Responses to the comments of anonymous reviewer #1

In this paper, the authors integrate existing rock glacier results from South Tyrol region, including the Autonomous Province of Bolzano/Bozen (PAB) rock glacier inventory data and the DInSAR-derived movement status by Bertone et al., (2019). By combining geomorphological characteristics of the rock glaciers, climatic driving factors, and InSAR products, the statistical model is calibrated and validated. This model is then used to optimize the identification of A (Active), T (Transitional), and R (Relict) states of rock glaciers in the region, while also describing the relationship between rock glacier states and multiple driving variables.

General comments

1. The reliability of optimizing rock glacier state. The author combines the PAB (2010) and Bertone (2019) rock glacier inventories in South Tyrol and uses various statistical factors to setup the GAM model, which is then applied to optimize the rock glacier states in the study area. However, it should be noted that if the original rock glacier states are not entirely accurate, the resulting GAM will inevitably carry uncertainties, making it inappropriate to use such a model to further optimize these states. Further assessment of the classification accuracy should be implemented or discussed.

We fully agree that starting from an initial classification with inaccuracies can introduce uncertainties into the results derived from the GAM (Generalized Additive Model). Recognizing this, we have taken a cautious approach to minimize these uncertainties.
In our initial reclassification (Table 1), we adopted a conservative strategy to establish a reliable baseline:
  - Landforms classified as "active" were included only if they were consistently categorized as active by both methods.
  - Similarly, landforms showing no movement were classified as "relict."
This selective approach ensures that the initial dataset used to train the GAM is as robust and accurate as possible. The GAM is then employed to refine and improve this initial classification by incorporating additional morphometric parameters and velocity descriptors. By integrating these complementary datasets, we aim to enhance the reliability and comprehensiveness of the classification process.
Discussions on this aspect are provided in the results and validation sections to highlight the model's reliability and areas for potential refinement.

2. In Section 3.4, it is unclear on the training data used to support the setup of GAM model. How many rock glacier samples were used and treated to train the model, including the samples for each status type (A, T, R), should be clearly presented.

In our analyses we applied the GAM model on the entire dataset of transitional, relict and active features (after reclassification in table 1) without splitting it for training and testing. This can be justified by the nature of the dataset and the objectives of the study. The initial dataset was already subject to a preliminary reclassification (Table 1), which we recognized as an approximation rather than a definitive classification. Given this context, our goal was to refine and improve upon this initial classification by leveraging the relationships between the parameters identified through the GAM.

Using the full dataset allowed us to maximize the information available for extracting these parameters relationships and constructing a predictive model capable of reclassifying all features into more reliable and meaningful activity classes. A predicted probability was also assigned to each landform, providing a quantitative measure of the confidence and reliability of the classification.

To ensure the robustness and generalizability of the results, we also evaluated the predictive model using k-fold cross-validation with varying sample sizes (2-fold, 5-fold, and 10-fold). This step allowed us to test the model's performance across different subsets of the data, ensuring that the reclassification was not overfit to the full dataset. The use of multiple cross-validation strategies further validates the consistency and reliability of the model, demonstrating that the relationships and classifications derived from the full dataset are representative and robust.

3. The paper uses SBAS-InSAR products, including velocity and coherence, as inputs to implement the statistical model, which is a distinctive aspect of the study. However, when the movement rate map of existing rock glaciers is available, classification can be conducted directly from a kinematic perspective (RGIK, 2023): for example, 10 cm/yr > v > 1 cm/yr for T (Transitional), v > 10 cm/yr for A (Active), and v < 1 cm/yr for R (Relict). This quantitative description of rock glacier movement status would be more straightforward. Moreover, if the prerequisite for identifying rock glacier states is to perform DInSAR or SBAS-InSAR to obtain product input for the statistical model, it further limits the application of rock glacier analysis in mountainous regions. To comprehensively define rock glacier states by integrating climatic driving factors, displacement rates, and morphological parameters, it is advisable to compare the results obtained from the current comprehensive definition with the states identified solely based on movement velocity data, or to use empirical data to demonstrate that the states identified by this comprehensive method are more accurate.

We appreciate the reviewer's comment regarding the use of velocity maps for directly classifying rock glaciers activity. We acknowledge that velocity-based classification offers a straightforward and quantitative approach. However, as the reviewer rightly noted, obtaining reliable and comprehensive velocity maps over mountainous regions is challenging. Issues such as topographic masking and low coherence often hinder the generation of accurate velocity data using DInSAR or SBAS-InSAR techniques.

