CCI+ PHASE 2
PERMAFROST

CCN4 & CCN5
MOUNTAIN PERMAFROST: ROCK GLACIER INVENTORIES (ROGI) AND ROCK GLACIER VELOCITY (RGV) PRODUCTS

D4.1 Product Validation and Intercomparison Report (PVIR)

VERSION 2.1

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Executive summary

The European Space Agency (ESA) Climate Change Initiative (CCI) is a global monitoring program, which aims to provide long-term satellite-based products to serve the climate modelling and climate user community. The objective of the ESA CCI Permafrost project (Permafrost_cci) is to develop and deliver the required Global Climate Observation System (GCOS) Essential Climate Variables (ECV) products, using primarily satellite imagery. The two main products associated to the ECV Permafrost, Ground Temperature (GT) and Active Layer Thickness (ALT), were the primary documented variables during Permafrost_cci Phase 1 (2018–2021). Following the ESA Statement of Work for Permafrost_cci Phase 2 (2022–2025) [AD-1], GT and ALT are complemented by a new ECV Permafrost product: Rock Glacier Velocity (RGV). This document focuses on the mountain permafrost component of the Permafrost_cci project and the dedicated rock glacier products.

In periglacial mountain environments, permafrost occurrence is patchy, and the preservation of permafrost is controlled by site-specific conditions, which require the development of dedicated products as a complement to GT and ALT measurements and permafrost models. Rock glaciers are the best visual expression of the creep of mountain permafrost and constitute an essential geomorphological heritage of the mountain periglacial landscape. Their dynamics are largely influenced by climatic factors. There is increasing evidence that the interannual variations of the rock glacier creep rates are influenced by changing permafrost temperature, making RGV a key parameter for cryosphere monitoring in mountain regions.

Two product types are therefore proposed by Permafrost_cci Phase 2: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). This agrees with the objectives of the International Permafrost Association (IPA) Standing Committee on Rock Glacier Inventories and Kinematics (RGIK) (www.rgik.org) and concurs with the recent GCOS and GTN-P decisions to add RGV time series as a new product of the ECV Permafrost to monitor changing mountain permafrost conditions [AD-2 to AD-4]. RoGI is an equally valuable product to document past and present permafrost extent. It is a recommended first step to comprehensively characterise and select the rock glacier units to be used for RGV monitoring. RoGI and RGV products also form a unique validation dataset for modelling in mountain regions, where direct permafrost measurements are very scarce or lacking. Using satellite remote sensing, generating systemic RoGI at the regional scale and documenting RGV interannual changes over many landforms become feasible. Within Permafrost_cci, we mostly use Synthetic Aperture Radar Interferometry (InSAR) technology based on Sentinel-1 images, which provides a global coverage, a large range of detection capability (mm–cm/yr to m/yr) and fine spatio-temporal resolutions (tens of m pixel size and 6–12 days of repeat-pass). InSAR is complemented at some locations by SAR offset tracking techniques and spaceborne/airborne optical photogrammetry.

This Product Validation and Intercomparison Report (PVIR) presents the observations of the quality assessment of the Climate Research Data Package (CRDP) from iteration 1 [RD-6] and iteration 2 [RD-7]. We describe the conclusions of multi-operator RoGI exercise in the 12 selected areas, analyse the preliminary RoGI results in the new regions, discuss the findings of the RGV intercomparison group, and compare the InSAR-RGV trends against GNSS-RGV in the Alps. We summarise the current findings and identified limitations, and describe the plan for future work.

1 Introduction

1.1 Purpose of the document

The mountain permafrost component of Permafrost_cci Phase 2 focuses on the generation of two products: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). The Product Validation and Intercomparison Report (PVIR) presents the observations of the quality assessment of the rock glacier products delivered in Permafrost_cci Phase 2 iterations 1 and 2. It summarises the current findings and identified limitations, and describes the plan for future work.

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 compares the results of the RoGI production from both iterations. Section 3 describes the findings of the RGV intercomparison exercises and provides a preliminary validation of the InSAR-RGV products in the Alps. Section 4 summarises the main conclusions and describes foreseen activities. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 5.1. A list of acronyms is provided in Section 5.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-18].

1.3 Applicable documents

[AD-1] ESA. 2022. Climate Change Initiative Extension (CCI+) Phase 2 – New Essential Climate Variables – Statement of Work. ESA-EOP-SC-AMT-2021-27.

[AD-2] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-3] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

[AD-4] GTN-P. 2021. Strategy and Implementation Plan 2021–2024 for the Global Terrestrial Network for Permafrost (GTN-P). Authors: Streletskiy, D., Noetzli, J., Smith, S.L., Vieira, G., Schoeneich, P., Hrbacek, F., Irrgang, A.M.

1.4 Reference Documents

[**RD-1**] Rouyet, L., Pellet, C., Schmid, L., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Kääb, A, Strozzi, T., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.1 User Requirement Document (URD), v2.0. European Space Agency.

[RD-2] Rouyet, L., Schmid, L., Pellet, C., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.2 Product Specification Document (PSD), v2.0. European Space Agency.

[RD-3] Rouyet, L., Pellet, C., Schmid, L., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Wendt, L., Lauknes, T. R., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.2 Algorithm Theoretical Basis Document (ATBD), v2.0. European Space Agency.

[RD-4] Rouyet, L., Pellet, C., Schmid, L., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Wendt, L., Lauknes, T. R., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.3 End-to-End ECV Uncertainty Budget (E3UB), v2.0. European Space Agency.

[RD-5] Rouyet, L., Pellet, C., Schmid, L., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Wendt, L., Lauknes, T. R., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.5 Product Validation Plan (PVP), v2.0. European Space Agency.

[RD-6] Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D3.2 Climate Research Data Package (CRDP), v1.0. European Space Agency.

[RD-7] Rouyet, L., Pellet, C., Echelard, T., Schmid, L., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Brardinoni, F., Wendt, L., Lauknes, T. R., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2025. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D3.2 Climate Research Data Package (CRDP), v2.0. European Space Agency.

[RD-8] Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Sirbu, F., Onaca, A., Poncos, V., Brardinoni, F., Kääb, A., Strozzi, T., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D4.1 Product Validation and Intercomparison Report (PVIR), v1.0. European Space Agency.

[RD-9] Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Bartsch, A. 2025. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D4.2 Product User Guide (PUG), v1.0. European Space Agency.

[RD-10] RGIK. 2023. Guidelines for inventorying rock glaciers: baseline and practical concepts (version 1.0). IPA Action Group Rock glacier inventories and kinematics, 25 pp. https://doi.org/10.51363/unifr.srr.2023.002.

[RD-11] RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories. Practical InSAR guidelines (version 4.0). IPA Action Group Rock glacier inventories and kinematics, 33 pp.

[RD-12] RGIK 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.2). IPA Action Group Rock glacier inventories and kinematics, 12 pp.

[RD-13] RGIK. 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: practical concepts (version 1.2). IPA Action Group Rock glacier inventories and kinematics, 17 pp.

[RD-14] RGIK. 2023. Instructions of the RoGI exercises in the Goms and the Matter Valley (Switzerland). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

[RD-15] Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Christiansen, H. H., Darrow, M. M., Delaloye, R., Etzelmüller, B., Humlum, O, Lambiel, C., Lilleøren, K. S., Mair, V., Pellegrinon, G., Rouyet, L., Ruiz, L., Strozzi, T. 2022. Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide. The Cryosphere. 16, 2769–2792. https://doi.org/10.5194/tc-16-2769-2022.

[RD-16] Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Kaufmann, V., Noetzli, J., Thibert, E., Vivero, S., & Kellerer-Pirklbauer, A. (2024). Rock glacier velocity. In Bull. Amer. Soc. Vol. 105(8), State of the Climate in 2023, pp. 44–45. https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

[RD-17] Adler, C., P. Wester, I. Bhatt, C. Huggel, G.E. Insarov, M.D. Morecroft, V. Muccione, and A. Prakash. 2022. Cross-Chapter Paper 5: Mountains. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2273–2318. https://doi.org/10.1017/9781009325844.022.

[RD-18] van Everdingen, R. Ed. 1998, revised in May 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. http://nsidc.org/fgdc/glossary.

2 Rock glacier inventory (RoGI) products

2.1 Status of the RoGI production, intercomparison and validation

The RoGI product consists of three files for each Permafrost_cci area: the Rock Glacier Unit (RGU) Primary Markers (PM), the InSAR-based Moving Areas (MA), and the RGU Geomorphological Outlines (GO). Common instructions and GIS templates were used for the production in each area. They are summarized in the ATBD [RD-3] and follow the guidelines defined by the International Community on Rock glacier Inventories and Kinematics (RGIK) [RD-13] [RD-10]

The RoGI results in the 12 areas of the Permafrost_cci Phase 2 iteration 1 (CRDP v1.0, RD-6) have been compiled and released in the open repository *Zenodo* (Rouyet, et al., 2025a). An associated article has been published in *Earth System Science Data* (Rouyet et al., 2025b). In parallel to the dissemination of the results from Permafrost_cci Phase 2 iteration 1, RoGI production in 8 new regions started in 2024 as part of iteration 2. Preliminary results were delivered in May 2025 (CRDP v2.0, RD-7). The location and reference numbers for all Permafrost_cci RoGI areas are provided in Figure 1.

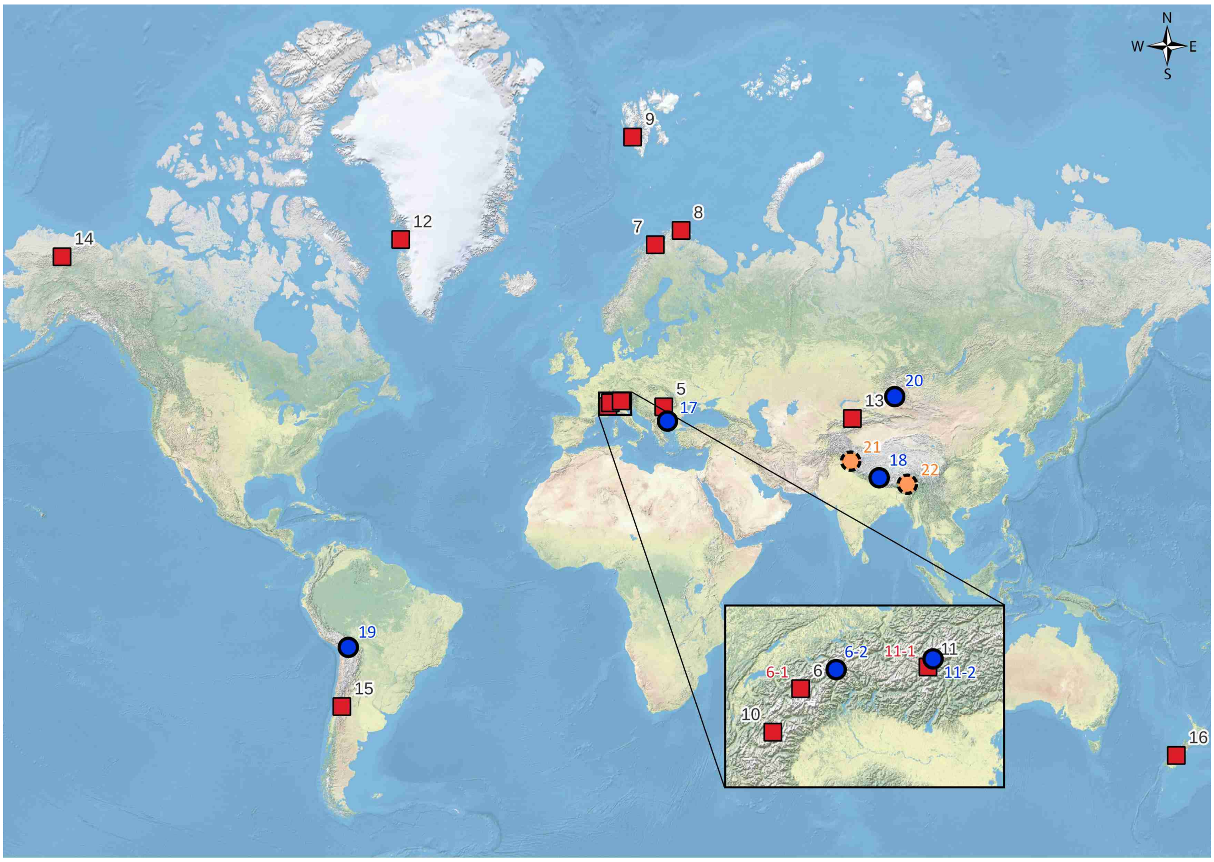


Figure 1. *Location map of areas selected for the RoGI from Permafrost_cci Phase 2 iteration 1 (red squares), new regions from iteration 2 (blue circles) and regions from side-projects (orange circles). The area numbering corresponds to the format defined in the PSD [RD-2].*

2.2 Methods for quality assessment

In the attribute tables of the three GeoPackages, various fields document the reliability of the mapping and morpho-kinematic assessment according to identified uncertainties and limitations:

- For the PM files, the attribute "uncertain" describes ambiguous areas that should be investigated in the future (need for additional data and/or field visit). For educational purposes, the attribute "not a rock glacier" could also be used to highlight landforms that are likely to be misinterpreted as rock glaciers. The level of uncertainty and complexity can be highlighted for many morpho-kinematic attributes, either in the selectable categories (for example "active uncertain", "transitional uncertain", and "relict uncertain" for the attribute "Activity") or using an additional reliability attribute for the kinematic assessment. Additional comments describing the uncertainty sources and ambiguities in the interpretation can be written in two "Comment" fields.
- For the MA files, the reliability (or the degree of confidence) of the results is qualitatively documented in accordance with the quality of the detection, the delineation of the moving areas based on the available InSAR data, the signal interpretation, and the resulting velocity estimation. When medium–low reliability is set (uncertain InSAR signal and/or unclear MA outlines), information on the uncertainty sources and ambiguities in the interpretation can be described in a "Comment" field.
- For the GO files, the reliability of the delineation at different locations of the rock glacier (front, left/right lateral margins, upslope boundary) is estimated with a score of 0 (low), 1 (medium), or 2 (high). It consists of a qualitative assessment depending on the data quality and the geomorphology complexity of the landform. The automatic summation of the scores (0–8) gives a general estimate of the outline reliability for the entire landform. Information regarding the data source(s) used for the delineation and the uncertainties impacting the reliability of the resulting polygon can be documented in a "Comment" field.

