CCI+ PHASE 2
PERMAFROST

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

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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 will be 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 of cryosphere monitoring in mountain regions.

Two product types are therefore proposed by Permafrost_cci Phase 2: Rock Glacier Inventories (RoGIs) and Rock Glacier Velocity (RGV) time series. This agrees with the objectives of the International Permafrost Association (IPA) Action Group on *Rock Glacier Inventories and Kinematics* (RGIK) [RD-5] 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 landforms that can be used for RGV monitoring. RoGI and RGV products also form a unique validation dataset for climate models 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 that provide 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) describes the procedure and conclusions of the analysis and validation of the results presented in the Climate Research Data Package (CRDP) delivered in November 2023 [RD-6], and updated in attachment of this report (v.1.1). We present the conclusions of multi-operator RoGI exercise in the 12 selected areas and validate the InSAR-based RGV trends against GNSS time series measured on similar rock glaciers.

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) describes and discusses the results of the validation and intercomparison activities of the rock glacier products delivered in CCI CCN4 iteration 1.

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 describes the procedure and results of the comparison between the RoGI operators and areas. Section 3 describes the procedure and results of the comparison between the InSAR and GNSS RGV trends from the pilot sites in the Swiss Alps. Section 4 summarizes 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-22]. The PVIR also contains two Annexes with the feedback forms from the PIs of the RoGI exercise and additional statistics on the RoGI products.

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., 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. D1.1 User Requirement Document (URD), v1.0. European Space Agency.

[RD-2] Rouyet, 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. D1.2 Product Specification Document (PSD), v1.0. European Space Agency.

[RD-3] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., 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. D2.2 Algorithm Theoretical Basis Document (ATBD), v1.0. European Space Agency.

[RD-4] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., 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. D2.3 End-to-End ECV Uncertainty Budget (E3UB), v1.0. European Space Agency.

[RD-5] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., 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. D2.5 Product Validation Plan (PVP), v1.0. 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., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., 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. D4.2 Product User Guide (PUG), v1.0. European Space Agency.

[RD-8] RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2). IPA Action Group Rock glacier inventories and kinematics, 13 pp.

[RD-9] RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

[RD-10] RGIK. 2022. Optional kinematic attribute in standardized rock glacier inventories (version 3.0.1). IPA Action Group Rock glacier inventories and kinematics, 8 pp.

[RD-11] RGIK. 2023. Guidelines for inventorying rock glaciers: baseline and practical concepts (version 1.0). IPA Action Group Rock glacier inventories and kinematics, 25 pp. DOI:10.51363/unifr.srr.2023.002.

[RD-12] 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-13] 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-14] 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-15] 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-16] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2021. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.1 Product Validation and Intercomparison Report (PVIR), v1.0. European Space Agency.

[RD-17] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2020. ESA CCI+

Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.2 Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.

[RD-18] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2020. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.3 Product User Guide (PUG), v1.0. European Space Agency.

[RD-19] 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-20] Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Kaufmann, V., Noetzli, J., Thibert, E., Vivero, S., & Kellerer-Pirklbauer, A. (2023). Rock glacier velocity. In State of Climate 2022 (Vol. 104, pp. 41–42). https://doi.org/10.1175/2023BAMSStateoftheClimate.1.

[RD-21] 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-22] 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

The RoGI multi-operator exercise performed between June and November 2023 resulted in a dataset of InSAR-based Moving Areas (MA), Rock Glacier Unit (RGU) Primary Markers (PM) and outlines for all the 12 selected areas. Common instructions for inventorying were delivered to all operators. They are summarized in the ATBD [RD-3] and follow the guidelines defined by the International Community on Rock glacier Inventories and Kinematics (RGIK). The RoGI guidelines developed iteratively since 2018 [RD-8] [RD-9] [RD-10] have been recently merged in a first complete release [RD-11].

In each area, the results delivered in the CRDP [RD-6] include the final consensus-based results, and the initial suggestions from the involved operators. Some corrections have been made between December 2023 and February 2024, leading to a new version of the CRDP datapackage (v.1.1), delivered to ESA in attachment of this report. The corrections have been made on the final consensus-based files only, the results from the individual operators have not been modified. After potential corrections from the Principal Investigators (PI), UNIFR made a final check of the files to get rid of minor errors/inconsistencies. In the coming months, additional modifications (for educational purpose: improvement of commenting and uncertainty documentation and for comparability: correction of technical errors with some vector files) will lead to a CRDP v.1.2, that will be used for the final release of the dataset (see Section 4.1).

2.1 Methods for quality assessment

In the attribute tables of the three geopackages that the operators/PI had to filled, there are various fields documenting the reliability of the assignment of morpho-kinematic attributes:

- For the InSAR-based MA, the reliability (or the degree of confidence) of the results had to be qualitatively documented in accordance with the quality of the detection, velocity classification and delineation of the moving areas. When medium-low reliability is set (uncertain signal and/or outlines), comments describing the uncertainty sources could be added.
- For the PMs, an attribute “uncertain” or “not a rock glacier” could be added to the landforms that are likely to be wrongly interpreted as rock glaciers or to highlight ambiguous areas that need to be further investigated in the future (need for additional data and/or field visit). The level of uncertainty and complexity can be highlighted for many morpho-kinematic attributes (see Section 4.1 in E3UB [RD-4].
- For the outlines, the reliability of the delineation at different locations of the rock glacier (front, left/right lateral margins, upslope) is estimated with a score of 0 (low), 1 (medium) or 2 (high). The summation of the scores gives a general estimate of the outline reliability for the entire landform.

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 or between the areas. However, in the final release all the reliability fields will be filled in a consistent manner by the PI of each area, which will provide a useful quality estimate within each area (i.e. relatively to the other inventoried landforms in the area).

We compared systematically selected elements (attributes, count, size) of the operator’s results to document the level of (dis)agreement between multiple operators performed the same work in the same area. It should be noted that due to the consensus-based procedure, the quality of the final products has evolved throughout the exercise timeline. Minimum two digital meetings have been organized for each area (at the two phases of the exercise, as explained in the ATBD [RD-3]). Additional bilateral discussions and email consultation took place in many of the inventorying teams. Consequently, the final product can not be seen as the arithmetic average of the individual results, they are much more. It is expected that the final consensus-based products have a better quality than the individual results from each operator separately, because they take advantage of the diverse and often complementary background/knowledge of the various people involved. 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. In addition, technical limitations intrinsic to vectorization in GIS have been identified. Some bugs in the attribute tables (e.g. restricted numbers of character for specific fields) or the object geometries (e.g. polygons with self-intersections) led to partly corrupted files that currently limit the inter-comparison possibilities. There are ways to fix these errors without any data loss, but we could not do it yet for all areas due to late delivery from some teams. A complete clean dataset is being prepared for the final release and more comparisons will be performed.

At the end of the exercise, we asked the Principal Investigators (PI), in collaboration with their operators, to fill a standard feedback form to communicate their experience regarding the multi-operator consensus-based procedure, inform about the main findings of the exercise, identify the challenges in the inventorying procedure and suggest potential changes to improve the guidelines. The form included the following points we asked each PI to answer to:

- General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators)
- General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?)
- Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines)
- Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines)
- Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines)
- Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines)
- Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data)

The delivered feedback documents in their original format (except for some minor typing/orthographic corrections) can be found in Annex 1. In the following, we only summarize the main points to qualitatively assess the quality of the product in each area (Section 2.3). We also identify common elements between regions and redundant positive/negative conclusions identified by several PIs to assess the quality of the general procedure and the current guidelines (Section 2.4).

A comparison between the generated RoGI 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).

2.2 Statistics on the delivered primary markers, moving areas and outlines

For each area, we quantified the following elements:

- Number of certain and uncertain RGU, as an indicator of the difficulty to interpret the geomorphology in each area (Figure 1). In average of all areas, 40% of the identified PMs remain uncertain.
- Number of moving areas and their velocity classes in each RoGI area, as an indicator of the range of movement rates in each area (Figure 2). The distribution of the detected velocity greatly varies within and between the areas.
- Degree of (dis)agreement between operators for three essential attributes (upslope connection, kinematic category, activity), as an indicator of the difficulty to categorize the morpho-kinematic characteristics of the rock glaciers in each area (Figure 3). Differences highlighted the specific challenges of each area. For example in area 7 (Tromsø, Norway), several landforms are poly-connected (landslide+talus). The upslope connection has been therefore categorized differently despite an overall similar interpretation. The comparison of the degree of (dis)agreement between the kinematics attribute and the activity category shows that the variability in InSAR interpretation (and the resulting kinematic attribute) has little impact on the activity categorization.
- Rock glacier size within the extended outlines for each operator and in the final PM file, as an indicator of the difficulty the delineate the boundaries of the RGU in each area. As explained In Section 2.1, this comparison is preliminary. The number of comparable landforms and operators is reduced to technical issues (e.g. partly corrupted geometries due to polygons with self-intersecting polygons).

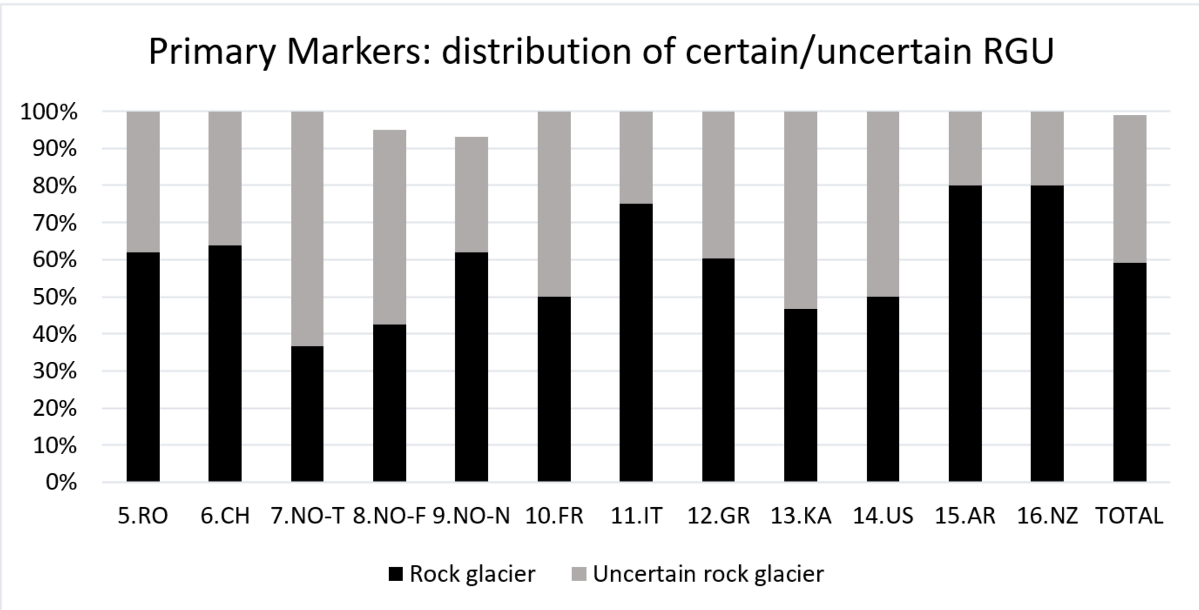

Figure 1: Distribution of the rock glaciers identified as certain or uncertain in each RoGI area (consensus-based final results). The numbering of the area follows the standard format defined in the PSD [RD-2] and the PUG [RD-7]. See also the corresponding table in Annex 2.

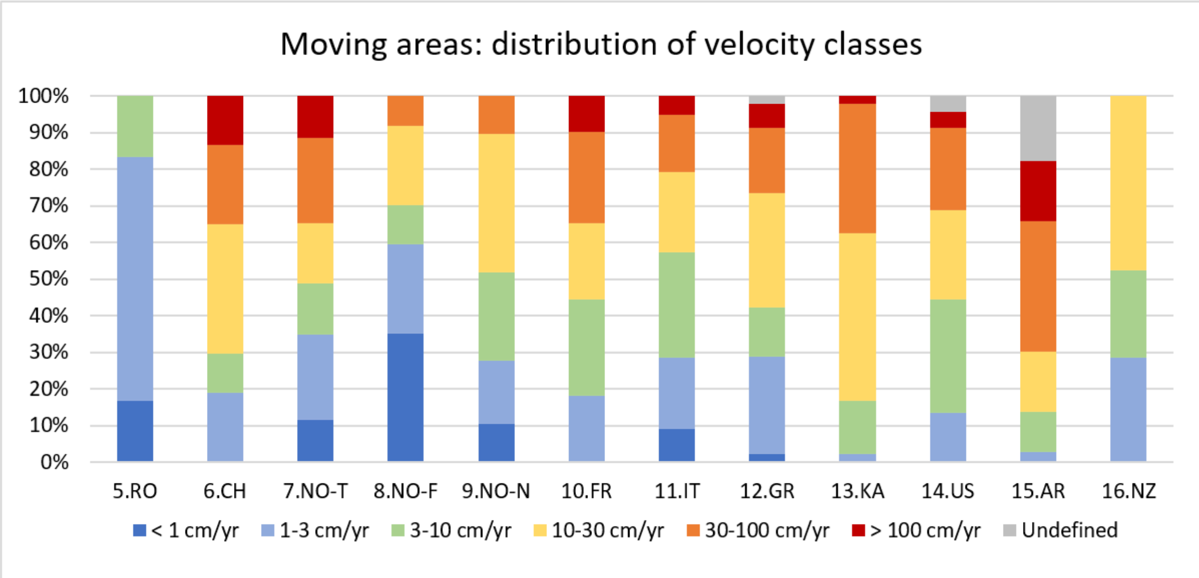

Figure 2: Distribution of the velocity classes of the InSAR-based moving areas in each RoGI area (consensus-based final results). The numbering of the area follows the standard format defined in the PSD [RD-2] and the PUG [RD-7]. See also the corresponding table in Annex 2.

