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Optimizing rock glaciers activity classification in South Tyrol (North-East Italy): integrating multisource data with statistical modelling

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Response to the editor's comments:

General comments

1. There is some similarity (e.g. similar study region, InSAR velocity calculation; rock glacier classification, LST calculation) with the study by Agliardi et al., (2024) where the main authors of this study is co-author of and which was submitted to TC at a similar time. The similarities and differences to this study need to be better shown. Also, the reviewers of the Agliardi et al. (2024) study were critical. Clarify the impacts to this study.

We acknowledge the reviewer's observation regarding the similarities with the study by Agliardi et al. (2024). While both studies address the broad topic of rock glacier activity and share some methodological elements, such as the use of InSAR velocity data and LST as relevant environmental parameters, the two works are fundamentally distinct in several key aspects. First, the studies focus on different geographic areas and datasets. The current study is specifically centered on the South Tyrol region and is part of the PNRR-funded iNEST project, which has the explicit objective of investigating high mountain hazards in this area. In contrast, the Agliardi et al. study targets a different region (the uppermost portion of Valtellina, IT) and was developed independently. Second, the methodological approaches differ significantly. While Agliardi et al. rely primarily on wrapped interferograms for their InSAR analysis, our study employs unwrapped interferograms integrated in a SBAS procedure. Moreover, we enhance our approach by incorporating statistical modeling through Generalized Additive Models (GAMs), which offers a novel and more flexible interpretation of the controls on rock glacier dynamics. Although some variables such as LST are common between the two studies, this choice is based on their relevance to periglacial processes and not on methodological overlap. Thus, aside from addressing a broadly similar research theme, the two studies are distinct in their aims, datasets, methodologies, and spatial contexts.

2. I find the abbreviations A, T, R a bit confusing (T is usually used for temperature etc.). E.g. readers that first read the abstract and conclusions and look at the figures won't understand. These are also uncommon and not needed as there is no character limitation with TC. I suggest to write in full, but in italic.

As suggested, we changed the abbreviations through the text with the italic extended words. We only kept some abbreviations in the figures for sake of simplicity and a better representation but integrated the captions accordingly.

3. *The snow cover duration is important as also your analysis shows. However, the temperature condition when the snow cover starts to develop is also quite important to consider as is the snow thickness (in particular for the blocky material on rock glaciers). You may want to discus this at least with some sentences.*

We agree that these parameters play a crucial role in controlling ground thermal regimes and, consequently, permafrost dynamics. However, in the present study, being on a regional scale, we did not have access to widespread in-situ ground temperature data or detailed snow thickness measurements across the study area. As such, our analysis focuses on remotely sensed variables such as snow cover duration and land surface temperature (LST), which, while informative, do not fully capture the thermal insulation effects of snowpacks or the timing and nature of early-season snow cover.
Nonetheless, land surface temperature is indirectly accounted for in the snow cover duration (SCD) retrieval approach, as detailed in Notarnicola et al. (2013). Specifically, temperature thresholds derived from MODIS band 31 (11 µm) are used to filter out snow-free areas, thereby improving the accuracy of snow cover detection. These thresholds are seasonally adjusted (e.g., 283 K for winter, 290 K for summer) to reflect variations in surface temperature and to minimize false snow detections, especially in transitional periods and over complex terrain.
The reference to this work and the explanation for why we do not consider snow thickness or temperature can be found in lines 200–205.

Specific comments:

4. *L12: I suggest avoiding the term "climate warming". Although frequently used it is physically not correct. You may think about writing "atmospheric warming". More important: write "clear signs" and not "the clearest". The polar cryosphere shows also clear signs of degradation.*

We agree with the Editor on these points. We updated the text as suggested.

5. *L36: I suggest referring also to another reference for rock glaciers (e.g. Berthling et al. 2011) or from encyclopaedia entries (e.g. Kääb 2013 or Janke & Bolch, 2022).*

We thank the editor for the suggested references. We integrated them in the text and in the bibliography.

6. *L78: "a" digital terrain model. And omit "to derive" as it refers only to the DTM bit not to the other data or add the info what variables are derived from the satellite data etc. for consistency.*

We accept the suggestion and modify the sentence as: “We derived the input variables by integrating multiple data sources, including multispectral satellite imagery (Landsat, MODIS), radar data (Sentinel-1), interpolated ground measurements from weather stations, and variables extracted from digital terrain model (DTM) analysis.

