CCI+ PHASE 2
PERMAFROST

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

D4.2 Product User Guide (PUG)

VERSION 2.1

16 JANUARY 2026

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Document status sheet

Issue	Date	Details	Authors
1.0	15.02.2024	First version CCN4 D4.2	L. Rouyet, T. Echelard, L. Schmid, C. Pellet, R. Delaloye, F. Sirbu, A. Onaca, V. Poncos, F. Brardinoni, A. Kääb, T. Strozzi, A. Bartsch
2.0	15.09.2025	Second version CCN4 D4.2 (iteration 2): Format adjustments after open release of the RoGI products. Changes of RGV data properties after adjustment of the production procedure. Additional minor corrections.	L. Rouyet, C. Pellet, T. Echelard, L. Schmid, R. Delaloye, F. Brardinoni, F. Sirbu, A. Onaca, V. Poncos, T.R. Lauknes, L. Wendt, A. Kääb, T. Strozzi, P. Bernhard, A. Bartsch
2.1	16.01.2026	Updated cover page to ensure it correctly represents the CCN5 contributions and the change of ESA Key Personnel	T. Strozzi and A. Bartsch

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Executive summary

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

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

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

This Product User Guide (PUG) describes the properties of the rock glacier products from the Climate Research Data Package (CRDP) from Permafrost_cci Phase 2 iteration 1 [RD-6] and iteration 2 [RD-7]. We specify the spatio-temporal resolutions and coverages, the formats, the attributes and the known limitations of the RoGI and RGV products.

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 User Guide (PUG) provides to the users the description of the data properties, formats, attributes and known limitations of the mountain permafrost Climate Research Data Package (CRDP) [RD-6] [RD-7].

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 describes the properties of the RoGI products. Section 3 describes the properties of the RGV products. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 4.1. A list of acronyms is provided in Section 4.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-18].

1.3 Applicable documents

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

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

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

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

1.4 Reference Documents

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

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

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

[RD-4] Rouyet, L., Pellet, C., Schmid, L., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Wendt, L., Lauknes, T. R., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2024. ESA

CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.3 End-to-End ECV Uncertainty Budget (E3UB), v2.0. European Space Agency.

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

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

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

[RD-8] Rouyet, L., Pellet, C., Echelard, T., Schmid, L., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Brardinoni, F., Wendt, L., Lauknes, T. R., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2025. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D4.1 Product Validation and Intercomparison Report (PVIR), v2.0. European Space Agency.

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

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

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

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

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

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

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

[RD-16] Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Kaufmann, V., Noetzli, J., Thibert, E., Vivero, S., & Kellerer-Pirklbauer, A. (2024). Rock glacier velocity. In Bull. Amer.

Soc. Vol. 105(8), State of the Climate in 2023, pp. 44–45. https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

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

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

2 Rock glacier inventory (RoGI) products

2.1 Background and terminology

The Rock Glacier Inventory (RoGI) products of the Permafrost_cci Phase 2 iteration 1 have been generated during a multi-operator exercise performed between June and November 2023. The exercise was performed in 12 areas selected in 10 countries and 5 continents (see PSD [RD-2] and CRDP [RD-6]). A Principal Investigator (PI) was designated to coordinate the work in each area. The inventory teams were composed of 5 to 10 operators (incl. the PI). The exercise involved in total 41 persons. The work was performed in similar QGIS projects, with common file structure, background data, and dialog boxes for semi-automatic attribute filling (see ATBD [RD-3]). The inventorying procedure follows up on prior work aiming to reduce discrepancies between different operators and produce homogenous consensus-based RoGI (e.g. Brardinoni et al., 2019; Way et al., 2021). The work was performed in two main phases between June and November 2023:

- Phase 1 (June–Sept. 2023): The operators individually identified Rock Glacier Units (RGUs) with Primary Markers (PMs) and detected potential Moving Areas (MAs) based on Synthetic Aperture Radar Interferometry (InSAR) data. The PI compared the individual results and suggested a final solution. After discussion during an online meeting between operators, consensus-based PM/MA layers were adopted.
- Phase 2 (Sept–Nov. 2023): Based on the consensus-based results from Phase 1, the operators outlined and documented the RGU morpho-kinematics characteristics. The PI compared the results and suggested a final solution. After discussion during a second online meeting between operators, the consensus-based PM layer (incl. attributes) and the Geomorphological Outlines (GO layer) were adopted.