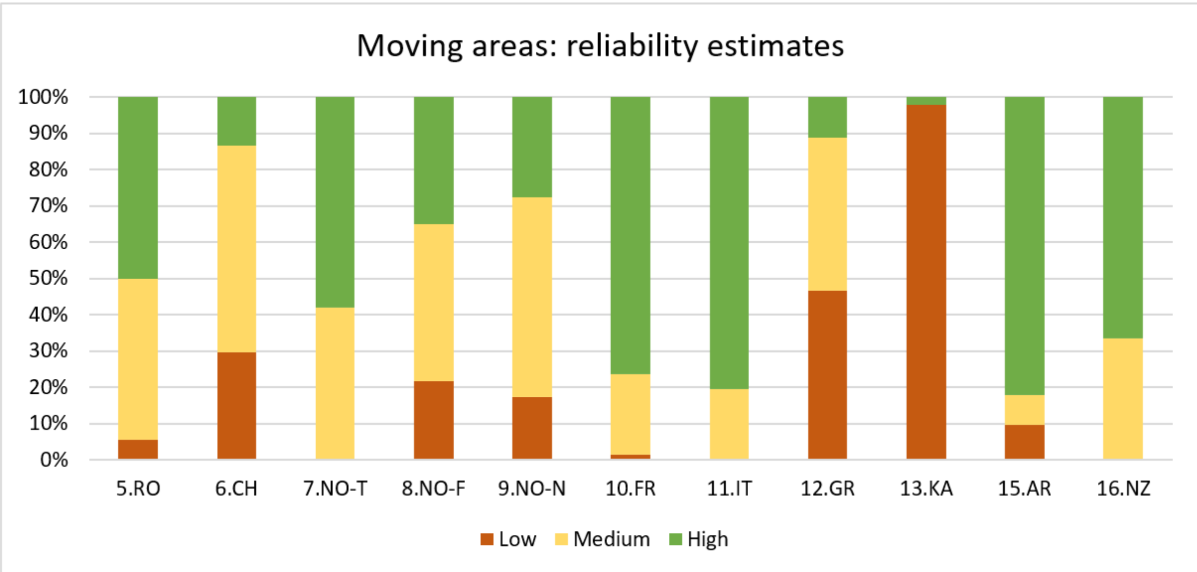

Figure 3: Reliability estimates of the final (consensus-based) moving areas files. The estimates are currently missing in the final RoGI for Area 14 (Brook Range, Alaska, USA). The numbering of the area follows the standard format defined in the PSD [RD-2] and the PUG [RD-7]. See also the corresponding table in Annex 2.

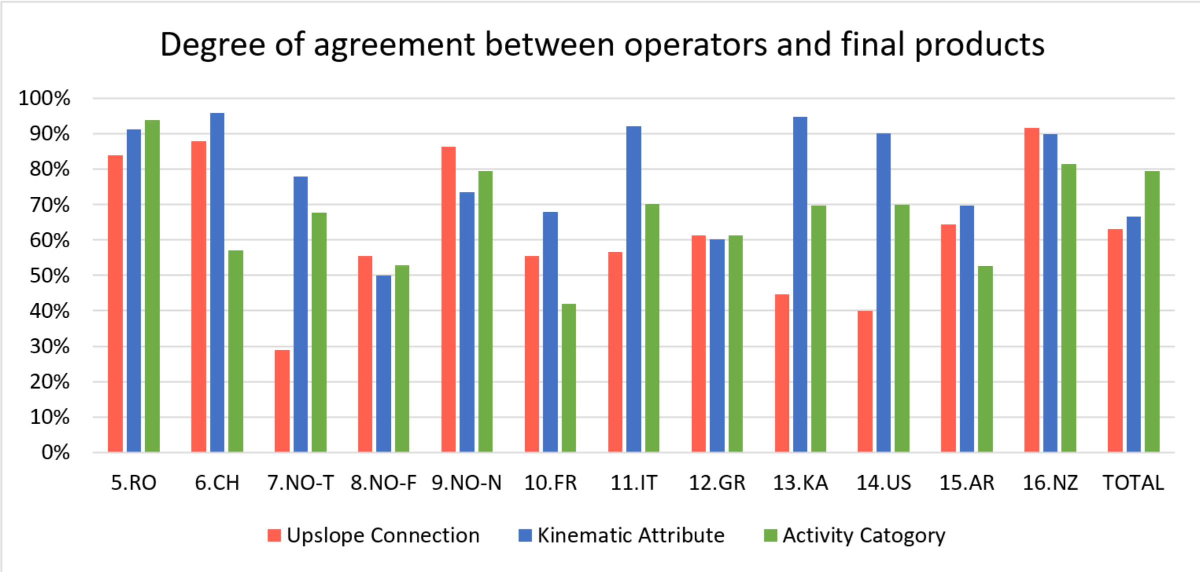

Figure 4: Degree of agreement between the individual operators and the final consensus-based products for three essential attributes (upslope connection, kinematic and activity). The numbering of the area follows the standard format defined in the PSD [RD-2] and the PUG [RD-7]. See also the corresponding table in Annex 2.

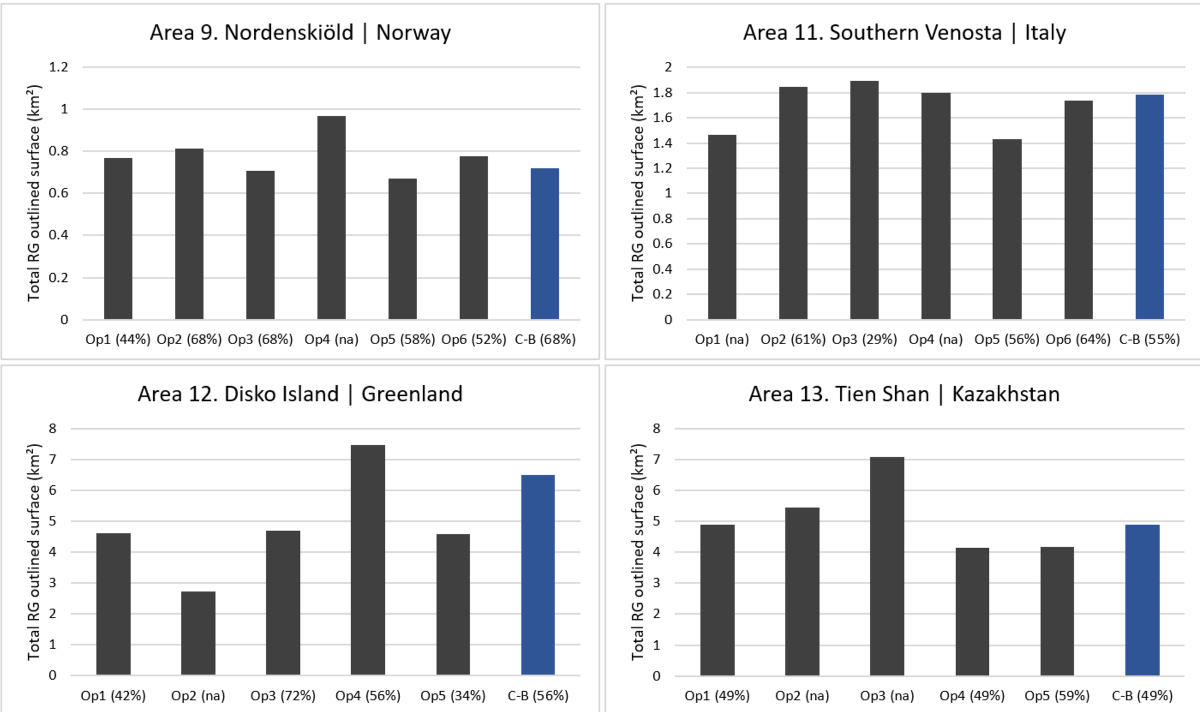

Figure 5: Selected examples showing the variability of surface of the mapped rock glaciers between operators (within the extended outlines). The values correspond to the summation of the outline extents for all comparable rock glaciers available in the area. The numbering of the area follows the standard format defined in the PSD [RD-2] and the PUG [RD-7]. See also the corresponding table in Annex 2.

2.3 Quality assessment of the multi-operator RoGI products in each area

Here we present a brief summary of the main conclusions regarding the RoGI products of each area. More comments are available in Annex 1. The numbering of the areas follows the PSD [RD-2] and the PUG [RD-7].

Area 5: Carpathians, Romania

The Carpathians are in the marginal permafrost zone with warm current conditions. Most rock glaciers are relict or in a transitioning stage. Relict rock glaciers are often covered by vegetation (shrubs and even forest).

- Quality of the InSAR-based moving areas: The rock glaciers are characterized by little (or no) movement. The MAs are small and with low velocity, and can therefore be hard to identify compared to other areas with strong InSAR signal on short temporal baseline interferograms.
- Quality of the primary markers and attributes: Most of the rock glaciers were easy to identify. The main challenge is related to the relict landforms with vegetation cover, that may be hard to identify without looking at detailed terrain shading (from LiDAR DEM that filters out the vegetation).
- Quality of the outlines: The main difficult was in the delineation between the rock glacier and its contributing area. In areas with a high uncertainty in the limit with the upslope, a curved line was drawn (continuing the delineation of the front and margins while following the topography).

Area 6: Western Swiss Alps, Switzerland

The Swiss area includes a good variety of landforms in a relatively small extent, which is ideal to train the community to inventory typical alpine rock glaciers in high-relief terrain. Due to good quality of the available geodata in this area, the RoGI team could take advantage of a very complete and rich dataset (high-quality hillshade, orthoimages and interferograms).

- Quality of the InSAR-based moving areas: InSAR interpretation shows some discrepancies between operators. While most of the time, the same MAs have been well detected and delineated, the velocity were sometimes assigned differently.
- Quality of the primary markers and attributes: There was no major difficulty in the identification of the landforms thanks to the high-quality data sources in the area. However, some operators judged that there were too many attributes to document.
- Quality of the outlines: There was no major difficulty in the delineation of the landforms thanks to the high-quality data sources in the area. Several multi-units initially identified with different PMs were not outlined separately in the second phase of the exercise (too complicated).

Troms, Norway

Troms displays a very wide range of morphologies, kinematics and activity states, which makes it an interesting area to train to RoGI practice and apply InSAR. Due to the geomorphological diversity, the area includes several complex cases, hard to map and for which various decisions can be made (all potentially right) depending on the chosen level of details.

- Quality of the InSAR-based moving areas: The most obvious patterns were identified by most operators. However, it appeared that a consensus-based process is practically hard to perform for the MAs, due to variable levels of experience with InSAR, the different ways to look at all available datasets and the variable levels of details in systematically outlining the MAs.

- Quality of the primary markers and attributes: Troms includes many landforms that are "landslide-connected". This upslope unit is somewhat ambiguous, as it often practically means that there is a poly-connection (talus+landslide). It explains the high level of discrepancy between operators for this specific attribute.
- Quality of the outlines: PM identification and outlining can be partly iterative in complex cases, as we discover during the outlining process that multi-unit discrimination is hard/not wise to do. In many cases, the delineation was difficult in the upslope in cases of several generations of partly overlapping rock glacier units.

Finmark, Norway

The Finmark subarea is close to sea level and in a cold-climate region in northern Norway. The region is transitioning from permafrost to permafrost-free terrain and includes many interesting periglacial landforms that can be misinterpreted as rock glaciers (e.g. large coarse solifluction lobes, rock avalanche debris) which make it an interesting area to train the community.

- Quality of the InSAR-based moving areas: Finnmark is a quite simple case in term of movement interpretation due to a large set of InSAR data, processed with different algorithms (single interferograms, stacking and PSI) to have complementary detection capabilities. When the MA analysis is done comprehensively in such case, the areas with no MA can quite reliably be interpreted as "no movement" (or movement < cm/yr).
- Quality of the primary markers and attributes: Finnmark displays an overlap of many periglacial processes that leads to lobated features, that are not always easy to discriminate or delineate (continuum between landforms). There are many "uncertain" PM and several cases with ambiguous upslope-connection due to old (relict) landforms.
- Quality of the outlines: There are georeferencing shifts between some open services for optical imagery (e.g. Bing), which may explain some discrepancies. The scale and level of details used to perform the outlining work varied between operators.

Nordenskiöld, Svalbard

The subarea focuses on a mountain ridge along a flatland in the southwestern part of Spitsbergen, in a region characterized by cold conditions and continuous permafrost. During the thawing season, the ground is highly dynamic all over Svalbard, which makes it challenging to discriminate and quantify rock glacier movement using InSAR.

- Quality of the InSAR-based moving areas: Svalbard is a difficult area for analysing ground movement with InSAR considering the many processes that can causes surface deformation at different time scales. This is especially challenging when focusing on small and slow-moving talus-connected rock glaciers.
- Quality of the primary markers and attributes: There was no major disagreement in the location of the main landforms. The main challenge is related to the kinematic and activity attributes. Although it is clear that the considered landforms are "active" in the traditional sense (intact, with presence of permafrost), they are very slowly creeping and so may fall in the transitional-relict category according to the current RGIK guidelines.
- Quality of the outlines: There are georeferencing shifts between some open services for optical imagery (e.g. Bing). The rock glacier morphology in the area is relatively simple and therefore

there are no major differences at the front/lateral margins. Main discrepancies were found in the limit with the upslope and in the way to set the limit of adjacent/overlapping units.

Vanoise, France

In the French area, the rock glaciers are generally well defined and relatively small. In addition, very high-resolution and multi-temporal WMS services are freely available, which helped the interpretation.

- Quality of the InSAR-based moving areas: InSAR was mostly useful to locate/identify moving rock glaciers. Estimating the velocity is a more challenging task due to various levels of InSAR backgrounds. Some operators have been confused about how to correctly interpret InSAR data, which shows the need to improve the guidelines.
- Quality of the primary markers and attributes: The variable level of detail applied by the operators led to differences in the way to interpret complex landforms (e.g. several identified units or one main complex unit only).
- Quality of the outlines: Different data sources with different configurations (shadows, source of sunlight, etc.) helped to correctly map some rock glaciers.

Southern Venosta, Italy

The area is composed of two main tributary hanging valleys and hosts a variety of rock glacier types and configurations with respect to upslope connection, dynamic state and size. It is an ideal area for such exercises.

- Quality of the InSAR-based moving areas: Not all the operators conducted this step, one due to colour-blindness. Others stated that additional training would be necessary before conducting this exercise. The MA component appears to be difficult to implement on a consensus-based fashion as it is too complicated to tackle during meetings with multiple operators.
- Quality of the primary markers and attributes: The main challenges were associated with the identification of small and relatively shallow rock glaciers developed on debris-mantled slopes, which for the most part did not exhibit well-defined rooting zones and lateral margins.
- Quality of the outlines: The delineation was consistent across operators, except for the handful of rock glaciers developed on debris-mantled slopes. The final products only include extended outlines. The PI questions the added value of drawing the restricted footprint at this scale.