To address these limitations, we have integrated morphometric and velocity attributes into our methodology. By combining these two approaches, we aim to overcome the weaknesses inherent in relying solely on velocity data. This integration allows for a more robust and comprehensive classification of rock glaciers activity.

Our approach has demonstrated clear advantages. Specifically:

- Expanded Classification: We successfully classified more polygons than the existing dataset, leaving only 63 out of 1779 landforms unclassified. Previously, considering only the morphological classification 235 rock glaciers were not classified, while 331 remained unclassified considering the coherence-based approach.
- Alignment with Existing Classifications: The results show that 67% of activity labels remain unchanged compared to previous classifications. The 32% of the old polygons were reclassified into different categories.

In conclusion, although velocity maps offer a direct means of classifying rock glaciers, our integrated approach overcomes the practical challenges of obtaining accurate velocity data in wide and difficult terrains. Furthermore, it improves classification accuracy by incorporating complementary datasets, resulting in a more thorough and consistent understanding of rock glacier dynamics.

Specific comments

1. Line 28: "Our approach improved classification accuracy, leaving only 3.5% of features unclassified compared to 13% in morphological classification and 18.5% in DInSAR-based methods." If "feature" here refers to the number of rock glaciers, such as the 3.5% representing 63 out of a total of 1,779, then it doesn't represent accuracy. Instead, it should be considered an enhancement over previous work, providing a more complete or comprehensive cataloging of rock glacier states.

We agree with the reviewer on this observation. We modified the sentence accordingly.

2. Line 60: "Although widely used, this classification brings two relevant limitations both from subjectivity point of view (activity attribution based on geomorphological approach is depended on the operator skills) as well as categorization since the activity of rock glaciers is considered constant over time at the scale of decades to centuries." The classification into "intact" and "relict" does not inherently introduce subjectivity; rather, it is the geomorphological classification process that carries subjective factors. If we classify Active (A), Relict (R), and Transitional (T) states based on geomorphological characteristics, it would also involve subjectivity. The use of initial identification data, such as the x-axis in Table 1, which is also based on geomorphological characteristics, introduces subjectivity into the GAM as well. Please explain why the assumption of long-term invariability in activity state identification would be considered a limitation of the "relict" and "intact" classification.

The sentence at line 60 was ambiguous and therefore was changed. However, in our view, classifying rock glaciers as intact or relict is based on the presence of inner permafrost, and without subsurface data, this classification remains somewhat subjective. Of course, this is also true for the classification in active, relict and transitional, but this latter classification is not merely based on the presence or lack of permafrost, instead it takes into account several potential descriptive factors that, if used together, could provide a more comprehensive description of the activity state of each landform.

3. Line 125: Bertone et al., (2019)

Added

4. Lines 193-199: What role does precipitation play in the overall text? Precipitation was not included as an input in the GAM; is it meant to be part of the discussion on precipitation? However, there doesn't appear to be any statistical information provided to support the author's discussion on precipitation.

We thank the reviewer for this observation and agree that precipitation is an important factor influencing rock glacier activity. As noted in the discussion section (lines 464-471), precipitation was not included as an input in the GAM due to the absence of a clear correlation between mean summer and winter precipitation values and activity classes at the regional scale.

While precipitation events are known to contribute to short-term and seasonal variations in rock glacier velocity (Kenner and Magnusson, 2017; Kenner et al., 2021), our analysis highlights that such relationships are less evident at broader regional scales. This is likely due to the influence of local factors, such as temperature, aspect, and other site-specific conditions, which can modulate the impact of precipitation on rock glacier dynamics.

Furthermore, as discussed in Zhang et al. (2023), precipitation interacts strongly with other climatic and environmental factors, making it challenging to isolate its effect on activity classes. For these reasons, further investigation is required to quantitatively understand the relationship between precipitation and rock glaciers activity at regional scales. Thus, precipitation was excluded from the current analysis but remains an important avenue for future studies.

5. Section 3.3: How were the velocity datasets from ascending and descending InSAR results integrated? Why was the calculation of slope velocities for rock glaciers not performed, given that both ascending and descending InSAR maps were derived?

We thank the reviewer for his observation regarding the integration of ascending and descending InSAR datasets and the decision not to calculate slope velocities for the rock glaciers. The ascending and descending datasets were analyzed by selecting independently the most suitable acquisition for each landform according to its topographic orientation.