7. L95ff: Please add the info about the elevation the precip and temp data are representing.

We appreciate the comment but are not fully sure what additional information is requested regarding elevation, precipitation, and temperature. The details and references about precipitation, temperature, and elevation are already included in lines 95 to 100 (now from lines 98 in the new revisited manuscript version).

8. L100: Is there a reference of the permafrost map from South Tyrol? If not provide a short info how it was derived and clarify the relation to Boeckli et al. (2012).

The available reference is the one indicated at line 101 (line 105 of the new manuscript version). The permafrost map of South Tyrol is based on the initial Alpine Permafrost Index (API) map developed within the PERMANENT project. This map was later refined and enhanced using results from subsequent projects such as Permaqua (https://www.permaqua.eu/de/ergebnisse.asp). The spatial resolution was improved from the original 30 m to 10 m. The mapping methodology is conceptually related to Boeckli et al. (2012) but was adapted to regional conditions using updated input data and localized calibration.

9. Figure 1: Include the data sources.

Done

10. L108: Clarify which sensors where uses for LST extraction; also the OLI bands? TIR bands have a resolution of 100m but the OLI MS bands have 30m (as the authors are certainly aware, but it is not written as such).

We modified the sentence as: “Using Landsat 8 Collection 2 Tier 1 data, we extracted Land Surface Temperature (LST), an Essential Climate Variable (ECV) recognized by both the Global Climate Observing System (GCOS) and the European Space Agency’s Climate Change Initiative (CCI) (Galve et al., 2022; Parastatidis et al., 2017; Ermida et al., 2020). LST was derived from the thermal bands (B10 and B11) of the Thermal Infrared Sensor (TIRS), which have a native spatial resolution of 100 m. Additionally, multispectral surface reflectance bands (SR_B1 to SR_B7) and the QA_PIXEL band from the Operational Land Imager (OLI), with a spatial resolution of 30 m, were used for preprocessing tasks such as cloud masking and emissivity correction.”

11. L122: What is the approximate spatial resolution of the ortho images?

We added the resolution of each image: 2000 (1 m resolution), 2006 (50 cm resolution), 2008 (10 cm resolution) and 2014 (20 cm resolution).

12. L135: What is meant by "inner permafrost"?

We refer to the permafrost core inside the rock glacier. We agree that it can sound redundant and, for this reason, we removed it along the manuscript.

13. Table 1: You may omit "table reporting the" and start with "Activity attributes…"

Done

14. Table 2: Lithology and Insolation are not morphometric variables. Is the total insulation the potential or actual one? The column "Description" is not consistent; partly the impact partly the variable itself is described.

We thank the Editor for the correction. We have modified the definition as "Geomorphological and Environmental variables" both in table 2 and in the header of section 3.2.1.
The insolation is the total one, as written in the table. We modified the "description" column to make it more consistent and avoid mixing with the impact.

Type of variable	**Parameter**	**Unit of measure**	**Description**
Geomorphological and environmental variables	Lithology	categorical	Classification of surface geology by rock type
	Total insolation	kWh / m^2	Amount of solar radiation received by a surface over a specific period
	Slope	°	Angle of terrain inclination derived from elevation data
	Aspect	°	Angle of the slope direction measured towards north, derived from elevation data
	Elevation	m.a.s.l.	Height above sea level; derived from a digital elevation model (DEM)
	Vector Ruggedness Measure (VRM)	/	Index quantifying terrain ruggedness based on variation in slope and aspect
	Convergence	/	Measure of terrain convergence and divergence, identifying ridges and valleys
	Profile Curvature	1/m	Curvature of the land surface in the direction of the maximum slope; distinguishes convex and concave forms
Climatic	Land surface temperature (LST)	°C	Radiative skin temperature of the land surface, derived from thermal satellite data
	Precipitations	mm	Total amount of rain and snowfall, interpolated from ground weather station data
	Snow cover duration (SCD)	days	Number of days with snow cover

15. L165: Which version of SAGA GIS?

SAGA GIS 9.03. Added

16. L211: Mention the revisit time considering the failure of S1B and launch of S1C. See also L216-

Thank you for the suggestion. Since our analysis covers the period from 2000 to 2022, some 6-day revisit acquisitions were still available prior to the failure of Sentinel-1B in December 2021. In the SBAS procedure we thus included the available 6-days pairs as well as longer baselines from 12days on. As we did not use Sentinel-1C data in our study, we prefer not to include information about this satellite to avoid potential confusion for the reader.

