Replies to Referee 2:

Our replies are embedded in the referee's comments.

We wish to thank the referee for the useful insights offered.

Comments by Referee 2:

The paper A climate driven, altitudinal transition in rock glaciers dynamics detected through integration of geomorphological mapping and InSAR-based kinematics (authors: Bertone et al.) presents a rock glacier inventory in the western South Tirol established through a combined geomorphic approach and InSAR analysis. The research underscores the significance of InSAR in inventorying rock glaciers and assessing their surface kinematics. The paper is clearly structured and well-illustrated, containing sufficient critical reflections and arriving at appropriate conclusions. The methodology is rigorous and consistent, integrating several complementing techniques, whit data supporting the interpretations. The results align with the findings and there are no factual errors. Therefore, I recommend accepting the manuscript with minor revisions. These are outlined below.

It is not clear if for this study area previous rock glacier inventories were compiled. Please, clearly refer to this issue in the Introduction and refer to the nearby inventories.

We agree. The geomorphologic inventory for south-western South Tyrol presented here relies on a broader regional effort compiled between 2018 and 2020. When we submitted the original manuscript, the publication of the geomorphologic inventory of South Tyrol was under preparation. Now it is in press as a full paper in the context of ICOP 2024 (Scotti et al., in press).

Scotti R, Mair V, Costantini D, Brardinoni F. In press. A high-resolution rock glacier inventory of South Tyrol. Evaluating lithologic, topographic, and climatic effects. Full paper, 8 pp. ICOP 2024, 16-20 June 2024, Whitehorse, Yukon, Canada.

Now that the inventory is in press, we have added reference to the geomorphologic inventory in line 124-125:

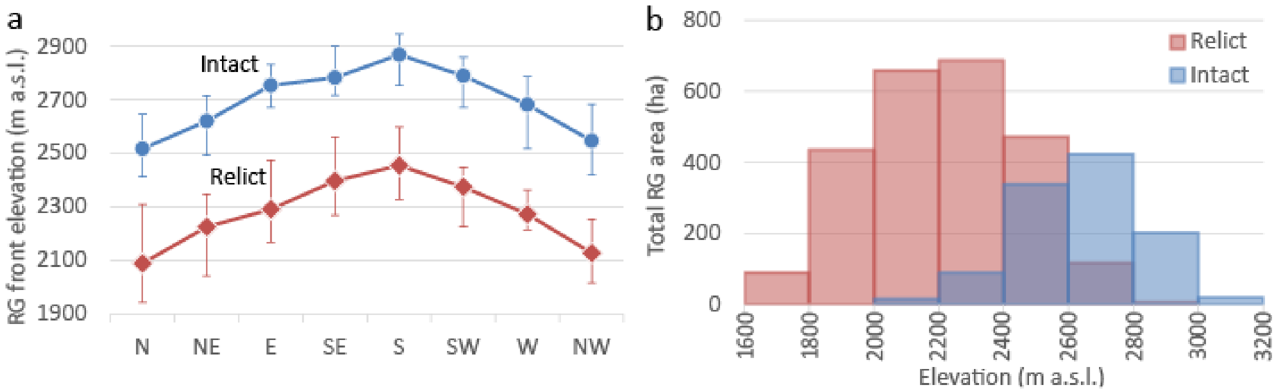
"The geomorphologic rock glacier inventory in south-western South Tyrol is part of a broader mapping effort conducted across the entire Autonomous Province of Bozen/Bolzano (Scotti et al., in press)."

Line 126: what type of optical imagery you used?

We agree. Web links to arial photo-imagery and LiDAR-derived hillshade raster were provided in the captions of Figures 3, 5, 12 and 13. To address the reviewer's concern we have added such information in section 3.1. Accordingly, the revised sentence in lines 125-128 now reads as follows: "The identification, mapping and dynamic classification of each rock glacier relies primarily on the visual interpretation of 0.2-m gridded, optical imagery (i.e., orthophoto mosaics flown in 2014, 2017, and 2020) and a 2.5-m LiDAR-derived hillshade raster (i.e., 2006) -- all available as WMS resources at the Geological Web Portal of the Autonomous Province of Bolzano (https://geoportale.retecivica.bz.it/geodati.asp) -- and where available, on information drawn from local reports on road closure or damage to infrastructure associated with the advance of rock glacier fronts."