Not all operators have filled these fields and there is a high level of subjectivity in this assessment. It is therefore difficult to compare these reliability fields between operators and between the areas. However, in the final release of the RoGI results from Permafrost_cci Phase 2 iteration 1, all the reliability fields have been filled in a consistent manner and provide a useful quality estimate within each area. These quality estimates will be similarly documented in the new RoGI products from iteration 2.

Due to the multi-operator consensus-based procedure, the quality of the RoGI results evolved throughout the production timeline. Team meetings, bilateral discussions and email consultation to discuss and adjust the results took place in all inventorying teams. Consequently, the final product can not be seen as the arithmetic average of the individual results of single operator, they are much more. The final consensus-based products have a better quality than the individual results from each operator separately, because they took advantage of the diverse and complementary background/knowledge of the various people involved. However, because of the iterative process, locations of PMs may have changed or been merged/removed between the first and second phases of the exercise, which make the systematic comparison of the operator results with the final product not always possible. For this reason, the quality assessment was performed by compiling feedback from the RoGI teams and comparing key product attributes between the areas.

2.3 Summary of the RoGI intercomparison from iteration 1

As part of the RoGI multi-operator exercise from iteration 1, we made a comprehensive analysis of the procedure and findings within and across the 12 areas, accounting from the extensive feedback from the PIs and the members of the inventorying teams. The uncertainties and limitations of each RoGI product are discussed in detail in Rouyet et al. (2025b) and summarised in Figure 2. Rouyet et al. (2025b) also summarise observations regarding the multi-operator RoGI procedure, highlighting both the value and challenges of the exercise and providing a list of suggestions to improve the RGIK procedure and guidelines.

We compared the following key product attributes between the areas:

- The number and relative distribution of certain and uncertain Rock Glacier Units (RGUs) from the Primary Marker (PM) layers, as an indicator of the difficulty to interpret the geomorphology in each area. In average of all areas, 40% of the identified PMs remain uncertain.
- The number and relative distribution of the Moving Areas (MAs) and their velocity classes, as an indicator of the range of movement rates in each area. The distribution of the detected velocity greatly varies within and between the areas. In average of all areas, the categories 1-3, 3-10, 10-30 and 30-100 cm/yr are relatively evenly represented.
- The number and relative distribution of the RGU activity (active, active uncertain, transitional, transitional uncertain, relict, relict uncertain, uncertain) from the PM layers, as an indicatory of the diversity of the permafrost state and the uncertainty of the categorisation. In average of all areas, 40% of the identified RGU are active, about 30% are transitional, 20% are relict. The remaining 10% correspond to uncertain categories.
- The range of RGU sizes within the extended geomorphological outlines (GOs), as an indicator of the heterogeneity of the landform sizes (median values between 0.01 and 0.25 km^2). The GO size depends on the way the rock glacier has been decomposed into several units. The differences between areas are therefore due both to the variable degree of complexity of the landforms and the variable quality of the remotely sensed data (orthoimages, InSAR, DEM) used to divide the systems into multiple units.
- The density of the rock glaciers (number of RGU per km^2 and percentage of the area covered by rock glaciers according to the mapped extended GOs), as an indicator of the heterogeneity of the distribution in the studied areas (between 2 and 15% of the area covered by the extended GOs).

The five figures corresponding to these five indicators are available in Rouyet et al. (2025b).

A comparison between the generated RoGIs and the results from the permafrost model has been performed as part of the PVIR of the global modelling products. The distribution of the inventoried active, transitional, and relict rock glaciers is overall consistent with the modelled permafrost distribution (permafrost fraction).

	5-1	6-1	7-1	8-1	9-1	10-1	11-1	12-1	13-1	14-1	15-1	16-1
PM detection and characterisation												
Optical imagery affected by shadows, clouds, snow	O	O	O	O	X	O	O	X	O	X	O	O
Dense vegetation cover on relict rock glaciers	X											
Dominance of large RGU and small RGU likely overlooked								O	X	X	X	
Ambiguous imbrication of periglacial landforms	O	O	X	X	O	X	O	O	O	X	O	
Ambiguous rock glacier and glacier/forefield continuum	O	X	O	O	O	O	O	O	X	X	X	
Variable categorisation of landslide-connected RGU	O	O	X	O	O	X	O	O	O	O	O	
Difficulty with selecting RGU for complex multi-unit systems	O	O	X	O	O	O	O	O	X	X	X	O
Ambiguity in activity in Arctic cold regions with slow/no MA					X		O		O			
Difficulty with discriminating active/transitional		O	O		O	O	O	O	O	O	O	X
MA detection, delineation, and characterisation												
Fewer available Sentinel-1 images and longer repeat-pass								X	X	X	X	X
Challenge of velocity estimate for operators with little InSAR experience	X	X	X	X	X	X	X	X	X	X	X	X
Difficulty with documenting and interpret small and slow MA	X	O	O	X	O	O	O	O	O	O	O	O
Difficulty with discriminating creep from other processes	O	O	O	X	X	O	O	X	O	X	O	O
GO delineation and characterisation												
Uncertainty in the delineation of the upper boundaries	X	X	X	X	X	X	X	X	X	X	X	O
Uncertainty in the delineation of eroded, reworked or exaggerated fronts	X	X	O	X	O	X	X	O	O	X	X	O
Unclear lateral margins for small rock glaciers	O	O	O	X	O	O	X	O	O	O	O	O
Difficulty with outlining complex RGSs with multiple RGUs	O	O	X	O	O	O	O	O	X	X	X	O
Variable quality of optical imagery and georeferencing shifts	O	O	O	X	X	O	O	X	X	X	O	O

Figure 2. *Overview of the main uncertainties and limitations of the RoGI products and how they apply to the 12 areas (Rouyet et al., 2025b). The crosses (X) show where the problem has been explicitly reported by the RoGI team/PI. The circles (O) show where the problem might happen for specific landforms but was not reported as a main limitation by the RoGI team/PI. See Figure 1 for references to the area numbers.*

2.1 Preliminary RoGI intercomparison from iteration 2

Similarly to the results from iteration 1, we compared the following key product attributes between the areas of iteration 2:

- The number and relative distribution of certain and uncertain RGUs from the PM layers, as an indicator of the difficulty to interpret the geomorphology in each area (Figure 3).
- The number and relative distribution of the MAs and their velocity classes, as an indicator of the range of movement rates in each area (Figure 4).
- The number and relative distribution of the RGU activity (active, active uncertain, transition, transitional uncertain, relict, relict uncertain, uncertain) from the PM layers, as an indicatory of the diversity of the permafrost state and the uncertainty of the categorisation (Figure 5).
- The range of RGU sizes within the extended GOs, as an indicator of the heterogeneity of the landform sizes (Figure 6). The GO size depends on the way the rock glacier has been decomposed into several units. The differences between areas are therefore due both to the variable degree of complexity of the landforms and the variable quality of the remotely sensed data (orthoimages, InSAR, DEM) used to divide the systems into multiple units.
- The density of the rock glaciers (number of RGU per km^2 and percentage of the area covered by rock glaciers according to the mapped extended GOs), as an indicator of the heterogeneity of the distribution in the studied areas (Figure 7).

The RoGI production is not finalised in some regions (not fully mapped and/or remaining undocumented attributes, see status in CRDP [RD-7]). In such cases, the information remains empty (to be updated) in the following graphs. Even for areas in which the mapping is completed, some adjustments (minor corrections) might occur before final publication.

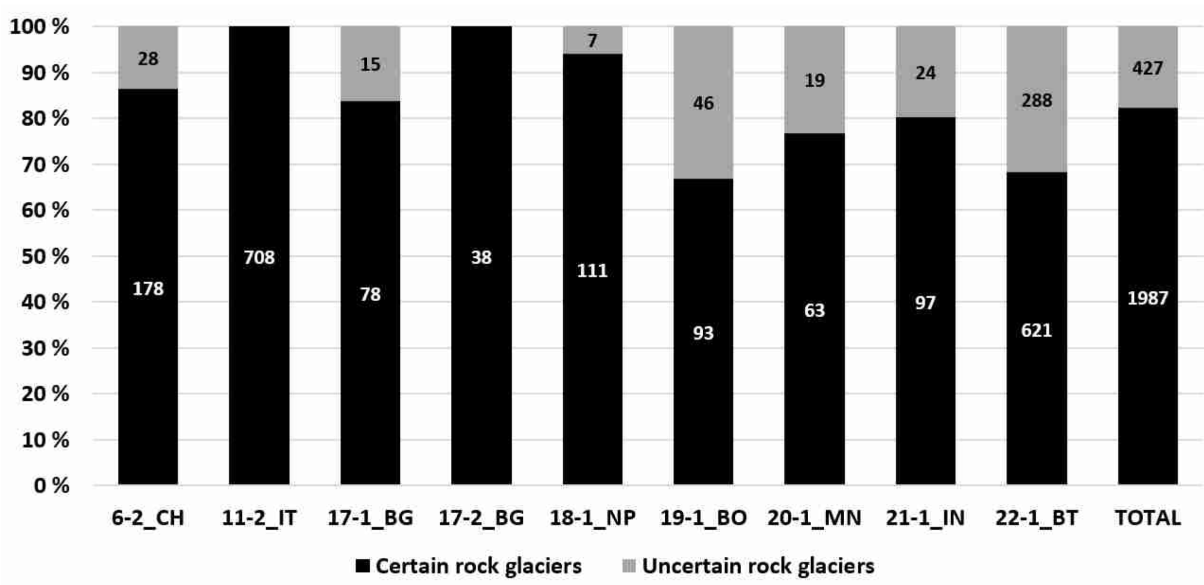


Figure 3. *The number and relative distribution of certain and uncertain RGU from the PM layers. The area numbers follow the standard format defined in the PSD [RD-2] and the PUG [RD-9]. See Figure 1 for geographical reference.*