In the CRDP from Permafrost_cci Phase 2 iteration 1 [RD-6], the delivered products included the final consensus-based products (names formatted as described in Section 2.10). The data package comprises three types of files:

- The Primary Markers (PMs), i.e. the points identifying and locating rock glaciers within the 12 areas. “Certain” and “Uncertain” RGUs can be differentiated and landforms that could be misinterpreted as rock glaciers but are not attributed to permafrost creep (e.g. glacial features, solifluction lobes, landslides) have in some cases been highlighted with an extra category “not a rock glacier”. Attributes documenting the morpho-kinematic characteristics of the identified landforms are assigned to each “Certain” RGU.
- The Moving Areas (MAs), i.e. the polygons detected, delineated, and characterized (assignment of a velocity class) using Synthetic Aperture Radar Interferometry (InSAR) data. The MA files were used to categorize the kinematic attribute in the PM files.
- The Geomorphological Outlines (GOs), i.e. the polygons outlining the restricted and/or extended geomorphological footprints of the rock glacier units categorized as “Certain”.

Common instructions for inventorying were delivered to all operators. They are summarised in the ATBD [RD-3] and follow the guidelines defined by the International Community on Rock glacier Inventories and Kinematics (RGIK) [RD-10] [RD-11].

The RoGI production in Permafrost_cci Phase 2 iteration 2 follows the same RoGI guidelines. The CRDP version 2.0 [RD-7] includes new RoGI products that have the same properties and formats as in the previous iteration.

2.2 Input data

Each RoGI folder delivered to the operators included: 1) the subfolder "INSTRUCTIONS" with the documents and links to applicable guidelines; 2) the subfolder "VECTOR" includes the initial GeoPackages (gpkg) templates for digitalizing the PMs, MAs and GOs; 3) the subfolder "INSAR-DATA" including wrapped interferograms from Sentinel-1 (and where available from ALOS, SAOCOM, Cosmo-SkyMed, and/or TerraSAR-X), potential complementary InSAR products processed with alternative methods (e.g. velocity maps from Stacking or Persistent Scatterer Interferometry algorithms), a layer displaying an index to reproject the LOS displacement along the direction of the steepest slope (normalization factor) or a mask highlighting N–S facing slopes where the movement is likely to be underestimated on InSAR data; 4) the QGIS project structuring the available data and in which the operators performed the work. In addition to the InSAR data and initial vector files (gpkg templates), each GIS project incorporates links to Web Map Services (WMS) such as the Google Earth, Bing and ESRI orthoimages. Before delivery to the operators, some PIs have added additional data (high-resolution DEMs-based products and orthophotos available at the PI institutions or from other national/regional mapping services).

2.3 Temporal coverage

Rock glaciers identification (PM points) and outlining (GO polygons) are performed using the most recent optical imagery from Google Earth, Bing and ESRI WMS, potentially complemented by national/regional datasets (additional high-resolution DEMs-based products and orthophotos). The imagery date varies between the areas but was similar within each inventory team.
MA polygons are spatially identified and characterised using InSAR images acquired during the snow-free periods. The velocity class assigned to the MAs is expressed in cm/yr. Sentinel-1 was the primary data source with images between 2016 and 2022. Additional data based on ALOS, SAOCOM, Cosmo-SkyMed and TerraSAR-X SAR sensors were used where/when available.
The kinematic attribute refers to a category of annual velocity, expressed in cm/yr, dm/yr or m/yr. Specific translation rules are followed to derive the rock glacier kinematic attributes from the original velocity classes of the MAs. These rules are defined in the InSAR guidelines [RD-11], also described in the ATBD [RD-3].

