EGUSPHERE-2025-4630: Answers to Reviewer Comments

Glacial decline next to stable permafrost in the Dry Andes? Vertical glacier surface changes and rock glacier kinematics based on Pléiades imagery (Rodeo basin, 2019–2025)

Comments by Anonymous Referee #1

General comment

The paper presents a detailed investigation of glacial and, in particular, periglacial landforms in the Rodeo Basin of the Dry Andes. Using Pléiades stereo and tri-stereo imagery, the authors derive both vertical and horizontal surface displacements through DEM generation, DEM differencing, and feature-tracking techniques. They also provide an in-depth assessment of their methodology, including a rigorous quantification of landform velocities and the associated Levels of Detection (LoD).

The results indicate that the monitored rock glaciers show no consistent trend toward acceleration or deceleration. This suggests that permafrost-related landforms in the region currently exhibit a relatively stable deformation regime, highlighting their greater resilience to climate warming when compared with the faster melt rates observed for glaciers and debris-covered glaciers.

The paper is well structured, but some improvements and minor reorganizations could help make the text more fluent and clearer. Additionally, a broader discussion addressing some of the open issues (outlined in the following section) would strengthen the manuscript and contribute to a more comprehensive and robust overall presentation.

I suggest refining the writing in sections 4.5 and 5.3 to enhance fluency. Section 4.5 is presented largely as a sequence of results, and section 5.3 combines multiple themes, which affects the coherence of the argument.

Dear reviewer, thank you for your thorough analysis of our manuscript and for the time you invested. We will pay specific attention to sections 4.5 and 5.3 when revising our manuscript.

Detailed comment

Abstract: The abstract is clear and presents the analyses conducted with a good level of detail. However, reading it, it sounds like a list of activities done, with maybe too many “we” in a row. E.g. “We investigate”, “we calculate”, “we follow”, “we conduct”, “we detect”, “we find” in only few lines. I would suggest revising it making the text more homogeneous and fluent. *We have adapted the abstract accordingly.*

Line 28: please insert the extended name of LoD acronym. *We have inserted the extended name ‘Level of Detection’ for LoD.*

Line 130: Do the mapped rock glaciers already have an activity attribute (active/ inactive)? How is this attributed to them? *Yes, the rock glaciers as mapped by Argentine Institute for*

Snow, Ice and Environmental Sciences (IANIGLA-CONICET) in collaboration with the Argentine Ministry of the Environment and Sustainable Development (Zalazar et al. 2017) are attributed with a status of activity. The differentiation is based on visual inspection of remotely sensed imagery (Zalazar et al. 2017, 2020). We do not use this state of activity as we can rely on our Pléiades-based monitoring of rock glacier surface changes indicative of a rock glacier's activity attribute. We have added the reference below to our manuscript to provide additional details to Zalazar et al. 2017. The revised version reads "For our analysis, we treat rock glaciers indifferent of their mapped state of activity allowing us to rely on measured activity rather than the visual interpretation of surface features as conducted during the establishment of the inventory (Zalazar et al. 2017, 2020)."

Zalazar L. et al. (2020): Spatial distribution and characteristics of Andean ice masses in Argentina: results from the first National Glacier Inventory. Journal of Glaciology. vol. 66, no. 260, pp. 938–949. DOI:10.1017/jog.2020.55

Line 170 and caption of Tab. 2: Stammler et a., YEAR (?) *The data used in this manuscript is in review with PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.988303). We adapted the manuscript and include Stammler et al. (2026) in both instances, as well as the full reference in the reference list. The revised version reads "We publish the additional DGNSS measurements used in this study in the paper-accompanying dataset (Stammler et al. 2026)." It further reads "All other DGNSS data are published in Stammler et al. (2026)."*

Lines 177-178: It is not clear how the bounding box are created. First a buffer of 500m is extracted around glacier and rock glaciers polygons and then a bounding box is created around the so extracted features, right? Please try to clarify this better. *Yes, we buffer the inventoried landforms first and generate rectangular bounding boxes after, resulting in bounding boxes with minimum 500 m distance to each of the landform polygons to clip our Pléiades-based DEMs. The entire processing is conducted in ArcMap 10.7.1. We make this point clear in the revised version of our manuscript. The revised version reads "We buffer the inventoried landforms and generate rectangular bounding boxes, resulting in bounding boxes with minimum 500 m distance to each of the (debris-covered) glacier and rock glacier polygons to clip our Pléiades-based DEMs."*

