

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 Dominik Amschwand

First, I would like to apologize for the last-minute submission of my review. I enjoyed reading the paper and have no major issues, just a remark on the methodology, a suggestion for an additional analysis, and a few minor points.

The authors analyse vertical and horizontal surface velocities over the 6-year period 2019–2025 of 19 glaciers, 3 debris-covered glaciers, and 59 rock glaciers in the Rodeo catchment in the Dry Andes of Argentina using Pléiades imagery. The detailed kinematic analysis includes validation using in-situ DGNSS measurements at selected sites, which is in itself a logistical feat in such remote terrain. The main finding is that downwasting clean-ice and debris-covered glaciers, showing consistent and considerable surface lowering, contrast with kinematically stable rock glaciers, showing no trend (small vertical changes fluctuating about zero). The key contribution is a large kinematic data set in an otherwise data-scarce region at a crucial point of time, providing a baseline observation to assess the future permafrost evolution in the Rodeo catchment.

The important methodological choice in this work is to approach glaciers and rock glaciers, i.e., glacial and periglacial landforms, from the surface kinematics and the mass conservation equation, essentially arguing with the geodetic mass balance (as pioneered by Cusicanqui et al. (2021) for rock glaciers). In that sense, this study adds a valuable complementary approach to that of assessing changes in the ground thermal regime (as e.g., in Koenig et al. (2025)), where rock glaciers as climate-conditioned permafrost landforms are investigated with the lens of the surface energy balance/energy conservation equation. However, while downwasting glaciers can be quite directly linked to climatic warming/drying (with little lag), kinematically stable rock glaciers are more indirect proxies of stable ground thermal conditions and the climatic forcing (L54–56, L548–556; Yu et al., 2025). The authors raise this point in L512ff: “The question here is the comparability between the meaning of vertical surface changes on glaciers and rock glaciers, which is why we focus on rock glacier velocities as indicator of (in)stability of permafrost conditions [...]”. Depending on the ground temperature and the soil freezing characteristic curve (SFCC), ground warming might not lead to excess (!) ice melt and subsidence. Furthermore, interannual ice storage changes as estimated by Halla et al. (2021) for the Dos Lenguas rock glacier could in principle mask (in their short monitoring period) a slow long-term subsidence (such processes could be discussed more thoroughly). Taking horizontal creep rates into account is a smart move that makes the correspondence between stable ground thermal conditions and surface kinematics convincing enough in the scope of this analysis, albeit future in-situ investigations of the ground hydro-thermal regime would of course be helpful for a more conclusive assessment.

Dear Dominik, thank you very much for taking the time to review our manuscript, for the sharp and thoughtful overall summary and for providing the very helpful comments. To address your points raised on more explicitly elaborating on the meaning of our findings in the scope of the rock glacier analysis, we add the following paragraphs into our manuscript.

Abstract: ... permafrost conditions in the Dry Andes based on borehole investigation and rock glacier kinematics for the last decade. **This apparent stability may partly reflect the extreme aridity conditions, limit snow insulation and liquid-water input, thereby damping inter-annual variability in ground thermal conditions and associated changes in rock glacier creep.** We investigate vertical surface changes of 19 glaciers, ...

Discussion: Thus, we highlight the strong need for continued monitoring of rock glaciers in this basin in this potentially dynamic point in time. Slow and small rock glaciers do not show any activity above the LoD, confirming our conclusion on little activity. **A plausible explanation for the absence of a basin-wide acceleration is that, in this semi-arid Andean setting, persistently low precipitation may limit both seasonal snow insulation and liquid-water input into the active layer, thereby damping interannual variability in ground thermal conditions and hydro-mechanical softening that can otherwise promote speed-ups in rock glacier creep (Cicoira et al., 2019).** This interpretation is consistent with evidence that aridity strongly constrains permafrost thermal regimes in the Dry Andes (Koenig et al., 2025) and with recent findings that precipitation scarcity can contribute to comparatively stable rock glacier behaviour (Stammler et al., 2025a). Under this hypothesis, the slightly higher velocities in 2024–2025 would reflect short-lived departures from typical moisture limitation (e.g., an anomalously wet season) similar to the variability described in Halla et al. (2021), a possibility that requires confirmation using local precipitation/snow proxies and longer kinematic time series. This lack of a regional trend in increasing velocities elucidates stable permafrost conditions in Rodeo basin during 2019 ...