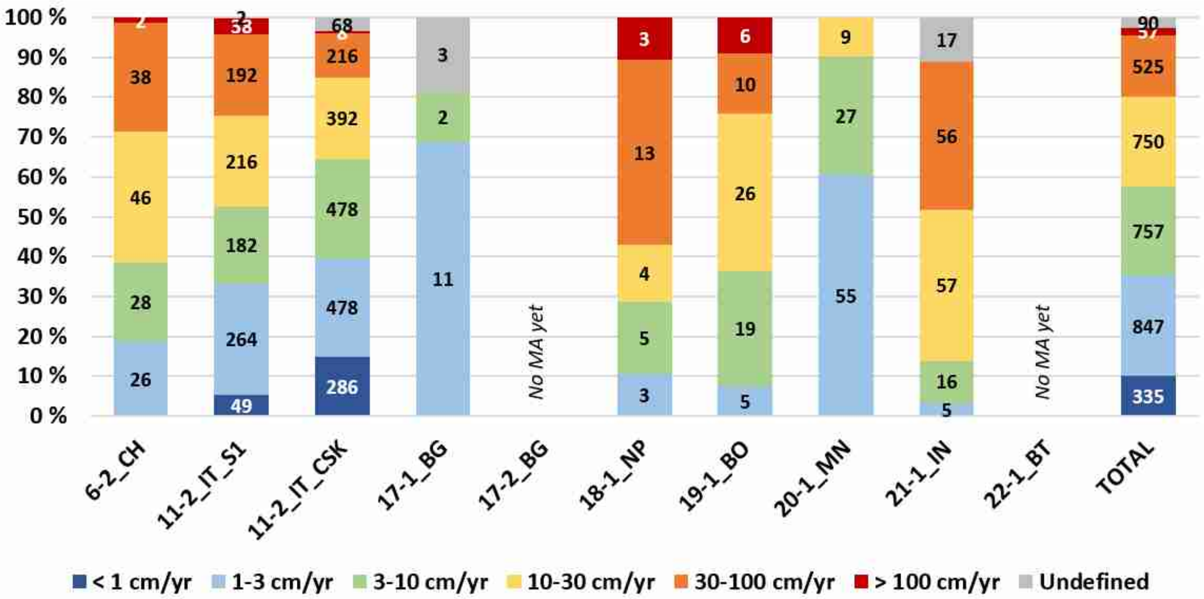


Figure 4. *The number and relative distribution of the MAs and their velocity classes. The area numbers follow the standard format defined in the PSD [RD-2] and the PUG [RD-9]. See Figure 1 for geographical reference.*

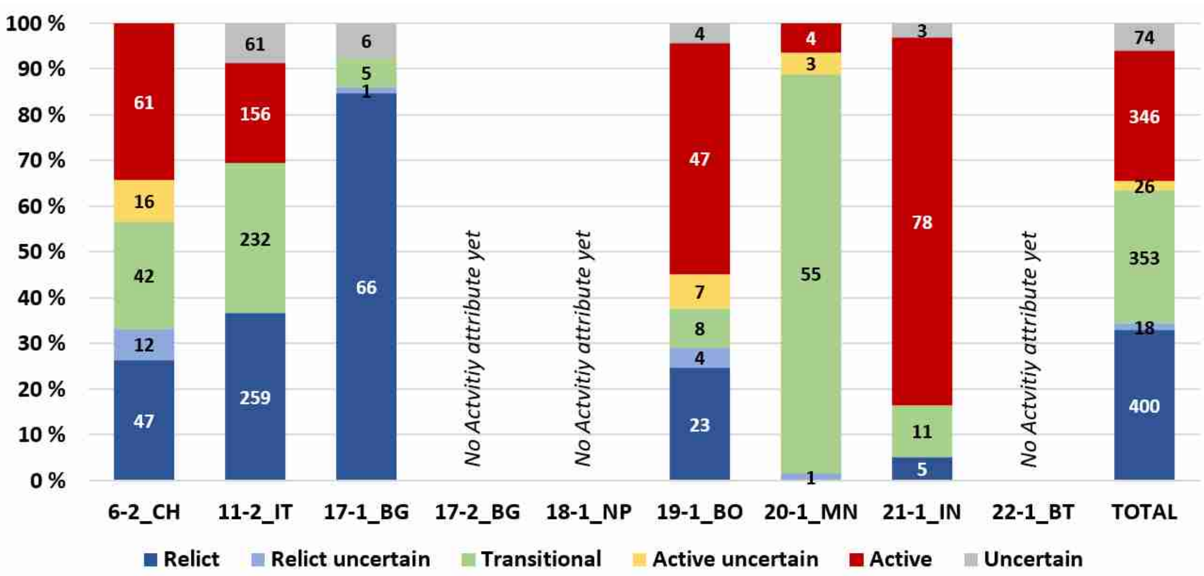


Figure 5. *The number and relative distribution of the RGU activity from the PM layers. The area numbers follow the standard format defined in the PSD [RD-2] and the PUG [RD-9]. See Figure 1 for geographical reference.*

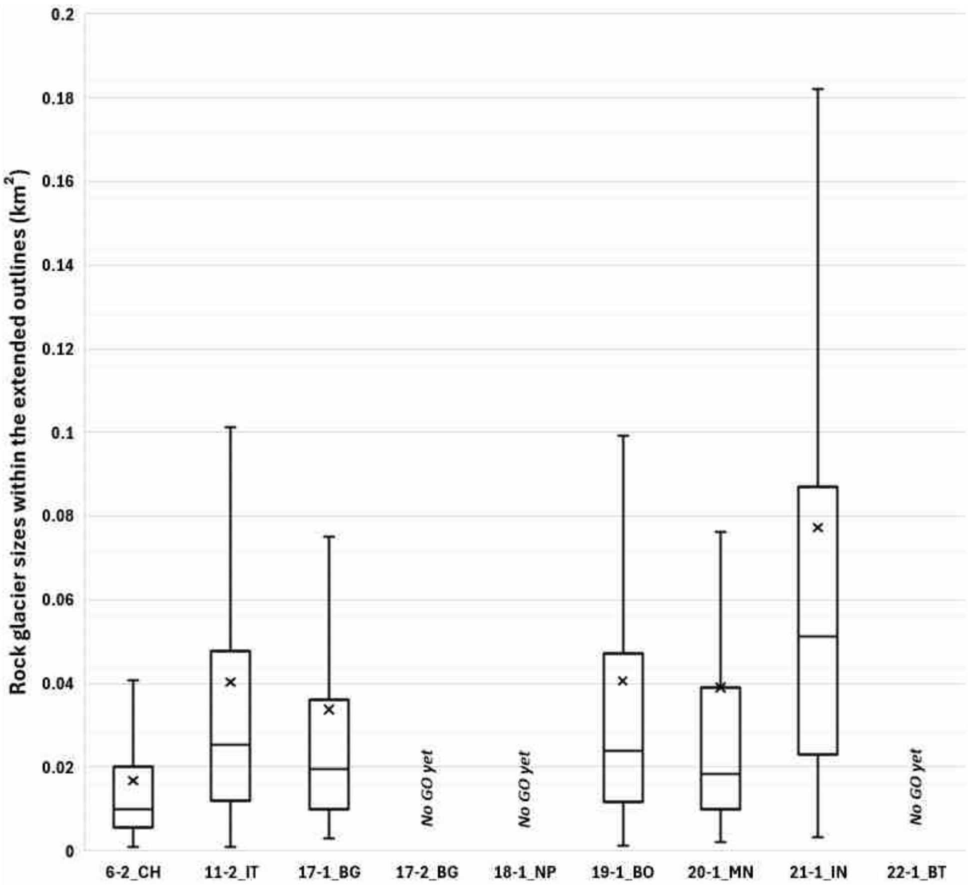


Figure 6. *The range of RGU sizes within the extended GOs. The area numbers follow the standard format defined in the PSD [RD-2] and the PUG [RD-9]. See Figure 1 for geographical reference. See Figure 1 for geographical reference.*

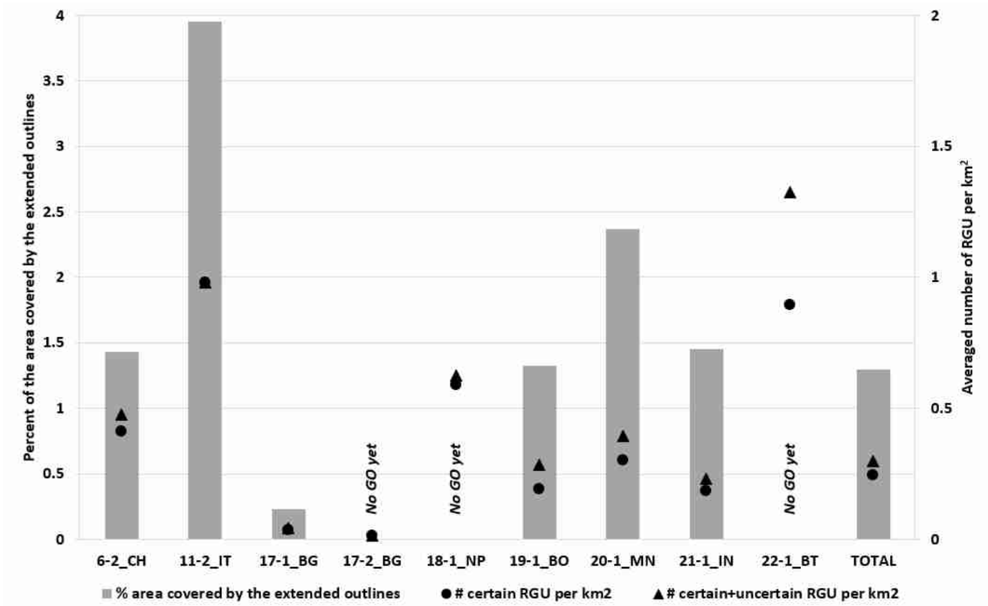


Figure 7. *The density of the rock glaciers (number of RGU per km^2 and percentage of the area covered by rock glaciers according to the mapped extended GOs). The area numbers follow the standard format defined in the PSD [RD-2] and the PUG [RD-9]. See Figure 1 for geographical reference.*

3 Rock glacier velocity (RGV) products

3.1 Status of the RGV production, intercomparison and validation

Rock glacier velocity (RGV) is defined as a time series of annualized surface velocity values expressed in m/y and measured/computed on a rock glacier unit or a part of it [RD-12]. RGV is produced with the objective to document the long-term changes of rock glacier creep rate in a climate-oriented perspective. RGV is a quantity of the ECV Permafrost aiming to complement the two other quantities (permafrost temperature and active layer thickness) to monitor changing permafrost conditions in mountains [AD-2 to AD-4]. Based on satellite remote sensing techniques, such as InSAR, a RGV is the result of flow field measurements for pixels assumed to be representative of the permafrost creep of the rock glacier unit (or part of it) [RD-12]. Temporally, the initial InSAR measurements are aggregated during a consistent observation time window each year.

In the first iteration of Permafrost_cci Phase 2, the development of InSAR-based RGV products has been performed in synergy with the M.Sc. study of Lea Schmid at the University of Fribourg (UNIFR) (Schmid, 2024). We showed that the proposed procedure was promising, and that the InSAR-RGV pilot products were overall consistent with similar GNSS-RGV products at the same sites [RD-8]. However, the few selected sites and the short overlapping periods between InSAR and GNSS measurements made it challenging to draw any definitive conclusion. In the second iteration of Permafrost_cci Phase 2, the InSAR procedure has been adjusted and tested on a large number of rock glaciers in the Alps (21 sites).

3.2 Methods for quality assessment

The quality assessment of the RGV products was performed using three methods:

- A RGV working group was launched in 2024. The RGV working group is organised in three teams corresponding to different techniques (in-situ, optical and radar remote sensing). The teams performed a multi-operator and multi-method RGV intercomparison exercise performed over three alpine rock glaciers. A workshop was organised in November 2024 to discuss the results and plan the way further (see RGV Working Group information on ESA website). The InSAR team consists of eight people, among which six persons acted as operators for processing tests. In 2025, the work continued to further evaluate the effects and impacts of various processing settings and tests solutions to reduce the discrepancies between individual RGV results. The findings of this initiative were presented at the ESA Living Planet Symposium in June 2025 (Buchelt et al., 2025). They are summarised in Section 3.3.
- The InSAR-RGV products were compared with GNSS data acquired using periodic terrestrial surveys or permanent GNSS stations, as a follow-up of the initial validation from the last PVIR [RD-8]. The comparison with in-situ data was performed for six rock glaciers (Bru, Distelhorn, Grosses Gufer, Réchy, Steintälli and Gran Sometta). The periodic terrestrial surveys were performed annually or biannually, at the end of June and October. The surveys were carried out in real-time kinematic (RTK) mode. This mode makes use of two separate receivers: the reference station, at a position assumed to be stable, and the rover used to measure the points of interest. By comparing the positions of survey points between two campaigns, the surface displacement can be determined. The 3D displacement is calculated by combining the horizontal and vertical components of the movement. The velocity is given in meters per year (m/yr). Accuracy is in the order of 0.12 m/yr for summer measurements, 0.04 m/yr for winter measurements and 0.03 for annual measurements. The main limitation of the method is related to the topography that can

limit the number of available satellites and consequently prevent the measurements (Lambiel and Delaloye, 2004). The periodic surveys have been carried out by members of the UNIFR Department of Geosciences. For Distelhorn, InSAR-RGV products were compared with permanent GNSS station data from Cicoira et al. (2022). The data is part of the dataset of GNSS observations at 54 sites in the Swiss Alps, published in PANGAEA (Beutel et al., 2022). The results of the site validation are shown in Section 3.4.

