIFF files of estimated velocity errors. It would be good to mention typical error values over the glacier from the velocity maps that you downloaded over the specific time periods that you analysed. At the very least, you could quantify velocities over unglaciated terrain to give an estimate of uncertainties.

Response: In subsequent revisions, we will provide uncertainty estimates for all glacier velocity observations over specific periods and update the relevant figures.

We have estimated velocities over unglaciated terrain: before 2012, velocities over unglaciated terrain were ~ 25 m/yr; after 2017, with more image pairs available, they fell below 10 m/yr. This indicates low uncertainties in velocities during the main trunk surge of NKG I.

Results:

17. L299–300: "A notable increase was observed in June 2015": please quantify this velocity increase.

Response: The velocity increased more rapidly between June 2015 (185 m/yr) and June 2017 (479 m/yr) than it did between June 2010 (92 m/yr) and June 2015. We have quantified the velocity increase in the revised manuscript.

18. L301–302 and L326–328: Once again, it would be helpful to provide specific values for these velocity peaks to clarify their magnitude and improve the interpretability of the text

Response: We have supplemented the velocities for the two peaks in November 2017 (573 m/yr) and July 2018 (607 m/yr) in the long-term time series and the two intra-annual peaks in May and June (90–95 m/yr) and September–October (~50 m/yr).

19. L352–354: While the elevation change rates are shown in Figure 6d, I suggest also mentioning them in the text for increased clarity.

Response: The elevation change rates over different periods in Region C have been specified in the text.

20. L376: Change "taking" to "taken".

Response: Done.

21. L376–377: Please specify uncertainties for the terminus position changes (i.e., 43 ± ?? m and 180.3 ± ?? m).

Response: We estimated the uncertainty in glacier terminus positions (σ_t) derived from Sentinel-1 SLC images by considering both the image geolocation uncertainty (σ_{co}) and the algorithm uncertainty (σ_{al}) (Guan, 2024). The geolocation uncertainty was taken from Senitnel-1's annual performance report, while the processing uncertainty was assumed to be half a pixel:

$$\sigma_t = \sqrt{{\sigma_{co}}^2 + {\sigma_{al}}^2} \quad (2)$$

The uncertainty in terminus position change (σ_{tc}) was then calculated by combining the positional uncertainties from both time periods (σ_{t1} and σ_{t2}):

$$\sigma_{tc} = \sqrt{{\sigma_{t1}}^2 + {\sigma_{t2}}^2} \quad (3)$$

Uncertainties in the terminus position changes were estimated to be 43 ± 28 m and 180 ± 29 m.

22. L398–400: In terms of glacier extent changes, have you quantified glacier area changes (with associated uncertainties)? If so, please mention these estimates and associated uncertainties here.

Response: The uncertainty in glacier area change (σ_A) was estimated by considering both the resolution of the data source and the clarity of glacier outlines (Minora et al., 2016; Guan, 2024).

$$\sigma_A = l \times \sqrt{{LRE_{yr}}^2 + {\sigma_{co}}^2} \quad (4)$$

Where l is the glacier boundary length (excluding ridgelines), LRE_{yr} denotes the resolution-related error (assumed as half a pixel), and σ_{co} indicates the geolocation accuracy of the imagery.

The uncertainty in glacier area change (σ_{Ac}) was then calculated by combining the positional uncertainties from both time periods (σ_{A1} and σ_{A2}):

$$\sigma_{Ac} = \sqrt{{\sigma_{A1}}^2 + {\sigma_{A2}}^2} \quad (5)$$

Between 2002 (RGI 6.0) and 2024, the glacierized area in the NKG basin decreased by 4.8

± 11.2 km². Excluding the surge-affected expansion of NKG V and bare terrain in high-altitude areas, small glaciers and permanent snow cover within the basin experienced an pronounced reduction of 21.3 ± 10.9 km². We will provide a revised description of these changes in the updated version.

23. L427: Change "has commenced" to "had commenced".

Response: We have corrected the tense.

Discussion:

24. L513: Change "data-scare" to "data-scarce".

Response: Done.

25. L537–538: Either state the revised glacier volume changes here or direct the reader to Table 2 for details.

Response: We have directed the reader to Table 2 for details.

26. L564–565: Briefly explain how enhanced the steeper surface slope and erosion from the former proglacial lake would have contributed to NGK V surging first.

Response: A steeper surface slope generates greater gravitational driving stresses that overcome bed friction (Round et al., 2017; Dehecq et al., 2019), making it easier for NKG V to accelerate once internal or basal resistance is reduced. After controlling for confounding variables, NKG V's steeper profile necessitates less cumulative mass than NKG I to achieve comparable driving stresses, thereby making it more susceptible to surge. This also facilitates faster ice flow during surging.

