CCI+ PHASE 2
PERMAFROST

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

D4.2 Product User Guide (PUG)

VERSION 1.0

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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 will be complemented by a new ECV Permafrost product: Rock Glacier Velocity (RGV). This document focuses on the mountain permafrost component of the Permafrost_cci project and the dedicated rock glacier products.

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

Two product types are therefore proposed by Permafrost_cci Phase 2: Rock Glacier Inventories (RoGIs) and Rock Glacier Velocity (RGV) time series. This agrees with the objectives of the International Permafrost Association (IPA) Action Group on *Rock Glacier Inventories and Kinematics* (RGIK) [RD-5] and concurs with the recent GCOS and GTN-P decisions to add RGV time series as a new product of the ECV Permafrost to monitor changing mountain permafrost conditions [AD-2 to AD-4]. RoGI is an equally valuable product to document past and present permafrost extent. It is a recommended first step to comprehensively characterise and select the landforms that can be used for RGV monitoring. RoGI and RGV products also form a unique validation dataset for climate models in mountain regions, where direct permafrost measurements are very scarce or lacking. Using satellite remote sensing, generating systemic RoGI at the regional scale and documenting RGV interannual changes over many landforms become feasible. Within Permafrost_cci, we mostly use Synthetic Aperture Radar Interferometry (InSAR) technology based on Sentinel-1 images that provide a global coverage, a large range of detection capability (mm–cm/yr to m/yr) and fine spatio-temporal resolutions (tens of m pixel size and 6–12 days of repeat-pass). InSAR is complemented at some locations by SAR offset tracking techniques and spaceborne/airborne optical photogrammetry.

This Product User Guide (PUG) describes the properties of the rock glacier products from the Climate Research Data Package (CRDP) delivered in November 2023 [RD-6]. 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].

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 in the 12 subareas selected for the multi-operator exercise. Section 3 describes the properties of the RGV pilot products from CCI CCN4 iteration 1. 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-22].

1.3 Applicable documents

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

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

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

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

1.4 Reference Documents

[RD-1] Rouyet, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.1 User Requirement Document (URD), v1.0. European Space Agency.

[RD-2] Rouyet, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.2 Product Specification Document (PSD), v1.0. European Space Agency.

[RD-3] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.2 Algorithm Theoretical Basis Document (ATBD), v1.0. European Space Agency.

[RD-4] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.3 End-to-End ECV Uncertainty Budget (E3UB), v1.0. European Space Agency.

[RD-5] Rouyet, L., Echelard, T., Schmid, L., Barboux, C., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D2.5 Product Validation Plan (PVP), v1.0. European Space Agency.

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

[RD-6] Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D4.1 Product Validation and Intercomparison Report (PVIR), v1.0. European Space Agency.

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

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

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

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

[RD-12] RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories. Practical InSAR guidelines (version 4.0). IPA Action Group Rock glacier inventories and kinematics, 33 pp.

[RD-13] RGIK 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.2). IPA Action Group Rock glacier inventories and kinematics, 12 pp.

[RD-14] RGIK. 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: practical concepts (version 1.2). IPA Action Group Rock glacier inventories and kinematics, 17 pp.

[RD-15] RGIK. 2023. Instructions of the RoGI exercises in the Goms and the Matter Valley (Switzerland). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

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

[RD-17] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2020. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV

Permafrost. D4.2 Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.

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

[RD-19] Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Christiansen, H. H., Darrow, M. M., Delaloye, R., Etzelmüller, B., Humlum, O, Lambiel, C., Lilleøren, K. S., Mair, V., Pellegrinon, G., Rouyet, L., Ruiz, L., Strozzi, T. 2022. Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide. The Cryosphere. 16, 2769–2792. https://doi.org/10.5194/tc-16-2769-2022.

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

[RD-21] Adler, C., P. Wester, I. Bhatt, C. Huggel, G.E. Insarov, M.D. Morecroft, V. Muccione, and A. Prakash. 2022. Cross-Chapter Paper 5: Mountains. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2273–2318. https://doi.org/10.1017/9781009325844.022.

[RD-22] van Everdingen, R. Ed. 1998, revised in May 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. http://nsidc.org/fgdc/glossary.