- We compared the regional interannual velocity change from the average of all InSAR-documented rock glaciers with similar time series based on GNSS measurements. Despite the different extent and selected landforms in both time series, this comparison provides a general indication on the similarities and differences of the interannual variations. We analysed the velocity changes relative to the mean of a reference period. There are three main reasons for focusing on relative velocity change: 1) InSAR often underestimates the velocity of rock glaciers and other mass movements, because the measurements are one-dimensional along the line-of-sight and rarely fully aligned with the creep direction; 2) Despite InSAR underestimation, if the movement direction is mostly constant in time, the relative change of InSAR measured velocity should correspond to the actual variability of the creep rate; 3) The objective of documenting RGV in a climate-oriented perspective is to document the interannual velocity changes, independently of the absolute values. The regional comparison is presented in Section 3.5.

3.3 Summary of RGV intercomparison exercise

The RGV working group intercompared results from different operators and methods for three selected rock glaciers in the Alps. Here we only present the results for Gran Sometta (Italy). This site was chosen as main focus for the second phase of the intercomparison exercise (from November 2024 to June 2025) due to some challenges of data quality for one of three methods for the two other sites. Figure 8 shows an overview map and InSAR velocity map.

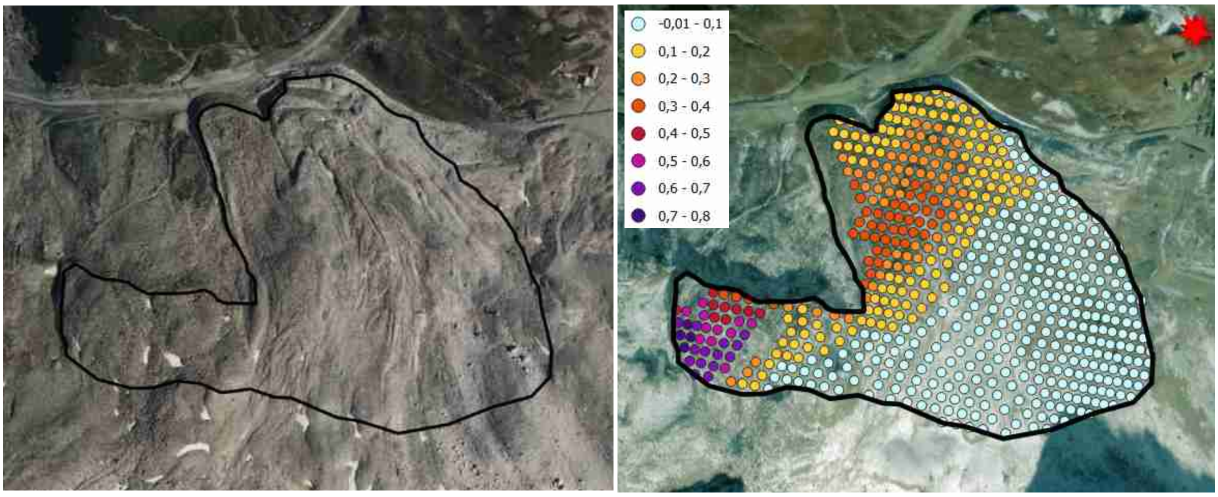


Figure 8. *Left: orthoimage view and outlines of the Gran Sometta rock glacier. Right: example of mean velocity map with 6d interferograms (2017-2021).*

In the first phase of the intercomparison exercise (Summer-Fall 2024), the only recommendations for producing RGV was to follow the RGIK guidelines [RD-12] [RD-13]. Six operators performed the work using similar initial data (Sentinel-1 images), but different InSAR software and processing settings. The first version of the results shows highly variable results (Figure 9). At this stage, it was impossible to identify from where the differences arose: From the processing and selection of the interferograms? From the spatio-temporal aggregation methodology? Both? The workshop in November 2024 allowed for listing the most likely hypotheses and planned further tests.

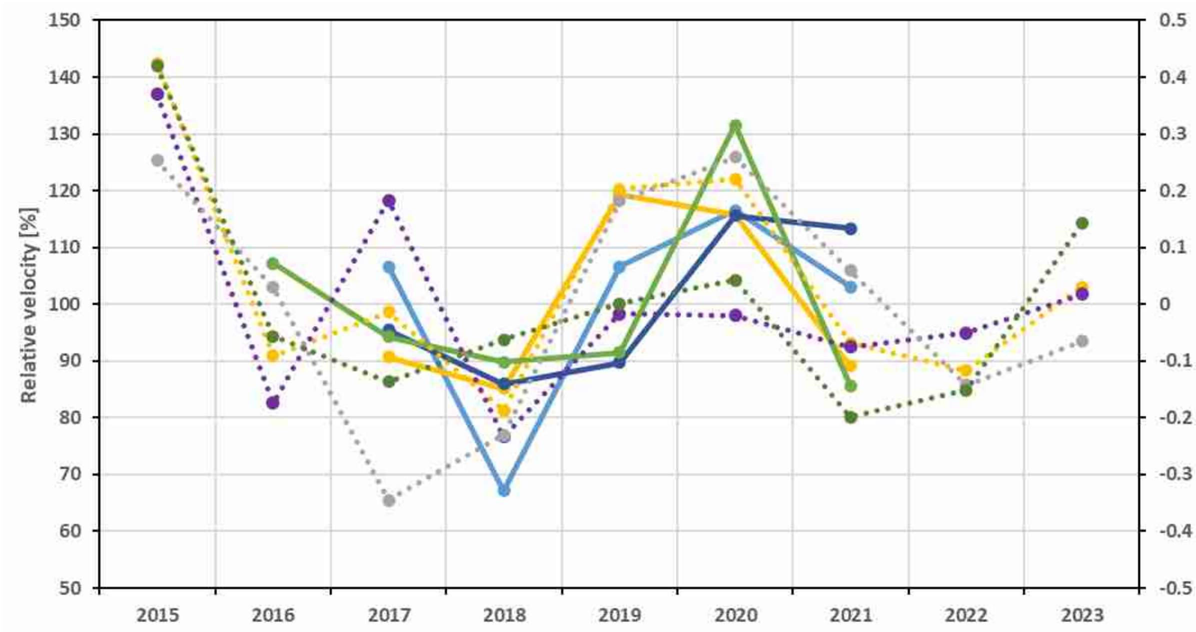


Figure 9. *First phase of the exercise. Relative InSAR velocity change on the Gran Sometta rock glacier. Results from six operators at the end of the first round of the exercise (November 2024). Solid lines: 6d interferograms. Dotes lines: 12d interferograms.*

At the beginning of the second phase of the intercomparison exercise (Spring 2025), a manually delineated AOI was set to define which pixels to use for the spatial aggregation. First, it was the only extra criterion commonly defined, while all other processing settings remained variable. We did not find any significant improvement at this stage. We therefore further tested the effect on defining data-driven criteria to select pixels to be averaged, based on different quality measures. The applied filter discarded pixels with too few numbers of valid observations (usable interferograms), too high standard deviation between the years, too low interferometric signal stability (coherence) for one or several years. The results show a significant improvement between the initial results (no common method for automated pixel selection, see Figure 10) and the latest results (similar criteria for automated pixel selection, see Figure 11). The last version of the results shows a low variability between the different processing versions and operators. The interannual changes are comparable to GNSS data at the same site (orange box blots on Figure 11).

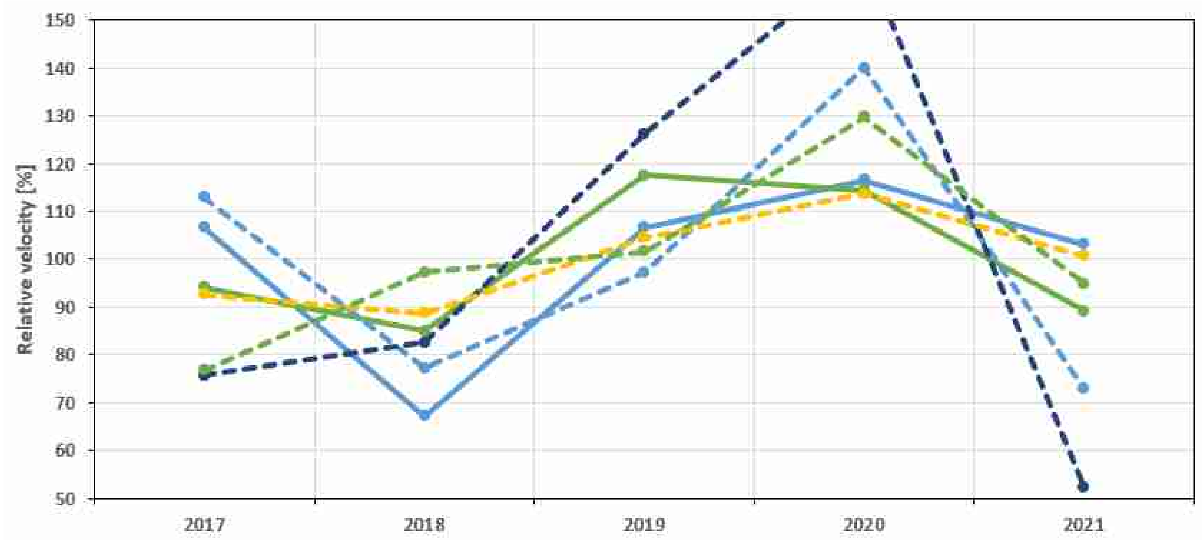


Figure 10. *Second phase of the exercise: results without any requirement for pixel selection and spatial aggregation. Relative InSAR velocity change on the Gran Sometta rock glacier. Results from 3 operators using 6 days interferograms (2017-2021). Solid lines: descending geometry. Dotted lines: ascending geometry.*

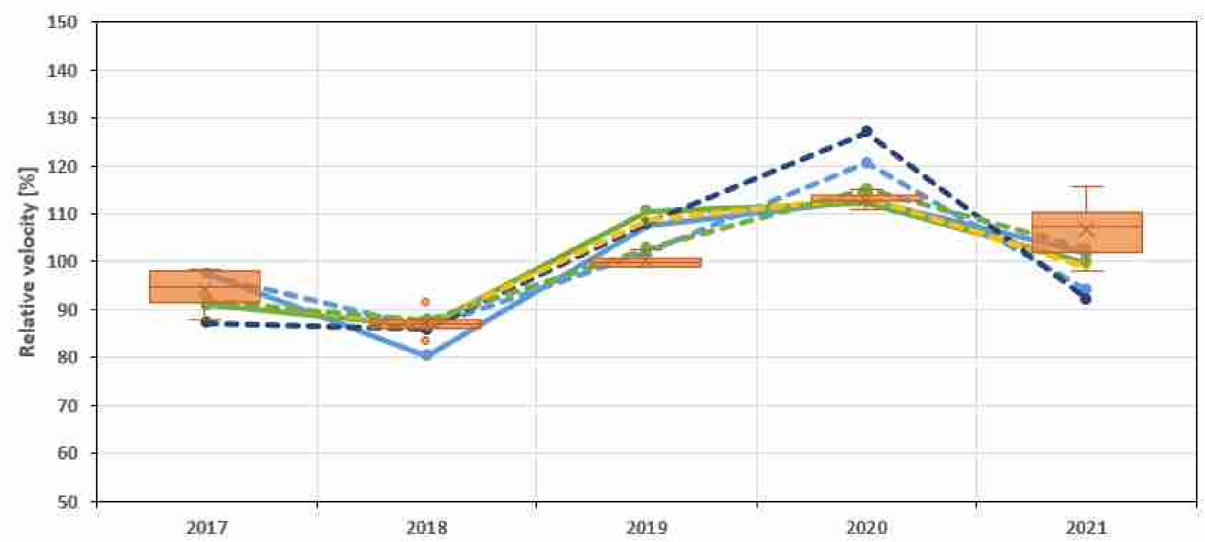


Figure 11. *Second phase of the exercise: results with data-driven criteria for pixel selection and spatial aggregation. Relative InSAR velocity change on the Gran Sometta rock glacier. Results from 3 operators using 6 days interferograms (2017-2021). Solid lines: descending geometry. Dotted lines: ascending geometry. Orange box plots: GNSS results.*

At the end of the second phase of the exercise, our tests allow for answering several questions regarding the effect and importance of certain processing steps (Figure 12, green checked boxes). Several questions remain (Figure 12, question marks) and will keep being studied by the InSAR team of the RGV working group in the future. The working group is now working on summarizing their observations to draft a InSAR-RGV Best Practice document, expected to be used as appendix of the RGIK RGV practical guidelines [RD-13]. A new workshop will be organised in December 2025.