The former proglacial lake calves the terminal and destabilizes the glacier front, reducing back pressure and allowing the glacier to advance more easily. Additionally, the lake water erodes NKG V, may form drainage channels (Gao et al., 2024), and modify subglacial water pressure systems. Lake water intrusion through crevasses or subglacial drainage further increases basal sliding.

Together, these factors lower the resistance to ice flow, enhance driving stresses, and create instability thresholds. Thus, the steeper surface slope and erosion from the former proglacial lake would have contributed to the earlier surge of NGK V.

27. L565–566: "Historical climate records indicate that from 1977 to 1980, temperatures in the NKG region were higher than average": 1980 appears to have been a relatively warm year, but 1979 was one of the coldest years according to Figure 13a. Therefore, from looking at the graph qualitatively, I would not say that 1977–1980 temperatures were higher than average, unless you can quantitatively prove that.

Response: Although 1979 was one of the coldest years, the mean temperature in the NKG region during 1977–1980 (−2.35 °C) was higher than the 1970–1980 average (−2.60 °C). Additionally, the annual mean temperature in 1980 was 2.11 °C higher than that in 1979, creating warmer conditions for the accumulation of basal water pressures—a key driver of glacier surges (Murray et al., 2003). We have added such quantitative description to support it.

28. L581–582: "This transition could lead to reduced surge magnitude, shorter return periods, and greater instability in glacier structure": While a transition to surging controlled by hydrological processes would not in itself cause reduced surge magnitude (hydrologically-regulated surges are often more intense than thermally-regulated ones, for instance), I believe you are referring instead to more negative mass balance conditions and a reduced ability of the reservoir zone to build up mass between more frequent surge events causing this decrease in surge magnitude. Please ensure to clarify this in your text.

Response: Climatic warming and precipitation phase changes amplify warm-season meltwater and rainfall inputs, elevating basal water pressures and inducing hydrological complexity (Harrison and Post, 2003). This shifts surge regimes toward seasonally hydraulic-controlled behavior. At the same time, enhanced ablation under higher temperatures reduces cumulative ice mass, potentially suppressing surge magnitudes due to diminished reservoir volumes. We have revised the text accordingly.

29. L606: Replace "remaining" with "maintaining".

Response: Done. We have replaced "remaining" with "maintaining".

Figures and tables

30. Figure 4: Mention how the extent of the black rectangle was determined. For example, "The two black rectangles highlight the extents of the identified glacier surges, showing where velocities increased by an order of magnitude over quiescent rates".

Response: We have revised it to "showing where velocities increased by 20-fold (2004) and 5-fold (2017) of magnitude over quiescent rates (~ 50 m/yr in 2023)".

31. Figure 5: For easier comparisons between the four graphs, I would suggest using the same y axis value range (i.e., 0–1400 m yr^{-1}), or to at least inform the reader that the y-axis scales differ between the graphs.

Response: If we used the same y axis value range, panels (a)–(d) would appear excessively sparse (Fig. R2). Therefore, we have explicitly noted in the figure caption that panels (a)–(d) employ different ranges for y axis.

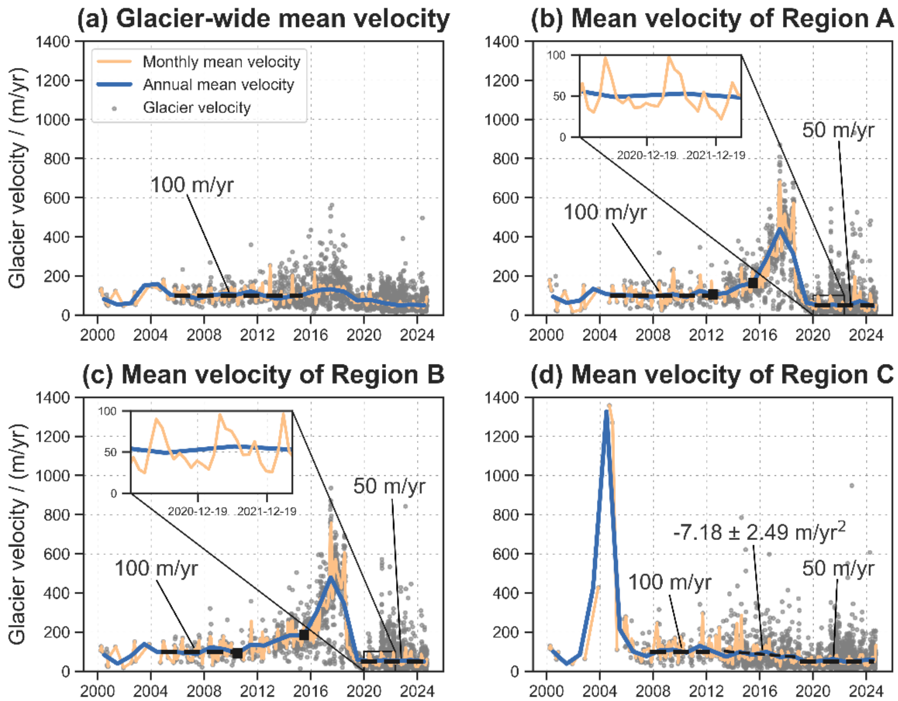

Figure R2: Fig. 5 (a)–(d) using the same y axis value range

32. Figure 7: Elevation change data in Figure 7e look rather noisy, especially in higher elevation areas. I recommend mentioning uncertainty estimates for these results in the text.