Lines 186-189: I find it quite difficult to understand the meaning of the cumulative median and how it is computed. Also, I don't get if the vertical change is computed only as cumulative median over time or as vertical surface change normalized to full years. Could you please better formulate this sentence? *We adapt this sentence to "Depending on the figure, vertical surface change across the cryospheric landforms in the Rodeo basin is compared as total change (sum of annual median change, Fig. 2A) or as vertical surface change normalized to full years, both calculated as median for the landforms' surfaces, Fig. 2B-D and Fig. 5A." We no longer use 'cumulative vertical surface change' but refer to 'Total vertical surface change'. The revised caption for fig. 2A now reads "Total vertical surface change for glaciers, debris-covered glaciers and rock glaciers for 2019-2025. Calculated as the sum of the median annual vertical surface change per landform polygon and within the landform surfaces (e.g., no rock glacier* *fronts) based on DEM differencing between clipped, co-registered Pléiades DEMs." In agreement, we adapt the y-axis label in fig. 2A to "Total vertical surface change".*

Vertical surface change calculated as annual vertical surface change normalized to full years is used in fig. 2 B-D and 5D. This corresponds to the change between two acquisitions normalized to 365 days instead of keeping the true time interval between the two acquisitions for better comparability between the changes.

Lines 192-195: I suggest moving the section explaining how the LoD is derived right after the description of the image coregistration process (around line 186). This will make it immediately clear how the LoD is determined before you introduce the vertical surface-change quantification. *We agree. The paragraph now starts out with the preprocessing and co-registration, continues with the LoD calculation and finishes with the DoD generation.*

Lines 212: In the LoD estimation, the terrain outside the landform polygons is assumed stable (line 194). Yet, the text notes that the LoD for horizontal displacements accounts for potential true surface change (e.g., fluvial processes) occurring outside these polygons. Could you clarify this apparent inconsistency? If fluvial dynamics may be active, how is the 'stable terrain' assumption justified for LoD estimation? *We acknowledge that this could be interpreted as an inconsistency and added "to be predominantly stable" to the L190. In our feature tracking approach as well as for the calculation of vertical changes, we need to set a reference frame that is stable in horizontal or vertical direction. The choice of a median instead of mean can be seen as a precaution for cases where singular points of the 1000 automatically selected and used for the LoD's calculation are coincidentally placed on a moving object. The assumption that terrain outside the glacier and rock glacier polygons is stable can be confirmed with our analysis. Moreover, note that a shifting river channel or a rock fall will likely not be matched by our approach, as the geometry and surface texture change will not make it recognizable as the same feature anymore. To increase clarity, we revise the sentence and write "We accept the median of the feature tracking results at these 1000 random points as LoD. Selecting the median serves as a precautionary measure against singular points coincidentally placed on moving objects."*

Line 271: "an LoD" *We adapted the manuscript to 'a LoD'.*

Line 322- 327: The manuscript states that large and fast rock glaciers occur at higher elevations, on gentler slopes, and exhibit lower median vertical surface change. Could you elaborate on the physical mechanisms that might explain this pattern? If vertical deformation is limited, motion must be predominantly horizontal. What factors, beyond surface slope, could control this horizontal displacement? *Based on the investigation of vertical surface change and horizontal velocity on selected rock glaciers that fall into this category (Dos Lenguas and El Paso rock glaciers in fig. 3C-D; fig. 6 A-B), permafrost creep is determined as dominant physical mechanism. While higher elevation likely contributes to suitable ice content, the reduced slope is mainly driven by the volume of the large rock glacier itself which fills, e.g., valley structures. As on Dos Lenguas rock glacier, reduced velocity approaching the rock glacier front indicates a* *compressional flow regime that leads to a typical ridge-and-furrow pattern with alternating positive and negative vertical surface changes of considerable magnitude, cf. fig. 3D. And it is this compressional flow regime that also leads to the growth of a steep front with a gentle surface above.*

In addition, the relationships between elevation, slope, and the different rock-glacier classes are not immediately clear from the current figure. I suggest expanding this section and perhaps exploring a combined plot of elevation versus slope, with median velocity represented through a color gradient. Such a visualization could help clarify the spatial distribution and dynamics of the landforms. *We derive correlation matrixes to quantitatively describe the correlation between the results, tab. 1. The coefficients support that rock glaciers located at higher location are faster, that smaller rock glaciers are characterized by higher slope than larger rock glaciers, and that larger rock glaciers are faster than smaller. Comparatively low correlation coefficients support the categorization in the original fig. 5 while indicating a complex interaction of processes. We add the table to the supplementary material.*

Tab. 1 Correlation matrixes between elevation, slope, median velocity and polygon size.

