permafrost
cci

CCI+ PHASE 2
PERMAFROST

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

D2.3 End-to-End ECV Uncertainty Budget (E3UB)

VERSION 2.0

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Executive summary

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

In periglacial mountain environments, permafrost occurrence is patchy, and the preservation of permafrost is controlled by site-specific conditions, which require the development of dedicated products as a complement to GT and ALT measurements and permafrost models. Rock glaciers are the best visual expression of the creep of mountain permafrost and constitute an essential geomorphological heritage of the mountain periglacial landscape. Their dynamics are largely influenced by climatic factors. There is increasing evidence that the interannual variations of the rock glacier creep rates are influenced by changing permafrost temperature, making RGV a key parameter 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) Standing Committee 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 End-to-End ECV Uncertainty Budget (E3UB) documents the sources of errors and uncertainties for the Permafrost_cci Phase 2 RoGI and RGV products. We focus on discussing the sources of errors and uncertainties using Synthetic Aperture Radar Interferometry (InSAR), defined in the PVASR and ATBD as the main technique to retrieve the required products. Methodologies to estimate uncertainties and report the accuracy are presented for both products. This is an updated version (version 2.0) including minor corrections and updates.

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), described in the PSD [RD-1]. The End-to-End ECV Uncertainty Budget (E3UB) documents the error sources and uncertainties of the products, generated with the processing lines described in the ATBD.

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 documents the sources of errors and uncertainties affecting the products. Section 3 describes the methodology to estimate uncertainties. Section 4 summarizes which accuracy will be reported in the final products. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 5.1. A list of acronyms is provided in Section 5.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-18].

1.3 Applicable documents

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

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

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

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

1.4 Reference Documents

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

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

[RD-3] Delaloye, R., Barboux, C., Bodin, X., Brenning, A., Hartl, L., Hu, Y., Ikeda, A., Kaufmann, V., Kellerer-Pirklbauer, A., Lambiel, C., Liu, L., Marcer, M., Rick, B., Scotti, R., Takadema, H., Trombotto Liaudat, D., Vivero, S., Winterberger, M. 2018. Rock glacier inventories and kinematics: a new IPA Action Group. Proceedings of the 5th European Conference on Permafrost (EUCOP), Chamonix, 23 June – 1st July 2018.

[RD-4] 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-5] 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-6] 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-7] RGIK. 2023. Guidelines for inventorying rock glaciers: baseline and practical concepts (version 1.0). IPA Action Group Rock Glacier Inventories and Kinematics, 25 pp. https://doi.org/10.51363/unifr.srr.2023.002.

[RD-8] 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-9] RGIK 2022. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.1). IPA Action Group Rock glacier inventories and kinematics, 12 pp.

[RD-10] 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-11] RGIK 2023. Instructions of the RoGI exercise in the Goms Valley (Switzerland). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

[RD-12] 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-13] Sirbu, F., Onaca, A., Poncos, V., Strozzi, T., Bartsch, A. 2022. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2. Rock Glacier Kinematics in the Carpathians (CCN1 Budget Extension). Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.

[RD-14] 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-15] 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-16] Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Kääb, A., Kaufmann, V., Thibert, E., Vivero, S. and A. Kellerer-Pirklbauer. 2023. Rock Glacier Velocity. In Bull. Amer. Soc. Vol. 105(8), State of the Climate in 2023, pp. 44–45. https://doi.org/10.1175/2024BAMSStateoftheClimate.1

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

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

2 Sources of errors and uncertainties

2.1 Rock glacier inventory (RoGI)

Generic sources of error and uncertainties when producing rock glacier inventories are discussed in the PVASR in terms of identified challenges for standardization and risk of discrepancies between RoGI operators. These elements are summarized here in *Table 1*.

Table 1. *Identified challenges for RoGI standardization and risk of discrepancies between operators.*

Identification and outlines		
Discriminate rock glaciers from other landforms	URq_03	With limited mapping experience and/or without knowing the environmental context, some landforms may express rock glacier-like morphology (e.g., solifluction lobe, earth flow, moraine and lava flow), leading to inconsistent mapping.
Minimum size of inventoried rock glaciers	URq_03	The minimal detectable size varies according to the input data and technical limitations. It also depends on the purpose and scale of the inventory.
Rock glacier outlines	URq_03	Technically, defining a rock glacier as a landform implies an outlining step, and for various practical issues (e.g., area calculation) it has to be a closed polygon. However, this operation retains some degree of subjectivity, in particular regarding the upper limit of the rock glacier.
Geomorphological characteristics		
Rock glacier morphological system and units	URq_04	Rock glaciers with complex morphology (e.g., multiple generations, multiple lobes, coalescent lobes, and heterogeneous dynamics) are common and difficult to characterize unequivocally. The variable spatial resolution and quality of input data may lead to discrepancies in the definition of the morphological system and units.
Spatial connection of the rock glacier to the upslope unit	URq_04	The geomorphological unit located directly upslope of a rock glacier system can hold implications on the characterization of the latter (e.g., internal structure and composition, ice origin, ice content), as well as the characterization of the attributes and the outlines. However, without information on the subground composition, we should avoid using terminology that implies an interpretation on the origin of both the debris and the ice.
Time frame and update	URq_02 and URq_05	Different times of production of rock glacier inventories (observation time window and time frame) can lead to products that are not fully comparable. Updates are recommended.
Kinematics and activity		
Identification and delineation of moving area (MA)	URq_08	The level of details varies depending on the operator. Isolated movement or unreliable areas can lead to an unrepresentative MA delineation. The amount and quality of the kinematic data vary from one region to another. The definition of uniformity or spatial consistency of the movement is partly subjective. The detected signal can be related to different processes, not only permafrost creep.
Velocity classes of moving area (MA)	URq_08 and URq_10	The detection capability and the dimensionality (1D to 3D displacement measurements) depend on the technology. The procedure to classify the MA velocity varies depending on the measurement technique. Using 1D InSAR data, the downslope velocity can be significantly underestimated if the movement direction strongly deviates from the line-of-sight. The reliability (degree of confidence) needs to be documented. The velocity class attribution is partly subjective, especially when the detected movement is close to the limit between two classes.
Semi-quantitative	URq_09	There is a subjectivity involved in the choice of a KA category (order of