2.4 Spatial coverage

The exercise was performed in 12 areas selected in Romania, Switzerland, Norway, France, Italy, Greenland (Danmark), Kazakhstan, Alaska (USA), Argentina and New Zealand (see PSD [RD-2] and CRDP [RD-6]). The size of the studied areas varies between 7 and 82 km^2. As part of iteration 2, RoGI products are generated in 8 additional regions in Switzerland, Italy, Bulgaria, Nepal, Bolivia-Chile, Mongolia, India, Bhutan. The size of the studied areas varies between 188 and 2672 km^2. The InSAR data were clipped to the AOI extent. However, the actual coverage of interpretable InSAR information depends on the signal quality (e.g. low on wet, snow-covered, or vegetated surfaces), as well as on the topography in respect to the sensor viewing geometry. Some areas cannot be documented with InSAR due to low coherence (decorrelation of the interferometric signal), layover or shadow. When the coverage was reduced on specific rock glaciers, the kinematic attribute remained "Undefined".

2.5 Temporal resolution

The temporal resolution of the InSAR data depends on the repeat-pass of the SAR sensor and the time interval used to generate the interferograms. For Sentinel-1, the maximal temporal resolution is 6 days. Fast movements were identified using summer interferograms, using time intervals from 6 days up to several months. Slow movements were identified using annual interferograms computed between two or more consecutive summers.

2.6 Spatial resolution

The recommended minimum size of rock glaciers to be included in a RoGI is about 0.01 km^2 [RD-10]. The primary marker positioning on the rock glacier should avoid, as far as possible, any temporal variation and updating. The point must be located somewhere in the lower half of the rock glacier unit [RD-10]. Optical aerial/satellite images and DEMs were used to morphological interpretation and rock glacier delineation (outlines). The resolution typically varies between < 0.5 m and a couple of meters depending on the data sources used for generating the orthomosaics in the WMS services, and the potential use of additional high-resolution datasets. Moving areas related to the inventoried rock glaciers were outlined primarily based on Sentinel-1 InSAR products (20–40 m final resolution). Additional InSAR products with higher resolution (e.g. 3–10 m final resolution for CosmoSky-Med and TerraSAR-X) were used when available.

2.7 Product accuracy

Permafrost_cci Phase 2 RoGI are produced following a morpho-kinematic approach for which both rock glaciers that are moving and those that are not moving were identified. The movement rates of the active rock glaciers were documented using InSAR, primarily based on the Sentinel-1 SAR satellites. Rock glaciers that are not moving have also been morphologically identified. They are either characterized with a kinematic attribute < cm/yr or remain kinematically undefined, depending on the InSAR signal quality. Minimum detectable displacement rates from Sentinel-1 InSAR are in the order of 1/10 of a wavelength (i.e. around 5–6 mm). For time intervals of 48–6 days, this translates to minimum detectable rates of around 4–34 cm/yr, respectively. Slower displacements can be detected using annual or bi-annual temporal baseline. Maximum detectable displacement is limited by phase coherence loss due to high deformation and are in the order of 1/2 wavelength (i.e. around 2.8 cm) during the time interval used to build the interferograms, i.e. 20–170 cm/yr for time intervals of 48–6 days. For a specific time interval, a movement rate higher than the maximal detectable value appears decorrelated on the interferogram. In this case, a moving area can be drawn but the velocity class remains undefined [RD-11].

The product accuracy is documented according to the Goal Requirement of URq_10 [RD-1]. For the moving areas, the reliability of the detection is qualitatively estimated (low, medium, high) based on the difficulty to interpret the signal and/or delineate the moving area. Similarly, the kinematic attribute of the rock glacier units is documented with low, medium and high categories depending on the quality and the spatial representativeness of the detected MAs. The reliability of the outlines is estimated with a scale from 0 (low) to 2 (high) for each boundary (front, lateral margins and upslope limit), and summed up to give a reliability estimate for the entire landform. The sources of uncertainties are further described in 'Comments' fields. Discussion about product accuracy and uncertainties are further detailed in Rouyet et al. (2025b).

2.8 Product projection system

The Coordinate Reference System (CRS) used for the RoGI products is the World Geodetic System 1984 (WGS84). The coordinates are specified in decimal degrees.

2.9 File format and size

All datasets are provided in a geopackage vector format (.gpkg). The total data volume is 10.2 MB.