	Elevation	Slope	Median Velocity	Polygon Size
Elevation	*1.000000000*	*0.019828470*	*0.197756716*	*-0.004271207*
Slope	*0.019828470*	*1.000000000*	*-0.003521543*	***-0.474669752***
Median Velocity	***0.197756716***	*-0.003521543*	*1.000000000*	***0.211467562***
Polygon Size	*-0.004271207*	***-0.474669752***	***0.211467562***	*1.000000000*

To showcase the relations between elevation and slope, but also median velocity and polygon size, we include the suggested figure, here fig. 1, as well as an adaption where polygon size is used to colour the datapoints, fig. 2. To take care of the effect of different time periods, e.g., the effect of snow cover in 2022-2023 cf. section 5.3 and fig. S1, we differentiate these in subplots. The new figures support the original fig. 5, provide more detail but do not add new insight. Therefore, we decide to keep the original fig. 5 in the manuscript as it highlights the main findings of the analysis and add the now produced figures, fig. 1 and 2, in the appendix to showcase the nuances of the analysis.

Large rock glaciers (fig. 1, row 2) clearly differ from the other two categories in slope, see original fig. 5C. In general, faster than the small and fast rock glaciers (row 3), annual difference challenge a very clear boundary between the two categories, see original fig. 5D. Small and fast (row 3) and small and slow (row 4) rock glaciers are characterized by similar slope and elevation but can be clearly separated by median velocity, see original fig. 5D. Large and fast rock glaciers (fig. 2, row 2) can be distinctively separated from the other two categories by polygon size while small and fast rock glaciers (row 2) and small and slow rock glaciers (row 3) are characterized by similar surface area, see original fig. 5A.