Question	Importance	Solution	
spatial aggregation	+++	automatic pixel selection based on time series statistics	☑
exclude phase unwrapping	+++	automatic pixel selection or manual correction/filtering	?
clustering	++		?
temporal baseline	++	6d due to higher coherence and less unwrapping issues optional: longer baselines for slower units	☑ ?
reference phase	+		?
acquisition geometry	site-dependent	complementary use possible?	?
multilooking	− (certain exclusion of unwrapping errors)		☑
observation period	− −	summer months + coherence threshold	☑
software	− − −	simple InSAR time series stacking approach	☑

Figure 12. *Main questions of the InSAR team of the RGV working group. Summary of the conclusions of the group after the first two phases of the intercomparison exercise. The InSAR team keeps working on testing the InSAR-RGV processing settings to answer the remaining unknowns (question marks in the right column of the table).*

3.4 Comparison between InSAR-RGV and GNSS-RGV at selected sites

The comparison has been performed for 6 of the 21 sites with InSAR-RGV, due to current lack of suitable in-situ data for the remaining sites. For several Italian rock glaciers, in-situ monitoring data are expected to become available in the future, which will allow updating the current document. InSAR-RGV processing is also ongoing on more landforms in Switzerland, which will also increase the number of available case studies for validation.

In general, the InSAR results show a variable level of quality depending on the site. Many selected areas are too fast to ensure good coherence during the whole documented period. The high spatial heterogeneity of the signal also increases the risk of unwrapping errors that can significantly bias the results in fast-moving areas and fast-moving periods. This issue is especially affecting the years with only one Sentinel-1 satellite, which leads to a 12d repeat-pass (2015-2016 and 2022-2024) and lower maximal detection capability (up to 85 cm/year). For this reason, the expected velocity peak in 2015 (based on GNSS data) is often not detected (too high velocity). Due to the identified unwrapping problems at many sites, a spatial aggregation approach (averaging many pixels over the rock glacier) was not always feasible. In such cases, the InSAR-RGV products consist of documenting velocity changes for a few selected pixels over the rock glaciers. In the future, the conclusions from Section 3.3 and future work to solve the remaining open questions might help solving this issue of spatial representativeness. The impact of the observation time window used for seasonal averaging also remains unclear. For rock glaciers with very strong seasonal variations (like Steintälli), the temporal criteria to average the results to get the yearly velocity might be of high significance.

3.4.1 Bru rock glacier

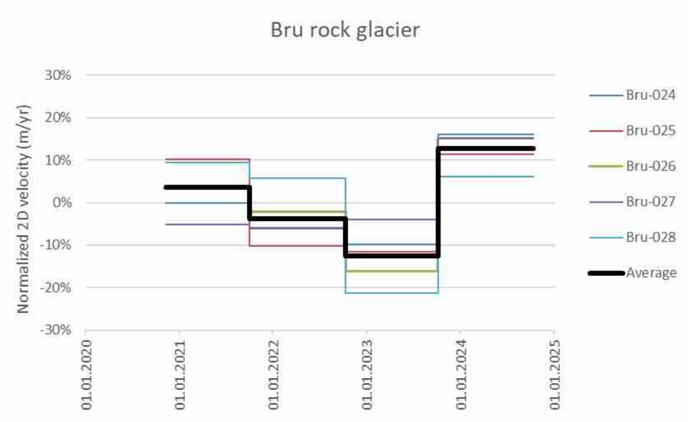
A location map can be viewed on the Swiss Geoportal (Bru map). GNSS locations with comments on the 2D velocity, 3D velocity, azimuth and slope angle are available in the Bru-GNSS.kml file, provided in attachment of this report.

GNSS survey has been performed annually at five locations since the autumn 2020. The measurements indicate average 2D velocities ranging between 0.14 m/yr in the lowermost section to +0.56 m/yr in the uppermost one. Much larger velocities occur upslope than downslope generating an overall compression of the rock glacier and resulting in surface movements close to the horizontal, sometimes even rising above the latter.

A seasonal survey was performed in summer 2020 (July-November). It indicated seasonal velocities which were larger by about 40% compared to the 2020-2021 annual values.

The InSAR target "Root" could be closely compared to GNSS "Bru-024", whereas "Front" neighbours "Bru-027" but, being closer to the front line, might behave more similarly to "Bru-028" (Figure 13). The magnitude order of the uncompressed LOS values is close to the annual GNSS one, but too small compared to the seasonal one. The latter might be explained by the dip angle of the surface displacement vector, which is less steep than the topographical slope.

Whereas the overall pattern of the normalized variations for the two InSAR targets fits well with those derived from the GNSS data, the amplitude of the change in 2024 appears to be exaggerated (> +30% vs. about +20%). The 12d normalized InSAR-RGV signal extracted on a large part of the rock glacier fits well with the GNSS-derived one (since 2021). The peak activity in 2020 and 2024 is well evidenced. The absence of any peak activity in 2015 is however suspicious.



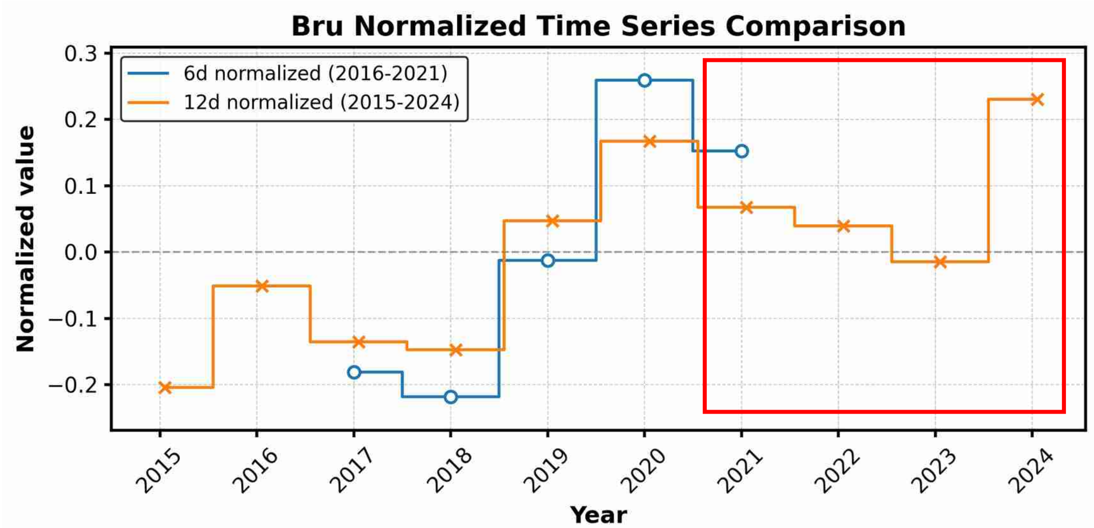


Figure 13. *Comparison between available GNSS-RGV data (upper graph) and Permafrost_cci InSAR-RGV (lower graph) on Bru rock glacier.*

3.4.2 Distelhorn rock glacier

A location map can be viewed on the Swiss Geoportal (Distelhorn map). GNSS locations with comments on the 2D velocity, 3D velocity, azimuth and slope angle are available in the Distelhorn-GNSS.kml file, provided in attachment of this report.

Distelhorn is a rock glacier with uncertain upslope connection. It shows a heterogeneous flow pattern with a faster moving front, a slower moving middle section, which includes another small front and again a faster moving rooting section. The rooting section is classified as a separate rock glacier unit, according to the Swiss Rock Glacier Inventory.

Two permanent GNSS stations are located on the Distelhorn rock glacier (Cicoira et al., 2022). Data is publicly available for the period between July 2012 and July 2019 (Beutel et al., 2022). The GNSS stations are still running, but the data is not publicly available after summer 2019. The two stations show different velocities: DIS1 is located on the fast-moving part. It moves around 3 m/yr and shows a strong seasonal fluctuation. In contrast, DIS1 is located on a small secondary front and moves about 0.3-0.4 m/yr. The seasonal signal is less pronounced. Due to data availability, the comparison can only be made for three years with 6d InSAR (Figure 14, green area), and five years with 12d InSAR (Figure 14, orange area). For 2019, the data is only available until July 2019.

The InSAR point "Front" is close to station DIS1. The InSAR point "Center" can be compared to station DIS2. The InSAR target "root" is too far away from the two stations, therefore the InSAR results cannot be validated. The observed 6d velocities of the point "Front" are significantly smaller than velocities from DIS1 for the 2017-2019 period (about 30-40% of the observed GNSS Station values). Even with the proposed scale factor, the velocities are underestimated. This is also valid for the 12d time series, the magnitude difference is larger, the observed LOS velocity is only about 20% of the observed velocity in 2015. The 12d velocity time series shows an increase in velocity over the whole series, whereas the GNSS data shows an acceleration until 2015, which is followed by a small decrease until 2017, before velocity increases again afterwards.

In contrast, the LOS velocities for the point "Center" agree better with the observed velocities of DIS2. The magnitude is about 60% of the GNSS velocities. With the proposed scale factor, this is corrected to about 80%. Neither the GNSS time series nor the InSAR series show an increase, the velocities remain similar for the observed period.

The InSAR-RGV results are also compared to the pilot results from iteration 1 (Schmid, 2024). In the previous work, the RGV was calculated as an average over the whole rock glacier, with the points being selected using a clustering algorithm. The results were only calculated for a 6d temporal baseline, as the observed velocity was deemed too rapid for a 12d temporal baseline. The behaviour of both the "Front" and the "Root" time series agrees with the relative RGV calculated by Schmid (2024) for the 6d time series (Figure 15).

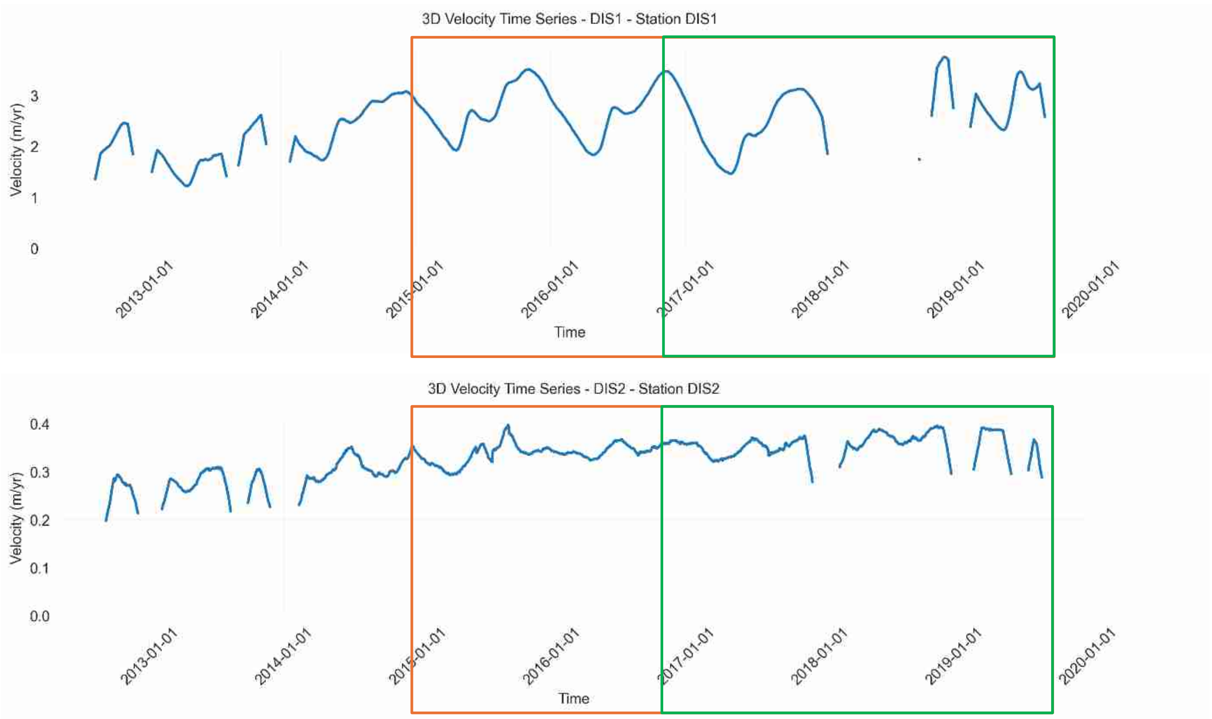


Figure 14. *Permanent GNSS data for Distelhorn rock glacier, based on Cicoira et al. (2022) and Beutel et al. (2022). Processing and plotting were performed using a modified version of the unpublished toolbox by Yan Hu (UNIFR). For the Station DIS1, a 30-day window was used to average the coordinates and calculate the velocity. For station DIS2, a 45d window was used for both.*