2.10 Product file naming convention

ESACCI-<CCI Project>-<Processing Level>_<Data Type>_<Product String>-<Additional Segregator>_<Layer Type>_<Indicative Date>-fv<File version>.gpkg

<CCI Project>
PERMAFROST for Permafrost_cci

<Processing Level>
Indicator (IND)

<Data Type>
This should be structured as: <SENSOR>-<METHOD>
<SENSOR> is the primary remote sensing data source used to document the kinematics, in this case: SENTINEL-1. <METHOD> is the primary method used to process the data, in this case: INSAR.

<Product String>
ROGI, when the product is Rock Glacier Inventory.

<Additional Segregator>
This should be structured as: AREA_<REGION_NUMBER>-<AREA_NUMBER>.
<REGION_NUMBER> follows the same numbering has for Permafrost_cci Phase 1: 5–Carpathians (Romania); 6–Western Alps (Switzerland); 7–Troms (Norway); 8–Finnmark (Norway); 9–Nordenskiöld Land (Svalbard); 10–Vanoise Massif (France); 11–Venosta (Italy); 12–Disko Island (Greenland); 13–Tien Shan (Kazakhstan); 14–Brooks Range (Alaska); 15–Central Andes (Argentina); 16–Southern Alps (New Zealand); 17–Pirin and Rila (Bulgaria); 18–Manaslu (Nepal); 19–Sajama (Bolivia–Chile); 20–Tsengel Khairbkhan (Mongolia); 21–Baralacha La (India); 22–Thana (Bhutan).
<AREA_NUMBER> is a one or more digit(s) number, depending on the area(s) in the region.

<Layer Type>
The individual layers of the vector product are provided as different files. The code of each layer is as followed:

- PM: layer 1, corresponding to the rock glacier primary markers
- MA: layer 2, corresponding to the associated moving areas
- GO: layer 3, corresponding to the geomorphological outlines of the rock glaciers

<Indicative Date>
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. Annual or multi-annual products are represented with YYYY only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (two digits followed by a point and one or more digits).

Example:
ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_ROGI-AREA_6-1_PM_2025-fv01.0.gpkg

2.11 Attributes

For the RGU Primary Markers, the following attributes are documented:

- ID (unique alpha-numerical identifier of the rock glacier unit).
- X and Y coordinates (WGS84 coordinate system).
- Morphological type (simple, complex).
  Additional related attribute: the “Completeness” field defining if the rock glacier is complete visible or not (complete, unclear connection the upslope, truncated front, uncertain).
- Spatial connection to the upslope unit (talus-, debris mantle-, landslide-, glacier-, glacier forefield-, poly-connected, other, uncertain, unknown).
  Additional related attributes: the “Upslope Current” field defining if the rock glacier is currently connected to the upslope unit or not, and a “Comment” field to further describe morphological characteristics.
- Kinematic attribute (< cm/yr, cm/yr, cm/yr to dm/yr, dm/yr, dm/yr to m/yr, m/yr, > m/yr, undefined).
  Additional related attributes: the “Type of Data” field to define the type of data used to assign the kinematic attribute (Optical, Radar, Lidar, Geodetic, Other), the “Kinematic Period” field to document the applicable period of the kinematic attribute (year(s) with available data), the Reliability of the kinematic attribute (low, medium, high, undefined) and a specific “Comment” field to further document the applied method and the data quality.
- Activity (active, active uncertain, transitional, transitional uncertain, relict, relict uncertain, uncertain) and the “Activity Assessment” field documenting how the activity has been assessed (morphological evidence only or with kinematic data).
- Destabilization signs (yes - ongoing, yes - completed, no, undefined).

For the Moving Areas, the following attributes are documented:

- ID (unique alpha-numerical identifier of the moving area)
- Velocity class (< 1 cm/yr, 1–3 cm/yr, 3–10 cm/yr, 10–30 cm/yr, 30–100 m/yr, > 100 cm/yr).
- Time observation window (text documenting the time window when the detection and characterization of the moving area has been performed).
- Reliability of the detected moving area (low, medium, high).
- Additional comments.