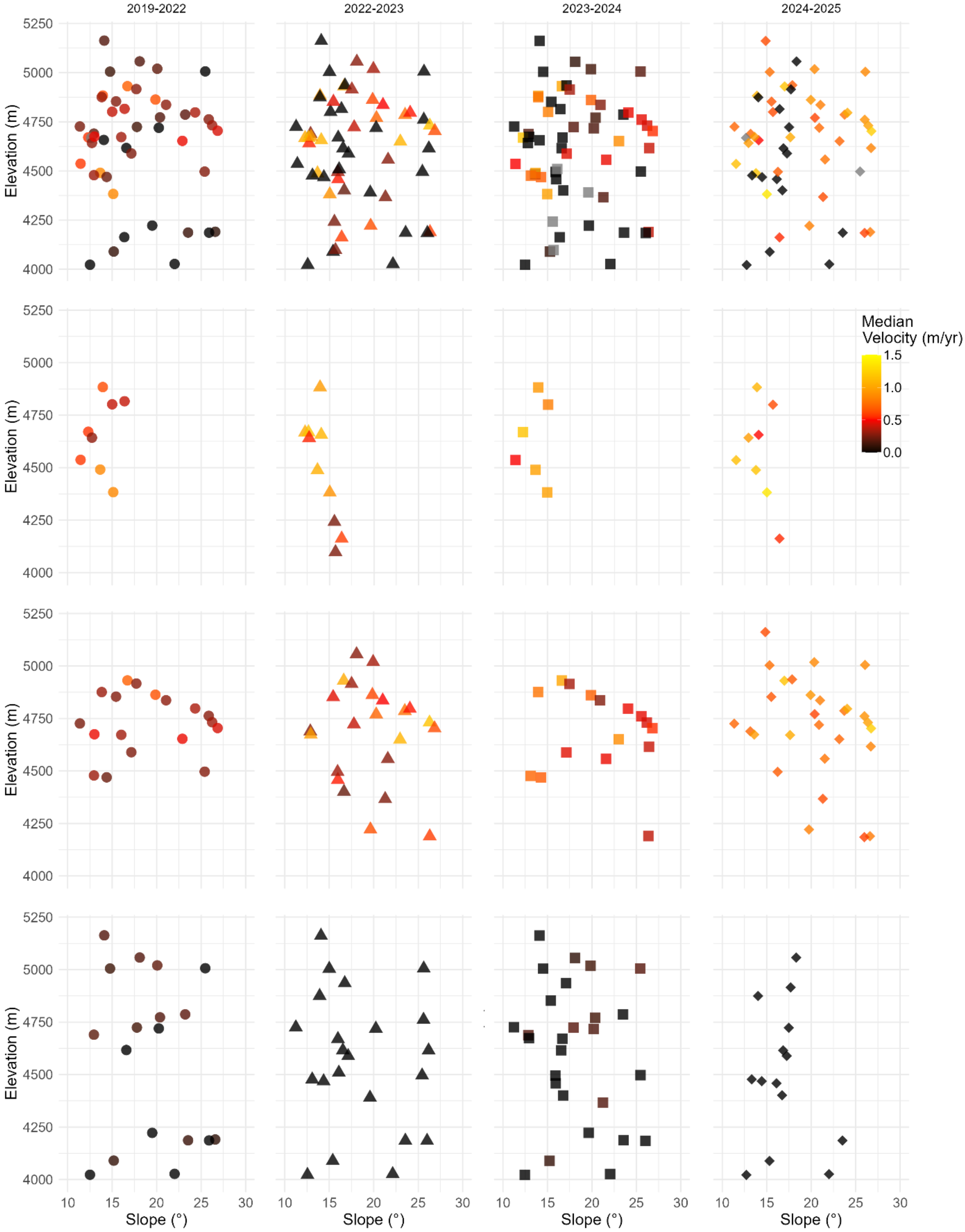

Fig. 1 Elevation vs slope for all rock glacier velocities (row 1), blue category of rock glaciers (row 2), pink category of rock glaciers (row 3), green category of rock glaciers (row 4), coloured by median velocity (m/yr). The categories refer to the original fig. 5. The columns and symbols correspond to the different time episodes: circles (2019-2022), squares (2022-2023), triangles (2023-2024), and diamonds (2024-2025).