4b: the bars should correspond to altitude intervals not to altitude values. Please correct the elevation values below the graph either by shifting all the values to the left, or replace it with elevation intervals.

Thank you for this comment. We had not realized this problem with Figure 4b. We have modified the Y axis accordingly. Please see figure below.



Line 298: Can you shortly present here the elevation range of all the moving areas?

We agree. The range and median elevations are presented in the following new sentence, added after line 298: “They range in elevation from 1935 m to 3177 m a.s.l., and display a median of 2680 m a.s.l.”

Based on the InSAR analysis 14 new rock glaciers were detected (fig. 6). I think it would be useful to shortly presents the elevation range of these rock glaciers.

We agree. The newly detected intact rock glaciers do not appear to be located at particularly low elevations: between 2440 and 3120 m. We have added the following sentence in line 300: “The latter landforms range in elevation between 2440 and 3120 m a.s.l.”.

Fig 6: 144 rock glaciers could not be classified, which means around 18% of the total inventory. For these rock glaciers (RG) you`ve used the geomorphologic criteria, which seems logical. However, it might be necessary to address this issue in the Discussion section, particularly when discussing the limitations. Perhaps, the notion to convey could be that the geomorphic interpretation should not be entirely supplanted by InSAR; instead a combination of both approaches is deemed desirable.

We agree with the referee that geomorphic interpretation should not be entirely replaced by InSAR characterization. This notion is incorporated in the title (i.e., integration of geomorphological mapping and INSAR-based kinematics), in the methodology (i.e., we build an “integrated inventory”, as well as in the opening paragraph of section 5.1 (Lines 421-429):

“In this contribution, we illustrate the importance of **complementing** a geomorphologic rock glacier inventory with InSAR-derived kinematic information. **Integration of the two inventorying approaches**, each of which characterized by specific strengths and weaknesses, allows reducing the overall uncertainty associated with the procedures of rock glacier detection, mapping and dynamic classification. On one hand, visual interpretation of multi-temporal optical imagery is crucial for outlining the morphological footprint of a rock glacier, and serves as a benchmark for developing automated mapping routines (e.g., Robson et al., 2020; Reinosch et al., 2021); on the other hand, visual interpretation of multi-temporal wrapped interferograms – except where decorrelation occurs – ultimately determines whether a rock glacier exhibits surface deformation, at what mean annual rate, and in which portion of its morphological footprint, thus confirming or rectifying prior evaluation solely based on the interpretation of morphological attributes.”.

To address the referee’s comment and reinforce this notion, we have incorporated the referee’s sentence at the end of section 5.1 (lines 482-483) as follows: “Based on the foregoing quantitative evaluations, we suggest that geomorphic interpretation should not be entirely supplanted by InSAR-based kinematic characterization; instead, a combination of both approaches is deemed desirable”.

Lines 348-349: You mention that the upper altitudinal limit of slow-moving areas (1-3 cm) are 300 m below the other faster classes. However, in Fig. 7a, this distinction is not very clear (please correct me if I`m mistaken). It appears that the upper green dots fall between 3000 and 3200 m, similar to the other graphs.

In 7b, c and d the upper dots occur a bit higher, but certainly not with a difference of 300 m. Please double-check!

We agree with the referee. Our description was not appropriate, since the upper altitudinal limit of 1-3 cm yr-1 moving areas drops by about 300 m across all but the southerly facing aspects (i.e., the cluster of 7 moving areas comprised between SE and SW aspects) that essentially share the same upper limit with the faster ones. Following this appraisal, we have modified lines 348-349 as follows: “Overall, the upper altitudinal limit of areas moving at 1-3 cm yr-1 plots 200-to-300 m below that of the faster classes (i.e., except for a cluster of 7 moving areas on southerly aspect; Figure 7a), which, by contrast, do not show altitudinal segregation from each other”.