categories of kinematic attribute (KA)	and URq_10	magnitude). The use of absolute velocity values would be valuable but problematic to include and compare measurements from different techniques. An order of magnitude estimate is enough to be used to assess the activity of a rock glacier unit (as a complement to morphological evidence) but is affected by subjectivity if the detected movement is close to the limit between two categories. There is a risk for subjectivity in the choice of a KA category and thus a need for explicit rules to transfer velocity classes from MAs to a single KA category representative of a rock glacier unit. The reliability (degree of confidence) needs to be documented.
MA/KA temporal representativeness	URq_10	Some techniques allow for the observation of displacement during summer time only, and not from one summer to the next (e.g., short interferograms). In such cases, the velocity value cannot be measured over an annual time interval. Other techniques only allow for the measurement of annual velocity or multi-annual velocity. There is a risk for focusing on unrepresentative kinematic patterns if the measurements are not documented for a variety of time periods and several years/seasons.
MA/KA spatial representativeness	URq_10	Isolated movement, unreliable areas and unrepresentative moving parts can lead to misleading documentation of kinematics. Incomplete coverage can be problematic, e.g., when using single point measurements that are not representative for larger moving areas.
Rock glacier activity	URq_06	Rock glaciers have been most commonly classified into the following categories of activity: intact (active/inactive) and relict. The classical categorization considers the activity rate of rock glaciers as almost constant over the long term (decades to centuries). Observations of the rock glacier kinematical behaviour, in particular in the European Alps, have shown that an acceleration by a factor of 2 to 10 of the surface velocities between the 1980s and the 2010s has been a common feature at many investigated sites, probably in response to increased permafrost temperature resulting from warmer air temperatures. Whereas a significant majority of the monitored rock glaciers follows this regional trend, some features manifest singular behaviour (e.g., reactivation, rapid acceleration, destabilization or decrease in velocity). In cold permafrost regions (e.g. Arctic or high-altitude Andes), rock glaciers with very low creep rate may accelerate in response to warming. These observations have revealed the need for redefining and/or refining the categorization of rock glacier activity.
Rock glacier destabilization	URq_07	The creep rate of some rock glaciers may be characterized by a drastic acceleration that can lead to abnormally fast behaviour (i.e. not following the regional trend anymore) of the landform, or a part of it, for several years. The term “destabilization” has been progressively used since the 2000s to refer to rock glaciers with obvious signals of abnormally fast behaviour.

2.2 Rock glacier velocity (RGV)

Generic sources of error and uncertainties when producing RGV are discussed in the PVASR in terms of identified challenges for standardization and risk of discrepancies when producing RGV. These elements are summarized here in *Table 2*.

Table 2. *Identified challenges for RGV standardization and risk of discrepancies between operators.*

Key criteria for RGV standardization		
Site selection	URq_12	In the context of ECV product generation, the goal is the generation of long-term time series in a climate-oriented perspective. There are various constraints that can prevent the feasibility of long-term monitoring, such as landform constraints (e.g., change in the landform kinematic behaviour, development of large scarps, occurrence of rock falls, instability of surface boulders, ice-melt induced subsidence), technical constraints (e.g., data availability and quality, feasibility of measurements, technological development), practical constraints (e.g., site accessibility, safety, permit for instrumentation) and resources/processing constraints (e.g,. available processing tools, computing power, data property).
Temporal resolution, i.e. observation time window and frequency	URq_13, URq_14 and URq_15	The ideal measurement frequency is once per year. The ideal observation time window is one year with measurement dates/periods that remain approximately the same every year (±15 days). However, depending on the chosen technique and the site characteristics, this may not be possible. Depending on the applied technique, this velocity value might only be obtained for an observation time window shorter than one year (e.g. snow-free summer period for InSAR). The consistency of the series can be affected if the observation time window is modified from one year to another. If we aim for including past data, it might be difficult to require an annual frequency due to data gaps.
Spatial resolution	URq_16 and URq_17	The spatial resolution depends on the measurement resolution of the technique chosen for measuring/computing initial data. It can range from single points or few discrete points to area-based measurements. The spatial representativeness of a selected point or area on a rock glacier is challenging to assess. Considerations from *Table 1* also apply.
RGV quality: relative error	URq_18	The error sources and measurement accuracy vary depending on the specificities of the sensor/platform and the algorithm used in the data processing. Depending on the observed velocity, different techniques can be better suited than others. The challenge is to provide a meaningful indicator of the measurement quality while fulfilling generic technique-independent requirements.
RGV quality: consistency	URq_19	During specific years or at specific locations, changes in the constraints controlling the initial data acquisition and the feasibility of long-term monitoring may occur and potentially affect the RGV consistency. The velocity value is an annualized displacement rate derived from methodologies allowing either for displacement measurement (Eulerian, see *Table 3–4* in the PVASR, i.e. from an area with constant coordinates, e.g., InSAR) or for position measurements (Lagrangian, see *Table 3–4* in the PVASR, i.e. from moving positions, e.g., GNSS). Long-term consistency may be endangered in the case of Eulerian measurements, as the location of the measurement is constant over time whereas the creeping mass is moving. In the case of Lagrangian measurements, the consistency may be endangered as the location is moving over time and the creeping mass may be subject to change of topography.