Response: Due to GF-7's 26° off-nadir angle (Zhu et al., 2021) and image oversaturation in high-altitude areas, the elevation uncertainty in these regions is relatively large, manifested as increased noise in the elevation differences. We will provide further explanation of this in the revised manuscript.

33. Figure 7: The colour bar, running from -25 m to 50 m of surface elevation change, is asymmetric. It would be better if it were around 0 (e.g., -50, -25, 0, 25, 50). This adjustment would make it easier to directly compare the intensity of elevation gains and losses through time, and would ultimately improve clarity and visual interpretation of the figure.

Response: Due to the glacier surge, the thickening of NKG I is significantly greater than the thinning. If a symmetric range ([−50, 50]) is used, the glacier thinning across most areas would appear insignificant (Fig. R3). Therefore, we retain the previous display range.

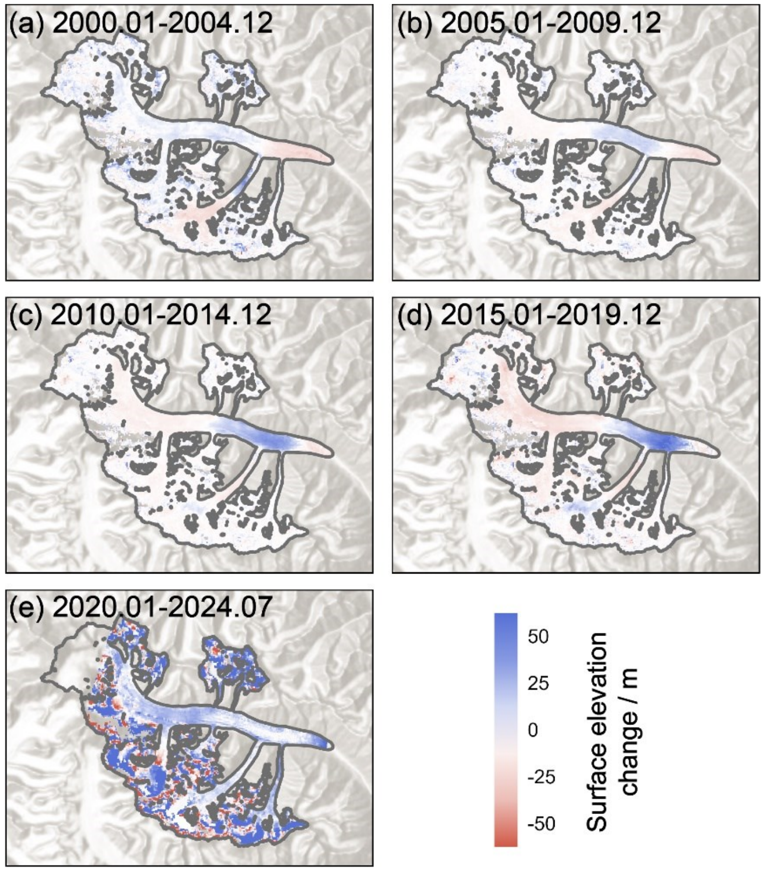

Figure R3: Modified Fig. 7

34. Figure 8: Why did you choose to display changes in the longitude of the terminus position on the y-axis? Displaying changes in terminus position in meters or kilometers would be much easier to interpret.

Response: Since the main trunk of NKG I follows a west-east orientation, longitude effectively captures the variations in terminus position. Therefore, in our previous figures, we displayed changes in the longitude of the terminus position on the y-axis. In the revised manuscript, we have updated the y-axis to represent the distance from the 1984 terminus position (Fig. R4).