Conclusions: ... domains of the Rodeo basin, we conclude a delayed response of the permafrost landforms to the increasing temperatures that are declining the glaciers and debris-covered glaciers alike. **We further hypothesize that the absence of basin-wide rock glacier acceleration is partly linked to extreme aridity, as persistently low precipitation can reduce snow insulation and liquid-water input to the active layer, damping inter-annual variability in ground thermal conditions and limiting kinematic changes.** Given the hydrological significance of all meltwaters, we highlight the strong need for continued monitoring of surface changes in the glacial and periglacial domains, supported by interdisciplinary studies focusing on their potential interaction.

Minor comments and a suggestion for further analysis

Fig. 7. The large number panels are somewhat hard to synthesize for a human but would be doable for a machine. Consider, for example, a hierarchical clustering (of absolute or normalized median velocities), and report the (few) representative trend pattern(s). This would really be a useful (and not too costly) additional analysis to more quantitatively ground

your key result (L541: “We do not detect a regional trend in increasing rock glacier velocities in the Rodeo basin between 2019-2025, Fig. 7”). (It would be interesting whether these clusters coincide with the three rock glacier groups “fast-large”, “fast-small”, and “small-slow/stagnant” as mentioned in L540f). *We agree with your comment and have redesigned the original fig. 7, see fig. 1. We use the revision as fig. 7 and relocate the original fig. 7 to the appendix. To be able to synthesize the different velocity patterns while including the respective LoDs, we decide to move towards LoD exceedance: For each rock glacier category and time step, we calculate the median exceedance from the corresponding LoD, fig. 1A. We filter the rock glaciers and count them towards a category when velocities are > 0 m/yr and at all time periods coherent with the respective category. Rock glaciers that do not fulfill this filtering are attributed ‘other’ and are shown in grey. To keep the information on residue correlation coefficients and to exemplify the LoDs, we include a selection of three rock glaciers in fig. 1B-D – with the rest now remaining in the appendix. We adapt the corresponding text sections to the new figure.*