In addition, several specific error sources and uncertainties must be considered when using InSAR for measuring ground displacements. They are well documented in reference InSAR literature (e.g. Massonnet and Feigl, 1998; Bamler and Hartl, 1998; Rosen et al., 2000; Rocca et al., 2000; Hanssen, 2001; Kampes, 2006; Ferretti, 2014). With the specific objective to generate RGV products, the following elements are important to consider (see also Strozzi et al., 2020; [RD-8] and ATBD Annex 2: InSAR guidelines):

- **Spatial resolution:** When extracting velocity time series for defined coordinates, we must always remember that the extracted "points" actually refer to a *pixel* with a specific footprint. The spatial resolution of the SAR images varies according to the sensor (and its acquisition mode). The initial SAR data have a different resolution in azimuth and range direction. The initial ground resolution of the main inputs of the project (Sentinel-1 Interferometric Wide swath mode) is approx. 5 m (range) x 20 m (azimuth). The final resolution used for delineating moving areas is about 15–20 m, or 30–40 m, depending on the *multi-looking* factors (averaging looks to provide a better signal quality). If the velocity of a rock glacier is heterogeneous, InSAR may smooth the results in an unrealistic way and small areas affected by high velocity can be missed by averaging.

- **Geometrical distortions:** In mountainous areas, SAR images are affected by *geometrical distortions* due to the side-looking geometry of the satellite. *Foreshortening* appears on the slopes facing the radar, resulting in compressed pixels on the ground. The opposite effect gives better resolution on slopes facing away from the radar. For steep-looking spaceborne radar systems, the slant range differences between two points located on foreslopes of mountains are smaller than they would be in flat areas. In the extreme case, *layover* appears when the top of a hill is closer to the radar than the foot of the hill. In this case, the received signal from at least two different altitudes is added into one slant range resolution cell, leading to an ambiguous and very high radar amplitude return. On the other side of the mountain, *shadow* occurs in the area not being illuminated by the radar. Both layover/shadow areas cannot be documented when using a single geometry, but this limitation can be overcome by using different geometries.

- **One-dimensional measurements:** The analysis of phase changes between two acquisitions at two different times can provide information about ground deformation along the *line-of-sight (LOS)* of the SAR sensor. InSAR is only sensitive to displacements that have a component in the LOS direction, which depends on the flying orientation of the satellite (track) and the incidence angle of the radar beam. Steeper incidence angles lead to better sensitivity to vertical displacements. Looking toward the West, a descending orbit gives mainly non-distorted coverage in west-facing slope, and an ascending orbit covers mainly east-facing slopes. Sensitivity is very low in cases where the actual surface displacement vector is near perpendicular to the LOS. Due to the polar orbit direction, the sensitivity to horizontal displacement in the North-South plane is near zero. The underestimation of the velocity is not necessarily a problem when studying interannual relative changes of rock glacier velocity. However, if the detected velocity is too low, the relative error of the measurements can rise above an acceptable threshold (see Section 3).

- **Relative measurements:** InSAR is a relative geodetic measurement method. The InSAR velocity measurements are relative to a chosen area (reference or calibration point). Usually, the operator choses a point assumed to be stable. However, if this assumption is wrong, the velocity may be shifted. When the objective is to document the interannual changes of velocity, this is especially a problem if the movement at the reference point is nonlinear (variable in time) as it may differently affect each interferogram (and thus the relative changes in the time series). Several methods can be used to ensure the selection of a good reference point: rely on complementary measurements (e.g., GNSS-based station), use geomorphological criteria (e.g. identify stable bedrock outcrop) and/or apply an iterative approach (test several reference points and compare the results).

- **InSAR coherence and decorrelation:** The phase accuracy in SAR interferometry is affected by noise and decorrelation. Phase decorrelation is due to changes in position of individual scatterers within the resolution cell and is one of the main limitations for successful use of InSAR. Decorrelation is mainly due to either SAR imaging geometric effects (*spatial decorrelation*), or temporal backscattering changes (*temporal decorrelation*). Spatial decorrelation is related to the spatial baseline between the sensor at the different acquisitions. Temporal decorrelation is due to changes in geometrical or electrical properties of the surface, as a function of time between the acquisitions. The interferometric SAR signal will decorrelate when the variability within a pixel is higher than half the wavelength during the selected time interval. This variability may be caused for instance by moving parts of the vegetation or changes of the land surface. Terrain containing variable liquid water, such as areas covered with wet snow, will also have different scattering properties from one observation to the next. The scenes acquired during the winter season can be unusable if snowfall occurs, which reduces the observation time window in mountainous areas. The temporal decorrelation phenomenon is dependent on the radar wavelength; longer wavelengths are less sensitive to small scale surface scattering changes, but with reduced sensitivity to displacement.

- **Atmospheric effects:** A radar interferometer measures the phase difference with accuracy on the order of a fraction of the wavelength; more than accurate enough to be influenced by *atmospheric path delay*. Phase propagation delay due to atmospheric variability is one of the main error sources in repeat-pass InSAR. It is common to divide the atmospheric path delay into one component coming from *turbulent mixing processes*, and a *stratified component correlating with elevation*. Turbulent mixing comes from mixing processes in the inhomogeneous atmosphere, while stratification results from variations in the vertical refractive index profile. The second is correlated with the local topography. Both can be mitigated during the processing using digital elevation models and spatial-temporal filtering techniques, but unwanted phase components can remain. However, as rock glaciers are relatively small landforms, they highlight a deformation-related phase component at a scale that is easily differentiable from the atmospheric effects.