Disko Island, Greenland

Disko Island is a challenging area for RoGI generation due to the relatively poor quality of the available remote sensing data (optical and DEM). The area is characterized by several imbricated processes/landforms that may be difficult to differentiate.

- Quality of the InSAR-based moving areas: The moving areas were diverging a lot between the operators. The helpfulness of this layer was not as obvious as expected, because they did not directly relate to the rock glacier outlines.
- Quality of the primary markers and attributes: Due to limited optical data and large areas affected by shadowing, PM identification was challenging. The main challenge was to differentiate rock glaciers from other land moving processes, such as landslides, soli/gelifluction and glaciers.

- Quality of the outlines: While the frontal and lateral boundaries are most of the time clearly visible and not diverging much between the operators, the upslope limit is difficult to determine, depending on the type of connection.

Tien Shan, Kazakhstan

The region is challenging with a large variety of rock glacier types: a few large rock glaciers that are obvious but also complex (multi-units); and several small ones, more ambiguous that were often mapped as “uncertain”. The exercise provided some important insights into the glacier-rock glacier interaction and helped to plan future intended fieldwork.

- Quality of the InSAR-based moving areas: There was quite a bit of variation amongst the operators. Some put more effort in this step than others. Some had previous experience in interpreting SAR interferograms, other not. However, the major moving areas were detected by all with little variation.
- Quality of the primary markers and attributes: Some discrepancies are reported in the way to choose between certain, uncertain and “not a rock glacier”. It was also unclear how to deal with multi-units’ rock glaciers. Some operators considered the landforms as one, some as several units.
- Quality of the outlines: The identification of clear upper boundaries was in many cases not possible. The upper outline was therefore challenging to draw.

Brooks Range, Alaska USA

There is generally a lack of data for Alaska (limited high-resolution optical imagery, no lidar DEM of the study area). This made mapping some of the rock glaciers in the study area difficult due to snow cover, cloud cover, or shadows.

- Quality of the InSAR-based moving areas: The InSAR interpretation was the trickiest part, as many operators have little experience on determining which data to use. However, overall the final moving areas and their rates had good agreement from the group.
- Quality of the primary markers and attributes: There were not many problems at the step of PM identification. The attribute assignment is challenging to perform in a consensus-based fashion, it was no time in the meetings to discuss these in any detail.
- Quality of the outlines: It was initially not clear on how to draw the upper outline: straight line on the upslope area of the rock glacier, versus drawing a curved connection to avoid the inclusion of talus cones feeding the rock glacier. A similar discussion took placed about the toe of the rock glacier, potentially reworked by other processes, such as solifluction.

Central Andes, Argentina

The Central Andes region is a very challenging area. It is not a well-known area, there are not many previous studies or high-resolution images to rely on. It is an interesting case to test and show the usefulness of the guidelines.

- Quality of the InSAR-based moving areas: The InSAR part, particularly the assignment of the velocity class attribute, was the step where most deviations between operators were found.
- Quality of the primary markers and attributes: The location and number of Primary Markers identified by operators were variable due to complex rock glacier systems with many rock glacier units. Although most of us could identify the same rock glaciers, some identified more units within the same rock glacier complex. In the consensus version, the number of PMs was reduced as much as possible (simplification).

- Quality of the outlines: The very complex rock glacier system with debris-covered glaciers as upper slope units were the most challenging landforms to outline, particularly the upper boundary. For sake of simplicity, rock glacier units within rock glacier systems were not outlined. During the second step of the exercise (outlines and attributes), the PM number and location were revised. The PM location and outlining steps were performed iteratively.

Southern Alps, New Zealand

In the area, the contrast in surface material between the rock glacier surface and the front is generally low, with the latter rarely displaying abundant fine-grained and unweathered material. The front is generally smooth, which makes it is hard for discriminating active from transitional rock glaciers in case of lack of kinematic data. This is an area where InSAR is especially valuable to use.

- Quality of the InSAR-based moving areas: Outlining of the MA was quite heterogeneous, partly due the generally noisy interferograms. It was difficult to systematically compare all MAs from the operators; it takes too much time.
- Quality of the primary markers and attributes: Some discrepancies were identified and attributed to the different operator backgrounds, the variable level of expertise (geomorphological training) and field knowledge. It is difficult and too time-consuming to systematically compare all the attributes from the operators.
- Quality of the outlines: The outlines were very homogeneous. The main differences were at the upper limit for talus slopes connected RG, and some problems are identified in cases of exaggerated fronts (blended with the downside talus slope).

2.4 Quality assessment of the RoGI inventorying process in all areas

Based on the results in the 12 areas and feedback forms, we here summarize common observations identified by several (or all) teams/PIs.

Value of the RoGI exercise and the multi-operator procedure:

- The steps and instructions of the exercise were generally assessed as clear and easy to follow. Most PIs/teams reported that they liked the structure and clarity of the provided GIS and data packages.
- Most PIs report positive involvement and motivation from their operators. Each team had two multi-operator meetings, with about 3-10 people attending. The size of the team was ideal for a such exercise, more people would have been challenging to have good discussions. In some cases, the digital meetings have been complemented with complementary modes of communication (email discussions, sharing of comments in documents, prints screens, powerpoints, sending recording of meetings). The discussion at the meetings (and through other communication modes) were found very valuable; both for personal learning purpose and for improving the quality of the final products.
- Having operators with different skills and backgrounds brings value to the final result. The combination of different points of view and experiences from several regions around the World ensures that various morpho-kinematic elements are identified and taken into consideration.
- Although InSAR interpretation has been identified as the most challenging step due to little experience for some operators, several teams report that the data is useful at different levels, e.g. simply to detect landforms that may not be so obvious on optical images only, even when not focusing on quantifying their movement rates.

Challenges and suggestions to improve the current procedure/guidelines:

- The consensus-based procedure worked generally well for the PM identification, the outlines and some specific attributes. However, it is practically not possible to discuss all details in the meetings. It is hard to apply for the moving areas (no time to go through each interferograms to discuss/validate each MA). Practically, most PIs compared their own results with the others, and potentially adjusted their results when major differences were found. A real consensus-based process could work but only on a small set of rock glaciers, which could then be used for agreeing on the main principles before upscaling.
- The InSAR interpretation was challenging for many operators and described as time-consuming. The teams/PIs suggest various ways to improve this point: 1) improvement of the InSAR guidelines, adding more concrete examples on how to read the interferograms, 2) processing/providing the data in different formats (unwrapped and converted results, e.g. from stacking) that are easier to use/interpret (less data and with a velocity unit easily understandable by non-experts), 3) split the multi-operator process in two separated teams (one with InSAR expertise focusing on the MA part, one with geomorphological expertise focusing on the PMs/outlines and using the final MA files for the characterization).
- The assignment of the kinematic and activity attributes may require clarification/adjustment in the guidelines. The teams/operators have understood differently the way to set the "Activity Assessment" attribute. For example, it is generally recommended to avoid overinterpreting the absence of movement, because no MA can also mean no data. In that case, some may choose "geomorphological" as activity assessment, others "kinematic" (understood as geomorphological+kinematic); the lack of movement being an additional indicator, not the main criterion but an info confirming the geomorphological interpretation. In other cases, a kinematic attribute from a MA with low reliability may be documented (as a vague indication) but chosen not to be used to set the activity. There is currently no clear way to document this.
- The quality of the final products is highly dependent on the data availability and quality, and the level of details of the analysis. The scale of analysis/digitalization had not been specified at the beginning of the exercise, which led to discrepancies in the outlining level of details and size of the considered landforms. Currently it is also not clear where/how to document the data source, imagery date and scale of analysis. When using Bing, Google or ESRI WMS imagery, it is important to specify the date that work has been performed as these open services have frequent updates. It was encouraged to do it in the field "Comments" or "Kin.Comments" but several other elements can be written in the fields, which led to very variable metadata documentation depending on the operator/PI.
- Several operators/PIs judge that there were too many elements/variables to document. The entire process is consequently time-consuming. Shorter/more compact versions of the RoGI protocol could be available to avoid discouraging some groups to follow it. It should be noted that in the framework of this exercise, all steps were required although several elements are presented as "optional" in the guidelines. For example, the outlines are valuable but are not mandatory to draw in case of too complex cases. A combination of PMs with and without outlines is possible within the same RoGI. One could decide to delineate a large system and mark the locations of several units using PMs (but without outlining at the same level). We need flexibility about this.
- The guidelines/instructions are long to read and split in many cross-referencing documents. Several people asked for a way to summarize the essential steps/info in a very short summary

document, e.g. one-pager with a flow-chart of the steps and all the links to the documents necessary for the further work.

- For specific steps where more discrepancies were found, the guidelines should include more concrete examples (with different types of landforms, from different places in the world). For example the upper outline (between rock glacier and its contributing area) has been identified by all teams as the most challenging part to delineate. The question of how to display the upper outline when there is a high level of uncertainty is not clearly explained in the guidelines (straight line or curved line following the topography).

3 Rock glacier velocity (RGV) products

3.1 Methods for quality assessment

The InSAR-RGV products were compared with GNSS data acquired using periodic terrestrial surveys and/or permanent GNSS stations. All GNSS data is summarized in Table 1. The comparison has been performed as part of the UNIFR M.Sc. study of Lea Schmid (2023–2024). The final M.Sc. thesis has been submitted in January 2024 and will be defended in February 2024 (Schmid, 2024). Since CRDP v.1.0 delivered in November [RD-6], small code adjustments have been made, which led to minor modifications of the results (v.1.1). The procedure described in the ATBD is still valid and the main findings from the CRDP have not changed. The v.1.2 of the RGV data package is provided in attachment of this report.

Table 1: Overview of the GNSS data used for validation of the RGV products (modified from Schmid, 2024).

Periodic GNSS measurements (annual-biannual UNIFR surveys)					
Rock glacier	Operator	Number of survey points	Start of the measurements	Surveying frequency	Time interval used in this study
Becs-de-Bosson	UNIFR	ca. 200	2004	Bi-annual	2017–2021
Steintälli	UNIFR	24	2020	annual	2020–2022
Bru	UNIFR	5	2020	annual	2020–2022
Permanent GNSS stations (Beutel et al., 2022; Cicoira et al., 2022)					
Rock glacier	Station name	Station name	Location	Date first measurement	Date last measurement
Distelhorn	DIS1	DIS1	E: 2'632'748.500 N: 1'115'588.990 Alt. 2'427.0 m.a.sl.	19.07.2012	27.08.2019
	DIS2	DIS2	E: 2'632'911.58, N: 1'115'403.717 Alt. 2'501.0 m.a.s.l	19.07.2012	27.08.2019
Steintälli	ST02	ST02	E: 2'630'237.445 N: 1'108'650.981 Alt: 3'029.1 m.a.s.l	18.05.2011	26.08.2021
	ST05	PERMASENSE	E: 2'630'157.142 N: 1'108'556.446 Alt: 2'997.01 m.a.s.l.	18.05.2011	26.08.2021

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). Periodic GNSS data were used for three sites (Becs-de-Bossons, Steintälli and Bru). Steintälli and Bru only started in 2020, with seasonal surveys in 2020 and 2021. On the fourth site, Distelhorn, no periodic GNSS data is available. All surveys have been carried out by members of the UNIFR Department of Geosciences.

For Steintälli and Distelhorn, InSAR-RGV products were compared with permanent GNSS station data from Cicoira et al. (2022). The data is part of the dataset of continuous GNSS observations of 54 sites in the Swiss Alps, published on PANGAEA (Beutel et al., 2022). In total, four permanent GNSS stations were used: two on Steintälli rock glacier (ST02 and ST05) and two on Distelhorn rock glacier (DIS1 and DIS2). The station setup consists of a GNSS antenna, a GNSS receiver, a data logger, and an inclinometer, placed inside a fibreglass tubular mast, together with a 12V power supply. The mast is anchored to a large boulder (Beutel et al., 2022). Reference stations have been installed on stable terrain to allow double-difference GNSS post-processing. Positions are measured hourly, but only daily data is available in the published dataset (Beutel et al., 2022; Cicoira et al., 2022). The GNSS data from the four stations used for InSAR-RGV comparison was processed using a script which first calculates a 6-day rolling mean of the positions and then calculates the 3D velocity for 12-day intervals. As InSAR has a summer observation window, only GNSS data from July-October (or July-August for the last year) was used to calculate the mean. Data gap is visible for Distelhorn (Figure 6).

Only absolute velocities are compared for Distelhorn and Bru due to the short overlapping time period between InSAR and GNSS. When there are several years of overlap between the InSAR and GNSS documented periods (as for Becs-de-Bosson and Steintälli rock glaciers), the relative changes in velocities are also compared, relative to the overall mean of the time series. There are three main reasons for this choice: 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.

3.2 Comparison between the InSAR and GNSS RGV trends at the pilot sites

Distelhorn rock glacier

GNSS data is available between 2012 and 2019, while InSAR has been processed between 2017 and 2021. InSAR and GNSS can therefore only be compared between 2017 and 2019. Here, only absolute values are compared, due to the different observation periods with short overlap. The InSAR-RGV is based on time series averaged from 662 pixels covering a large part of the rock glacier. In contrast, the GNSS information is only based on two stations, one location on the fast-moving frontal lobe (DIS1) and one located on the second, slower, lobe (DIS2).

Both in GNSS and InSAR time series, a slight velocity increase is measured between 2017 and 2019 (Figure 6). This tends to indicate that InSAR is suitable for extracting interannual changes comparable to GNSS stations on Distelhorn rock glacier. More years are needed to confirm this preliminary conclusion.