The decision to not calculate slope-parallel velocities (V_{SLOPE}) was made in order to avoid reprojection and consequently reduce the uncertainties associated with this process. Specifically, reprojection requires dividing the line-of-sight (LOS) velocities by the C factor and, as noted by Notti et al. (2014), this process introduces significant uncertainty, particularly for values of $-0.2 < C < 0.2$, where reprojection becomes unreliable. Additionally, reprojection assumes that all motion occurs as pure downslope sliding, which oversimplifies the complexity of rock glacier dynamics. These considerations, as stated in lines 547–550, guided our decision to rely on LOS velocities instead of slope-parallel velocities for the analysis.

6. Line 253: Is the 100m value an empirical choice? If a unit within a rock glacier system is entirely occupied by other units within a 100 m buffer zone, how is this situation handled? I agree with the author's idea of calculating the increment by comparing the values inside and outside the buffer zone. This increment can potentially distinguish between the rock glacier's intrinsic movement and movement caused by external factors. It seems that further analysis or application of this increment has not been addressed in the following sections.

The selection of a 100 m buffer was chosen since it provides a balance that ensures meaningful data extraction for analysis while avoiding excessive noise from unrelated features.

In cases where adjacent or coalescing rock glaciers occur, the rims were cut to avoid any overlap between features, ensuring that the boundaries of one rock glacier do not encroach upon another. Additionally, due to differences in the orientation and spatial distribution of the landforms, it is highly unlikely for an entire rock glacier to fall entirely within the 100 m buffer zone of another.

Regarding the suggestion for further analysis of the increment values: we concur that differentiating between intrinsic movement and externally driven movement is an interesting prospect. However, this aspect was not explored further in the current study, as our primary focus was on classifying rock glaciers activity. The incremental differences derived from buffer-based analysis could indeed serves as a basis for future investigations into the dynamics of rock glacier systems, particularly in distinguishing between intrinsic and external movement drivers.

7. Line 285: Cross-validation is generally used because the data is limited, and it helps improve the model's generalization capability. It also allows for better evaluation and enhances the model's ability to fit data outside the training set. Please clarify the rationale for consecutively using 2-fold, 5-fold, and 10-fold cross-validation.

In this study, we applied 2-fold, 5-fold, and 10-fold cross-validation consecutively to provide a more robust and comprehensive validation of our model. The rationale behind this approach was to ensure that the model's performance metrics remained consistent across different levels of data partitioning regardless of the chosen partitioning method.

8. Line 309: From the boxplot (Figure 5c), it appears that VRM (Vector Ruggedness Measure) doesn't show a significant signal, which might suggest that surface roughness is unrelated to the activity status. Therefore, the inclusion of VRM in the GAM model seems unjustified. There are many other potential factors that could serve as surface condition indicators, such as terrain curvature and vegetation cover.

We agree with the reviewer on this point. Curvature was not included in the analysis because our exploratory data analysis (EDA) did not reveal clear differences between the classes based on this parameter (boxplots below). Similarly, as noted by the reviewer, the VRM does not show a sharp distinction between classes, although the median value is slightly higher for the transitional and active classes compared to the relict class (Figure 5c). Despite this, we chose to retain VRM as a parameter because it is more closely related to local-scale surface irregularities, which, in our opinion, makes it a relevant descriptor of activity. While the differences are not particularly pronounced due to the scale and heterogeneity of our mapped landforms, we believe that VRM still offers useful information for understanding the activity levels of rock glaciers.
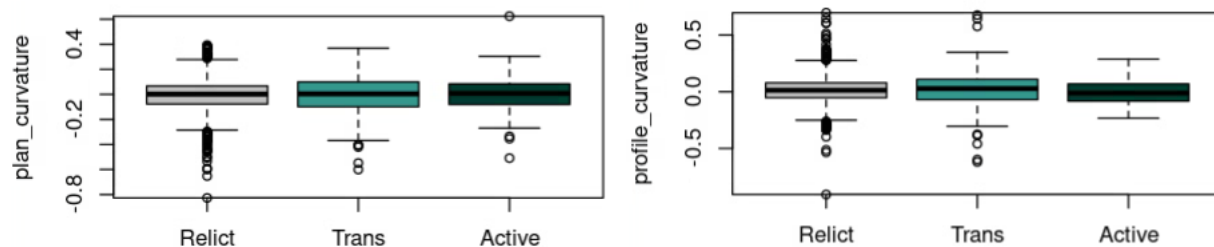
9. Section 4.2: Were the normalized or raw values of the eight variables used in the GAM model? How many rock glacier samples were used? Is it the number of A+T+R as mentioned in Table 1? Additionally, how did the author deal with the rock glaciers located in the layover/shadow regions of the SAR data?