2   Rock glacier inventory (RoGI) products

2.1   Background and terminology

The Rock Glacier Inventory (RoGI) products of the Permafrost_cci Phase 2 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 40 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 RoGIs (e.g. Brardinoni et al., 2019; Way et al., 2021). The work was performed in two steps between June and November 2023:

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

In CRDP v.1.1, the delivered products include the final consensus-based products (names formatted as described in Section 2.10) and the individual results from operators (unmodified). In both cases, the data package comprises three types of files:

- The PMs, i.e. points identifying and locating rock glaciers within the 12 areas. "Certain" and "uncertain" RGU 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 MAs detected, delineated, and characterized (assignment of a velocity class) using Synthetic Aperture Radar Interferometry (InSAR) data. The MAs were used to categorize the kinematic attribute in the PM files.
- The outlines (polygons) following 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 summarized in the ATBD [RD-3] and follow the guidelines defined by the International Community on Rock glacier Inventories and Kinematics (RGIK). The RoGI guidelines developed iteratively since 2018 [RD-8] [RD-9] [RD-10] have been recently merged in a first complete release [RD-11].

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 outlines, 3) the subfolder "INSAR-DATA" including wrapped interferograms from Sentinel-1 (and potentially 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 (PMs) and outlining 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 for all members of each inventory team.

MAs are spatially identified and characterized 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-12], also available in attachment of 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. 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 the topography in respect to the sensor viewing geometry. Some areas can therefore not 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 applied threshold for the minimum size of a rock glacier within a RoGI is around 0.01 km^2 [RD-11]. 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

The multi-operator exercise followed 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 were documented rates using InSAR, primarily based on the Sentinel-1 SAR satellites. Rock glaciers that are not moving have also been morphologically identified. They were 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-12].

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.

2.8   Product projection system

The Coordinate Reference System (CRS) used for the RGI 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), a platform-independent database container that is a more flexible alternative to the shapefile (.shp) format. The total data volume is 90.7 MB. The data volume in each area (incl. the files from individual operators) varies between 6 and 11 MB. The total data volume of the final consensus-based products (names formatted as described in

Section 2.10) is 10.0 MB. The data volume of the final consensus-based products in each area varies between 0.7 and 1.1 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: SUBAREA_<REGION_NUMBER>-<SUBAREA_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–Southern Venosta (Italy); 12–Disko Island (Greenland); 13–Tien Shan (Kazakhstan); 14–Brooks Range (Alaska); 15–Central Andes (Argentina), 16–Southern Alps (New Zealand). <SUBAREA_NUMBER> is a one or more digit(s) number, depending on the subarea(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:
* RG: 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-SUBAREA_6-1_RG_2024-fv01.1.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" attribute 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 Outlines, the following attributes are documented:
- ID (unique alpha-numerical identifier of the moving area)
- 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 inscriptions of the exercise (incl. references to the applicable sections of the RGIK guidelines). These explanations are also reported in the Section 5 of the ATBD [RD-3].

2.12 Metadata

For each inventory, a separate documentation file will be provided building on the PUG. The metadata must include information about the SAR satellite scenes that were used for InSAR analysis (date, path, row, sensor, processing), the date, source, spatial resolution of the available DEM and orthoimages, the name of the PI and the date of the analysis. References to be cited, acknowledgments and any other important metainformation will be mentioned. The complete metadata file will be released together with the CRDP version 1.2 (see Section 2.14).

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.

Similar quality variability 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 characterization. In general, slow movements were investigated mainly using annual interferograms. However, using a long-time interval, the quality of the single wrapped interferograms gets sometimes lower, due to loss of phase coherence. The number of suitable 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 40 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. Several suggestions to solve that issue are summarized in the PVIR [RD-7]. 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 currently limit the inter-comparison possibilities. There are ways to fix these errors without any data loss, but we could not do it yet for all areas due to late delivery from some teams. A complete clean dataset is being prepared for the final release (CRDP v.1.2, see Section 2.14).

2.14 Product version and data dissemination

The CRDP version 1.1 provided in attachment of the PUG is a corrected version of the initial delivery from November 2023 (CRDP v.1.0) [RD-6]. A version 1.2 is foreseen (adjustments to improve the metadata, filling reliability fields currently missing in some areas, additional comments for educational purposes) and is planned to be released openly together with a data paper.