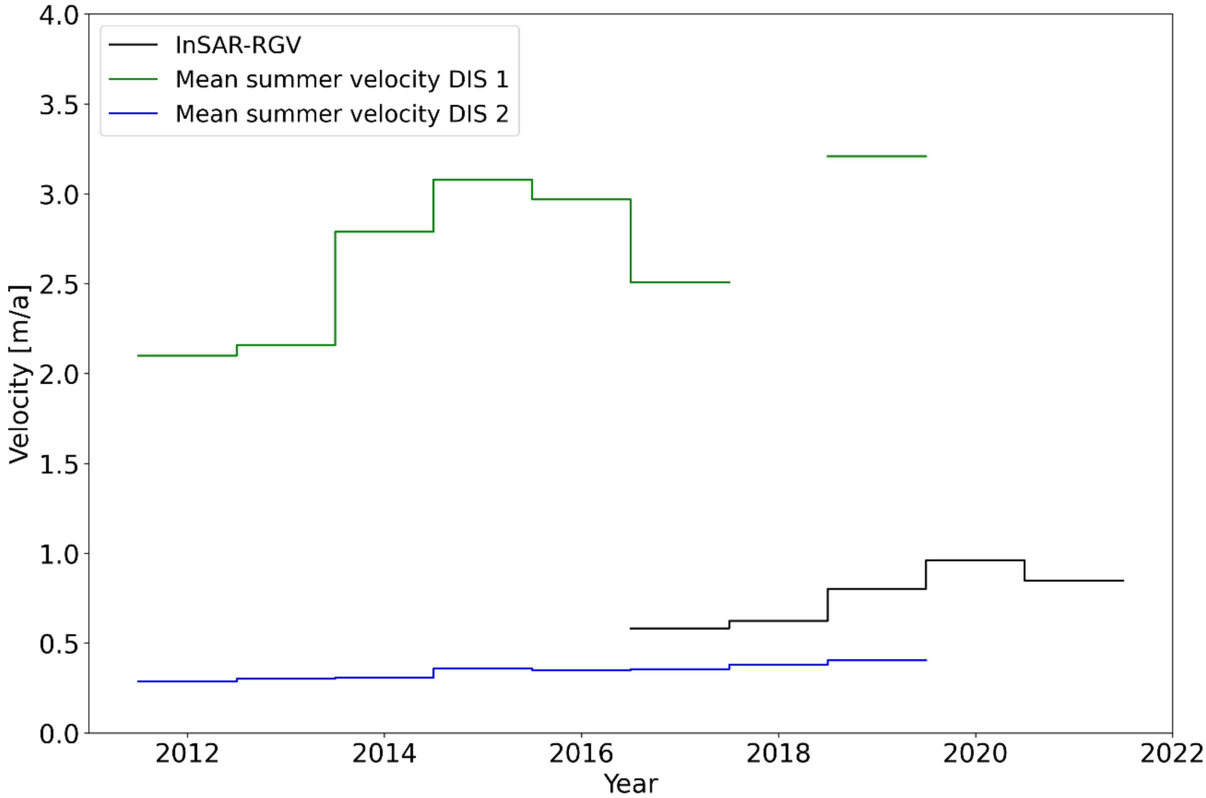

Figure 6: Comparison of the GNSS-based and InSAR-based RGV for Distelhorn rock glacier. The blue and the green lines are the summer velocity time series from the permanent GNSS. The black line is the InSAR-RGV. From Schmid, 2024.

<u>Becs-de-Bosson rock glacier</u>

Based on GNSS data, two different RGV trends were identified for Becs-de-Bosson rock glacier: an accelerating trend since 2015 and a smaller overall acceleration with a decelerating trend the last years (Figures 7–8, Group I (green line) and Group II (blue line)). Both RGVs are compared with the InSAR-RGV, for both absolute (Figure 7) and relative velocities (Figure 8). The absolute velocities show that the InSAR-based RGV has lower absolute velocities compared to dGNSS measurements. This is due to different location/coverage and measurement dimensionality (1D LOS vs 3D). Group I of the GNSS-RGV and the InSAR-RGV exhibit similar trends, with a peak in 2020 (Figure 5). The increase, however, is more gradual for the GNSS-RGV. In 2020, the relative velocity of the InSAR-RGV was up to 20%, whereas the GNSS-RGV was only 10%. In contrast, the GNSS Group II continues to accelerate in 2021.

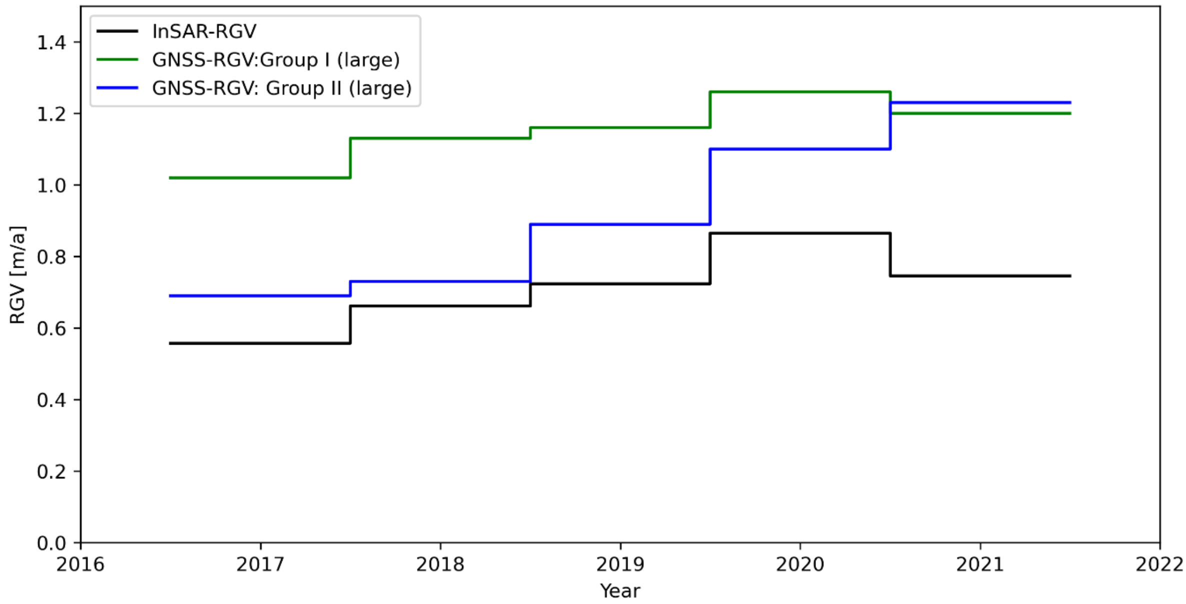

Figure 7: Comparison of the GNSS-based and InSAR-based RGV for Becs-de-Bosson rock glacier. The blue and green lines are the GNSS-RGV based on the annual survey (two different trends identified at different locations on the rock glacier). The black line is the InSAR-RGV. From Schmid (2024).

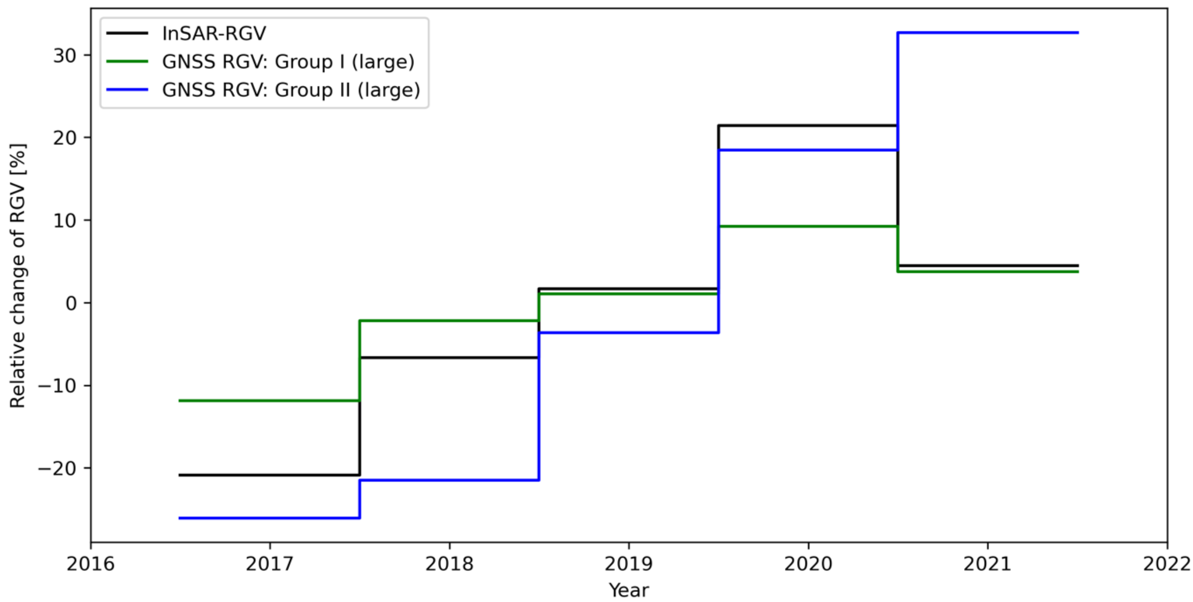

Figure 8: Comparison of the relative velocity change of GNSS-based and InSAR-based RGV for Becs-de-Bosson rock glacier. The blue and green lines are the GNSS-RGV relative velocity. The black line is the InSAR-RGV. From Schmid (2024).

Bru rock glacier

Bru rock glacier is a slow-moving rock glacier, which can be measured with a 12-days temporal baseline. While the InSAR-RGV covers 8 years (2015–2022), GNSS measurements only started in 2020, which makes this site difficult for direct comparison. InSAR and GNSS can only be compared in 2021 and 2022. Only absolute values are compared due to the short overlapping observation period (Figure 9). InSAR underestimates the velocity compared to the GNSS. Whilst the InSAR-RGV is based on 69 points, the GNSS-RGV is only calculated from four points. Two of the four GNSS points used to calculate the GNSS-RGV are located in areas not represented in the final InSAR-RGV. For the two years with data overlap, the overall trend (decrease) is relatively similar although the magnitude of the changes is very different: InSAR shows a small deceleration between 2020 and 2022, and GNSS shows a strong velocity decrease during the same period.

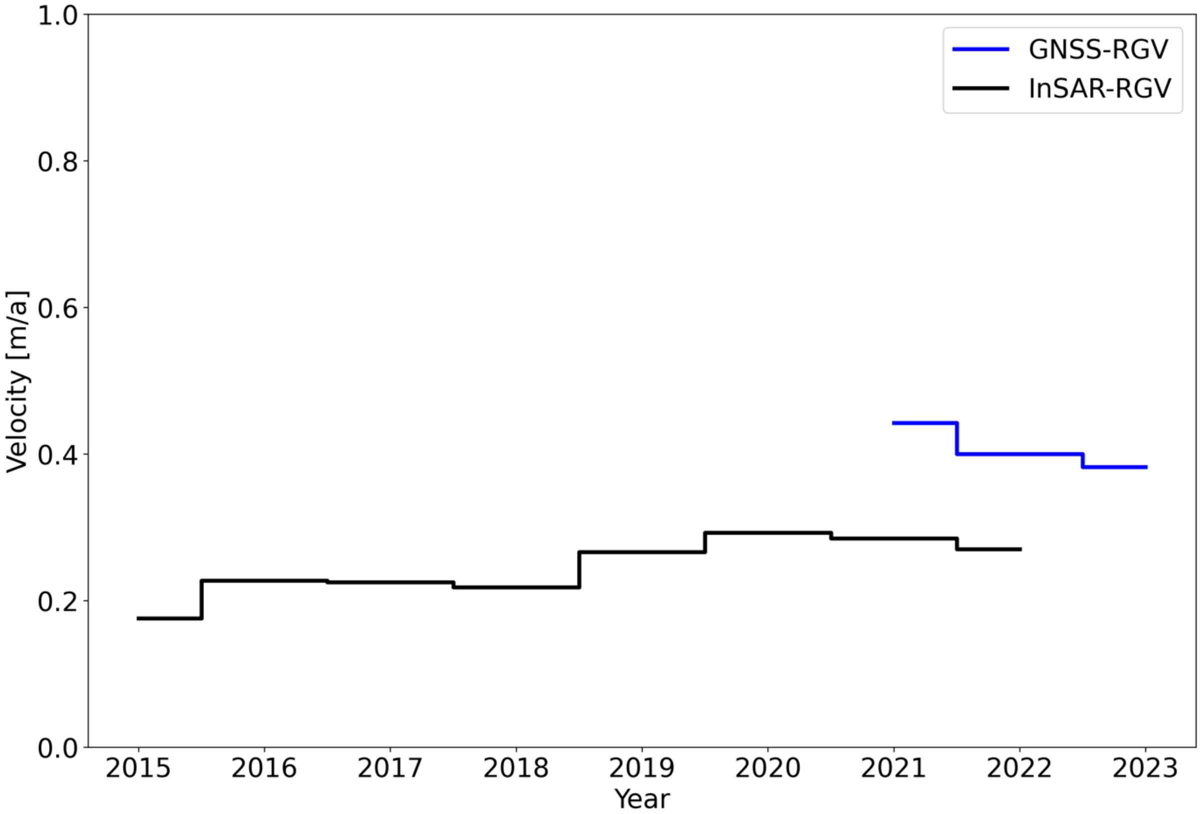

Figure 9: Comparison of the GNSS-based RGV (blue line) and the InSAR-based RGV (black line) for Bru rock glacier. From Schmid, 2024.

More years of data are required to draw any conclusion about this site. Nevertheless, we can take advantage of observations performed on a neighbouring rock glacier, Dirru, which has been surveyed since 2007. There, a velocity peak was measured in 2015 and has been followed by a deceleration between 2015 and 2018, and then an acceleration until 2020 (Figure 10). The InSAR-RGV for Bru is therefore consistent with what is observed at this neighbouring site.

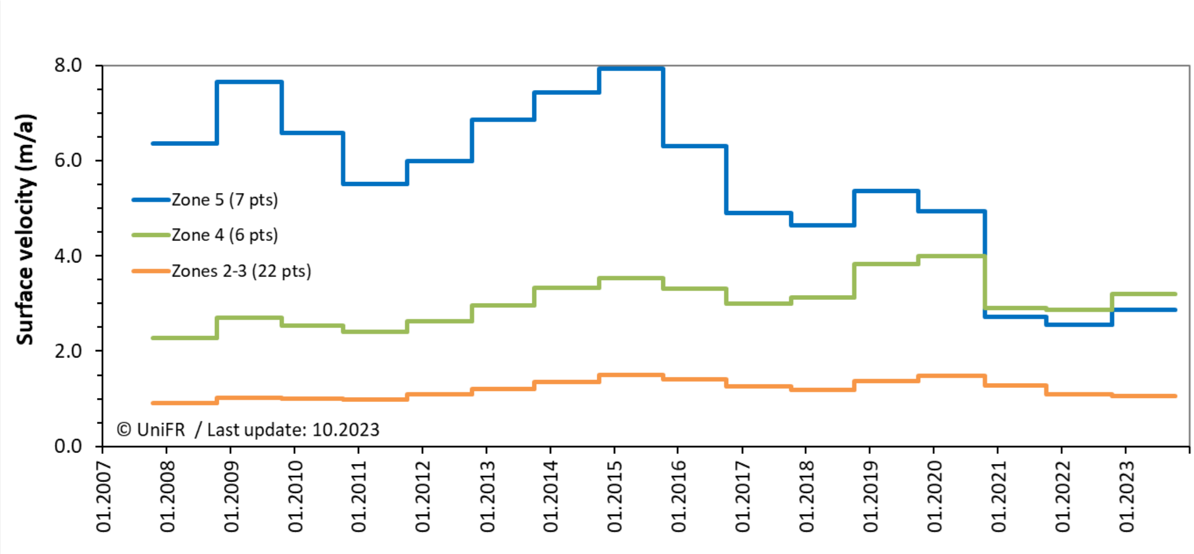

Figure 10: Annual surface velocity for Dirru rock glacier. Mean of a set of points selected respectively in the lower and most active part of the rock glacier (blue), the median section (green) and the uppermost area (orange) (UNIFR, 2023). From Schmid, 2024.