For the Geomorphological Outlines, the following attributes are documented:

- ID (unique alpha-numerical identifier of the outline).
- Outline type (extended, restricted, other).
- Reliability of the front, the left margin, the right margin, and upslope limit (2 – high, 1 – medium, 0 – low) and Reliability Index (automatic summation of the values assigned to the reliability attributes of these four different boundaries).
- Additional comments.

Each attribute was explained into detail in the instructions of the RoGI exercise (incl. references to the applicable sections of the RGIK guidelines). These explanations are also reported in the ATBD [RD-3].

2.12 Metadata

Building on the PUG, a metadata file is available in the Zenodo data repository (Rouyet et al., 2025a) and in the associated data description paper published in Earth System Science Data (ESSD) (Rouyet et al., 2025b). The metadata includes information about the type and properties of the input data: the orthoimages, the DEMs and the SAR satellite scenes used for InSAR analysis: The name of the PI and the reference time period of the RoGI production are reported. References to be cited, acknowledgments and any other important metainformation are mentioned.

2.13 Known limitations

The quality of the data sources has an obvious impact on the quality of the final RoGI products. For the geomorphological characterization of the rock glaciers, the variable availability and quality of the optical and topographical data led to different levels of details and uncertainties between the 12 selected areas.

A similar observation applies to the InSAR interpretation. In some areas (e.g. extra-European), only 12-days Sentinel-1 repeat-pass is available in the archive. The availability of InSAR data based on complementary SAR sensors or alternative processing algorithms also varies from area to area. The fewer the variety of available InSAR data with complementary coverages, detection capabilities and resolutions, the higher the uncertainty of the moving area delineation and characterisation. In general, slow movements were investigated mainly using annual interferograms. However, using long-time intervals, the quality of the single wrapped interferograms gets sometimes lower, due to loss of phase coherence. The number of suitable interannual interferograms is generally lower than the number of suitable interferograms with shorter time intervals. Slow movements are therefore more complicated to analyse, and the MA reliability is consequently lower. However, for some areas characterized by slow-moving features (e.g. Carpathians in Romania and Finmark in Norway), additional InSAR data more suitable for low velocity (e.g. processed with PSI) were delivered to the operators to overcome this issue.

Many operators took part to the exercise (in total 41 persons). All have different backgrounds and variable experience in inventorying rock glaciers and working with InSAR data. This diversity is positive when applying a consensus-based approach but is also challenging to provide a homogenous dataset and systematically analyse the results (individual files against the final products). In many cases, the individual results are partial: some operators did not dare to assess elements for which they had weaker experience, or they had not enough time to do all the steps. The reliability fields are highly subjective and the way to assess this attribute varies from an operator to an operator. However, in the final product, this limitation is overcome by systematic documentation by the PI and good commenting in the remark fields. The final reliability assessment is consistent within each RoGI.

The InSAR interpretation (MA and resulting kinematic assessment in the PM attribute table) was the most challenging step according to all the PIs of the exercise. Suggestions to solve that issue are discussed in Rouyet et al. (2025b). For other inventorying steps and attribute characterisation, the multi-operator exercise allowed to identify elements that need to be better explained and exemplified in the guidelines (e.g. how to draw the upper outline, difference between “Uncertain” and “Unknown” upslope connection, relevance and applicability of the “Upslope Current” field). Minor technical things must also be fixed in the file/project templates (e.g. intuitive order of the attributes, unambiguous standard layer colours).

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 limited the intercomparison possibilities of all operator files. These errors were fixed for the final products, which have been openly released (see Section 2.14).

2.14 Product version and data dissemination

The RoGI products from Permafrost_cci phase 2 iteration 1 have been openly released in the Zenodo data repository (Rouyet et al., 2025a; https://doi.org/10.5281/zenodo.14501398). An associated data description paper has been published in Earth System Science Data (ESSD) (Rouyet et al., 2025b; https://doi.org/10.5194/essd-17-4125-2025).

The preliminary RoGI results in the new regions of Permafrost_cci Phase 2 iteration 2 have been delivered in May 2025 [RD-7]. The products are being finalized and will be published separately by each inventorying team, before to be compiled in the upcoming RGIK RoGI database.