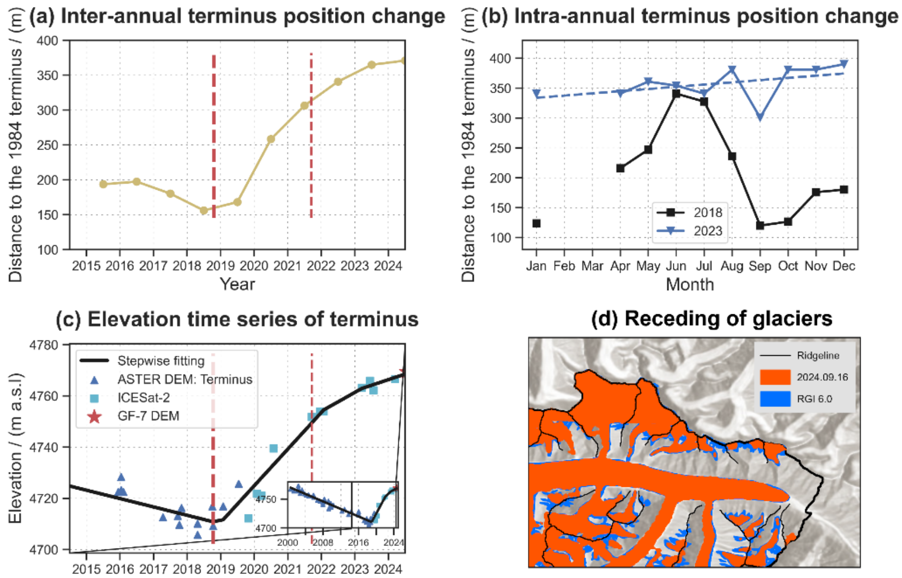

Figure R4: Modified Fig. 8. (a) Inter-annual and (b) Intra-annual terminus position variations derived from Sentinel-1 imagery; (c) Surface elevation time series at the glacier terminus, with the lower right subfigure displaying elevation changes from 2000 to 2024; (d) Glacier recession of NKG I, where blue represents the glacier extent derived from the RGI 6.0 inventory (August 2, 2002) and red depicts its configuration as of September 16, 2024.

35. Figure 10: In line 434 of the figure caption, change "insert map" to "inset map".

Response: Done.

36. Figure 12: This is a nice figure, but as with Figure 7 (see previous comment), it would be better to center the surface elevation change scale on 0 with the following labels: -100, -50, 0, 50, 100.

Response: During glacier surges, the thickening in the receiving area significantly exceeds the thinning in the reservoir area. If we used symmetrical axis ranges ([−100, 100]), the thinning in the reservoir area would appear insignificant (Fig. R5). Therefore, we retain the previous display range.

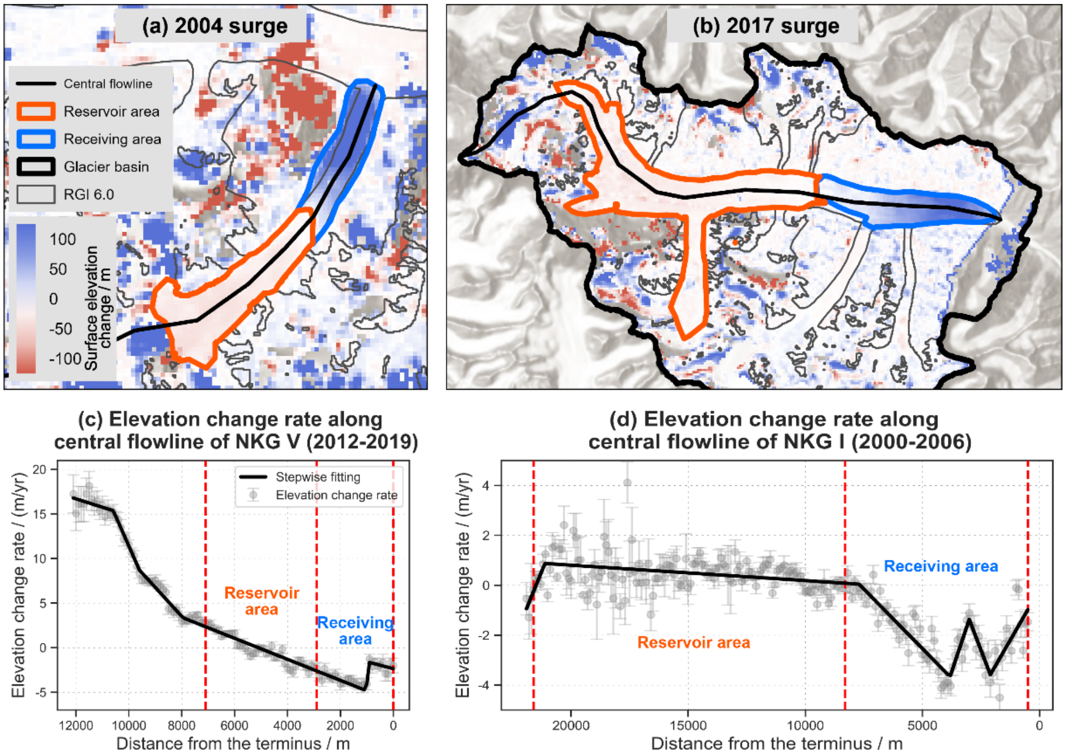

Figure R5: Modified Fig. 12

References

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