Steintälli rock glacier

In Steintälli, there are five years of overlap to compare GNSS and InSAR products (2017–2021). Both absolute and relative velocities are compared (Figures 11–12). The two GNSS stations (ST02, ST05) are displayed separately (green and blue lines). Steintälli consists of three consecutive lobes with different movement rates. The InSAR-RGV (black line) is based on time series from 127 pixels, all exclusively located on the third lobe, whereas each GNSS time series is only based on one GNSS-Station, one on the third lobe (ST05) and one on the second lobe (ST02). The second, slow-moving, lobe is not included in the final InSAR-RGV.

Due to different location/coverage and dimensionality (1D LOS vs 3D), the trend comparison is hard to perform using absolute velocity (Figure 11). When looking at relative velocities, the time series have a good agreement (Figure 12). However, whilst the InSAR-RGV peaks in 2019, Steintälli rock glacier still accelerates in 2020 according to the two GNSS stations. The relative velocity changes slightly differ in magnitude. Based on InSAR, relative velocities are about 5% below average in 2017 and 2018 and about 15% faster than average in 2019. ST02, the GNSS station located on the lower lobe, has increased strongly between 2017 and 2020, with more extreme negative and positive relative values than InSAR-RGV (from about 20% below average to about 28% faster than average). The overall patterns are very similar between ST05 and InSAR-RGV, except for the difference between 2019 and 2020. ST05 GNSS is located on the fast-moving front of the rock glacier. A part of this fast-moving area is excluded at the clustering step of the InSAR-RGV product generation (due to outliers potentially resulting from unwrapping errors). This may be the cause of the apparent deceleration between 2019 and 2020.

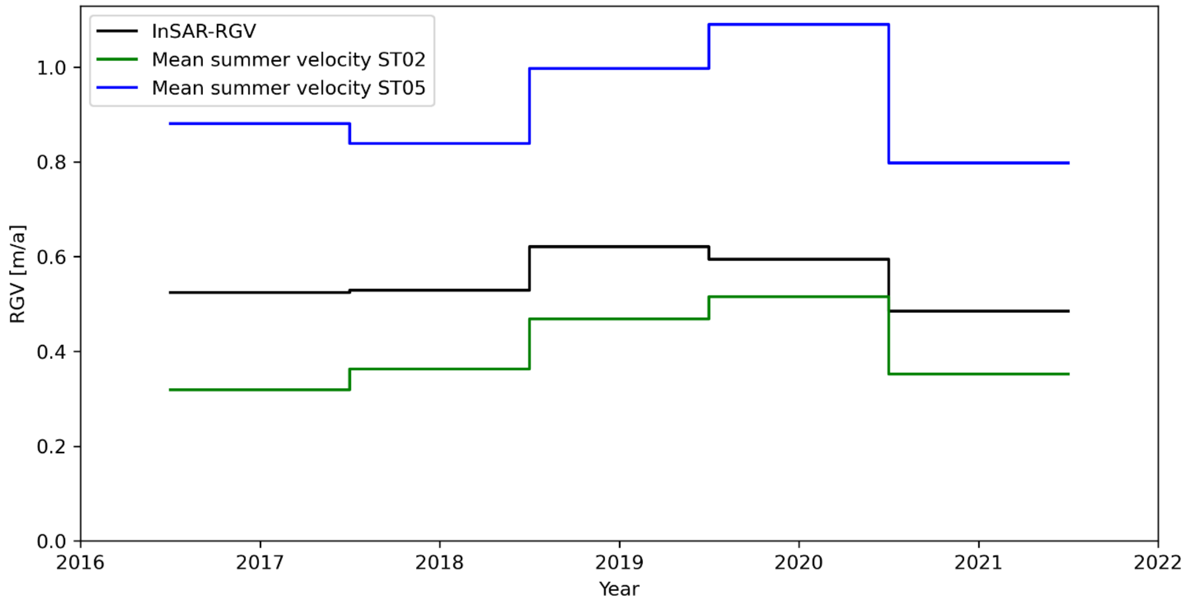

Figure 11: Comparison of the GNSS-based and InSAR-based RGV for Steintälli rock glacier. The blue lines are the GNSS-RGV at the locations of the two permanent stations. The black line is the InSAR-RGV. From Schmid (2024).

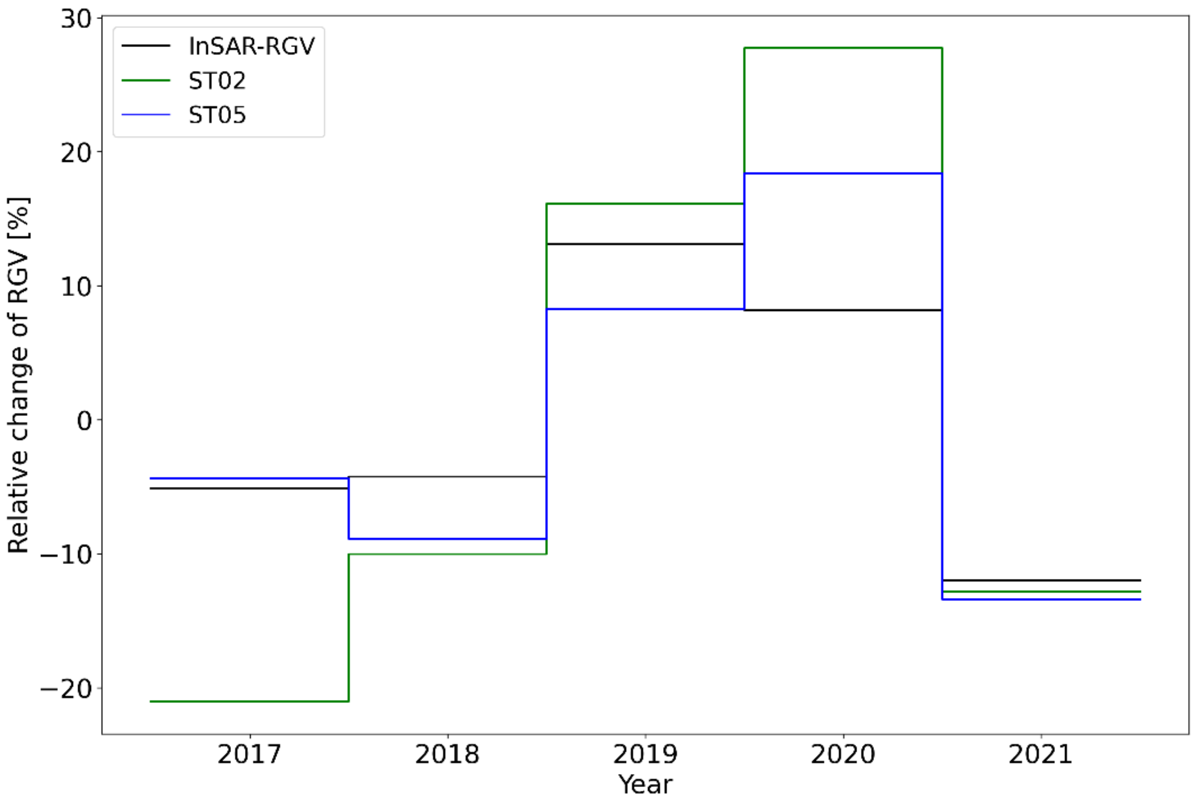

Figure 12: Comparison of the relative velocity change of GNSS-based and InSAR-based RGV for Steintälli rock glacier. The blue lines are the GNSS-RGV at the locations of the two permanent locations. The black line is the InSAR-RGV. From Schmid (2024).

3.3 Comparison between the pilot RGV products and regional trends

Four different InSAR-RGV were produced at selected sites. For the four sites, the relative velocity changes are homogenous. On average, the four rock glaciers all accelerated during the observation period, which matches both the trend shown by all UNIFR monitored rock glaciers in Valais and Central Swiss Alps (Figure 13) and the trend from all rock glaciers monitored by the Swiss Permafrost Monitoring Network PERMOS (Figure 14). In general, all sites fit well with the trend documented by the regional and PERMOS averages. The results also match with the findings of Kellerer-Pirklbauer et al. (accepted), who observed accelerating trends between 2018 and 2021 on multiple rock glaciers in the European Alps. The magnitude of the relative change of the PERMOS cannot be compared because the time series covers a longer period, and the reference period is 2011–2020. Based on InSAR-RGV, all sites increase the most between 2018 and 2019, as for the PERMOS results. Steintälli rock glacier is the only rock glacier which show minor deviation from the PERMOS average.

To sum up, the produced RGV time series matches the overall trend of similar trends generated with in-situ geodetic measurements. The presented method appears to be suitable to produce consistent InSAR-RGV, which are comparable to GNSS-RGV, although we need to include more years of data to confirm this primary conclusion. The InSAR-RGV products are an average of several pixels on the main moving areas of each rock glacier, providing a better spatial representativity than single GNSS points. In addition, because of the availability of historical data, time series can be computed since 2015 and 2017 with 6-days and 12-days interferograms, respectively, whereas in-situ measurements are only available from the first measurement onwards. As long as regular open access data is available, the RGV time series can updated each year.

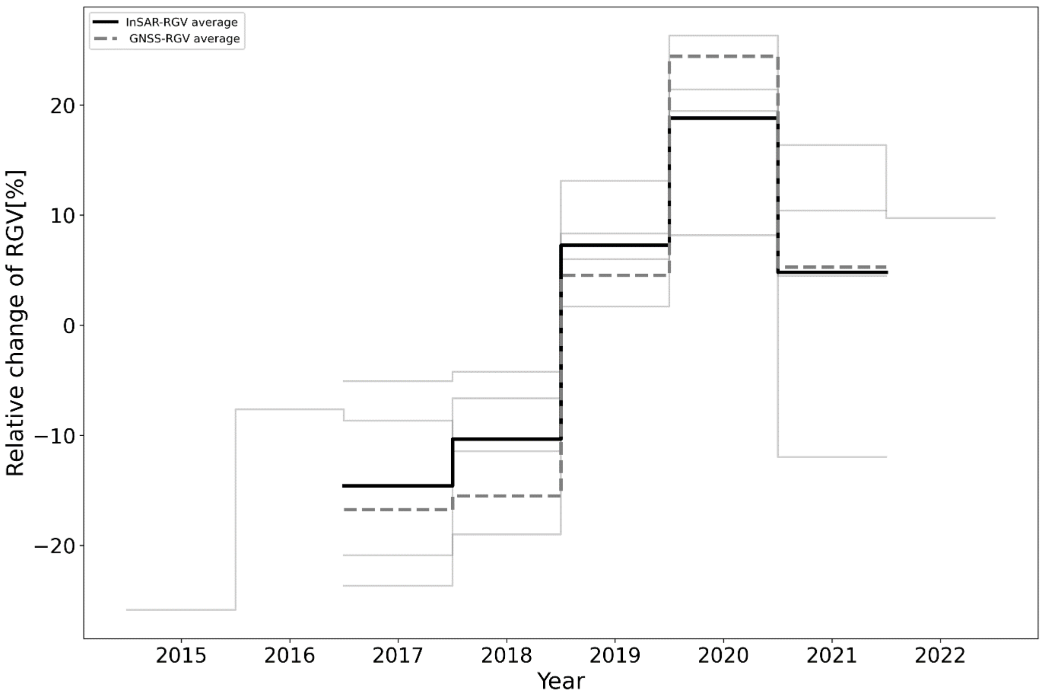

Figure 13: Relative change of RGV in % for all four rock glaciers, relative to the overall time period (2017-2021 for Distelhorn, Becs-de-Bosson and Steintälli, 2015-2022 for Bru). The average of all four relative RGV time series is represented by the black line. The regional average from the Valais and Central Swiss alps is represented by the dashed line. From Schmid (2024).

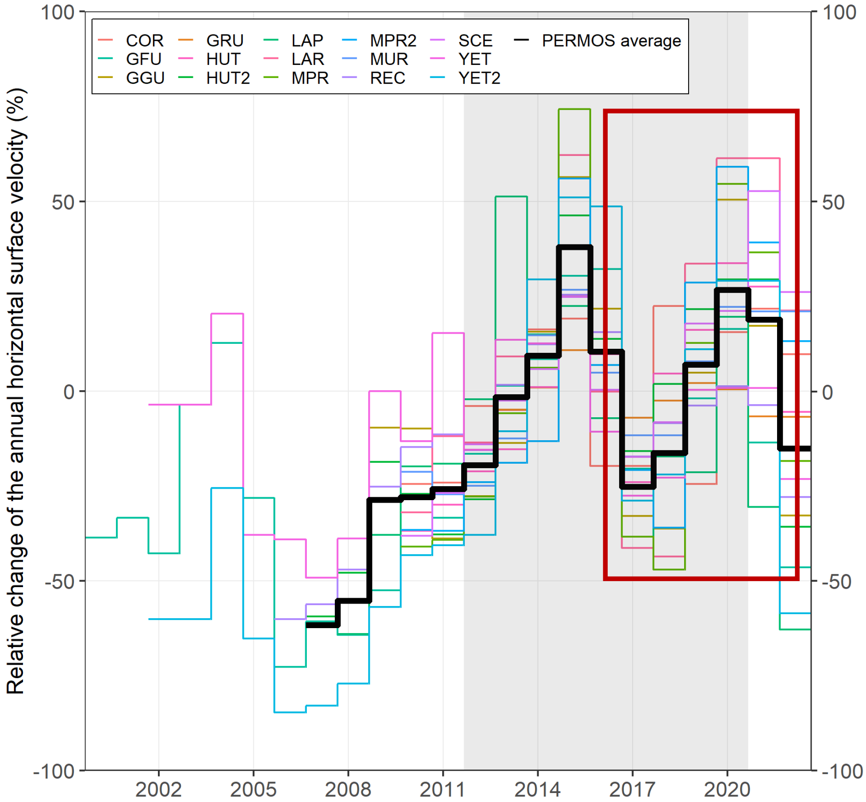

Figure 14: Mean annual relative horizontal surface velocity (reference period 2011-2020, grey area). The average of the Swiss Alps is represented by the black line The red area marks the main period for which InSAR-RGV are available. Modified from PERMOS (2023).