Additionally, high-velocity MA`s (> 1m) do not seem to occur at very high elevations. There are several RG below 2600 m which move very rapidly (which might be interesting to investigate further in the future), even if they fall below the elevation band 2600-2800 m, where the majority of the intact rock glaciers are found. However, it seems that very fast rock glaciers are not strongly constrained by elevation. An analysis over a more extended period of time might help to understand their recent behavior.

Thank you for the insight on the > 1m MAs. We think it is important to incorporate a comment on this in the manuscript. We do this in lines 348-349: “This is particularly the case of areas moving > 1 m yr-1, which cluster on easterly and westerly aspects, and appear to be not strongly constrained by elevation.”

As for “very fast” rock glaciers, none of these have been detected in the study area within the 2018-19 period – the highest category represented being rock glacier moving annually from dm to m – and therefore it would seem difficult to draw conclusions on them. We agree that further analysis on extended baselines might be an interesting future task to pursue.

For completeness, below we report a table showing the descriptive statistics of rock glaciers stratified by kinematic classes, in which although not strongly constrained by elevation, we observe consistent increase of median and minimum elevation across progressively faster classes. We think that this progression agrees with the representation and the main message conveyed in Figure 15.

		Elevation (m asl)			
RG vel class	n. obs.	average	median	min	max
cm yr-1	145	2460	**2475**	1883	3102
cm to dm yr-1	63	2630	**2625**	2209	3043
dm yr-1	68	2660	**2720**	2104	3101
dm to m yr-1	64	2660	**2770**	2334	3030

Line 365: I think it might be useful to create a graph similar with 4b for intact/relict RG after considering the velocity because otherwise, it might be confusing. Ultimately, the rock glacier inventory based on InSAR data represents the final version of this work. Upon examining these figures, it becomes apparent that no intact RG occurs below 2200 m (fig. 4b), whereas in 8b there are MAs below 2000 m. These low-altitude permafrost sites might also be an interesting finding of this work, so I recommend briefly referring to this in the Discussion (similar sites are found in various locations below 2000 m across mid-latitude mountains). Earlier, I asked you to present the elevation range of the 14 new rock glaciers detected because I am curious to know if these occur particularly at lower elevations.

Thank you for the useful comment. On the premise that Figure 4b shows “intact” rock glaciers solely classified through visual interpretation of morphological expression, InSAR-based dynamic reclassification of rock glaciers shows that these rock glaciers exist below 2000 m asl elevation band (i.e., a handful of RGs that “become intact” in Figure 11b, all facing dominantly north). To highlight the presence of these low-lying landforms we have added the following text (lines 478-479): “It is noteworthy to highlight that dynamic reclassification allowed uncovering a cluster of low-lying rock glaciers (i.e., below 2000 m a.s.l.), dominantly facing north. This finding agrees with previous reports on the occurrence of intact rock glaciers around (or slightly above) 2000 m a.s.l. in other mid-latitude mountain settings, such as the Southern Carpathians (Vespremeanu-Stroe et al., 2012; Necsoiu et al., 2016).”

Following the referee’s suggestion, we have also added the InSAR-based version of Figure 4b, here labelled Figure 11c.

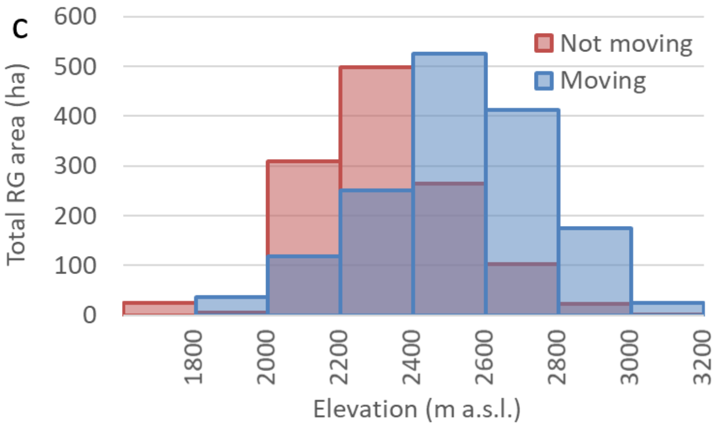


Figure 11 …. (c) Total rock glacier area across altitudinal bands, stratified into moving and not moving categories after InSAR analysis. This representation excludes undefined landforms. In panel c, note generalized altitudinal overlap between moving and not moving rock glaciers (cf., Figure 4b).