3 Rock glacier velocity (RGV) products

3.1 Background and terminology

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

The development of InSAR-based RGV products has been performed in synergy with the M.Sc. study of Lea Schmid at the University of Fribourg (UNIFR) (Schmid, 2024). After a pilot stage (Permafrost_cci Phase 2 iteration 1), the InSAR procedure has been adjusted and tested on a large number of rock glaciers (Permafrost_cci Phase 2 iteration 2).

3.2 Input data

Sentinel-1 Single-Look Complex (SLC) SAR images in Interferometric Wide (IW) swath mode have been processed to generate interferograms with a 6–12 days temporal baseline between July and October. The numbers of selected interferograms varies between years (6–19) but always cover the different months (early to late season). The observation time window is therefore consistent.

3.3 Temporal coverage

Using Sentinel-1 12-days temporal baselines, 2015–2024 (10 years) years have been processed. Using Sentinel-1 6-days temporal baselines, the temporal coverage is reduced to 2017–2021 (5 years). All time series are within the Breakground Requirement of URq_15 (5–10 years) [RD-1].

3.4 Spatial coverage

The RGV product represents the InSAR flow field over one or more area(s) representing the downslope movement of a rock glacier unit (Goal Requirement of URq_17 [RD-1]). Velocity time series are produced for several pixels across the Permafrost_cci sites to document the variability of the velocity patterns, evaluate these differences and potentially divide the landforms in areas affected by different kinematics. The final time series either correspond to selected pixel(s) assumed to be representative of the landform behaviour, or to a spatially averaged velocity based on a group of pixels. For each site, the selected pixel(s) and/or the aggregation procedure (e.g. size and location of the considered area(s), number of pixels used to average the time series) are documented and remain consistent over time.

3.5 Temporal resolution

The initial velocity data is based on Sentinel-1 InSAR time series with a 6–12 days frequency collected during snow-free periods for the years 2015–2024 (observation time window < 1 year but covering at least one month). The velocity data is then annualised, following the URq_13 Goal

Requirement [RD-1]. The observation time window is at least one month (between June–October), following the URq_14 Breakthrough Requirement [RD-1]. The chosen period is documented and consistent throughout the entire time series for each site (max. ±15 days of difference), as required by URq_14 [RD-1].

3.6 Spatial resolution

Sentinel-1 InSAR data used for RGV production has a 25 m resolution. The final products correspond several selected pixel(s), provided separately and/or averaged spatially, as described in Section 3.4.

3.7 Product accuracy

Based on a single interferogram procedure, the expected accuracy of Sentinel-1 InSAR is 6 to 7 mm for each measurement (Strozzi et al., 2020). The accuracy can go down to a mm accuracy using multi-temporal InSAR, but these techniques are mostly applicable for slow-moving landforms. The accuracy is expected to have a relative error lower or equal to 10%, correspond to the Breakthrough Requirement of URq_18 [RD-1].

3.8 Product projection system

The Coordinate Reference System (CRS) used for the RGV products is the World Geodetic System 1984 (WGS84). The coordinates are specified in decimal degrees.

3.9 File format and size

All datasets are provided in comma-separated values (.csv) format. The data volume is 587 MB.

3.10 Product file naming convention

ESACCI-<CCI Project>-<Processing Level>_<Data Type>_<Product String>-<Additional Segregator>_<Indicative Date>-fv<File version>.csv

<CCI Project>
PERMAFROST for permafrost_cci

<Processing Level>
Indicator (IND)

<Data Type>
This should be structured as: <SENSOR>-<METHOD>
<SENSOR> is the primary remote sensing data source used to document the kinematics, in this case: SENTINEL-1. <METHOD> is the primary method used to process the data, in this case: INSAR.

<Product String>
RGV, when the product is Rock Glacier Velocity.