4 Conclusions and future activities

4.1 Rock glacier inventory (RoGI)

The mutli-operator exercise is now finished but work remains to systematically analyse, interpret and publish the results. The feedback from the PIs and operator teams are overall very positive, and the preliminary analysis of the current CRDP (v.1.1) highlights the value of the datasets for various usage: further detailed analysis in the considered area, selection of landforms for RGV generation, training dataset for machine learning, dissemination as online exercise for educational purpose.

In term of dissemination, here are some outcomes related to RoGI:

- Additional modifications (for educational purpose: improvement of commenting and uncertainty documentation and for comparability: correction of technical errors with some vector files) will lead to a CRDP v.1.2, that will be used for the final release of the dataset. We plan to disseminate the products together with a data paper (e.g. ESSD).
- The consensus-based results will be used to train the community. Online exercises for the 12 areas will be released on RGIK website to complement the two existing exercises based on Swiss examples [RD-15].
- An abstract presenting the results of the multi-operator RoGI exercise (Rouyet et al.) have been accepted for an oral presentation at the ICOP conference in Whitehorse (June 2024).

In the second iteration, the results may be used as training data for RoGI using machine learning. This is planned to be performed by third parties, in synergy with an upcoming RGIK working group on the same topic. Based on the findings of the exercise, we will also encourage all partners institutions to correct their initial regional inventories (Permafrost_cci Phase 1). Identified sections of RGIK guidelines showing a lack of clarity will be adjusted based on the exercise conclusions. Based on the updated guidelines, we will evaluate the potential to generate inventories in new regions. Further support for external partners will be further discussed at the end of iteration 1.

4.2 Rock glacier velocity (RGV)

The InSAR-RGV result from the iteration 1 Permafrost_cci Phase 2 are promising. We propose an easily transferable method to automate the production of RGV by averaging unwrapped Sentinel-1 interferograms. The results show that the proposed procedure is able to provide consistent products comparable with GNSS-RGV.

In term of dissemination, here are some outcomes related to RGV:

- New version of the baseline concepts on Rock Glacier Velocity as an associated parameter of ECV Permafrost [RD-13] and first release of the practical guidelines for RGV generation [RD-14];
- Review paper on rock glacier velocity (Hu et al. in prep.) likely to be submitted before the end of the first iteration;
- M.Sc. thesis of Lea Schmid focusing on developing a method for the generation of InSAR multi-annual velocity products (Schmid, 2024);
- Abstract discussing the influence of ground surface temperature on rock glacier velocity (Pellet et al.) accepted as oral presentation at the International Conference on Permafrost (ICOP) in Whitehorse (June 2024);

- Abstract discussing the InSAR-RGV pilot results (Schmid et al.) accepted as in-person poster at the International Conference on Permafrost (ICOP) in Whitehorse (June 2024).

There are several open questions regarding the operationalization of the InSAR-RGV production, as this part was designed as a pilot study in the first iteration. The generic RGV guidelines are still under development and advances in this field are highly expected in the coming years, under the umbrella of the RGIK community. The InSAR procedure applied at the Swiss pilot sites needs to be tested on a large number of rock glaciers and the time series should be compared with other techniques (e.g. optical remote sensing). This will be the focus of the second iteration of Permafrost_cci Phase 2 and the Option 8 (PermaSeries: Integration of complementary rock glacier velocity time series for the monitoring of mountain permafrost).

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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
MAGT	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

Annex 1: Feedback forms filled by the RoGI PIs

Feedback on Multiple Operator RoGI exercise in Carpathians (Romania)

PI: Flavius Sirbu. **Involved operators:** Line Rouyet, Cristina San Martin, Reynald Delaloye; Alexandru Onaca, Razvan Popescu.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- The steps and instructions of the exercise are clear and easy to follow.
- Having operators with (slightly) different backgrounds (e.g. geomorphology, remote sensing) brings value to the final results as having different points of view that are discussed among the team assures that most/all aspects of the landform are taken into consideration.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- The main characteristics and also the main challenge is the slow to little movement of the rock glaciers.
- Another challenge (but one that was found in other areas also) is the delineation between the rock glacier and its contributing area.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Most of the rock glaciers in the Carpathians are somewhat easy to identify. After some debates among the team members, the final consensus is strong.
- One particularity of this area is the large amount of rock glaciers covered by vegetation (covered by shrubs and even forest). They are relict and the best and maybe the only way to identify them is by using a detailed terrain shading (preferably from a LiDAR DEM that filters out vegetation).

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The slow movement of the rock glaciers presented some challenges, but the final version of the inventory managed to overcome this.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- From the perspective of an area with most of the rock glaciers being relict, the current attributes are sufficient to describe the inventory while also keeping it simple enough.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- There is a need to establish how to symbolize the outline when the delineation between rock glacier and its contributing area is not accurate or it has a high uncertainty. In the Carpathians we decided to have the outline with a curved line (continuing the delineation of the front and margins) following the most likely line but other regions and operators have decided to use a straight line for the back of the rock glacier.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- Given de diversity of the test sites, the used data and that of the people involved, the GIS structured was perfectly suited for the task.

Others?

- -

Feedback on Multiple Operator RoGI exercise in the Western Swiss Alps

PI: Echelard Thomas. **Involved operators:** Rafael Caduff, Thibaut Duvanel, Julie Wee, Reynald Delaloye.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- Instructions were clear for all operators.
- Relevance of the consensus-based approach for moving areas: too long and complicated to discuss in detail during meetings (no time to go through each interferograms to discuss/validate MAs). Maybe just let the PI choose based on the operators results?
- Compared with the other sub-areas in which I was involved, there were no major difficulties, probably because we had a very complete and rich data set for Switzerland (high-quality hillshade, several ortho-images with very good resolution, good quality interferograms, etc.). It sounds obvious but I think it’s one of the most important things that leads to quality work in this kind of exercise.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- Relevance of the kinematic table and automatic activity class assessment. For example, cm/year in Disko or Svalbard does not necessarily mean Relict or Transitional.
- It's important to have regional specificities. I was an operator also for Disko and, for example, the assessment of activity was done differently than in the Alps: if there is a “classic” glacier just upslope to the rock glacier but no evidence of movement (based on kinematic assessment), it's probably not true to fill the attribute table with ‘relict’.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Need to indicate at which scale the mapping was (or need to be) done: 1/1000 is very different than 1/10 000.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Need to indicate at which scale the mapping was (or need to be) done: 1/1000 is very different than 1/10 000.

- InSAR interpretation shows some discrepancies between operators. Most of time MAs are pretty much well detected but the kinematic values are often between two classes depending on the operator. For example: operator1 filled 3 cm/a to 10 cm/a while operator2 chose 10 cm/a to 30 cm/a.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Some operators (not only in Swiss area) judged that there were too many variables.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Need to indicate at which scale the mapping was (or need to be) done: 1/1000 is very different than 1/10 000.
- Even if multi-units are identified during the Primary Markers step, it's often too complicated to draw the outline during the outlining step. But drawing the entire feature is possible (I mean 1 RG containing several units).

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- Optical imagery from Bing, Google or ESRI are probably updated sometimes, it could be great to add the date of the orthoimage which has served for the drawing.

Others?

- A bug regarding the limited number of characters in specific fields (e.g. upslope connection) must be systematically checked and fixed in the RoGI template.

Feedback on Multiple Operator RoGI exercise in Troms (Norway)

PI: Line Rouyet**. Involved operators:** Thomas Echelard, Benjamin Robson, Cristina San Martin, Nina Jones, Reynald Delaloye.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- For some operators, it was not clear that we needed to map all rock glaciers, not only those assumed to be active/moving.
- Agree on a level of detail and scale of the digitalization for unit discrimination before starting the process? Would reduce discrepancies.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- Troms displays a very wide range of morphology, kinematics and activity. Very interesting area to train to RoGI practice and apply InSAR to document the kinematics.
- Due to the geomorphological diversity, the area included several complex cases, very hard to map and for which various decisions can be made (all potentially right) depending on the chosen level of details. Especially the case for multi-generations of overlapping RGs, partly reworked/eroded.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- PM identification and outlining can be partly iterative in complex cases, as we may discover during the outlining process that multi-unit discrimination is hard/not wise to do. In Troms, we had to change our mind on several cases during the second meeting, i.e. remove/merge units we had initially selected during the first meeting.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Moving area consensus-based process is practically hard to perform (variable level of experience with InSAR, different way to look at the various available datasets, variable level of detail in systematically outlining the MAs).
- Should we democratize the use of InSAR data to identify MA or provide final MA to operators (InSAR-experts as data providers) instead of asking all operators to do the MA analysis. In the framework of this exercise, it was an interesting/useful training and dialog, but for operational applications at larger scale: it may be more effective to have an InSAR operator group for the MAs and geomorphological experts as operator group for the PM/outlines.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Landslide-connected is an ambiguous category, as it often practically means “poly-connected” (talus+landslide).

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Difficult delineation in the upslope and in cases of several generations of partly overlapping rock glaciers.
- We had not specified at which scale/which level of details the outlining work should be performed + not all regions had specified which main optical source to use > discrepancies to be expected.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- When we have changed an attribute in the table, it is not always possible to go back to “nothing” (NULL). For ex. if by mistake you set ‘Radar’ to ‘Type of Data’ and finally do not apply a kinematic assessment method, you would like this field to be empty.
- PM Notice: the order of the attributes differs from the file table – would be easier to have the exact order + we should change the order of the upslope connection / the current connection in the dialog box/formulation.
- In some areas, the QGIS setting added to a comma in the lat/long identifier, which led to a bug in the automatic update of the point location when moving the point (after creating it).
- Initially, there were restrictions/criteria for filling some attributes (linked to other attributes, e.g. enable for filling only if another field is filled): this must be systematically modified in future versions (check that it does not apply to the current online templates). Remove all criteria constraining the attribute table filling: it should be as flexible as possible.

Others?

- Detail: Hard to differentiate yellow to light orange / orange to light red in the generic MA colour scale.
- Detail: Enable snapping in all initial projects (clearer delineation of outlines for neighbouring units).

Feedback on Multiple Operator RoGI exercise in Finnmark (Norway)

PI: Line Rouyet. **Involved operators:** Flavius Sirbu, Nina Jones, Lidia Ferri, Kaytan Kelkar, Ivanna Pecker, Reynald Delaloye.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- Clear procedure, good participation to meetings and useful inputs from the operators – no major issue to be reported.
- The mutli-operator procedure was especially useful to discriminate between simple cases (obvious rock glaciers, clear delineation, high velocity well observable on InSAR, for which most operator results were in agreement) and more complex ones (uncertain rock glaciers, unclear limits, ambiguous moving patterns). For the complex questions (grey zone), the meetings were useful to take a common decision.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- Finmark subarea is close to sea level and in a cold-climate region in northern Norway. The region is transitioning from permafrost to permafrost-free terrain.
- Many interesting periglacial landforms that can be misinterpreted as rock glaciers (e.g. large coarse solifluction lobes, rock avalanche debris) which make it an interesting area to train the community.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Finnmark displays an overlap of many periglacial processes that leads to lobated features, not always easy to discriminate what is (or is not) a certain rock glacier and how to delineate it (continuum between different landforms). We ended up with many “uncertain” PM.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Moving area consensus-based process is practically hard to perform (variable levels of experience with InSAR, different ways to look at the various available datasets, variable levels of details in outlining the MAs).
- Finnmark is a quite simple case in term of movement interpretation: many good InSAR data, processed differently to have different detection capabilities (single interferograms, stacking, PSI). When the MA analysis is done comprehensively in such cases, the areas with no MA can quite reliably be interpreted as “no movement” (or movement < cm/yr).

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Ambiguous upslope connection in several cases due to old (relict) landforms.
- Not necessarily clear for operators what is the difference between "uncertain" and "unknown" when for ex. assigning the attribute "upslope connection".

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- We had not specified at which scale/which level of details the outlining work should be perform + not all regions had specified which main optical source to use > discrepancies to be expected.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- When we have changed an attribute in the table, it is – for most attributes – not possible to go back to "nothing" (NULL). For ex. if by mistake you set 'Radar' to 'Type of Data' and finally do not apply a kinematic assessment method, you would like this field to be empty.
- PM Notice: the order of the attributes differs from the file table – would be easier to have the exact order + we should change the order of the upslope connection / the current connection in the dialog box/formulation.
- In some areas, the QGIS setting added to a comma in the lat/long identifier, which led to a bug in the automatic update of the point location when moving the point (after creating it).
- Initially, there were restrictions/criteria for filling some attributes (linked to other attributes, e.g. enable for filling only if another field is filled): this must be systematically modified in future versions (check that it does not apply to the current online templates). Remove all criteria constraining the attribute table filling: it should be as flexible as possible.

Others?

- Detail: Hard to differentiate yellow to light orange / orange to light red in the generic MA colour scale.
- Detail: Enable snapping in all initial projects (clearer delineation of outlines for neighbouring units).