17. L294: I suggest "The boxplot…"

Corrected

18. Figure 5: What are the yellow bars? Include this info in the legend for better readability. And "The boxplots show …"

We corrected the caption as suggested and integrated the information on the yellow bars of the histogram, which shows the distribution (frequency) of the current variable's value across all observations (regardless of class).

19. L300ff: Be consistent with the abbreviations LST, SCD and VRM; they are commonly used, and partly written in full even though already introduced earlier in the manuscript.

Thanks for pointing this out. We modified to keep only the abbreviations.

20. L304: A rock glacier shares (or rock glaciers share)

Corrected in "active rock glaciers share".

21. L416: You may mention here or in the intro that rock glacier velocity was therefore introduced as an ECV. A suitable recent reference to consider here is: Kellerer-Pirklbauer et al. (2024).

Thanks for the suggestion. We included the information in the intro, now in lines 77-79: "Notably, velocity has recently been recognized as a new Essential Climate Variable (ECV) (Kellerer-Pirklbauer et al., 2024), underscoring the need to incorporate velocity-based indicators when assessing the state of activity."

22. L422: You may also mention here Liu et al. (2013), who used this method already more than 10 years ago.

We thank the Editor for the reference. We added it.

23. L426: You may refer here to the discussion about the InSAR limitations.

We added the reference to the discussion section. Now line 439.

24. L461: Wood et al. (2025) found that highest velocities occur partly at the lower rock glacier near the front which corroborates your findings.

We thank the Editor for the reference, we added it.