We applied the GAM model to the entire dataset, which included all features with a preliminary classification attribute (1334 features, as detailed in Table 1) categorized as relict, active, or transitional. This approach aligns with the reasoning provided in response to General Comment 2, where we justified using the full dataset to refine the initial approximate classification.

For rock glaciers located in topographically unfavorable areas affected by layover and shadowing in the SAR data, we addressed these challenges by excluding only the pixels impacted by these effects. The features themselves were not excluded from the analysis; instead, their DInSAR data points were

reduced in number. This approach allowed us to retain as much useful information as possible while mitigating the influence of these data gaps on the overall analysis.

10. Line 383: The GAM is trained as a classifier based on the environmental factors of the original rock glacier data and the DInSAR products. However, it seems unreasonable to apply the trained GAM model to all 1,779 rock glaciers in the region, including those initially used as training datasets.

To clarify this point, we refer to our reply to the second general comment.

11. Lines 465-472: The paper lacks information on the statistical relationship between precipitation and rock glacier activity status.

We performed an exploratory data analysis on the relation between precipitation and rock glaciers activity, but we found no interesting correlation. We thus not included this variable in the GAM. We discussed our decision in lines 464-471.
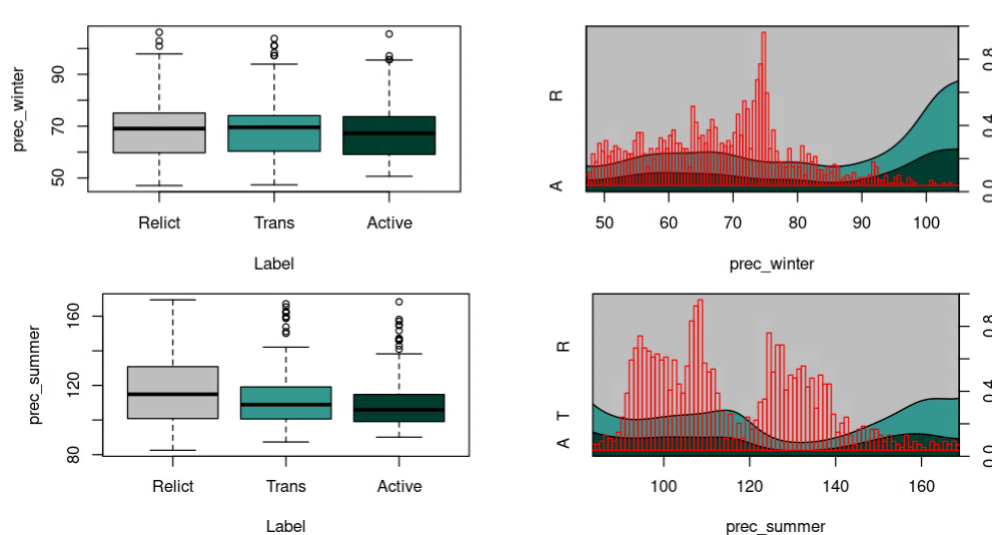
12. Lines 500-507: The current method for evaluating identification accuracy involves both InSAR movement signals and distinct morphological characteristics, providing a quantitative perspective first and then a subjective morphological identification perspective. However, if the current GAM identification method requires InSAR products, such as movement velocity and coherence as inputs, why not directly use the velocity map along with geomorphological features to evaluate the status?

Thank you for the comment. By integrating both velocity data and morphometric features into the GAM, we are indeed performing the type of analysis the reviewer is suggesting. The GAM approach inherently combines quantitative InSAR-derived velocity metrics and coherence with morphological characteristics to evaluate and classify rock glacier states.
This method is designed to leverage the strengths of both datasets: velocity maps provide direct kinematic information, while morphological parameters offer additional insights that may compensate for gaps or inconsistencies in InSAR data caused by factors such as topographic masking or low coherence. Thus, our approach moves beyond relying solely on a velocity map by

incorporating complementary geomorphological data, ensuring a more robust and comprehensive classification.

13. Lines 541-551: V_{los} cannot fully represent the true movement pattern of rock glaciers. Could this limitation affect the uncertainty of the GAM? There might be cases where some rock glaciers have a large V_{los} but a much smaller actual movement rate, thus introducing uncertainty.