Feedback on Multiple Operator RoGI exercise in Nordenskiöld Land, (Svalbard, Norway)

PI: Line Rouyet. **Involved operators:** Rafael Caduff, Lotte Wendt, Cécile Pellet, Thomas Echelard, Reynald Delaloye.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- Clear procedure, good participation to meetings and useful inputs from the operators – no major issue to be reported.
- The mutli-operator procedure was especially useful to discriminate between simple cases (obvious rock glaciers, clear delineation, high velocity well observable on InSAR, for which

most operator results were in agreement) and more complex ones (uncertain rock glaciers, unclear limits, ambiguous moving patterns). For the complex questions (grey zone), the meetings were useful to take a common decision.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- The subarea focuses on a mountain ridge along a flatland in the southwestern part of Spitsbergen. The rock glaciers are mostly talus-connected and easy to identify/delineate morphologically.
- The main challenge is related to the kinematic analysis. The velocity is quite low and hard to discriminate with the surroundings due to other periglacial processes ("everything is basically moving").
- Cold permafrost environment. Although it is clear that the considered landforms are "active" in the traditional sense (intact, with presence of permafrost), they are very slowly creeping and so may fall in the transitional-relict category according to the current definition.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- No major issue/disagreement regarding the location of the main landforms.
- Some disagreements/debates regarding the division of multi-units in cases of a succession of consecutive lobes, e.g. displaying different InSAR-kinematics.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Moving area consensus-based process is practically hard to perform (variable level of experience with InSAR, different way to look at the various available datasets, variable level of detail in systematically outlining the MAs).
- Svalbard is a difficult area for analysing ground movement with InSAR considering the many processes that can causes surface deformation at different time scales. This is especially challenging with focusing on a subarea with mostly talus-connected RGs (glacier/glacier-forefield connected are overall faster in Nordenskiöld).

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Due to slow creep rate and the challenges mentioned to delineate MAs, the kinematic attribute and resulting activity were the most challenging attributes to set. The ambiguity regarding the attribution of the activity in such cases (relict/relict uncertain/transitional?) led to some debates in the multi-operator meetings.
- Something is unclear regarding the "Activity Assessment" attribute. Should we choose "geomorphological" of "kinematic" assessment in cases where both criteria were partly used. We generally recommend avoiding overinterpreting when there is no MA (because no MA can also mean no data). In that case, most operators may choose "geomorphological" as activity assessment method, while it could theoretically be geomorphological+kinematic (the lack of movement being an additional indicator, not the main criterion but an info confirming the geomorphological interpretation). Currently: no good way to document this.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The RG morphologies in the area are relatively simple and therefore they are relatively few differences at least at the front/lateral margins. Main discrepancies were found in the limit with the upslope and in the way to set the limits between adjacent/overlapping units.
- Big georeferencing shift for some images available in open optical services (e.g. Bing). Seems to be more severe problems at high latitudes. Important to specify on which image the outlining must be performed. Even if it was mentioned, not understood by all operators, which led to significant discrepancies in the outlines.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- When we have changed an attribute in the table, it is – for most attributes – not possible to go back to “nothing” (NULL). For ex. if by mistake you set ‘Radar’ to ‘Type of Data’ and finally do not apply a kinematic assessment method, you would like this field to be empty.
- PM Notice: the order of the attributes differs from the file table – would be easier to have the exact order + we should change the order of the upslope connection / the current connection in the dialog box/formulation.
- In some areas, the QGIS setting added to a comma in the lat/long identifier, which led to a bug in the automatic update of the point location when moving the point (after creating it).
- Initially, there were restrictions/criteria for filling some attributes (linked to other attributes, e.g. enable for filling only if another field is filled): this must be systematically modified in future versions (check that it does not apply to the current online templates). Remove all criteria constraining the attribute table filling: it should be as flexible as possible.

Others?

- Detail: Hard to differentiate yellow to light orange / orange to light red in the generic MA colour scale.
- Detail: Enable snapping in all initial projects (clearer delineation of outlines for neighbouring units).

Feedback on Multiple Operator RoGI exercise in the Vanoise area (France)

PI: Diego Cusicanqui. **Involved operators:** Xavier Bodin, Thibaut Duvanel, Paula Johns, Javiera Carrasco, Francesco Brardinoni, Reynald Delaloye.

General comments on the Consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- From a general point of view, the second part of the RoGI process in the French Alps was very rich. All the operators have made an amazing job outlining rock glaciers, their moving areas and filling their attributes. This process of double checking the results should be maintained if several operators are available.
- From my point of view, the most challenges will be data availability notably on InSAR datasets (at regional scale) and high-resolution optical images (WMS) as well as more detailed DEMs.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- From a general point of view, the French Alps are not a very complex area when compared with the Central Andes and Tie Shan, for example. Rock glaciers are generally well defined and relatively small. In addition, very high resolution and multi-temporal WMS services are freely available, which helps a lot on the interpretation. There are very specific cases where rock glaciers are complex and linked to multiple processes (e.g. landslides, glaciers, etc.). However, the most difficult part was related to relict rock glaciers and the presence of (LIA?) moraines. During the discussions with the operators and with other colleagues working in geochronology, several phases of rock glacier advance were identified (e.g. RG superimposed on others), so the analysis quickly became very complex, interpreting where are the limits of these units and how to assign the attributes. For now, we have identified those that are easy to qualify/identify. Some others still remain within the uncertainty bar (triangle).

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- I think that the process of double-checking the results between all the operators was very valuable, as the discussion and different interpretations of several processes were very rich.
- The discrepancies were at the level of detail of each operator, with one identifying a single point over a complex landform (be aware that this is a complex landform), and another (usually an expert) identifying several points within the same complex landform. Both are useful, but it was very difficult to reach agreement.
- Most of the discrepancies were related to geomorphological interpretation (using optical images) and data availability. I found it very useful to have many WMS in the European Alps to compare different time periods. However, this was not the case everywhere.
- One improvement could be to make the guidelines more graphically explicit by adding images rather than pointing to the rock glacier images within the atlas. I have received feedback that it is sometimes annoying to click on the link instead of looking at the image within the document. This is a controversial point and should be discussed within the committee.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- I think the most positive point is how InSAR data can make moving features appear. However, I believe that guidelines could be more explicit regarding ascending and descending modes (both looking to the right, but in different directions of the orbits). Some operators have been confused about how to correctly interpret InSAR data based on the mode of acquisition (asc or desc). Otherwise, the guidelines are very detailed on how to map moving areas.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- As expected, this was the most controversial point, as the discussion focused mainly on the complex and relict landforms. As rock glaciers have different genesis (e.g. glacier-attached, glacier-field-attached, etc.) on different time scales (e.g. 50's, more recent, etc.), several questions arise as to when the attributes should be filled in.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- I think the most useful selection here is that the more different data sources we have, the richer the interpretation. For example, the use of WMS, very useful in the European Alps and very limited in the Andes and high mountain Asia. Different data sources with different configurations (shadows, source of sunlight, etc.) help to correctly map some rock glaciers. In the case of the French Alps, at the end of the exercise (October) I had access to a LiDAR DEM. This improved the interpretation of some landforms during the last discussion and solved some previous discussions.
- Regarding relict rock glaciers, I think there needs to be a discussion within the committee on how to map them and if we have to map them. Sometimes they are very easy to map (no problem here), but sometimes it is simply not possible, but it is certainly a relict rock glacier, with fuzzy edges or moraine/landslide connected.
- Another source of discrepancy is the level of expertise and knowledge of the study area. Most of the time, experts are more restrictive in their mapping than "newer" operators. This point is very difficult to solve :-). However, it could be partially solved by adding several data sources.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- I noticed that there is no way to select information about sensors and time span (e.g. from a drop-down list) when mapping a moving area. This could be done manually of course, but I think this data could be extracted in a semi-automatic way within QGIS. It's quite sure that you have already faced this question, however, thinking from a replicable point of view, if a new operator has to use moving area polygons, it's quite difficult to know if the main operator has used Sentinel-1 data, ALOS, TerraSAR-X, etc and what was the time span of the interferogram. I think if more data (metadata) could be added, it will be easier to replicate/share the RoGI.

Others?

- I suggest encouraging the use of Google Earth (or another 3D reference surface) in parallel when mapping rock glaciers. 3D relief helps to solve some ambiguities.

Feedback on Multiple Operator RoGI exercise in Southern Venosta (South Tyrol, Italy)

PI: Francesco Brardinoni. **Other operators involved:** Daniel Costantini, Diego Cusicanqui, Reynald Delaloye, Thomas Echelard, Christophe Lambiel, Monika Schnitzer, Riccardo Scotti, David Tonidandel.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- The Team found the description of the steps and instructions clear.
- We had two online meetings. Not all operators could attend both meetings. Two operators could attend neither of them.
- Overall, the involvement of multiple operators was seen positively by everyone. On the question of efficiency, as will become clear below, some caveats apply.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- The area, composed of two main tributary hanging valleys, was selected on purpose as it hosts a variety of rock glacier types and configurations with respect to: upslope connection (ie, talus, debris-mantled slope, and glacier forefield), dynamic state (active, transitional and relict), and size.
- The main challenges were associated with the identification of small and relatively shallow rock glaciers developed on debris-mantled slopes, which for the most part did not exhibit well-defined rooting zones and lateral margins. Most of the times, the main distinctive attribute was indeed the presence of a front (in some instances not well defined).
- Thanks to the multi-operator approach, we could identify: (1) a number of newly detected small rock glaciers developed on debris-mantled slopes (about 5 of them with some uncertain additional ones); (2) two very small talus rock glaciers located on very steep slopes besides active debris flow channels.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- It was perceived as a very useful preliminary step. The team is not sure that the category "not a rock glacier" is really useful, unless the study area is a small one. It does not add anything substantial to the inventory and requires additional work.
- The guidelines looked fine to everyone.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Not all the operators conducted this step. One due to colour-blindness. Others stated that an ad hoc training would be necessary before conducting this exercise.
- We believe the Moving Area component will be difficult to implement on a consensus-based fashion as it is too complicated to tackle during in person (or online) meetings by multiple operators. In our group, the PI evaluated all the MA inventory versions and compiled a "best" consolidated version.
- In our view, a consensus-based approach to MAs should be limited to a small set of rock glaciers. It could serve as a pilot teamwork to ensure that: (1) all operators are on the same page; (2) some principles for obtaining "homogeneous" MA inventories across a given study area are laid out before starting the compilation of a regional or sub-regional inventory.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The team found this part straightforward and well documented as it is.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Two operators did not understand correctly this point and some extra demo was needed from the PI. It might be useful to double-check the explanation of this part with extra figures.
- The delineation was extremely consistent across operators, except for the handful of rock glaciers developed on debris-mantled slopes mentioned above.

- As a PI, I question the added value of drawing the restricted footprint, unless conducted for a very limited study area.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- No complaints by the team members. In this study area, a number of high-resolution WMS are available (i.e., orthophoto mosaics, LiDAR-derived shaded relief).

Others?

- As a PI, I feel a more practical trade-off between number of attributes and the compilation of a consensus-based inventory. I fear that now: (1) the procedure is very time consuming for what you get at the end; (2) depending on the PI, different areas may end up mapped quite differently from each other.
- Perhaps, it could be worth building a compact summary table (one page maximum) in which different options of detail (ie, number of attributes entered) are provided: minimum, intermediate, and complete. This way, we do not risk discouraging groups (especially those covering large areas) from adopting the RoGI protocol.

Feedback on Multiple Operator RoGI exercise in Disko Island (Greenland)

PI: Rafael Caduff. **Involved operators:** Lotte Wendt, Francesco Brardinoni, Cécile Pellet, Thomas Echelard, Reynald Delaloye.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- In my opinion, the Steps of the consensus-bases are very clear and understandable AFTER going through the entire process. It can be a bit hard to step-in into the process without pre-existing knowledge on the approach and finding its way around the formal and RoGl-specific guidelines. While the guidelines itself are very well written and clear and understandable, I got lost several times browsing through the documents. I would propose to distil the document "RoGI_practice_instructions.pdf" into a one-pager somehow with a flow-chart of the steps and all the links to the documents necessary for the further work.
- The multi-operator approach is relatively time-consuming and needs a certain bit of organizational talent (which one might or might not have), but with online meetings, it is perfectly feasible. The challenge lies in finding time-windows for the meetings especially over different time-zones. In my opinion, the value out of the discussions is very high and the personal learning-curve can be steep. However, for large-scale inventories with many objects to discuss it will probably pass the threshold of efficiency, since we tend to "over-discuss" single cases.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- It was a bit more challenging, than expected but more because of the relatively poor available RS-data (optical and elevation). The main challenge is to differentiate RG processes from other Land moving processes such as landslides, soli/gelifluction, ice-covered Glaciers.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The PM identification was depending more on optical data than expected, since inactive systems are as well included. Therefore, the optical data was crucial in detecting the areas. Since only poor-quality public data was available, it was kind of difficult (and shadowing in the high relief areas in high latitudes is a problem for mainly north-facing topography!
- The guidelines itself are very clear for the marking of the RG (Units).

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The moving areas were diverging a lot between the operators. They were drawn in my opinion with less accuracy than I would have expected. It can be, that most of the operators are not used to work with InSAR data or, because of the coarse resolution of the data? However, the helpfulness of this layer was not as obvious as expected, because it could not be used directly for RGU-Outlines! I could imagine, that in future multi-operator approaches, it could make sense that the MA-Layers could be provided by a separate, more InSAR specialized person/group and then merged in the process of RGU-attribution? I think the MA Layer is the one, that was most time-consuming in the approach.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- For me personally, this was a new field for me. I did not have much pre-existing knowledge on the distinction and separation of the attributes. Therefore, I profited a lot of the discussions and comparisons with the other operators results.
- Would it be possible to include in the links provided by the PDF "Notice_RoGI_Primary_Markers.pdf" directly a bookmark to the specific section of the BC/PC and KA documents? THIS would be very time-saving instead of scrolling and going through the entire document.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- While (when high quality optical data is available!) the frontal and lateral boundaries are most of the time clearly visible and not diverging much within the different operators results, the up-slope limit is kind of difficult to determine. It depends as well on the connection (e.g. to debris covered glaciers or under a scree slope…).
- The question, whether a clearly faster (or even destabilizing) unit within a complex system should be treated separately could be addressed in greater detail, since we tend to encircle complex looking landforms to a single unit to save time, than go through the finding process…

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- I personally liked the structure and clarity of the provided GIS-Data Package! Thank you for putting so much effort into this (as well in pre-defining the attribute selection in the gpkg files)!
- As for the RS data: Of course they could always be better.

- One thing that should be addressed is, how to include the used "remotely streamed" data e.g. from Google/Bing/ESRI maps? They will certainly be updated in the future, and I could not find a good way to see the date/timestamp of the data. It will be necessary to a certain point, to point the precise date of the used RS data.

Others?

- The challenging point is to update operators that missed a progress meeting and should get and include the discussed topics in the next step.
  One possibility would be to use the labelling of the "comments" field as default in the symbology of the gpkg-layer. So, the comment is visible directly for each Feature without using the attribute table.