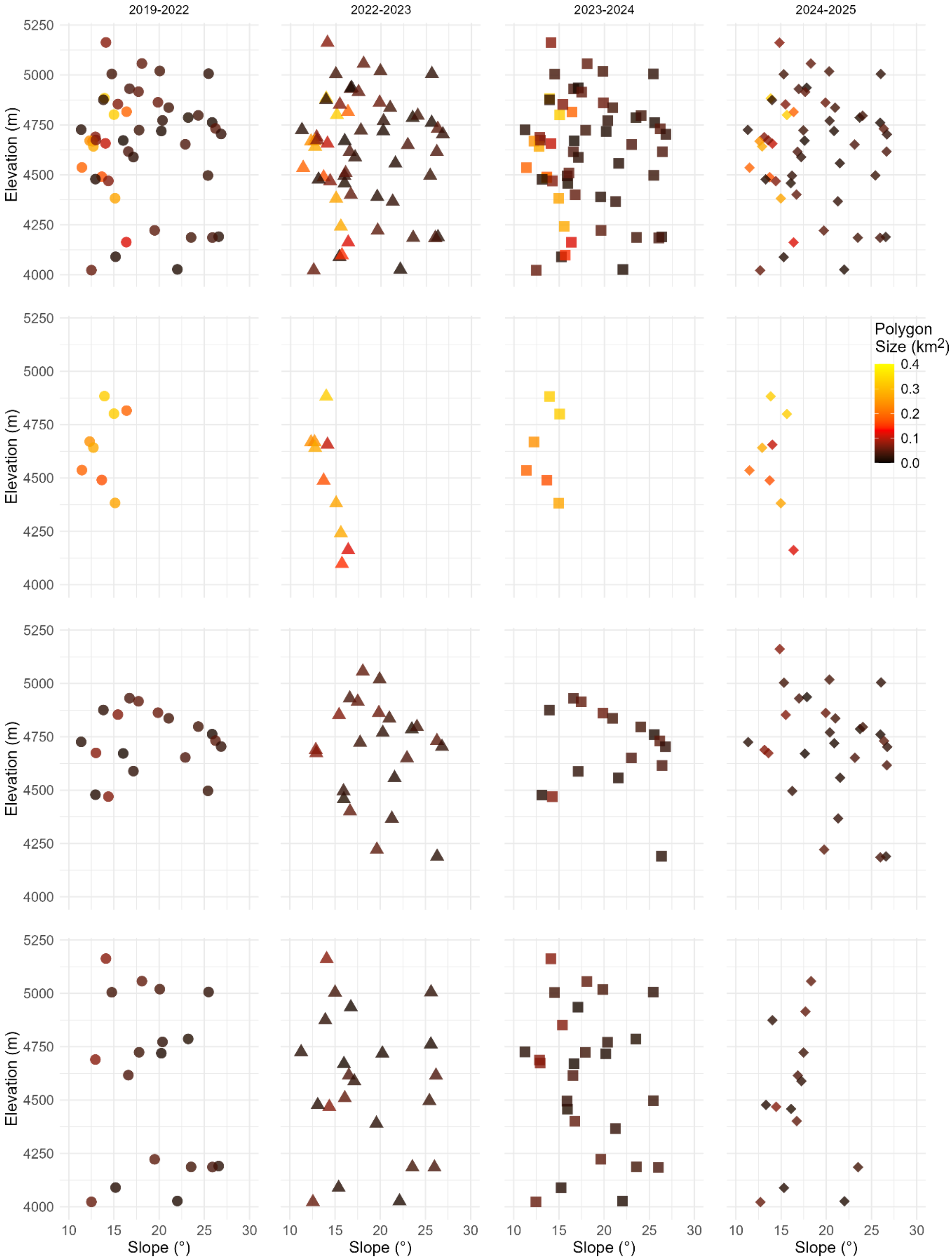

Fig. 2 Elevation vs slope for all rock glacier velocities (row 1), blue category of rock glaciers (row 2), pink category of rock glaciers (row 3), green category of rock glaciers (row 4), coloured by polygon size (km²) – equal to rock glacier surface area. The categories refer to the original fig. 5. The columns and symbols correspond to the different time episodes: circles (2019-2022), squares (2022-2023), triangles (2023-2024), and diamonds (2024-2025).

Line 340: are these vertical or surface velocities? I would suggest always clarifying this in the text. *In the submitted version, we addressed changes in the vertical component as vertical change and changes in the horizontal component as velocity. We adapted the entire manuscript and refer to the horizontal component with 'horizontal velocity'. Interchangeably, we use the term 'rock glacier velocity', as introduced in the original line 60. For example, the introducing paragraph now reads "In this paper, we investigate the current state of the cryosphere in Rodeo basin (Dry Andes of Argentina, 30ºS and 69ºW) by analysing vertical surface change on 19 glaciers, three debris-covered glaciers, and 59 rock glaciers, as well as horizontal surface velocity on, due to data coverage, 47 of the 59 rock glaciers for 2019-2025 based on (tri)stereo panchromatic Pléiades imagery."*

Lines 358-360: the sentence seems to miss a part, and it is not totally clear. *The lines now read: "No rock glacier is fastest for all time periods. The different rock glaciers fastest for a specific time period reach magnitudes of 0.86 m/yr in 2019-2022 (LoD ±0.15 m/yr, Dos Lenguas), 1.16 m/yr in 2022-2023 (LoD ±0.87 360 m/yr, ID 23), 1.18 m/yr in 2023-2024 (LoD ±0.56 m/yr, ID 9) and 1.38 m/yr in 2024-2025 (LoD ±0.64 m/yr, Dos Lenguas)."*

Lines 394-400: In these sentences, the differences between the DGNSS and Pléiades-based velocities are sometimes reported in meters (m), although velocities are expressed in m/yr. It is therefore unclear whether these values refer to differences in annualized velocities or to absolute positional offsets. Please clarify what these numbers represent and adjust the units or wording accordingly to avoid confusion. *The differences between the DGNSS and Pléiades-based velocities ought to be reported in m/yr. We have adapted the manuscript accordingly.*

Section 4.5: The section presents many numerical values (errors, medians, LoDs, differences, per year changes) for three sites and two time periods but rarely summarizes what these numbers mean. *We agree, and also in coherence with your comment at the very beginning, we reorganized the chapter transferring the results into tables and splitting the text in three paragraphs: DGNSS measurement error, DGNSS-based vertical surface change and horizontal surface velocity, and lastly to a comparison of the DGNSS- and the Pleiades-based rock glacier surface changes. Each of the paragraphs is introduced with an explicative sentence setting the intent of the analysis or comparison, e.g., "Vertical and horizontal errors of our DGNSS measurements describe their measurement quality. The magnitude of acceptable error depends on the magnitude of the surface changes investigated."*

Line 445: remove rock glaciers at the end of the sentence. *Our intention was to say that these bodies of rock and ice equal rock glaciers. To reduce potential confusion, we agree with removing 'rock glaciers'. The sentence now reads "This corresponds often with smaller landforms, as larger landforms with their elongated tongues 'flatten' the topography by building up bodies of rock and ice."*

