Five decades of Abramov glacier dynamics reconstructed with multi-sensor optical remote sensing

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Reply to reviewer 3

This paper effectively utilises a wide variety of remote sensing datasets and methods to enhance our understanding of the dynamics of Abramov glacier and address gaps in the existing observational record. The 55-year compilation of changes in glacier velocity, elevation, and terminus position convincingly demonstrates that this glacier undergoes cyclical dynamic instabilities, despite its use as a reference glacier for mass balance in this region. The manuscript is well-written, with the authors thoroughly explaining their methodology and the quantification of uncertainties. These methods have the potential for broader application, and the high level of detail achieved could be used to update regional inventories of surge-type glaciers, which likely overlook the dynamic instabilities of several smaller glaciers. Furthermore, this paper raises the question of whether other reference glaciers experience unstable flow, a possibility that a wider application of this approach might reveal. I recommend some minor revisions as outlined in the specific comments below.

We would like to thank the reviewer for the positive and constructive review of our manuscript. Below, we provide point-by-point answers to the comments. Any comments which are not mentioned here are considered accepted and fully implemented in the revised manuscript. The review text is reported in *black italic*, while our responses are in blue.

Specific comments

Introduction:

- *L41–65: In this paragraph, it would be beneficial to include more general information about glacier surging in Central Asia, such as the known ranges for the lengths of the active phase, quiescent phase, and recurrence intervals of surge-type glaciers in this region.*

In the revised manuscript we are adding this information: “The inventory of surge-type glaciers in High Mountain Asia compiled by Guillet *et al*. (2022) reports active phases lasting 1 to 18 years (median = 2 years, N = 30) in Tien Shan and 1 to 19 years (median = 3 years, N = 73) in the Pamirs. Information on recurrence intervals of surging activity is scarce in that and other inventories, because usually a single surge cycle takes place during the considered time interval. Reported values range from one to five decades (Murodov *et al*., 2024; Mukherjee *et al*., 2017)”.

- *L81: Consider slightly expanding on “a sudden shift in basal condition” for clarity.*

In the revised manuscript we are rephrasing this section to provide more information: “Using a minimal flow-line model, Glazirin *et al*. (1987) investigated the pulsation with various formulations of the basal sliding law. The best agreement with observed ice velocities was found by introducing a switch in the friction coefficient between two different values, as controlled by a threshold of basal shear stress: as such, the authors attributed the pulsation to a sudden shift in basal conditions, but the mechanism of such a shift was not examined.”

Methods*:*

- *L188: Change “aggregation polygons” to “aggregated polygons”*

We are opting to use the terminology “regions of interest” instead, to maintain consistency within the rest of the text (e.g., Sect. 2.3.2).

Results:

- *L299: The median rate would be a more appropriate measure than the mean rate, as it is less sensitive to outliers and would therefore be less skewed by the two periods of terminus advance. I therefore recommend using the median instead of the mean.*

The mean rate reported here is not computed as the arithmetic average of each year’s change, since the interval corresponding to each change is not constant (L297-298). Rather, the mean rate is derived from the total change of −1106 ± 4 m divided by 55.064 years – thus, the periods of terminus advance are not affecting the calculation. In the revised manuscript we are clarifying this by rephrasing the expression to “with a total change of −1106 ± 4 m corresponding to a mean rate of 20.09 ± 0.07 m yr^{-1}”.

- *L313: Once again, the median would be a more appropriate measure than the mean represent these velocities.*

We are not sure that we fully understand the reviewer’s comment. The velocities mentioned at L313 are not statistical aggregations of multiple measurements, but rather single measurements, computed by rescaling to 365.25 days the total displacements observed over different durations. As such, they are necessarily measurements of the mean velocity of the ice over each duration, and no median can be computed. In the revised manuscript, we are clarifying this point by using and explaining the expression “mean annual velocity” already in the methodological section 2.3.2. We note that where relevant (in the statistical aggregation of Sentinel-2 velocities) we indeed use the median (L227).

Discussion:

- *L343–344: “...ice thickness significantly increased at the terminus, reaching 90 ± 5 m in the first phase and 39 ± 4 m in the second one”: it is unclear whether you are reporting ice thickness values here or changes in ice thickness (dh). If you are reporting the latter, these maximum values of thickness change may be due to the glacier advancing over previously unglaciated terrain, which should be mentioned in the text if this is the case. For better representation of the overall trends of glacier thickness changes, you should also report median thickness changes over the terminus region and at higher elevations during both the active and quiescent phases, rather than just mentioning the maximum values.*

In the revised manuscript we are clarifying this point: it was the increase of ice thickness (not its absolute value) which reached maximum values of 90 and 39 m, and in both cases such a maximum increase took place at locations which were glacierized both at the start and end of the period covered by the DEM differences.
Concerning the better representation of overall trends of thickness changes, we note that the median change is not a suitable estimator in our case, due to the presence of gaps in the grids of DEM difference; the spatial distribution of these gaps is not uniform, and as such, the simple median is a biased estimate of overall change. At L350-351, we are instead providing values of mean change derived by the hypsometric method (L266), which provides an unbiased estimate of the change (McNabb *et al.*, 2019). For comparability, we compute such a change over a terminus region defined to match the regions of interest used in previous studies. In the revised manuscript, we are

additionally providing the hypsometric mean change over the regions of thickening and thinning during both active and quiescence phases (the time intervals presented in Fig. 5): +29 ± 4 m and -10 ± 4 m (1972-1973), +1.5 ± 1.2 m and -24.2 ± 1.1 m (1980-2000), +9.1 ± 0.6 m and -2.8 ± 0.5 m (2000-2003), +2.0 ± 0.4 m and -19.6 ± 0.2 m (2003-2020).