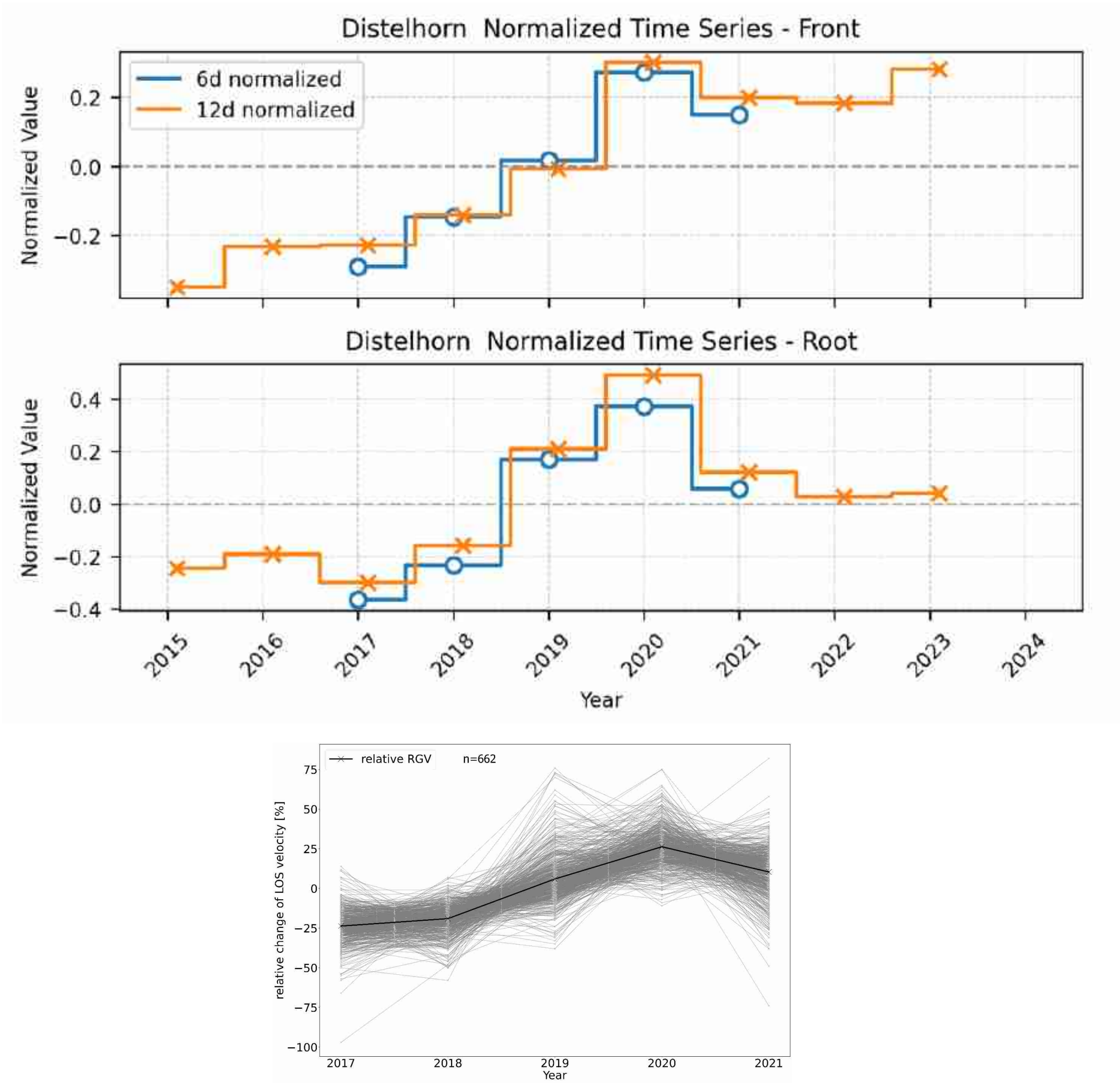


Figure 15. *Comparison between the InSAR-RGV products from iteration 2 (upper graphs) and pilot InSAR results from iteration 1 (lower graph; Schmid, 2024) on Distelhorn rock glacier.*

3.4.3 Grosses Gufer rock glacier

A location map can be viewed on the Swiss Geoportal (Grosses Gufer map). GNSS locations with comments on the 2D velocity, 3D velocity, azimuth and slope angle are available in the Grosses_Gufer-GNSS.kml file, provided in attachment of this report.

GNSS survey has been performed annually since autumn 2007 at more than 60 locations. Since 2015, the average 2D velocities range between 0.1 m/yr in the uppermost section and more than 3.0 m/yr in the fastest section downslope (see also GrossesGufer_CarteMvt.gif).There are two RGV trends on the rock glacier, namely RGV_A, which tending to accelerate on a decennial scale, and RGV_B, which conversely tends to decelerate.

No seasonal survey was performed on the site, but a permanent GNSS station shows that an acceleration almost systematically occurs at the onset of the summer period, making the warm season to synchronize with velocity which could be up to 20% faster than on annual average (see also

GrossesGufer_gps_fixe.png). Much larger velocities occur downslope. The difference is spatially sharp and reach one order of magnitude (10x).

The InSAR target "Front" could be compared to GNSS "ggr-028" and "ggr-037" in the RGV_B area and the point "Center" to "ggr-069" and "ggr-070" in the RGV_A zone. There is no GNSS-surveyed point close to the InSAR target "Root". The closest points "ggr-055" to "ggr-057" located more than 120 m downslope. The velocity at the "Root" target is not expected to largely differ from the latter.

The magnitude order of the uncompressed summer LOS values at the "Front" target corresponds to about 70-80% of those observed annually by the GNSS survey in the same section of the rock glacier. The peak around 2020 is quite well determined (Figure 15). Its relative amplitude compared to the surrounding low activity periods agrees well with the in-situ data, but the former peak which occurred around 2015 is completely missing in the InSAR results. The high velocities are presumably the source of unwrapping issues. Similar observations can be done for the "Center" target (Figure 16).

The very low velocity detected at the "Root" target (in the order of 0.1 m/yr) fits with the GNSS measurements performed downslope along the same flow line (0.15 m/yr).

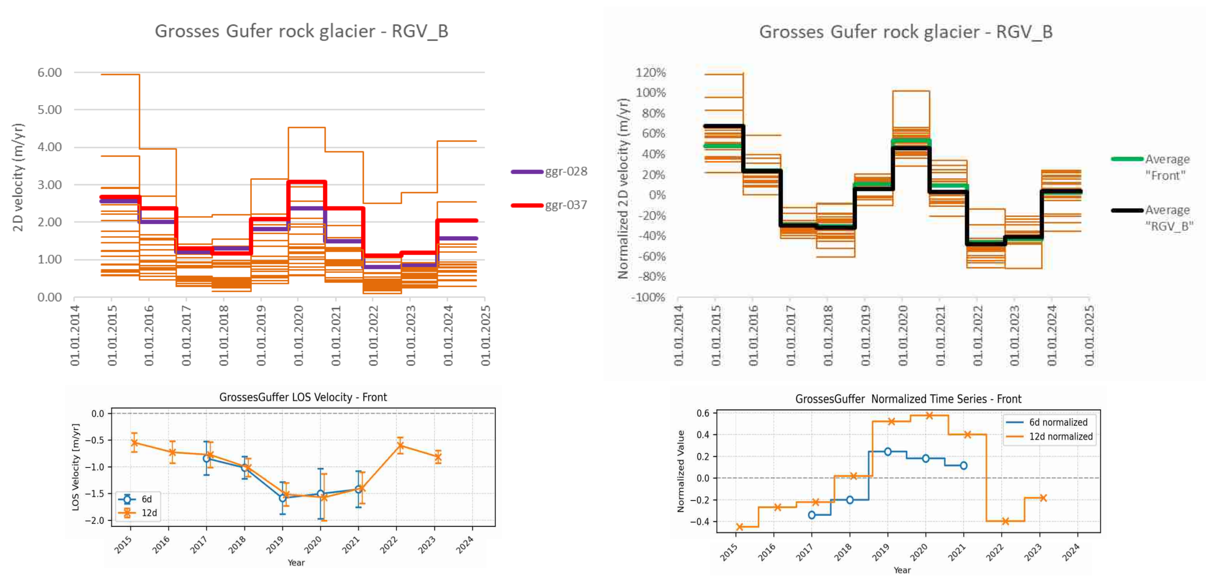


Figure 14. *Comparison between available GNSS-RGV data (upper graphs) and Permafrost_cci InSAR-RGV (lower graphs) on Grosses Gufer rock glacier (frontal part). Left: m/yr velocity time series. Right: Relative velocity changes.*

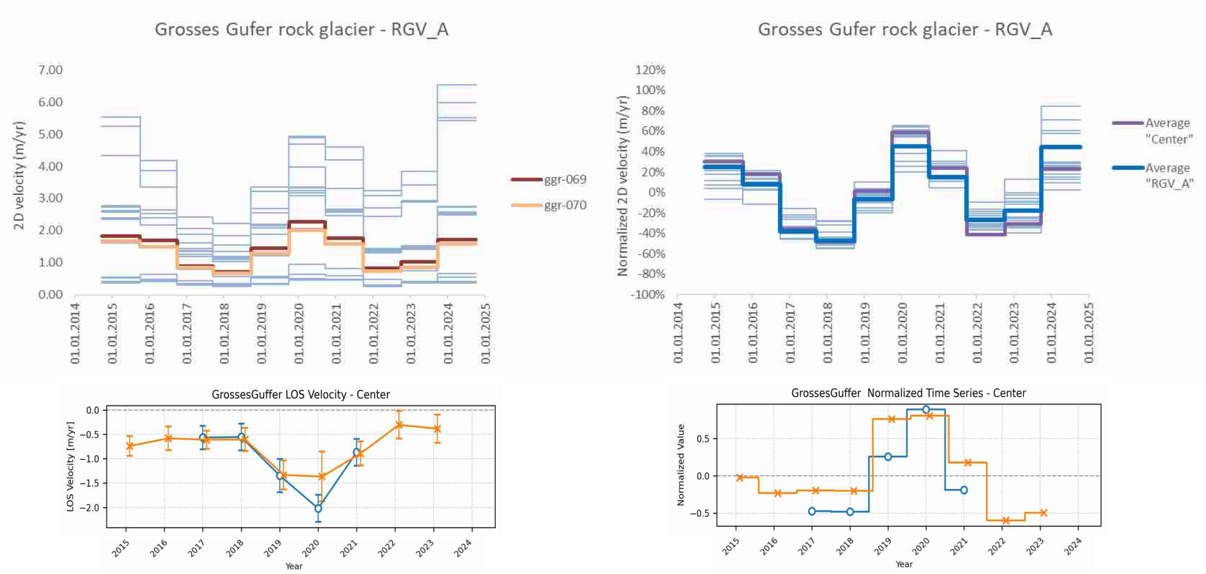


Figure 15. *Comparison between available GNSS-RGV data (upper graphs) and Permafrost_cci InSAR-RGV (lower graphs) on Grosses Gufer rock glacier (central part). Left: m/yr velocity time series. Right: Relative velocity changes.*

3.4.4 Réchy rock glacier

A location map can be viewed on the Swiss Geoportal (Becs-de-Bosson_map). GNSS locations with comments on the 2D velocity, 3D velocity, azimuth and slope angle are available in the Rechy-GNSS.kml file, provided in attachment of this report.

Réchy is a talus-connected rock glacier with spatially very heterogeneous flow rates. The rooting zone was covered by a small glacier during LIA and is today mostly deprived of any movement. On its southern margin, back-creeping motion has been observed.

Seasonal GNSS surveys have been performed in summer 2005 at more than 80 locations. More locations are monitored on an annual basis. Since 2015, the average 2D summer velocities range between 0.1 m/yr to more than 2.0 m/yr (see also Rechy_CarteMvt.gif). There are two RGV trends on the rock glacier, namely RGV_1, which tends to decelerate on a decennial scale, and RGV_2, which conversely tends to accelerate (see also Rechy_VEL.png and Becs-de-Bosson).

The summer 2D velocities are in average by 13% (std. dev. 10%) larger than the annual ones (calculation performed for points with average 2D velocity larger than 0.4 m/yr). For the 3D velocity the difference rises to 18% (std. dev. 12%).

The InSAR target "Front" could be compared to GNSS "bloc-323" and the target "Center" to the mean to "bloc-320" and "bloc-370". The target "Root" is close to GNSS "bloc-114". Whereas the target "Front" is situated within the RGV-1 area, both the "Center" and "Root" targets are located in the RGV_2 area.

The magnitude order of the LOS values at the "Front" target corresponds to about 50-70 % of those observed annually by the GNSS survey in the same section of the rock glacier (Figure 17, left). Applying the proposed factor (4.45) will provide values which are much too large. Since 2017, the behaviour of the normalized values is well determined and fitting with RGV_1, but the earlier peak in 2015 missing and the low activity in 2016 is not confirmed by the GNSS data (Figure 17, right). Almost the same observation can be done for both the "Center" target in RGV_2.