<Additional Segregator>
This should be structured as: <COUNTRY_CODE>-<SITE_NAME>.
<COUNTRY_CODE> currently includes: CH–Switzerland; FR-France; IT–Italy.
<SITE_NAME> currently includes: Bru; Distelhorn; GrossesGufer; Réchy; Steintälli; Laurichard; GranSometta; LaThuile; Lazaun; Luseney; Moline; MonteEmiliusRange1; MonteEmiliusRange2;

NorthArpignan; Rhemes; Similaun; ValGrisenche2; ValGrisenche3; Valnontey; Valsavaranche1; Valavaranche3.

<Indicative Date>
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. Annual products are represented with YYYY only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (two digits followed by a point and one or more digits).

Example:
ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_RGV_CH-Diestelhorn_2025-fv01.1.csv

3.11 Attributes

For each RGV time series the following attributes are documented:

- ID (unique alpha-numerical identifier of the RGV time series).
- Reference ID of the related rock glacier unit (when a RoGI is available).
- Data and technique used (description of the platform, sensor type and processing approach).
- Area considered for RGV processing (area-based, several discrete points, three discrete points or one single discrete point, and related specifications).
- Start date (date of first observation).
- Velocity data (computed RGV data in m/yr).

For each velocity data (each annual increment of the time series), the following attributes are documented:

- ID (unique alpha-numerical identifier of the RGV data).
- Reference ID of the related RGV time series.
- Start date (start date of the observation time window).
- End date (end date of the observation time window).
- Base data (data/platform/sensor used for the data acquisition).
- Velocity data (computed RGV data in m/yr).
- Relative error of the velocity data (ideal: < 5%, medium: 5–20%, minimal: 20%).
- Consistency of the RGV time series (ideal: no problem with newly added velocity data, medium: problems with newly added velocity data but no major change of procedure, high: problems with newly added velocity data and major change of procedure).
- Comments (documentation of any changes or specific aspect of the data production worth archiving and relevant for the data analysis and usage).

3.12 Metadata

For each RGV, a separate documentation file is provided, building on the PUG. Each file indicates the data and methodology used for deriving the RGV time series, as well as additional information regarding the observation time window, the temporal and horizontal resolution, and the spatio-temporal aggregation procedure applied to provide the RGV. The producer and the date of production are indicated in the metadata file.

3.13 Known limitations

In the first iteration of Permafrost_cci Phase 2, we showed that the proposed procedure was promising, and that the InSAR-RGV pilot products were overall consistent with similar GNSS-RGV products at the same sites. However, the few selected sites and the short overlapping periods between InSAR and GNSS measurements made it challenging to draw any definitive conclusion.

In the second iteration of Permafrost_cci Phase 2, RGV production was tested on a larger number of rock glaciers in the Alps (21 sites). The Product Validation and Intercomparison Report (PVIR) [RD-8] discusses the identified limitations. The regional comparison show that the InSAR-RGV results highlight overall similar trend comparable with GNSS-RGV. However, the InSAR results show a variable level of quality depending on the site. Many selected areas are too fast to ensure good coherence. The high spatial heterogeneity of the signal also increases the risk of unwrapping errors that can significantly bias the results in fast-moving areas and fast-moving periods. The years with only 12d of Sentinel-1 (2015-2016 and 2022-2024) are even more vulnerable to this issue. For this reason, the expected 2015 velocity peak (based on GNSS data) is often not detected due to 12d repeat-pass and too high velocity. Due to identified unwrapping problems for many sites, a spatial aggregation approach (averaging many pixels over the rock glacier) was not always feasible. In such cases, the InSAR-RGV products consist of documenting velocity changes for a few selected pixels over the rock glaciers. Remaining open questions on spatial representativeness need to be solved in the future, which might lead to an adjustment of the procedure. The impact of the observation time window used for seasonal averaging also remains unclear. For rock glaciers with very strong seasonal variations, the temporal criteria to average the results to get the yearly velocity might be of high significance.

3.14 Product versions and data dissemination

The CRDP from Permafrost_cci Phase 2 iteration 2 [RD-7] has been delivered in May 2025. The data package is not openly released yet. The production is still ongoing to include a larger number of rock glaciers. Based on the latest conclusions of the product validation and intercomparison (see PVIR), the procedure for RGV generation might still be adjusted, which will lead to a new update of the CRDP and PUG.

4 References

4.1 Bibliography

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4.2 Acronyms

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

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