As a consequence of this new figure, existing sentences in lines 474-478 have been modified as follows: “… thus indirectly weakening the altitudinal separation previously observed between morphologically intact and relict landforms both in terms of median front elevation across aspects (Fig. 4a) and total rock glacier area distribution (Fig. 4b). In particular, we observe that the median front elevation of rock glaciers that “become intact” (2375 m a.s.l.) approaches that of counterparts that “remain relict” (2270 m) (Table 4); vice versa, the median elevation front of those that “become relict” (2725 m) closely matches that of counterparts that “remain intact” (2675 m) (Table 4). With respect to total rock glacier area, the generalized altitudinal overlap between moving (i.e., intact) and not moving (i.e., relict) is striking, when compared to the corresponding output of the geomorphologic inventory (cf., Fig. 4b and Fig. 11c).”

As for the newly detected rock glaciers, they do not sit at particularly low elevations: between 2440-3120 m asl.

Vespremeanu-Stroe, A., Urdea, P., Popescu, R., Vasile, M. 2012. Rock Glacier Activity in the Retezat Mountains, Southern Carpathians, Romania. Permafrost and Periglacial Processes, 23, 127-137. https://doi.org/10.1002/ppp.1736.

Lines 379-380: you are correct, but the number of RG above 2900 m is also significantly low and this should be taken into consideration as well.

True, but still, out of 30 rock glaciers located > 2900 m asl (and that could be kinematically classified via InSAR), 22 have total moving area > 50% (they plot between the 1:2 and the 1:1 line). In this case, we think that our statement remains appropriate and not misleading.

To acknowledge the limited number of rock glaciers involved, we have rewritten the sentence as follows: "At elevations above 2900 m a.s.l., where clustering is highest (despite the limited number of observations involved) and data trend parallel to isometry (1:1 line), total moving area increases at about the same rate of rock glacier size."

Lines 393-394: This is an interesting finding, but keep in mind that the most extended RG in generally are not necessary moving the fastest presently. Additionally, in this study, I don`t believe the fastest rock glaciers are necessarily the most extended (please correct me if I`m mistaken). As you are aware, there are other factors influencing their extent, such as the duration of activity, contributing area, lithology and structural conditions etc.

We totally agree with the referee. Our representation and accompanying text refer to the percent surface of a rock glacier that is actively moving, regardless of rock glacier size. Indeed, the clustering trend being parallel to 1:1-1:2 lines confirms that rock glacier size does not matter. To make this point more explicit and avoid possible misunderstanding, we have added the following short bit to the sentence in line 393: "… irrespective of rock glacier size".