At the “Root” target, the maximal values around 2020 are close to the GNSS observations, when applying the compression factor. However, the first years of the time series are suspicious, displaying even reversed flow direction.

Figure 16. *Comparison between available GNSS-RGV data (upper graphs) and Permafrost_cci InSAR-RGV (lower graphs) on Réchy rock glacier. Left: m/yr velocity time series. Right: Relative velocity changes.*

3.4.5 Steintälli rock glacier

A location map can be viewed on the Swiss Geoportal (Steintälli map). GNSS locations with comments on the import the 2D velocity, 3D velocity, azimuth and slope angle are available in the Steintälli-GNSS.kml file, provided in attachment of this report.

The Steintälli rock glacier is a multi-unit system composed of 4 superimposed generations (I-IV). All of them are moving. The uppermost one (I) is the most active. The velocity decreases downslope and is the lowest on the unit IV. The uppermost unit (at least) is glacier forefield-connected and also partly landslide-connected.

GNSS survey has been performed annually since the autumn 2020 on 24 locations, among which 5 are located on unit II and 12 on the uppermost unit I.

The average 2D velocities ranges between 0.6 and 1.2 m/yr on the unit I. It decreases to 0.3 to 0.5 m/yr on the unit II and to about 0.15 m/yr on the unit III. Displacement rates in the range of 0.03 to 0.05 m/yr are measured on the unit IV, where the reference region for the InSAR RGV analysis is located. Corresponding to a velocity of about 0.001 m/12d, it is however insignificant.

A seasonal survey was performed over the summer (July-November) 2020. It has indicated velocities which were larger by about 15 and 26% compared to the annual values 2020-2021 on the units II and I, respectively.

The InSAR target “Root” could be compared to GNSS “STU-021”, whereas “Center” neighbours “STU-012” and “STU-015” at the front of unit I. “Front” is a point located at the front edge of the subjacent unit II, downslope of GNSS points “STU-006” and “STU-007”.

The magnitude order of the uncompressed seasonal 12d LOS values does not match with the annual GNSS one, being about 50% too low in all sections. Unwrapping issues are suspected on the faster unit I, whereas the location of the target at the front edge of unit II might not be adequate.

Moreover, the overall pattern of the normalized variations for the three InSAR targets does not match with those derived from the GNSS data (since 2021). One could however consider that the period of lower activity around 2017-2018 (and the two peaks around) has been almost correctly detected (Figure 18).

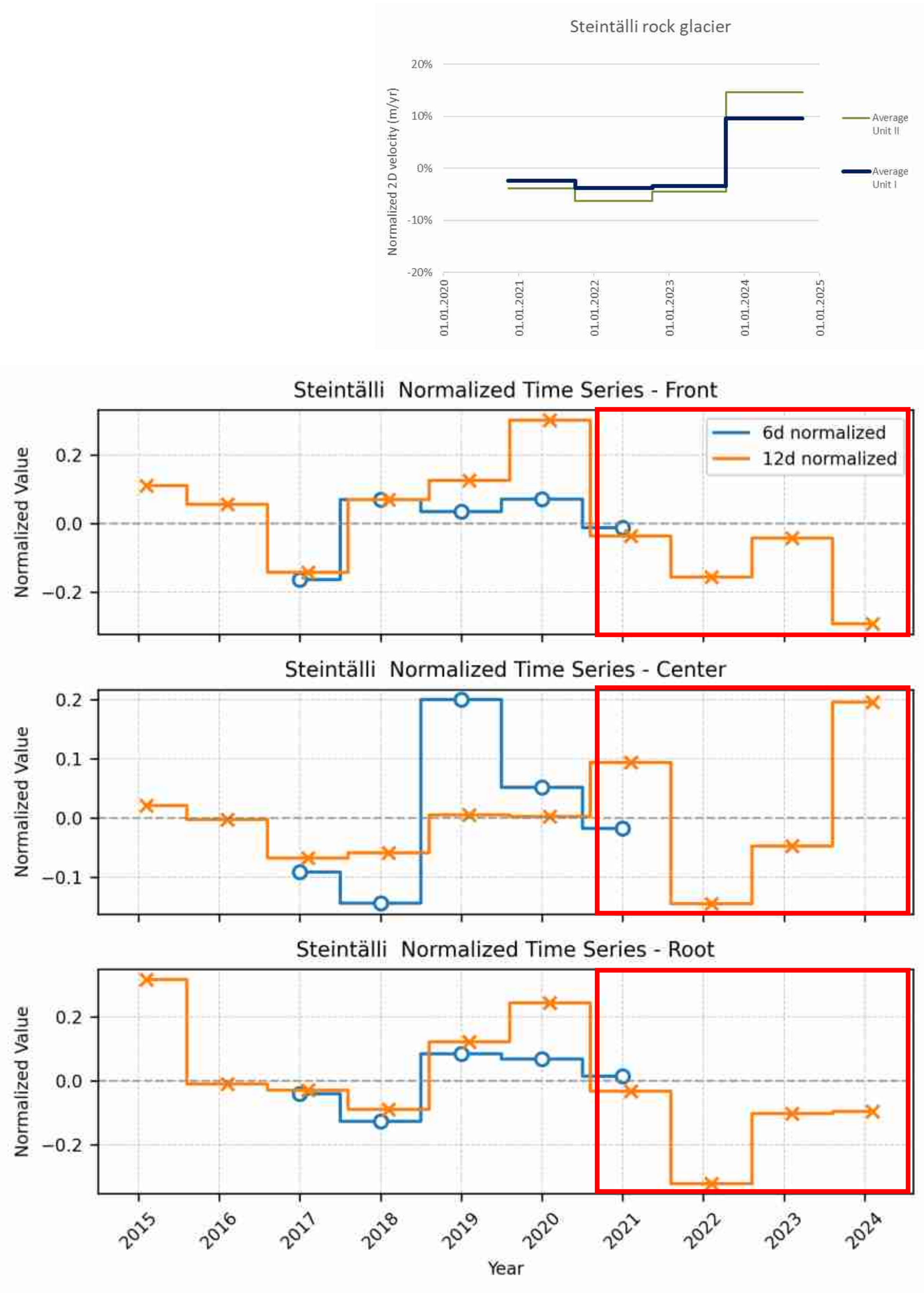


Figure 17. *Comparison between available GNSS-RGV data (upper graph) and Permafrost_cci InSAR-RGV (lower graphs) on Steintälli Gufer rock glacier.*

3.4.6 Gran Sometta

GNSS locations with comments on the 2D velocity, 3D velocity, azimuth and slope angle are available in the Gran_Sometta-GNSS.kml file, provided in attachment of this report.

Gran Sometta is a multilobate glacier forefield-connected rock glacier. GNSS survey has been performed annually since August 2012 at 50 locations (extended to 62 in 2015). There is no movement anymore in the rooting zone (GNSS markers GS-001 to GS-013). The so-called “white lobe” on the E (also called “main lobe”) moves in average since 2015 about 0.1 to 0.7 m/yr. On its eastern part, the vertical component (subsidence) tends to dominate. The twinned “black lobe” (“lower left lobe”) moves faster, with velocities rising from about 0.7 m/yr in its uppermost active section to 1.5 m/yr in its terminal part. The difference is spatially sharp and reaches one order of magnitude (10x). A smaller adjacent lobe (“upper left lobe”) has developed to the West. It is roughly moving 1.5 m/yr, locally reaching 2.5 m/yr (see also Gran Sometta (Cervinia), GranSometta_CarteMvt.gif and GranSometta_Vel.png).

Interannual variations are not pronounced. The 2015, 2020 and 2024 activity peaks overpass the phases of low activity by about 20-40%. Some sections tend to slightly accelerate on a decennial trend, whereas others decelerate. No seasonal survey was carried out on the site, but the summer velocity is expected to be somehow larger than the annual one.

In the ascending analysis, the InSAR target “Front (asc)” could be compared to GNSS “GS-058” (+ “GS-054 and 055”), which is moving about 1.7 m/yr. The target “Center (asc)” is located in the triangle drawn by GNSS points “GS-14, 15 and 17” and is expected to move annually about 0.7 m/yr or more. From the GNSS data, the displacement rate at the target “Root (asc)” is not known as the point is located at the uppermost margin of the rock glacier active part. It lays between 0 and 0.6 m/yr (Figure 19, left).

In the descending analysis, “Front 1 (desc)” is located close to “GS-057”, which has moved 2.7 m/yr in average since 2015. “Front 2 (desc)” is on the “black lobe”. According to the neighbouring points “GS-033, 034 and 044”, it should move about 1.4 m/yr in average (Figure 19, right). An InSAR target is missing on the “white lobe” and would be valuable to add in the future, somewhere between “GS-021 and 028” (motion rate about 0.5 m/yr). The “Root (desc)” target is in a non-moving area.

The magnitude order of the uncompressed LOS values at the “Front (asc)” target fits with those observed by the GNSS survey in the same section of the rock glacier. The apparent behaviour of the normalized values is overall fine, except for the missing 2015 peak and the too pronounced variations in 2018-2019. Conversely, the uncompressed LOS values at the “Center (asc)” are 2x larger than the annual GNSS-based observations. The velocity drop in 2018 is not visible and the other variations are too close to the uncertainty level to be significantly interpretated. Whereas the detected velocity level at the “Root (asc)” target is reasonable, its variations over the years are not.

The uncompressed LOS values are comparable with GNSS at the three targets in descending mode. No relevant comparison could be undertaken at “Front 1 (desc)”, moving too fast. At “Front 2 (desc)”, the overall behaviour of the normalized values is compared with GNSS, including the decreasing trend over the decade. However, the low activity in 2015 is improbable.

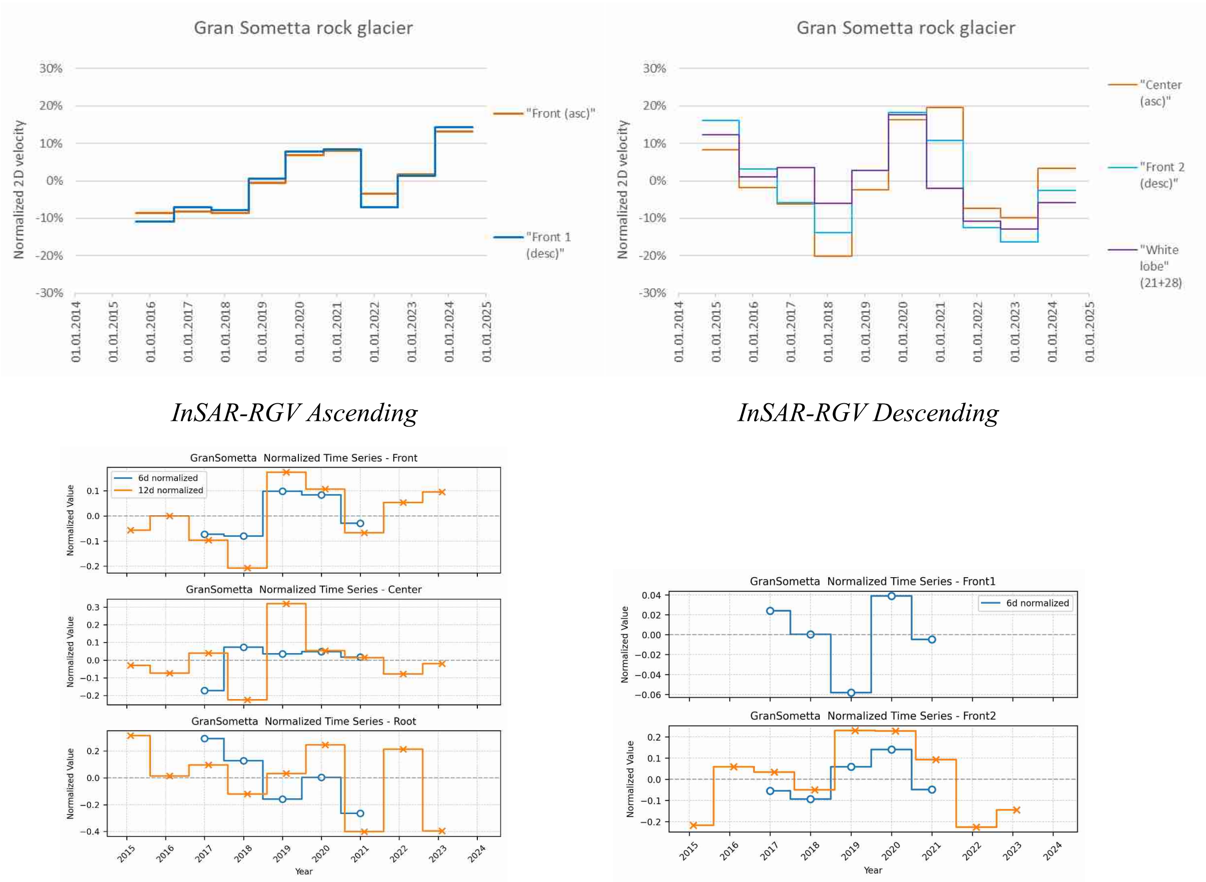


Figure 18. *Comparison between available GNSS-RGV data (upper graph) and Permafrost_cci InSAR-RGV (lower graphs) on Gran Sometta rock glacier.*

3.5 Comparison between InSAR-RGV and GNSS-RGV at the regional scale

Figure 20 (upper graph) gives an overview of the regional GNSS-RGV trend between 2000 and 2024. The analysis is performed on a set of 1 to >20 rock glaciers (depending on the year) with GNSS-based velocity time series. The measurements have been compiled over more than 10 years and were made available by UNIFR, with contributions from the Swiss Permafrost Monitoring Network (PERMOS) and the University of Lausanne (UNIL).