Line 494: by is repeated 2 times *We adapted the manuscript accordingly.*

Line 517: How were the UAV-derived surface changes obtained? From differences between point clouds or offset tracking on images? *In both Halla et al. (2021) and Stammler et al. (2025a) all surface changes are derived from UAV imagery based DEMs: Vertical surface changes are derived from differencing of georeferenced DEMs and the horizontal surface changes from feature tracking on UAV-DEM derived hillshades. No surface changes are based on differences between point clouds. For details on the processing, please kindly refer to the original publications.*

Section 5.3: Overall, the section contains valuable comparisons and a solid contextualization of your vertical surface change results with previous studies. However, the text would benefit from clarification and improved structure to enhance readability. Several paragraphs are dense, and the narrative flow is sometimes difficult to follow. For example a reorganization of the text into smaller thematic paragraphs on snow cover impact, comparison with published mass balances and debris-covered glaciers could make the text easier to read. *We rearranged original section 5.3 and split it into three sections: 5.3 Vertical surface change of glaciers in the Rodeo Basin, 5.4 Vertical surface change of debris-covered glaciers in the Rodeo Basin and 5.5 Rock glacier kinematics in the Rodeo Basin. This allows for a landform-oriented separation which increases readability.*

Figures:

Fig.2: What are the triangles, square and circles? It is not clear in the caption. *The different symbols are used to denote the different time periods, relevant in row 2 of fig. 2. Circles are used for 2019-2022, squares for 2022-2023, triangles for 2023-2024, and diamonds for 2024-2025. We now include legend entries to be more precise.*

Fig. 3: Is the reported vertical surface change derived directly from the DoD between the 2019 and 2025 DEMs, or is it calculated as the cumulative sum of DoDs from consecutive DEMs? *The vertical surface changes are derived directly from the DoD between the 2019 and 2025 DEMs. The revised caption of the original figure 3 now reads "Vertical surface changes (m) between 2019-2025, generated by DEM differencing of the co-registered Pléiades DEMs of 2019 and 2025, for Agua Negra Glacier (…). "*

Fig.5: As for Fig.2 it is not clear what squares, triangles and circles refer to. As also stated in the detailed comment (Line 322-327) I would suggest trying to plot elevation and slope in the same graph to see if the different types of rock glaciers cluster in specific areas. *Regarding the symbols and their reference to the different time periods, please see our answer to your comment on fig. 2. Regarding the additional plotting, please see our answer to your comment on the original line 322-327.*

Fig.7: In the vertical axis I would explicitly state "median horizontal velocity" *We agree and include your suggestions to our original fig. 7 which is now fig. S3 (supplementary material), as well as to the revised fig. 7, in coherence with the suggestions of reviewer 2.*

Fig.8: I suggest putting a title to this graph with also the position of the point considered. Which velocity is the one from Sentinel-1? Is it measured along LOS or projected on slope? For a more detailed comparison between SAR and optical data, a reprojection of the optical-derived velocity values onto the SAR line of sight is recommended. Have you tried this? I suggest adding a brief explanation of the criteria used to select the Sentinel-1 baselines, as their selection currently appears rather arbitrary. *We adapt the figure caption to increase readability and to answer some of the questions raised in your comment. The revised figure caption reads "Inter-method comparison between our Pléiades-based rock glacier velocity compared to Sentinel-1 InSAR (Strozzi et al. 2020; white, grey and black dots) and UAV-based rock glacier velocity (Stammler et al. 2025a; red and dark red solid lines), all for a coordinate located in the upper part of Dos Lenguas rock glacier, see Fig. 6B. The colour of the dots corresponds to differences in time interval caused by the observation scenarios of the Sentinel-1A and 1B satellites. The InSAR-based velocity is measured along LOS and is projected along the maximum slope direction, for details please see Strozzi et al. (2020). Given this projection, we do not reproject the optically-derived velocities - here presented with solid lines (red: UAV, dark red: Pléiades). Dashed lines indicate the corresponding LoDs. Note that velocities reached in the upper part of Dos Lenguas are higher than respective median values." To not duplicate information, we kindly refrain from including a title to the figure. However, we now include (Strozzi et al. 2020) and (Stammler et al. 2025) to the legend to indicate that this is not data from the current study.*

Assuming you refer to temporal baselines in your comment, the answer is that Strozzi et al. (2020) processed all the acquisitions in series. The differences in time interval are caused by the observation scenarios of the Sentinel 1A and 1B satellites and the changes that occurred during the time period investigated.

Thanks - *Thank you!*