- **Phase aliasing and unwrapping errors:** A wrapped interferogram is composed of a succession of fringes when the phase exceeds half the wavelength. The process of restoring the correct multiple of 2π to each point of the interferometric phase image, i.e. to convert the cyclic phase difference into a continuous phase difference, is called *phase unwrapping* and can be performed by visual interpretation or automatically. The procedure uses the assumption that the true displacement field of the landform under study has a spatial continuity and thus the spatial variation of the phase is rather smooth. If the movement is spatially discontinuous, for example in the case of a localized quick event, we can fail to retrieve correct solutions. The interferometric SAR signal can become ambiguous when the displacement gradient between adjacent pixels is higher than a quarter of the wavelength during the selected time interval. Areas can be decorrelated due to changes in scattering properties within the resolution cell between the two acquisitions. Such decorrelation effects can contaminate large areas in the interferograms and create discontinuous coherent patches. This makes the retrieval of the absolute phase a challenging task.

3 Methodology to determine uncertainties

3.1 Rock glacier inventory (RoGI)

For each attribute of the rock glacier inventories, the guidelines include possibilities to estimate and document the uncertainty. Several elements, summarized in Section 4.1.1 (*Table 3*), help the operator remaining careful in case of uncertainty when identifying, characterizing, and delineating rock glaciers.

Following the multi-operator consensus-based procedure reported in the ATBD, the RoGI production results in multiple output layers (i.e. Primary Attributes, Moving Areas and Outlines) delivered by each operator in all subareas. The comparison of these results is used to evaluate the variability of the assessment between operators following the approaches published by Brardinoni et al. (2019) and Way et al. (2021). The degree of subjectivity of the procedure is evaluated by documenting the discrepancies between operators (see Section 4.1.2). Examples of results from multiple output layers are shown in *Figures 1–3*.

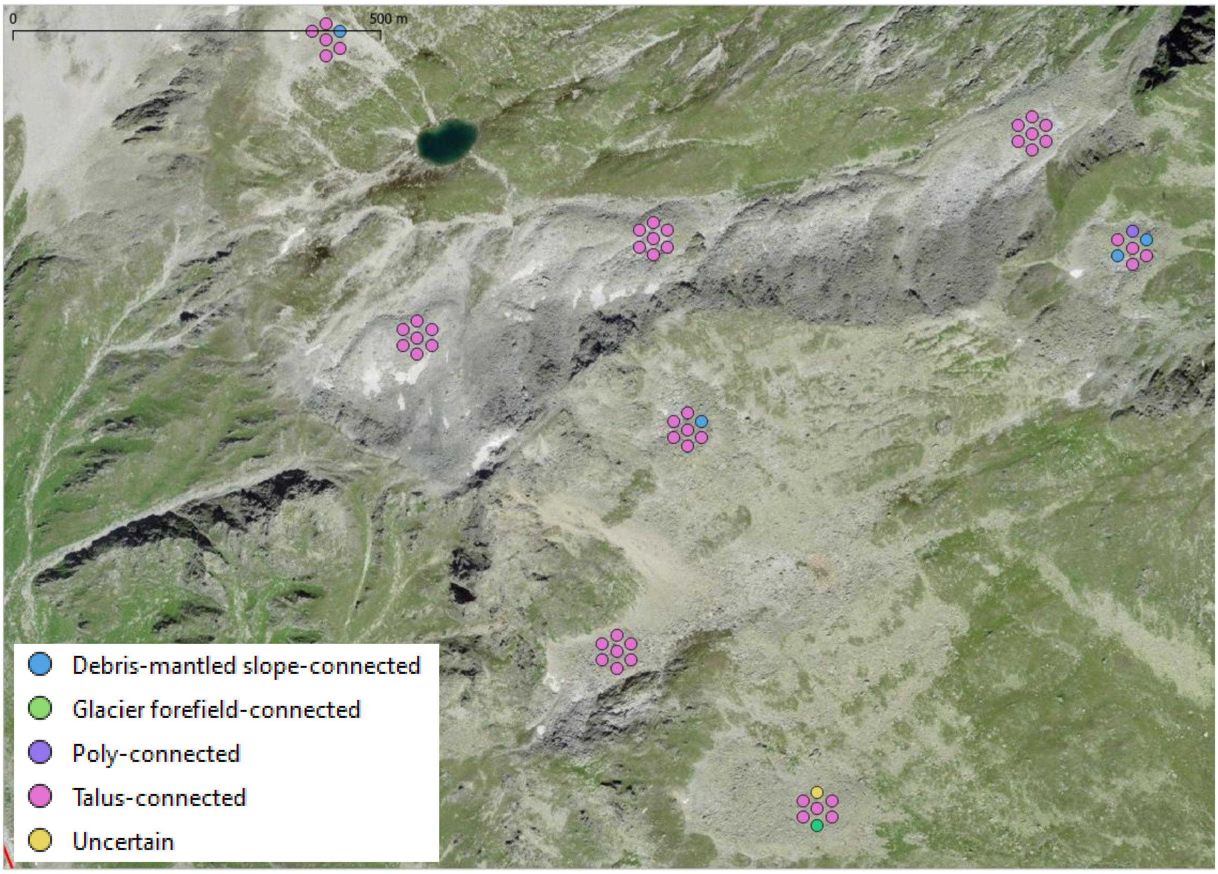

Figure 1. *Examples of discrepancies between 7 operators for the attribute "spatial connection to the upslope unit". In this case, the consensus-based final solution is "talus-connected" for all inventoried rock glaciers. The degree of disagreement varies from 0% (all operators agreed on the attribute) and 43% (3 operators initially gave different solutions).*