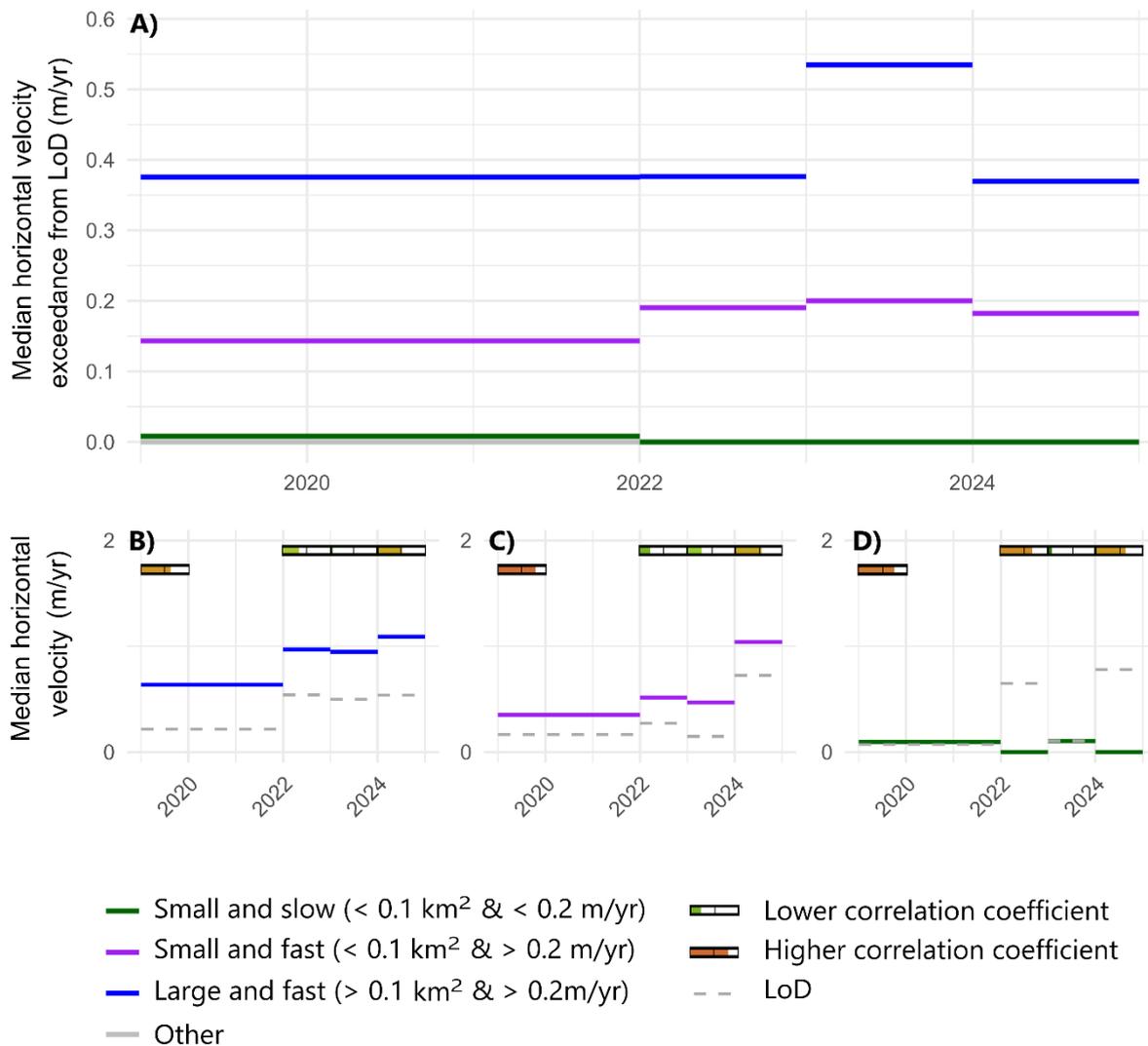


Figure 1 Temporal evolution of median rock glacier surface velocity exceedance from LoD (m/yr) between 2019-2025 based on feature tracking on panchromatic Pléiades imagery. Median horizontal rock glacier velocity is calculated for the rock glacier surface based on tracked horizontal velocity at 5 m resolution. Exceedance is calculated from the corresponding LoD. Rock glaciers are attributed to the three categories when > 0 m/yr and at all time periods coherent with the respective category (A). Selected rock glaciers and their temporal evolution of velocities over time including their LoD and the quality indication using residue correlation coefficients. The latter are included as bars – one each per time period (B-D).

The vertical changes over the landforms are aggregated in terms of the median and not the mean (or any other measure). Why was the median chosen, and wouldn't the mean value be more indicative of the whole-glacier geodetic mass balance? If the distribution of surface lowering is, say, right skewed, then the median is smaller than the mean and would underestimate the glacier-average changes. Are such considerations numerically relevant at all? *We chose the median to limit the influence of outliers on our aggregated results. After receiving your comment, we calculated mean values and plotted them against the median values, see fig. 2. While the differences between median and mean show a little higher difference for glaciers and debris-covered glaciers (polygon numbers > 60, colours purple to pink) compared to rock glaciers (polygon numbers < 60, colours orange to blue), all differences between median and mean are minor. We conclude based on the comparison of our vertical surface change results on glaciers compared to the literature that this effect is negligible.*