All the uncertainties and errors associated to the measure of a certain variable indeed propagates in the GAM model. However, we can only limit them and not totally remove them. So, it is true that the underestimation of the movement can affect the GAM, but this is an intrinsic limitation we know we have to take into account. For this reason, we filtered out noisy component from the velocity data. We just point out two examples for a clear explanation: (i) removal of shadow and layover areas or/and (ii) consider for each rock glacier the acquisition geometry that better catch movements over that slope.

Furthermore, we have few or none examples of rock glaciers exhibiting a large vLOS coupled with a small actual movement rate. In contrast, it is more common to observe the opposite: large displacement rates that are underestimated when measured along the LOS.

Comments on Figures

- Figure 2: The "calibration" step in the "multiclass GAM model" is vague. Typically, calibration involves adjusting something that was previously incorrect to make it correct. Could you clarify what this step entails in the context of your model?

In this context, model calibration refers to identifying a set of parameters that accurately describe the system's behavior. Specifically, it involves finding parameters that are relevant for describing the activity of rock glaciers.

- Figure 3: The units of the unwrapped phase should be "rad" rather than "cm/yr."

The unwrapped phase has been here already converted in cm/yr in the unwrapping procedure.

- Figure 4: Do the input dataset "look vectors" correspond to Figure 4b (the visibility map)?

The look vectors refer to the parameters of LOS and azimuth angles components that are considered to produce the map in fig 4b.

- Figure 5: How were the outliers identified, and how was the lower limit chosen, especially for the coherence, such as in Figure 5d? The median and quartile changes with R, T, A are quite reasonable, but I've noticed that there are many outliers close to your lower limit. Please explain how the lower limit was determined and why there are so many outliers, not just in Figure 5d. Also, why not calculate and present the "mean velocity," "variance of velocity," and "velocity outside delta (Δ)" plots like the coherence panel?

In the boxplot function the whiskers and box dimensions are defined: the lower edge corresponds to the 25th percentile (Q1), the middle line is the median, the 50th percentile, and the upper edge the 75th percentile (Q3). The whiskers extend to the most extreme data points that are not considered

outliers. This range is considered between 1.5*IQR from Q3 and 1.5*IQR from Q1. Beyond these limits points are considered outliers.

The high number of outliers in the coherence-related plot, particularly in Figure 5d, is largely due to the inherent characteristics of SAR imagery. These data are influenced by various independent decorrelation factors such as imaging geometry, processing artifacts, and thermal noise. On rock glacier surfaces, which are composed of heterogeneous materials and characterized by varying movement velocities, coherence values can be highly scattered. This variability results in both wide variance and a significant number of outliers. Particularly, relict features often exhibit slightly rolling blocks due to scree movement or surface disturbances, which sporadically decrease in coherence and contribute to these outliers.

Regarding the exclusion of mean velocity and velocity variance in the plot, we opted not to include mean velocity because it does not adequately represent displacement rates. Averaging positive and negative velocities could significantly underestimate the magnitude of movement for various features. Instead, we chose to focus on the highest negative velocity, as it provides a more accurate representation of displacement rates without averaging opposing values. The delta of velocity, while not included in this plot, was considered in Figure 11, where we demonstrated how the delta increases between active and relict features.

- Figure 5h: Is a velocity threshold (0.02 m/yr) being applied?

No, no filtering on velocity is here applied.

- Figure 6f: Although the relationship may not be immediately apparent, I have observed that many rock glaciers are frequently located in convergent areas. This pattern is intriguing, and any insights or explanation regarding this observation would be valuable.

We think this is mainly due to the fact that rock glaciers are located in valleys, so convergent areas where debris from rockwalls are channeled and accumulated.

- Figure 11b: Would replacing the LOS velocity values with slope velocity result in a smoother transition from red to blue?

In Figure 11b, we do not use LOS velocity values directly; instead, we present the velocity delta, which is calculated as the difference between the velocity of the rock glacier and its surrounding rim. This approach was chosen because the delta better captures relative movement dynamics, highlighting the distinction between the rock glacier and its immediate surroundings.

In our analysis, we did not compute velocity along the slope for reasons outlined in response to comment 5. Using the 1D LOS velocity alone did not sufficiently explain the observed differences in activity levels or provide the same clarity as the delta approach. The velocity delta offers a more meaningful metric for distinguishing activity states, as it accounts for both the internal dynamics of the rock glacier and its interaction with the surrounding environment. As a result, we believe this method provides a more nuanced depiction of the transition between active and less active states.