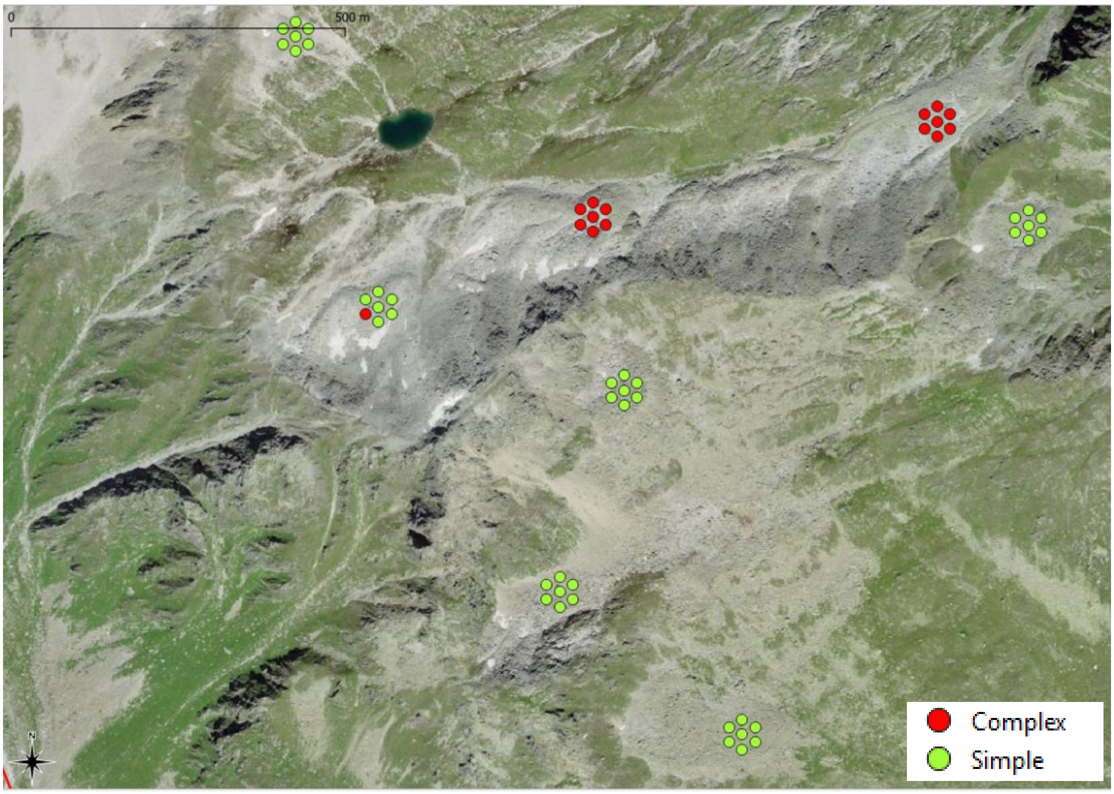

Figure 2. *Example of discrepancies between 7 operators for the attribute "morphology". The degree of disagreement varies from 0% (all operators agreed on the attribute) and 14% (1 operator initially gave a different solution).*

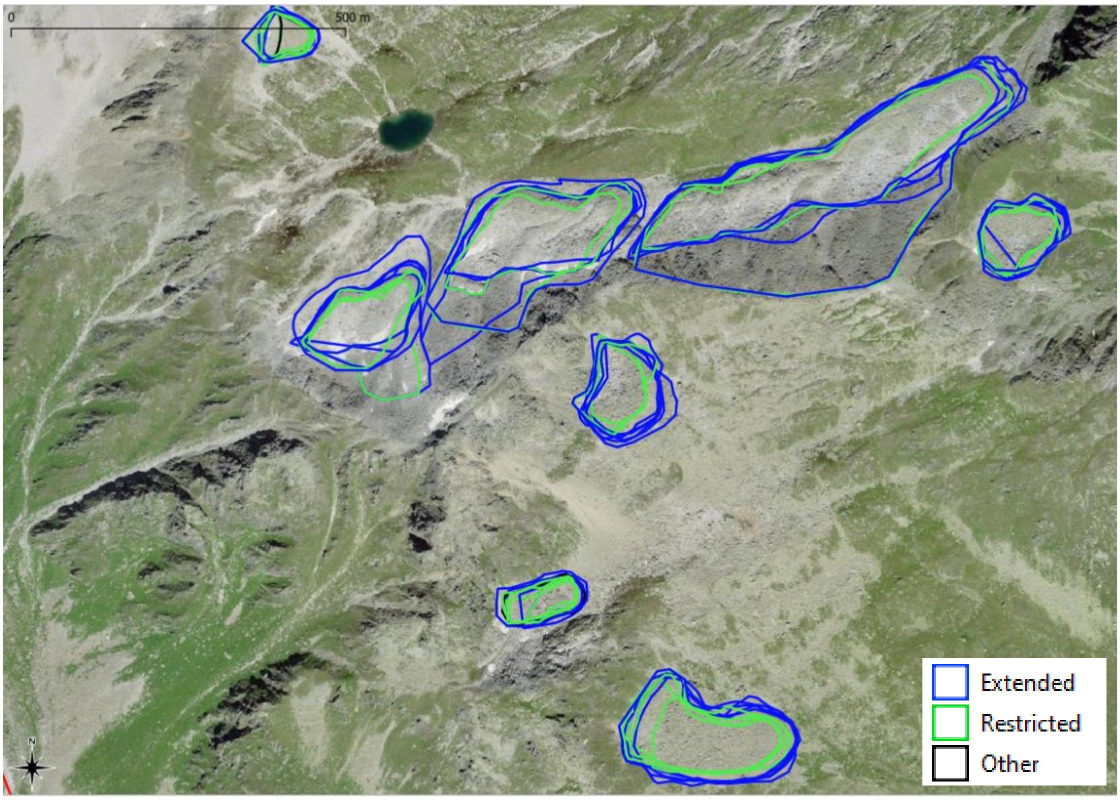

Figure 3. *Example of discrepancies between 7 operators for the rock glacier outlines. Here the degree of disagreement could be quantified by calculating the averaged distance between the outlines of each operator, compared to the final consensus-based solution.*