Feedback on Multiple Operator RoGI exercise in Tien Shan (Kazakhstan)

PI: Tobias Bolch. **Involved operators:** Ella Wood, Lea Schmid, Renald Delaloye, Flavius Sirbu, David Farias, Sun Zhangyu.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- The instructions are overall well written and clear.
- I am in line to use QGIS for this exercise; it was for me, however, more challenging than using ArcGIS. At least one operator worked with ArcGIS as I got the files in shp-format.
- We had very good discussions in the 2 meetings. It was, however, challenging to find a consensus. This was also as the regions is quite challenging.
- The time spent on this exercise and also the experience varied amongst the operators which was also visible in the quality of the provided results. But still the contribution of every operator was useful for the exercise.
- Overall, I liked the exercise as I got additional insights in about the rock glaciers which I am working on since several years.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- The region was quite challenging. There are few large multi-part rock glaciers and several uncertain rock glaciers
- It was unclear how to deal with some multi-part rock glaciers. Some operators considered the landforms as one, some as several single rock glaciers.
- Identification of clear upper boundaries was in many cases not possible.
- There was no real novel finding, but the exercise provided some important insights into the glacier-rock glacier interaction and helped to plan intended field work this summer. This might will lead to better understand the evolution of rock glaciers.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- This worked in general well. Main discrepancies were in the level the operators included uncertain rock glaciers or "not a rock glacier".
- Some more illustrations in the guidelines would be useful.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- There was quite a bit of variation amongst the operators. Some put more effort in than others. Some had previous experience in interpreting SAR interferograms, some not. However, the major moving areas were detected by all with little variation.
- It was unclear whether the operators shall include all moving areas or only those related to rock glaciers.
- There were quite a lot of SAR interferograms provided. This was great for the really interested operator but challenging for those with less experience and/or time.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- This was in general straight forward.
- Some more illustration in the guidelines would be useful.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- It was good to introduce extended and restricted outlines.
- It was in particular challenging to identify the upper boundary.
- Some more illustration in the guidelines would be useful.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- The GIS structure was overall clear and working with the templates was straight forward.
- As mentioned for me and some operators, it was more effort working with QGIS (but I liked it as I will anyhow work more with QGIS in the future).
- A higher resolution DEM would have been useful.
- A more selective provision of the InSAR data would have helped the less experienced operators or those who had limited time.

Others?

- It was a very valuable exercise, despite the effort.
- The provision of optical imagery with different resolutions (e.g. S2, Planet) in addition to the images available through Bing and Google would have been useful to learn about the identifiability and impact of the different resolutions.
- Some more financial support would have enabled me to support a scientist to process and provide additional data (e.g. very-high resolution stereo data and DEMs and velocity thereof) to further improve the results.

Feedback on Multiple Operator RoGI exercise in Brooks Range (Alaska, USA)

PI: Margaret M. Darrow. **Involved operators:** Flavius Sirbu, Nina Jones, Kaytan Kelkar, Line Rouyet, Alexander Handwerger, George Brencher, Reynald Delaloye, Nicole Schaffer, Francesco Brardinoni.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- Generally, the clarity of steps/instructions was excellent. It would be good to add one point to clarify that the PI MUST make a copy of his/her own results as a separate file before making the final shapefiles.
- There was no problem in getting this group of individuals together, despite the multiple locations/time zones. Everyone was flexible and understanding.
- Not everyone was able to attend every meeting (most likely due to the wide range in locations/time zones). For the last meeting, the PI recorded it. This helped for those unable to attend, and would be a good addition to the procedure for the future.
- The value in working with multiple operators was to see everyone's different opinions in mapping extents, and different interpretations of the landscape. The varied experience made a more robust product.
- Some operators provided screen shots of how their interpretations were different; others provided written comments with locations or identifiers. Both of these modes of communication were incredibly helpful to the PI in compiling everyone's results into the final products.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- There is a lack of data for Alaska (e.g., limited high-resolution optical imagery, no lidar of the study area). This made mapping some of the rock glaciers in the study area difficult due to snow cover, cloud cover, or shadows.
- The biggest problem with outlining the rock glaciers was determining their connection with the upslope source area.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- There were not many problems with this step. Some people had more PMs than others; a group discussion resolved this interpretation.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- For the PI, this was the trickiest part, mostly determining which data sets to use. There could be more instructions on the use of InSAR for operators who do not have a lot of experience with this.
- Mostly, the moving areas and their rates had good agreement from the group. There were a few final rates that were modified based on the thorough review of one of the operators.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Our group did not have time at our meetings to discuss these in any detail for this project.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- We had a good discussion of when to draw a straight line on the upslope area of the rock glacier, versus drawing a curved connection to avoid the inclusion of talus cones feeding the rock glacier.
- Another point of discussion was what is the toe of the rock glacier, or what is formed by other mass movement processes like solifluction.
- More examples from different places in the world would be handy for someone doing this for the first time.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- This was the first time the PI used QGIS. It was not too hard to learn, especially since there are a lot of resources online and within the program. The qpkg templates provided were fantastic!
- As previously mentioned, there is a lack of data for Alaska (e.g., limited high-resolution optical imagery, no lidar of the study area). There is a new dataset of high-resolution imagery available from the State of Alaska, for which the PI provided a link halfway through the mapping activity. This helped with the mapping.

Others?

- There could be overall improvement to the InSAR aspects of these mapping exercises. Examining individual wrapped interferograms is a pain. Given the high repeat of Sentinel-1, it can be better to use time series inversion methods with unwrapped interferograms to end up with a nice velocity map that is easily interpretable. Unwrapping brings other issues but overall it could lead to a better and more consistent (maybe?) velocity classification.

Feedback on Multiple Operator RoGI exercise in Central Andes (Argentina)

PI: Lucas Ruiz. **Involved operators:** Rafael Caduff, Diego Cusicanqui, Benjamin Robson, Mishelle Wehbe, Xavier Bodin, Reynald Delaloye, Nicole Schaffer, Laura Zalazar, Daniel Falaschi.

General comments on the consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- Steps and Instructions are easy to follow. Nevertheless, the kinematic assessments, particularly the velocity class attribute, were the step where more deviation between operators was found.
- Although it is always challenging working with multiple operators around the world. We had very constructive meetings after each task, and the operators had the time to review the consensus version.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glaciers in your region, any novel finding?):

- The Central Andes region where we work is a very challenging area. First, it is not a well-known area, so there are not many previous studies to rely on or high spatial-resolution images. Thus, we think it is a perfect example to show the usefulness of the guidelines.
- The very complex rock glacier system with debris-covered glaciers as upper slope units were the most challenging landforms to outline, particularly the upper boundary.
- We agree not to outline rock glacier units within rock glacier systems.
- We found that moving area outlines were helpful in some cases to delimit the upper boundary between rock glaciers and debris-covered glaciers. Also, we use other morphological criteria, like the presence of thermokarst.
- InSAR kinematic information helps us to identify destabilized rock glaciers.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The location and number of Primary Markers identified by operators are challenging for complex rock glacier systems with many rock glacier units. Although most of us could identify the same rock glaciers, some identified more rock glacier units than others in the same rock glacier complex. In the consensus version, we simplify the number of Primary Markers as much as possible.
- During the outlined and filling attribute table, we need to revisit the number and location of the Primary Markers. Thus, in our experience, we would say that it is an iterative process, not only the Primary Markers-Moving Area but also the Primary Markers-outlining.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The velocity class attribute was the step where more deviation between operators was found.
- Although it is explained in detail in the InSAR guidelines, a few more examples showing how and where the fringe cycle approach is used could help novel operators.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The guidelines are clear and easy to follow.
- The kinematic velocity class and time obs. assessment was the most challenging step and where we found the largest discrepancy between operators.
- Also, the stacked interferograms were easier for some analysts to interpret than the wrapped interferograms.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- The guidelines are clear and easy to follow.
- Not all the operators filled the attribute table of reliability of margin delimitation.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- We think the RoGI team has done a very good job creating the QGIS project. It would be great if the protocols or tools used to assess the difference between operators' results were also shared.

- Maybe it could be helpful to other teams and the RoGI to define the best or at least a common way to present the results of the RoGI exercise.

Others?

- -

Feedback on Multiple Operator RoGI exercise in Southern Alps (New Zealand)

PI: Christophe Lambiel. **Involved operators:** Flavius Sirbu, Lea Schmid, Paula Johns, Javiera Carrasco, Thibaut Duvanel, Reynald Delaloye.

General comments on the Consensus-based RoGI process (clarity of the steps and instructions, efficiency of the meeting with operators, value/challenges of involving multiple operators):

- Very clear and useful instructions, thanks!
- We have had 2 meetings with 4-7 people. This number was ideal; more would have been more challenging.

General comments on regional specificities (morphological characteristics of rock glaciers in your subarea, main challenges for inventorying rock glacier in your region, any novel finding?):

- On transitional rock glaciers, the contrast in surface material between the rock glacier surface and the front is generally low, with the latter rarely displaying abundant fine-grained and unweathered material. The angle between the front and the surface is generally smooth. Same characteristics on several active rock glaciers, which is a sign of low activity.
- The lack of contrast is not really a challenge for outlining rock glaciers, but rather for discriminating active from transitional rock glaciers in case of lack of kinematic data.

Comments on the identification of the Primary Markers (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Depends on the background of each operator.
- Depends on the level of expertise, of the training level of the geomorphologic eye. E.g. For discriminating RG from small morainic vallums.
- Depends on the knowledge of the field (already visited or not).
- Available oblique pictures highly useful.

Comments on the delineation and categorization of the Moving Areas (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Outlining of the MA was quite heterogeneous, partly due the general noisy interferograms.
- Very difficult to compare the outlines of the operators; takes too much time.

Comments on characterization of the Morpho-Kinematic Attributes (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Check if the criteria for the reliability of the kinematic attributes are clear enough; at this point this is rather subjective.
- Too difficult, or time-consuming to compare the attributes.

Comments on the delineation of the Rock Glacier Outlines (what did or did not work, what have we learnt, which discrepancies, potential need for refining the guidelines):

- Very homogenous outlines! The major differences were at the upper limit for talus slopes connected RG (i.e. all RG in this study area). I systematically used the topographic map to identify the basis of the talus slope, which the other operators did not do. Therefore, I was generally more generous in the upper extent.
- Problems when exaggerated fronts (blended with the downside talus slope)
- Problems when we use different orthoimages that are not perfectly aligned.
- Strongly depends on the quality of the orthoimage.
- Topographic map and hillshades very useful.

Technical comments on the GIS structure (common QGIS project, qpkq templates, dialog box) and on the data quality/availability (optical imagery, DEM, InSAR data):

- Impeccable!

Others?

- -

Annex 2: Statistics on RoGI products (additional tables)

In relation with Figure 1: Distribution of the rock glaciers identified as certain or uncertain in each RoGI area (consensus-based final results*)*.

	Rock glacier		Uncertain rock glacier		Total
	Number	**%**	**Number**	**%**	**Number**
5.RO	18	62%	11	38%	29
6.CH	30	64%	17	36%	47
7.NO-T	15	37%	26	63%	41
8.NO-F	17	43%	21	53%	38
9.NO-N	18	62%	9	31%	27
10.FR	51	50%	51	50%	102
11.IT	39	75%	13	25%	52
12.GR	29	60%	19	40%	48
13.KA	14	47%	16	53%	30
14.US	14	50%	14	50%	28
15.AR	72	80%	18	20%	90
16.NZ	24	80%	6	20%	30
TOTAL	341	**59%**	221	**40%**	**562**

In relation with Figure 2: Distribution of the velocity classes of the InSAR-based moving areas in each RoGI area (consensus-based final results).

	RO	CH	NO-T	NO-F	NO-N	FR	IT	GR	KA	US	AR	NZ
< 1 cm/yr	3	0	5	13	3	0	7	1	0	0	0	0
1-3 cm/yr	12	7	10	9	5	13	15	12	1	6	2	6
3-10 cm/yr	3	4	6	4	7	19	22	6	7	14	8	5
10-30 cm/yr	0	13	7	8	11	15	17	14	22	11	12	10
30-100 cm/yr	0	8	10	3	3	18	12	8	17	10	26	0
> 100 cm/yr	0	5	5	0	0	7	4	3	1	2	12	0
Undefined	0	0	0	0	0	0	0	1	0	2	13	0

In relation with Figure 3: Reliability estimates of the final (consensus-based) moving areas files.

	RO	CH	NO-T	NO-F	NO-N	FR	IT	GR	KA	US	AR	NZ
Low	1	11	0	8	5	1	0	21	47	na	7	0
Medium	8	21	18	16	16	16	15	19	0	na	6	7
High	9	5	25	13	8	55	62	5	1	na	60	14

In relation with Figure 4: Degree of agreement between the individual operators and the final consensus-based products for three essential attributes (upslope connection, kinematic and activity).

	Upslope Connection	**Kinematic Attribute**	**Activity**	**# Comparable RGU**
5.RO	84%	91%	94%	14
6.CH	88%	96%	57%	20
7.NO-T	29%	78%	68%	15
8.NO-F	56%	50%	53%	11

9.NO-N	86%	74%	79%	18
10.FR	56%	68%	42%	30
11.IT	56%	92%	70%	30
12.GR	61%	60%	61%	26
13.KA	45%	95%	70%	14
14.US	40%	90%	70%	9
15.AR	64%	70%	53%	46
16.NZ	92%	90%	81%	16
TOTAL	63%	66%	79%	249

In relation with Figure 5: Selected examples showing the variability of surface of the mapped rock glaciers between operators (within the extended outlines).

	Op1	**Op2**	**Op3**	**Op4**	**Op5**	**Op6**	**C-B (km²)**
5.RO	-0.40	0.00	0.27	0.00	na	na	1.19
6.CH	-0.41	0.02	na	na	na	na	0.94
7.NO-T	-0.22	0.36	-0.28	-0.11	-0.09	na	1.12
8.NO-F	-0.08	0.01	0.31	-0.11	0.05	na	0.83
9.NO-N	0.07	0.13	-0.02	0.34	-0.07	0.08	0.72
10.FR	0.02	-0.18	-0.16	na	na	na	1.70
11.IT	-0.18	0.04	0.06	0.01	-0.20	-0.03	1.78
12.GR	-0.29	-0.58	-0.28	0.15	-0.30	na	6.50
13.KA	0.00	0.12	0.45	-0.15	-0.14	na	4.88
14.US	0.14	0.08	0.62	0.62	0.99	na	0.95
15.AR	na	na	na	na	na	na	na
16.NZ	-0.01	-0.19	na	na	na	na	0.63