Since the launch of Sentinel-1, the most important aspect to highlight is the occurrence of three peaks of activity in 2015, 2020 and 2024 separated by periods of much lower activity in 2017-2018 and 2022-2023. Compared to previous high velocity peaks, the velocity decreases up to about -50 % during the first low activity phase, and up to about -30 to -40% during the second one. In addition to these large interannual fluctuations, some rock glaciers have accelerated on a decadal scale, whereas some others have not shown any acceleration trend or have even decelerated. Such observations concur with the conclusions of other studies discussing interannual rock glacier velocity variability at different spatial scales (e.g. Kellerer-Pirklbauer et al., 2024; PERMOS, 2025).

Figure 20 (lower graph) shows the averaged trend of the 21 Permafrost_cci InSAR-RGV. The results show overall similar variations as GNSS-RGV during the overlapping period. Although the geographical extent is not fully comparable (Swiss Alps vs Italian/French/Swiss Alps), the main accelerating and decelerating periods are at the same time. The main discrepancy compared to GNSS is at the start of the comparable period (2015), for which InSAR fails to detect high velocities, most likely due to the few scenes and the 12d repeat-pass at the beginning of the Sentinel-1 mission.

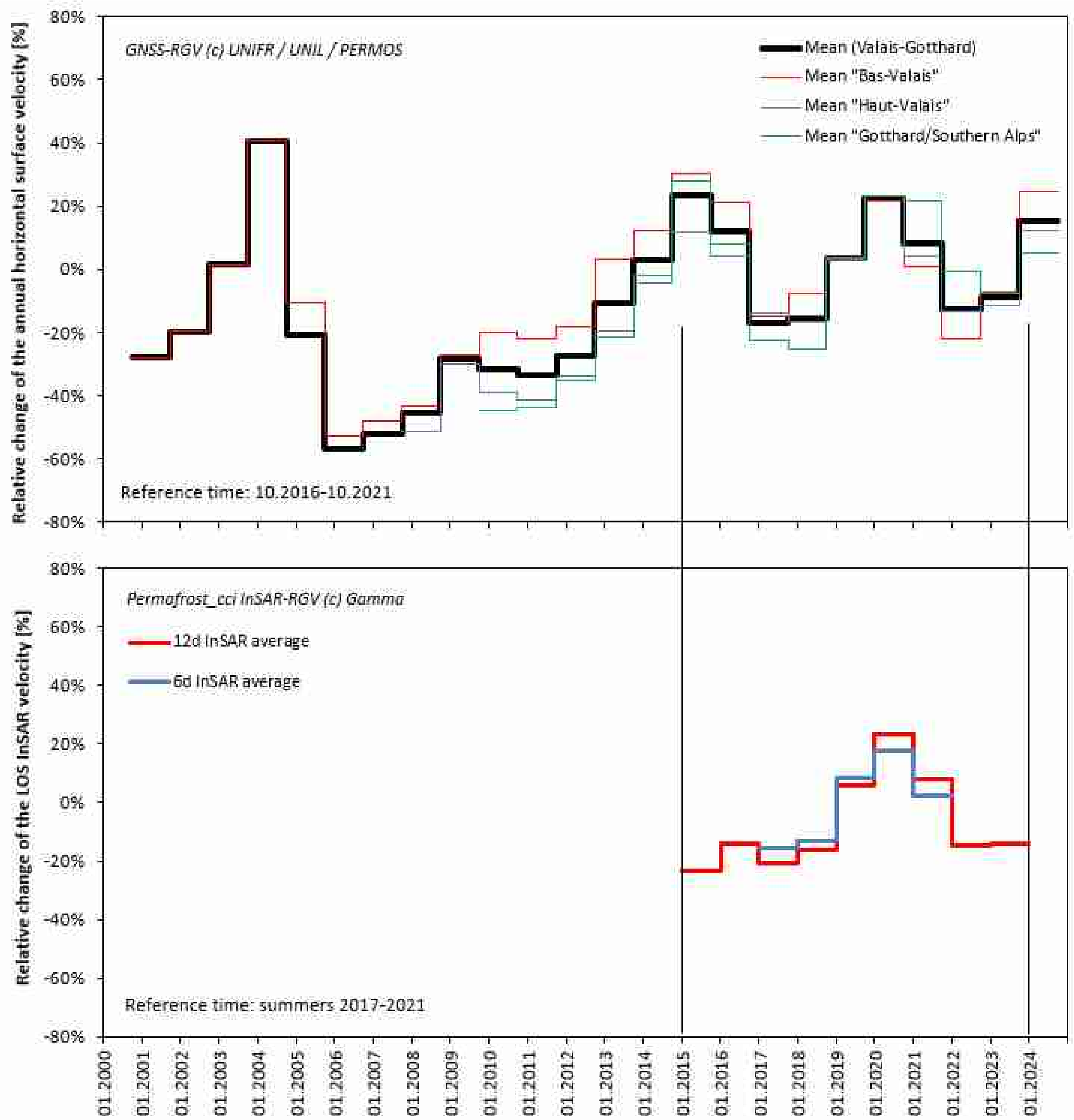


Figure 19. *Comparison of the interannual velocity variations at the regional scale. Upper graph: GNSS-RGV relative velocity change based on a set of 1 to > 20 alpine rock glaciers (depending on the year) measured by UNIFR, UNIL and PERMOS. Lower graph: InSAR-RGV relative velocity change based on 21 alpine rock glaciers processed as part of Permafrost_cci Phase 2 iteration 2.*

4 Conclusions and future activities

4.1 Rock glacier inventory (RoGI)

We finalised the work related to the multi-operator exercise and the resulting RoGI results from Permafrost_cci Phase 1 iteration 1 (systematic analysis, interpretation and dissemination). The conclusions are overall positive, highlighting the value of consistent products in different mountainous environments worldwide. The released datasets are expected to be valuable for various future usage: e.g. further detailed analysis in specific regions, selection of landforms for RGV generation, training dataset for machine learning, dissemination as online exercise for educational purpose. The work in the eight new regions of Permafrost_cci Phase 2 iteration 2 is well advanced. The RoGI process is completed in four regions (Switzerland, Italy, Mongolia and India). In two regions (Bolivia-Chile, Bulgaria), the work is finished in part of the region, but the RoGI will be geographically extended. In two regions (Nepal and Bhutan), the last steps of the RoGI process are ongoing.

In terms of dissemination, below the status regarding RoGI:

- The results of the multi-operator exercise in the 12 areas of Permafrost_cci Phase 2 iteration 1 are now published and available online (Rouyet et al. 2025a, 2025b).
- Complementary papers with detailed analysis in specific areas have been published (e.g. Bertone et al., 2024; Onaca et al. 2025) or are in preparation based on the results of the second iteration.
- A paper summarising and promoting the RGIK RoGI guidelines has been submitted in *Geomorphology* (Brardinoni et al., under review).
- Online exercises for the 12 areas are being prepared by UNIFR and will be released on RGIK website to complement the two existing exercises based on Swiss examples [RD-14].

In the Permafrost_cci extension phase (2026), we will focus on finalising the RoGI products of iteration 2, releasing the data and supporting the publication of associated scientific articles. We may also initiate RoGI work in a few extra areas to better cover some missing mountain ranges and countries (e.g. Canada). We will continue the ongoing collaboration for using RoGI products as training data for machine learning, as part of a PhD project at the University of Canterbury (New Zealand), co-supervised by the University of Bergen (Norway). We will support the collaborating work of the RGIK RoGI working group, currently focusing on 1) developing a RoGI database that will provide a valuable to compile and promote the Permafrost_cci outcomes; 2) improving/expending the RoGI guidelines, GIS tools and templates.

4.2 Rock glacier velocity (RGV)

The InSAR-RGV production has been extended to 21 sites in the Alps. The comparison with GNSS data shows that the results are promising, but also highlight limitations related to the detection capability of the method and the impact of unwrapping errors on rapid rock glaciers. The validation at the site scale remains preliminary. The analysis has only been performed for 6 of the 21 sites, due to current lack of suitable data to compare on the remaining sites. At the regional scale, the comparison show that the InSAR-RGV results highlight overall similar accelerating (2018-2020) and decelerating (2020-2022) periods, comparable with GNSS-RGV. Several questions regarding the spatial and temporal representativeness of the final products are still to be answered (e.g. criteria for pixel selection and spatial averaging based on quality measures; impact of the observation time window in case of large seasonal variability of the velocity).

In term of dissemination, here is the status regarding RGV:

- A review paper on rock glacier velocity (Hu et al., 2025) has been published in *Reviews of Geophysics*.
- Findings of the RGV intercomparison exercise have been presented at scientific conferences (e.g. Vivero et al., 2025; Buchelt et al., 2025).
- The drafts of InSAR-RGV Best Practice document, expected to become an appendix of the RGIK practical guidelines for RGV generation [RD-13], are being prepared by the RGV working group (next workshop in December 2025).
- Analyses of the relationship between rock glacier velocity and ground temperature is presented at scientific conferences (e.g. Pellet et al., 2025). A publication is in preparation.
- The Permafrost_cci InSAR-RGV results are presented at scientific conferences (e.g. Strozzi et al., 2025).

In the Permafrost_cci extension phase (2026), we will focus on extending the number of RGV-documented landforms in the Alps, while further working on solving the issues identified in Section 3. The site selection should follow a more careful and conservative analysis to perform the processing only on sites where we can ensure high quality. For ensuring long time series, 12d repeat-pass is required but the corresponding maximal detectable velocity (half wavelength: 28 cm/12 days, i.e. 85 cm/yr) is too low for many alpine rock glaciers. The InSAR-RGV Best Practice document being prepared as part of the RGV working group will discuss the cases where the use of InSAR should rather be avoided, and other techniques (in-situ, optical remote sensing) prioritised.

The extension phase will further investigate the suitable processing settings, especially in respect to the spatial and temporal representativeness of the products. Even on fast-moving rock glaciers, some parts of the landform might have low velocity suited to 6-12d Sentinel-1 InSAR. Considering the objective of the RGV production (documenting relative changes related to interannual climatic variability), selecting only low to medium velocity areas is a safe solution, still valuable if the considered areas are representative of the landform behaviour and following similar interannual trend. However, we still need to solve several questions regarding the way to ensure having both: 1) large enough velocities to be above the noise level to detect meaningful changes, and 2) slow enough velocities over all the years to avoid unwrapping issues. The impact of the observation time window has also to be further tested, especially for cases with very strong seasonal variations.

On the long-run, the upcoming availability of SAR data with better suited radar frequency (L-band) will allow for an enhanced detection capability, valuable for InSAR-RGV production. In preparation of ROSE-L, processing tests based on SAOCOM and NISAR are planned in the extension phase.

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5.2 Acronyms

AD	Applicable Document
AI	Artificial Intelligence
ALT	Active Layer Thickness
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
BR	Breakthrough Requirement
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CCN	Contract Change Notice
CRDP	Climate Research Data Package
DEM	Digital Elevation Model
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System
GR	Goal Requirement
GT	Ground Temperature
GTN-P	Global Climate Observing System

GTOS	Global Terrestrial Observing System
IANIGLA	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientale
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
KA	Kinematic Attribute
LOS	Line-of-sight
MA	Moving Area
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
PERMOS	Swiss Permafrost Monitoring Network
PI	Principal Investigator
PM	Primary Marker
PSD	Product Specification Document
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RD	Reference Document
RG	Rock Glacier
RGIK	Rock Glacier Inventories and Kinematics
RGU	Rock Glacier Unit
RGV	Rock Glacier Velocity
RoGI	Rock Glacier Inventory
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
UiO	University of Oslo
UNIFR	University of Fribourg
URD	Users Requirement Document
URq	User Requirement
UTM	Universal Transverse Mercator
TR	Threshold Requirement
WUT	West University of Timisoara
WMO	World Meteorological Organization