- *L387: "...which was quantified at about 50 % since the 1970s in the upper accumulation area (Kronenberg et al., 2021)": mention the specific time interval over which this increase in net annual accumulation rates was quantified.*

In the revised manuscript we are adding this information (between 1970–97 and 2011–18).

- *If you have space for it in the final manuscript, consider including a short section in the discussion that compares Abramov Glacier to the behavior of other surge-type glaciers in the region. This comparison could provide valuable context for understanding the unique dynamics of Abramov glacier, namely in relation to the frequency and magnitude of surges, active and quiescent phase durations, and responses to climate variability. Highlighting similarities and differences with other glaciers can also help elucidate the underlying mechanisms driving glacier behavior in this specific geographic and climatic setting.*

We agree with the reviewer that such a comparison is valuable to better understand the mechanisms driving unstable glacier behavior in the region. We are currently working on a detailed, regional-scale investigation of unstable ice flow in the whole of Pamir-Alay, which will be the topic of an upcoming publication including a discussion of the possible mechanisms of unstable ice flow. We believe that it is a more appropriate site to discuss the similarities and differences of unstable ice flow between this specific setting and other surge-type glaciers in Central Asia.

Figures and tables

- *Figure 1: Specify the source of the glacier outline used in this figure. Is it from RGI 7.0, or what is it manually created for this study?*

In the revised manuscript we are providing this information – the outline was created manually (L185) from the Pléiades orthoimage of 5 September 2022.

- *Table 1: To enhance clarity and make it easier for readers to compare the data across different platforms and sensors, I suggest providing consistent units of measurement for resolution (i.e., use either meters (m) or arc-seconds or (")).*

In this table, we are reporting the original resolution of the datasets as they are provided. The global NASADEM and Copernicus DEMs are provided in equirectangular projection (EPSG:4326) for which the actual resolution can only be expressed in arc-seconds, while all other products use projected coordinate systems whose resolution can only be expressed in meters. As an alternative, in the revised manuscript we are adding to the Table caption some information about the resolution which is commonly used in the mid-latitudes when re-projecting global DEMs to projected coordinate systems (30 m for 1", 90 m for 3"; we note that this is an approximation as the proper conversion is not spatially uniform).

- *Figure 5: The labels should be corrected from "(c) Active phase of 2000–2003. (d) Quiescence over 2003–2020" should be "(e) Active phase of 2000–2003. (f) Quiescence over 2003–2020" to match the letters in the figure.*

We thank the reviewer for catching this, it is being corrected in the revised manuscript.

- *Figure 5: Change "by a same amount" to "by the same amount" in the last sentence of the figure caption.*

We believe that an indefinite article is more appropriate here since the amount under question is unknown.

- *Table 3: Rows are not aligned. Ensure this is fixed in the final version of the paper.*

We are not sure that we fully understand the reviewer's comment. The table presents geodetic mass balance computed over several intervals, and the first column gives the boundaries of such intervals. As such, we find it reasonable to align the rows of the other columns (which provide values referring to each interval) to the middle of the intervals of the first column. We note that the first column has one more row compared to all others (7 dates, which define 6 consecutive time intervals).

References

Glazirin', G., Kamnyansky, G., Mazo, A., Nozdriukhin, V., and Salamatin, A.: Mechanism of the Abramov glacier advance in 1972-1975, Materialy gliatsiologicheskikh issledovaniy, 60, 84–90, 1987.

Guillet, G., King, O., Lv, M., Ghuffar, S., Benn, D., Quincey, D., and Bolch, T.: A regionally resolved inventory of High Mountain Asia surge-type glaciers, derived from a multi-factor remote sensing approach, The Cryosphere, 16, 603–623, https://doi.org/10.5194/tc-16-603-2022, 2022.

McNabb, R., Nuth, C., Kääb, A., and Girod, L.: Sensitivity of glacier volume change estimation to DEM void interpolation, The Cryosphere, 13, 895–910, https://doi.org/10.5194/tc-13-895-2019, 2019.

Mukherjee, K., Bolch, T., Goerlich, F., Kutuzov, S., Osmonov, A., Pieczonka, T., and Shesterova, I.: Surge-Type Glaciers in the Tien Shan (Central Asia), Arctic, Antarctic, and Alpine Research, 49, 147–171, https://doi.org/10.1657/AAAR0016-021, 2017.

Murodov, M.; Li, L.; Safarov, M.; Lv, M.; Murodov, A.; Gulakhmadov, A.; Khusrav, K.; Qiu, Y. A Comprehensive Examination of the Medvezhiy Glacier's Surges in West Pamir (1968–2023). *Remote Sens., 16(10),* 1730, 2024. https://doi.org/10.3390/rs16101730