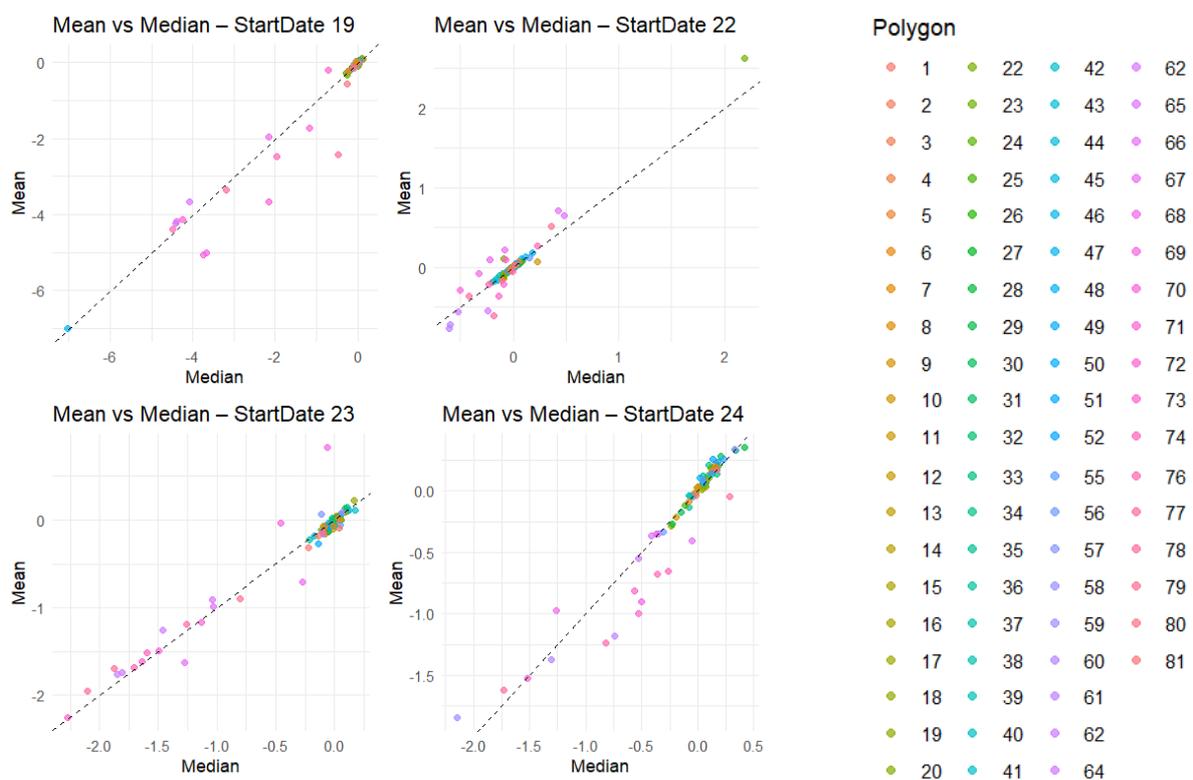


Fig. 2 Vertical surface change per polygon calculated as median or mean. Please note the differences in axis increments when comparing the four subfigures. Polygon IDs < 60 = rock glacier, > 59 and < 79 = glacier, > 78 and < 82 debris covered glacier. StartDate 19 corresponds to the vertical change 2019-2022, and so on.

L25, “dominantly negative annual surface lowering for all glaciers investigated.” Consider writing “surface lowering” instead of “negative surface lowering”. *We agree and have adjusted the manuscript accordingly.*

L190. LoD abbreviation not defined. *We missed the definition of the LoD and included it now at its first appearance, original line 28.*

Fig. 7: The bars show a “fill level” and a colour. What do they mean? Colour coding: There are 4 colours (black, purple, blue, green) in Fig. 7, but only 3 in Fig. 5. What do the black lines refer to? *The bars and fill levels describe the residue correlation coefficient of the residuals of the*

affine transformation during our feature tracking approach. The fill level scaled from 0 to 1 and the colours essentially show the same. Values are from 0 to 1 whereby low values (0 to 0.5, green to yellow) indicate a lower correlation coefficient meaning a high-quality feature tracking and higher values (>0.5 to 1, yellow to red) indicate a higher correlation coefficient referring to a lower quality feature tracking. This is exemplified in the lower, right corner of the original and the revised fig. 7 and explained in more detail in the original lines 216-222. Regarding the lines: blue corresponds to large and fast rock glaciers, pink to small and fast and green to small and slow. Selected rock glaciers that correspond with these categories are highlighted in these colours; the rest is shown in black. The revised fig. 7 includes a legend.

L309, L344, and others: Consider replacing “horizontal surface change” with “horizontal velocity” or “horizontal displacement (rates)” (the feature tracking gives labelled points whose position can be followed through time, not merely a change). This would make the terminology of “vertical surface change”, “rock glacier velocities” (always horizontally defined, correct?), and “glacier surface lowering” more consistent. *In agreement with your comment, we now refer to ‘vertical surface change’ and ‘horizontal velocity’ in the entire manuscript. The only exception is when introducing ‘rock glacier velocity’ in the introduction (original line 62).*

L533ff/L571. What do you mean by “volume dominated” vs. “creep-dominated” and “gravitational force to have a strong impact”? I do not fully understand this distinction, because all active rock glaciers move by gravity-driven creep. Do you refer to the material composition (ice content)? The motivation for this analysis could be better explained and better tied to the conclusions, currently it feels like an argumentative "dead end". *We agree that this analysis was only loosely tied to the main string of arguments and therefore decide to remove it from the discussion on rock glacier kinematics in the revised section ‘5.5 Rock glacier kinematics in the Rodeo Basin’. This section now focuses on the benefit of using Pléiades imagery to enlarge the analysis from the previously investigated Dos Lenguas rock glacier to the catchment as well as on the absence of a regional trend of increasing horizontal velocities. We add more details on the meaningfulness of this absence as inserted at the very beginning of this document.*

L540. Sentence unfinished (“Fig. 3C-D blue area on rock glacier front”). *With the as such perceived unfinished sentence we intend to refer the reader to the blue area on the rock glacier front in fig. 3C-D as an example of how the horizontal velocity imprints on the vertical change. We have adapted the sentence which now reads “Fast rock glaciers, independent of their size, are characterised by coherent areas of positive vertical surface changes on the rock glaciers front, cf. Fig. 3C-D, caused by the rock glaciers horizontal movement.”*

L554: Possible additional references are works from A. Kellerer-Pirklbauer for the Austrian Alps, from PERMOS for the Swiss Alps, and from M. Marcer for the French Alps. *Thank you for pointing out the references which we have added to our manuscript.*

References

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