25. Figure 11: Add the meaning of the circle size in the legend of the figure.

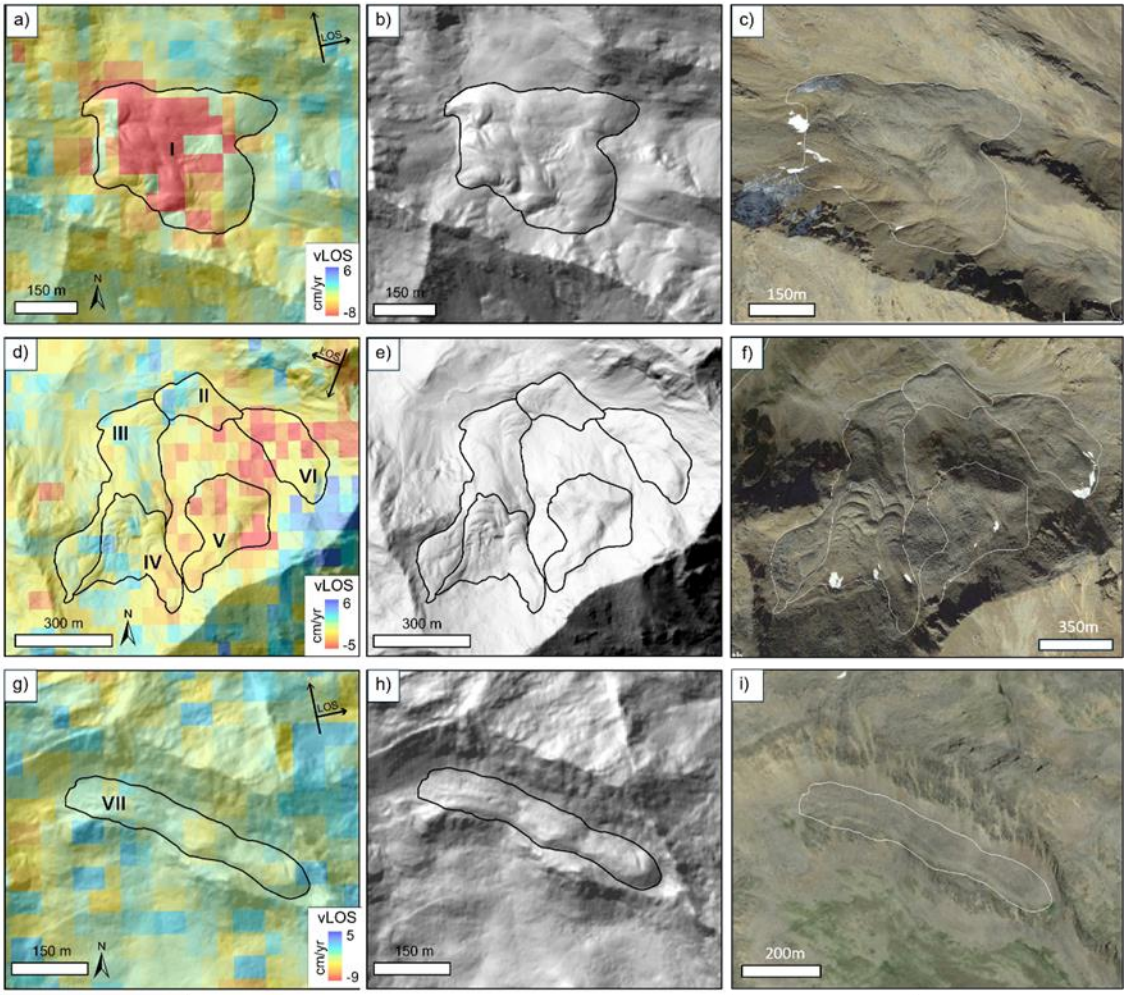
Done

26. L487: "debris cover" please clarify. You mean thickness of the ice-free debris; what is about the active layer thickness?

With "debris material," we refer to both the surface active layer and the debris within the permafrost body. Although we cannot directly quantify the thickness of the active layer, we acknowledge that its composition and depth significantly influence the thermal properties of the rock glacier, modulating its insulation capacity and damping effect on the underlying permafrost. In addition, the abundance and grain-size distribution of debris within the permafrost body play a key role in controlling its deformation behavior, affecting both its plasticity and the potential phenomena of sliding along discrete shear zones.
We reformulate the sentence, now lines 502-505 as: "This dynamic interplay is further highlighted by the complex interactions between ice presence, debris material (which plays a key role both as surface insulation in the active layer and in controlling deformation within the rock glacier body), permafrost content, and external factors such as temperature and precipitation."

27. Figure 12: Show also satellite (or aerial images) of the same subset, so that the reader gets a better impression of the rock glaciers.

We added images from Google Earth.



j)

Rock glacier	PAB	Bertone et al.2019	New class	Confidence
I	Relict	A	A	0.9
II	n.d.	F	R	0.6
III	n.d.	A	R	0.6
IV	Active	F	T	0.1
V	Inactive	A	T	0.1
VI	Active	A	A	0.4
VII	Relict	A	R	0.8

28. L521ff: You may also discuss the impact of the atmosphere.

We have already addressed the influence of atmospheric effects in Section 3.3 and further discussed the potential limitations of the filtering CNN approach with respect to atmospheric phase screen (APS) effects in the discussion (see lines 571ff).

29. L537: What is the "GAMMA procedure"? Is it related to the GAMMA software?

Exactly, as stated in HyP3 Product Guide: "The InSAR workflow used in HyP3 was developed by ASF using GAMMA software. The steps include pre-processing steps, interferogram preparation, and product creation."
https://hyp3-docs.asf.alaska.edu/guides/insar_product_guide/

30. L583f: I agree that the lithology is of minor importance for the velocity. However, the rock glacier velocity is predominantly driven by the shear horizon and not ice-deformation process (e.g. Arenson et al. 2002, Cicoira et al. 2021).

Thank you for the comment. We agree that rock glacier velocity is predominantly driven by shear zone processes rather than ice deformation. We modified the sentence into “while lithology may play a minor role,” but chose to retain the statement because some studies (e.g., Seppi et al., 2012) have noted correlations between lithological characteristics, such as fracturing properties, debris supply, and the ability of certain rocks to retain snowmelt, and rock glacier development.

31. L609: Be more specific with the variables; e.g. in the discussion section before you state the lithology is usually unimportant.

Thank you for the suggestion. Rather than listing specific individual variables influencing rock glaciers activity, which we believe require more detailed investigation at the local scale due to their complex interplay, we have revised the sentence to the following:
"These local settings, characterized by the dynamic and complex interplay of geomorphological, environmental, and climatic variables, shape the dynamics of rock glaciers, resulting in varying rates of progression between different activity states."
This phrasing refers to the macro-classes defined in Table 2 and better reflects the integrated nature of these factors.