3.2 Rock glacier velocity (RGV)

There are various approaches to estimate the uncertainty of InSAR measurements, including a formal description of the error terms, the documentation of internal quality measures, the analysis of the interferometric phase on stable ground, the comparison with results from in-situ measurements (e.g., from GNSS) or from other remote sensing techniques:

- **Formal description of error terms:** For single measurements at C-band, an error of 6 to 7 mm, partly attributed to noise (1 to 2 mm) and partly to atmospheric artefacts (5 to 6 mm), was estimated in a major validation project over urban areas (Crosetto et al., 2009), where a similar high degree of coherence over a multiannual period is typically observed as in 6 to 12 days over rock glaciers. This error translates to a LOS measurement uncertainty of ±0.4 m/yr for Sentinel-1 interferograms over six days, ±0.2 m/yr for Sentinel-1 interferograms over 12 days and can go down to a mm accuracy using multi-temporal techniques. A similar phase error of one quarter of a phase cycle due to signal noise and atmospheric artefacts is also observed for X-band (Strozzi et al., 2010). With 11-days TerraSAR-X interferograms, this error corresponds to a measurement uncertainty of ±0.1 m/yr. With L-band sensors, the total phase error is estimated to one eighth of a phase cycle, leading to an equivalent error of ±0.1 m/yr for an 88-days JERS-1 interferogram (Sandwell et al., 2008).

- **Internal quality measure:** An internal quality measure of the interferometric phase is the complex correlation coefficient, or *complex coherence* $|\gamma|$. The $|\gamma|$ values are between 0 and 1, where a coherence value of 1 corresponds to perfect phase correlation between the two measurements. Coherence values under 1 correspond to reduced phase correlation. The phase noise standard deviation as a function of the coherence varies with the applied multi-looking factors (*Figure 4*). The estimate tends to be biased (overestimation of low coherence) with a low multi-looking factor (*Figure 5*). This leads to a trade-off decision: high multi-looking factor improving the signal statistics and the coherence estimate but reducing the spatial resolution (Bamler & Hartl, 1998). An expected error on the measured interferometric phases can estimated using the Cramer Rao bound (Rosen et al., 2000). For each InSAR measurement an error can be estimated. When several interferograms are averaged (stacking), this error can be combined using error propagation.

- **Uncertainty estimates based on velocity variability:** Two additional uncertainty estimates can be documented:
  - Uncertainty estimation based on temporal variability: By considering all measurements within the seasons, the variance and standard deviation can be computed and used as an uncertainty estimate for each pixel.
  - Uncertainty estimation based on the spatial variability: By considering all pixels used in the final spatial aggregation, the variance and standard deviation between pixels can be computed and used as an uncertainty estimate for the full rock glacier.

  It should be noted that spatio-temporal velocity variability is expected on rock glaciers. These metrics are therefore not representing errors; they may also document the natural variability of the landform behaviour. However, large changes of variance and standard deviation from a season to a next may be used as indicator of increasing uncertainty. Processing tests in that direction will be performed during Permafrost_cci Phase 2.

- **Comparison with other measurements:** A quantitative way to determine the uncertainties is to compare the InSAR-measured displacement values with other independent displacement measurements (e.g., in-situ) at the same location. This is done at the validation stage (see PVP). However, several issues complicate the comparison of space-borne and in-situ estimates. Though highly precise, the temporal and spatial representativeness of the in-situ data compared to the area and time covered by the InSAR data vary and is not strictly known. Also, in-situ measurements refer to a single point, whereas image-based measurements represent a larger area. In Permafrost_cci, we aim to document the long-term RGV trend with the objective to develop regional indices to be used as climate change indicators. We are therefore focusing on comparing the interannual relative velocity change (InSAR against GNSS; see PVP). The comparison of displacement fields generated from other independent datasets from different sensors or based on different remote sensing technique (e.g., optical photogrammetry) can also be considered if the coverage and documented periods are overlapping. However, the temporal and spatial properties of the datasets (resolution and observation window) are often different, introducing additional constraints on the validation.