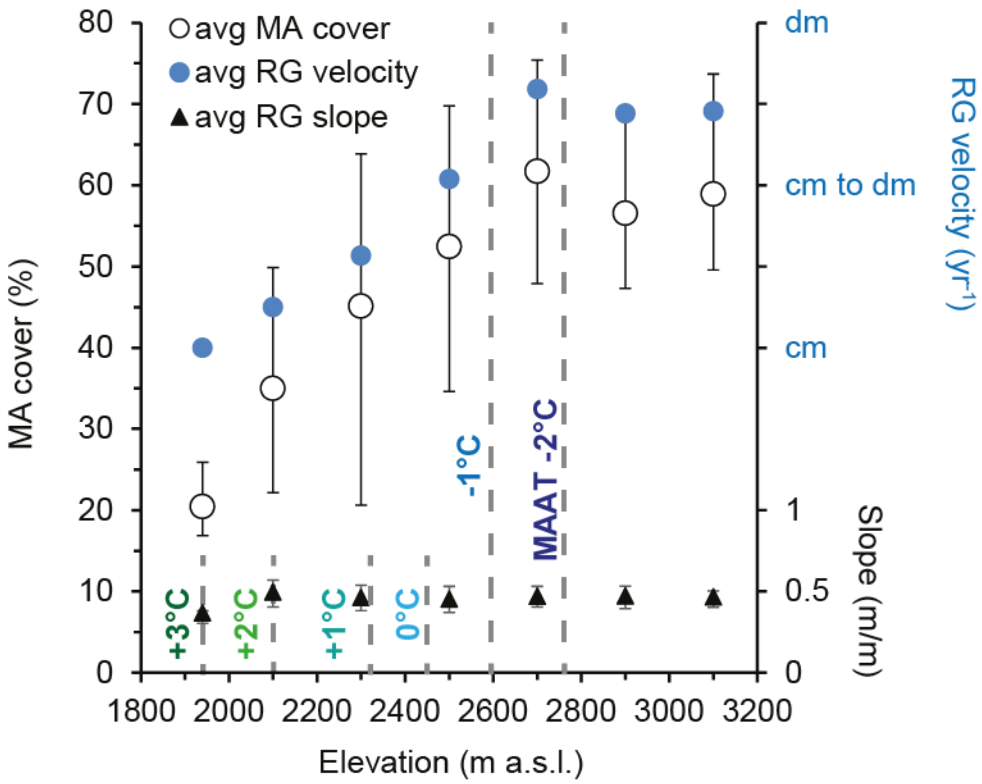
Figure 15: This is a very useful graph, but what is somehow surprising is the big number of intact RG occurring at MAAT above -1o Maybe would be interesting to add other few isotherm with a different color and to discuss on the reliability of this theoretical threshold (-1o C or -2o C) for discontinuous permafrost, respectively to refer to a threshold for sporadic permafrost in Tirol because it seems that there are enough moving areas/intact rock glaciers in areas with positive MAAT.

Although the figure now looks a little busier (i.e., the new isotherms overlap with the slope whiskers). We have modified Figure 15 adding isotherms 0, +1, +2 and +3 °C. We agree with the referee. To recap, we believe that: (i) the inferred altitudinal threshold for discontinuous permafrost is depicted by the inflection in MA percent cover and RG annual velocity functions at 2600-2800 m asl; (ii) an altitudinal threshold for sporadic permafrost may be inferred at 1880-2000 m asl; and (iii) a number of rock glaciers hold moving areas at positive MAAT values.

The following text was added in lines 578-580: "Interestingly, this representation aids elucidating that a number of moving areas, and relevant hosting intact rock glaciers, are located at positive MAAT values, and that locally a lower limit for sporadic permafrost may be set around the 1880-2000 m elevation band (i.e., + 3°C MAAT)."

Similarly, the sentence in lines 603-604 (section 6) was integrated as follows:

"We find that InSAR-based dynamic reclassification of rock glaciers: (i) aid detecting a cluster of low-lying intact rock glaciers (i.e., < 2000 m a.s.l.) associated with positive MAAT values; and (ii) induces substantial increase in the altitudinal overlap between relict and intact rock glaciers across slope aspects."



Lines 587-588: it`s hard to determine the importance of erosion rates for the acceleration of RGs in South Tirol. The reality is that using only a 1-year interval of velocity measurements makes it challenging to draw definitive conclusions. This could be related to various factors such as: snow cover regime, characteristics of the zero curtain, the freezing period in the active layer, intense summer rainfalls among others.

In our view, the main point is not the 13-month time window, as we believe that the trend shown in Figure 15 (based on hundreds of rock glaciers) is going to be relatively stable/resilient, even when using a 4-to-5 yr interval of InSAR data (as opposed to the temporal variability in the kinematics of a single, or a handful of rock glaciers); rather, as pointed out by the reviewer, the number of other factors potentially involved that might contribute to the altitudinal kinematic transition observed.

In this context, our statement wishes to make no inference on long term erosion rates associated to rock glaciers in SW South Tyrol, it plainly aims at highlighting similar altitudinal increase in RG kinematics (Fig 15) and rock wall erosion rates as constrained via cosmogenic nuclides by Draebig et al (2022). However, we also state that the extent to which the RG kinematic altitudinal increase may be due to frost cracking/rockfall rates feeding the rock glaciers -- besides permafrost occurrence alone -- is clearly beyond our reach with available data (lines 586-589).