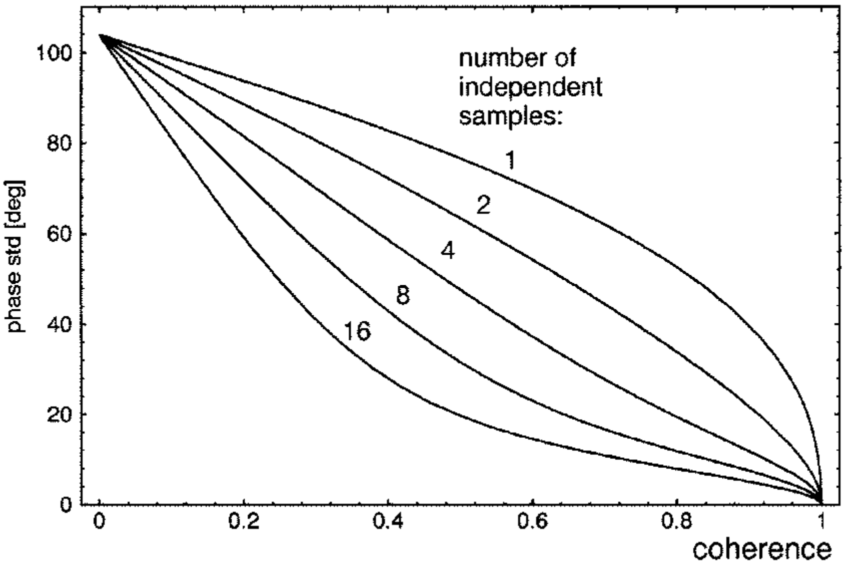

Figure 4. *Interferometric phase dispersion (in degrees) as function of the interferometric coherence for various multi-looking factors (Bamler & Hartl, 1998).*

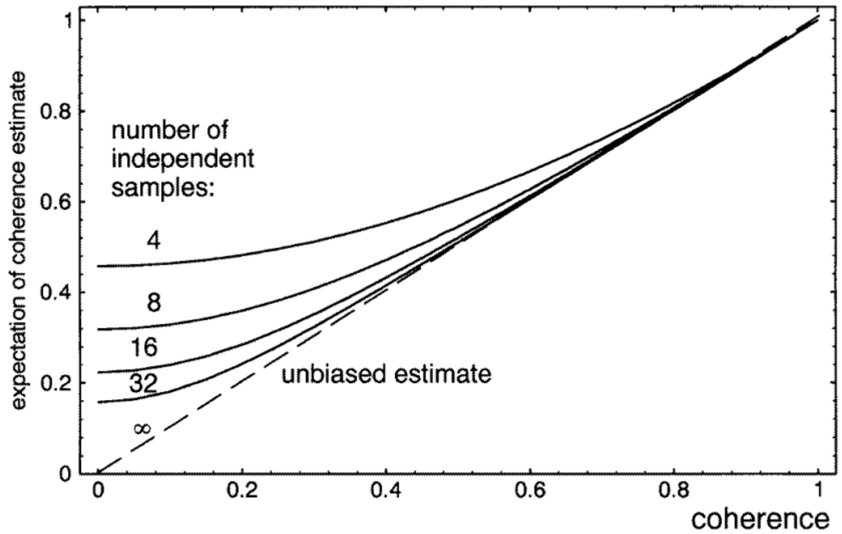

Figure 5. *Bias of the coherence estimate, depending on the multi-looking factor (Bamler & Hartl, 1998).*

4 Accuracy to be reported

4.1 Rock glacier inventory (RoGI)

4.1.1 Uncertainty reported for each individual operator product

For each attribute of the RoGI output layers, the uncertainty can be documented by each single operator. Possibilities for qualifying and documenting uncertainties are summarized in *Table 3*.

Table 3. *Documentation of uncertainties for RoGI products*

<table>
<tr><th colspan="2">Identification and outlines</th></tr>
<tr><td>Discriminate rock glaciers from other landforms</td><td>During the inventorying process, an attribute “uncertain” or “not a rock glacier” can be added to the landforms that are likely to be wrongly interpreted as rock glaciers or to highlight ambiguous areas to be further discussed with other operators (consensus-based approach).</td></tr>
<tr><td>Minimum size of inventoried rock glaciers</td><td>It is recommended that the minimum rock glacier size to be included in a global compilation should be 0.01 km^2. Nevertheless, inventories at higher resolution are encouraged. The minimal size of inventoried rock glaciers may depend on the properties of the input data. The type and spatial resolution of the input data used for identifying rock glaciers must be documented.</td></tr>
<tr><td>Rock glacier outlines</td><td>The recommendation is to identify each rock glacier unit with a point manually positioned on the landform, to be able to identify the location of the unit and discriminate it from other units without ambiguity. Delineating rock glacier boundaries with a closed polygon (extended and restricted geomorphological footprint) is optional. If the delineation is performed, the reliability must be documented for the different locations of the rock glaciers (front, margins, upslope). If the outlines are too uncertain, the inventory must remain at the level of the primary marker.</td></tr>
<tr><th colspan="2">Geomorphological characteristics</th></tr>
<tr><td>Rock glacier morphological system and units</td><td>Recommendations consider complex cases, i.e. composite rock glaciers (multiple lobes). Simple or complex (sub)-units must be characterized.</td></tr>
<tr><td>Spatial connection of the rock glacier to the upslope unit</td><td>Category “Other”: if none of the other categories corresponds to the geomorphological sequence.
Category “Poly-connected”: Two or more upslope connections in case there is no large dominance of one type of upslope connection.</td></tr>
<tr><th colspan="2">Kinematics and activity</th></tr>
<tr><td>Identification and delineation of moving area (MA)</td><td>The reliability (or the degree of confidence) of the moving area must be qualitatively documented in accordance with the quality of both the MA detection and the velocity classification (low, medium, high). “High” defines an evident signal that is easily identified. “Medium” indicates that signal interpretation (velocity estimation) or outlining is uncertain. “Low” indicates that signal interpretation (velocity estimation) and outlining are uncertain.</td></tr>
<tr><td>Velocity classes of moving area (MA)</td><td>The velocity refers to the 1D LOS InSAR measurements performed on back-facing slopes. The velocity class “Undefined” is used if it is possible to delineate a moving area but the velocity cannot be accurately estimated (reliability of input data is too low, North/South-facing slopes for 1D LOS InSAR measurements, etc.). Uncertainty sources are documented in the field “Comments”.</td></tr>
<tr><td>Semi-quantitative categories of kinematic attribute (KA)</td><td>The default category is “Undefined”. The rock glacier unit falls into this category when no (reliable) kinematic information is available, or if the kinematic information is derived from a single point survey that cannot be related to any moving area, or if a dominant part of the rock glacier unit is characterized by a moving area of undefined velocity.</td></tr>
<tr><td>MA/KA temporal representativeness</td><td>Observation time window and temporal frame must be documented.</td></tr>
<tr><td>MA/KA spatial representativeness</td><td>The characterization of kinematic attributes can only be performed when a dominant part of the rock glacier unit is described by reliable moving areas. If the available data is too uncertain or unreliable due to specific technical limitations (e.g. North/South-facing slopes for 1D LOS InSAR</td></tr>
</table>

	measurements, etc.), the category should be left undefined. If moving areas show a large heterogeneity over the unit (e.g., more than three moving areas with velocity classes falling into various categories), the category should be left "Undefined". Minor heterogeneities should be documented (field "Comments") and is one criterion to consider when defining the degree of reliability of the KA.
Rock glacier activity	The default category is *Undefined*. if data are inadequate for discriminating between the activity classes
Rock glacier destabilization	Optional attribute. The attribute remains undefined if data are inadequate to evidence destabilization.

Metadata should include information about satellite scenes (date, path, row, sensor, processing), additional kinematic data (applied techniques, acquisition dates, measured points/areas, accuracy, precision), date, source and spatial resolution of other geospatial data (DEM, orthoimages, topographical/geological maps, etc). Metadata should indicate the data used for assigning the kinematic attribute (data/technique used, dimensionality of the measurement, observation time window, temporal frame). Reliability of the MA delineation and KA assignment (low, medium, high) is documented. The producer and the date of production should be indicated.

4.1.2 Uncertainty reported for the final consensus-based products

The degree of subjectivity of the procedure is evaluated by documenting the discrepancies between operators for the attributes listed above. The uncertainty may be reported as **the degree of disagreement, expressed as the percent of results disagreeing with the consensus-based final decision**. For the moving area and the rock glacier delineation, the averaged distance between the outlines of each operator and the consensus-based final solutions can be calculated.

4.2 Rock glacier velocity (RGV)

The reported uncertainty for RGV has been designed to be technology-independent with the objective to develop generic ECV product requirements applicable to different measurement techniques [AD-2] [AD-3]. The RGV quality is therefore described by the relative error of the RGV values and the consistency of the RGV [RD-8] [RD-9]:

- **Relative error** (*Table 4*): The relative error of the RGV values is defined as the ratio between the absolute error of a measurement, which depends on the technique and the effective observation time window, and the absolute value measured/computed over the same observation time window. The relative error is expressed as a percentage and has no unit. It must be specified for each RGV value. A relative error of maximum 20% is allowed. However, to produce a reliable analysis of long-term temporal changes in rock glacier velocity, the smallest possible relative error should be obtained. Thus, the technique must be chosen in accordance with the absolute value measured/computed on the observed rock glacier.
- **RGV consistency** (*Table 5*): The consistency is defined as the coherence of the time series over time. It depends on the coherence over time of the monitoring technique and the monitored surface. The monitoring technique can for instance be affected by changes in the measurement technique, sensor drift and weaknesses of the aggregation method. The monitored surface can for instance be affected by changes of the observed rock glacier surface geometry, deviations from the expected rock glacier flow/creep model and false measurements caused for instance by landslides, rock fall or rotation. The consistency of the velocity time

series must be evaluated for each addition of new RGV values and must be ensured over time. The technique used to measure/compute the velocity data and compile RGV must be as constant as possible over time. If any major changes are detected, the time series must be adjusted and recomputed accordingly, or stopped.

Table 4. *RGV product requirements in terms of relative error of the RGV value*

Quality	Value	Additional information
Ideal	<5%	Relative error of the RGV value allows a reliable analysis of long-term temporal changes in RGV. The technique is chosen in accordance with the absolute velocity of the rock glacier.
Medium	>5% <20%	Relative error of the RGV value allows a reliable analysis of temporal changes in RGV. Specific attention should be paid in the future, especially if the rock glacier velocity is decreasing. In that case, a change of the measurement technique or its temporal settings should be applied.
Minimum	20%	Maximum allowed relative error of the RGV value to produce an analysis of temporal changes in RGV. If the error exceeds 20%, the site must be discarded, or other techniques should be considered in accordance with the absolute velocity of the rock glacier.

Table 5. *RGV product requirements in terms of consistency of the RGV*

Quality	Value	Additional information
Ideal	High	No adaptation of the processing steps to obtain consistent RGV required. The RGV consistency is ensured with high confidence.
Medium	Medium	Minor adaptation(s) of the processing steps to obtain consistent RGV required. The RGV consistency is ensured with medium confidence.
Minimum	Low	The RGV consistency is not ensured (low confidence) due to either major adaptation(s) of processing steps to obtain consistent RGV or change of the entire monitoring strategy. The RGV must either be recomputed and replaced with adjusted temporal/spatial settings and/or methodologies/procedures or stopped definitively.

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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
FT	Feature Tracking
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
OT	Offset Tracking
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
SfM	Surface from Motion
TR	Threshold Requirement
UAV	Unmanned Aerial Vehicle
UiO	University of Oslo
UniBo	University of Bologna
UNIFR	University of Fribourg
URD	Users Requirement Document
URq	User Requirement
UTM	Universal Transverse Mercator
WUT	West University of Timisoara
WMO	World Meteorological Organization