3   Rock glacier velocity (RGV) products

3.1   Background and terminology

RGV is a time series of annualized velocity produced with the objective to document the long-term changes of rock glacier creep rate in a climate-oriented perspective. Based on satellite remote sensing techniques, such as InSAR, one RGV is the result of a spatial aggregation of flow field measurements for pixels assumed to be representative of the downslope movement of the rock glacier unit. 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) The development of the InSAR procedure for RGV generation is still at a pilot stage.

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

Used 12-days temporal baselines, 2015–2022 (8 years) years have been processed. Using 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

Velocity time series are produced for several pixels across the pilot sites to document the variability of the velocity patterns, evaluate these differences and divide the landforms in subareas affected by different kinematics using a hierarchical clustering algorithm based on the squared Euclidean distance between observations (Ward's minimum variance method, Ward, 1963; Jain and Dubes, 1998). According to URq_17 [RD-1], the velocity is aggregated for the cluster with the largest number of pixels, so the RGV 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]). For each pilot site, the aggregation procedure (e.g. size and location of the considered area(s), number of pixels used to average the time series) is consistent over time.

3.5   Temporal resolution

The initial velocity data will be based on Sentinel-1 InSAR time series with a 6–12 days frequency collected during snow-free periods for the years 2015–2022 (observation time window < 1 year but covering at least one month). The initial velocity data is annualized, following the Breakthrough Requirement of URq_13 [RD-1]. The observation time window is at least one month (between June-October), following the Breakthrough Requirement of URq_14 [RD-1]. The chosen period is documented and consistent throughout the entire time series for each pilot 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 product corresponds to a spatial aggregation of several pixels, 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 RGI 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 5 KB. The data volume of each pilot site varies between 1 and 2 KB.

3.10   Product file naming convention

ESACCI-<CCI   Project>-<Processing   Level>_<Data   Type>_<Product   String>-<Additional Segregator>-<Indicative Date>-<Indicative Time>-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: SUBAREA_<REGION_NUMBER>-<SUBAREA_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–Southern Venosta (Italy); 12–Disko Island (Greenland); 13–Tien Shan (Kazakhstan); 14–Brooks Range (Alaska); 15–Central Andes (Argentina), 16–Southern Alps (New Zealand). <SUBAREA_NUMBER> is a one or more digit(s) number, depending on the subarea(s)/site(s) in the region. Current pilot sites: 0–Diestelhorn; 1–Rechy-Becs-de-Bosson; 2–Steintälli; 3–Bru; 4–Gänder; 5–Breithorn; 6–Grabengufer; 7–Perroc.

<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-SUBAREA_6-1-2024-fv01.1.csv

3.11   Attributes

For each RGV time series the following attributes will be recorded:
- 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 single discrete point, and related specifications).
- Start date (date of first observation).
- Velocity data (computed RGV data in m/y).

For each velocity data (each annual increment of the time series), the following attributes will be recorded:
- 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/y).
- 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 will be provided building on the PUG. Metadata must indicate the data and methodology used for deriving the RGV time series (InSAR, GNSS, optical photogrammetry, etc.) 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 will be indicated. The complete metadata file will be prepared in relation with the production and release of the products from the second iteration of Permafrost_cci Phase 2 (see Section 3.14).

3.13   Known limitations

The InSAR-RGV products generated in the first iteration of Permafrost_cci Phase 2 show that the proposed procedure is promising and that the results are consistent with similar GNSS-RGV products at the same sites (see PVIR [RD-7]). However, the few selected sites and the short overlapping periods between InSAR and GNSS measurements make it challenging to draw any definitive conclusion.

There are several open questions regarding the operationalization of the InSAR-RGV production, as this part was designed as a pilot study in the first iteration. The generic RGV guidelines are still under development (current version in [RD-13] [RD-14]) and advances in this field are highly expected in the coming years, under the umbrella of the RGIK community. The InSAR procedure applied at the Swiss pilot sites need to be tested on a large number of rock glaciers and compare time series from other techniques (e.g. optical remote sensing). This will be the focus of the second iteration of Permafrost_cci Phase 2.

3.14   Product versions and data dissemination

The CRDP version 1.1 provided in attachment of the PUG is a corrected version of the initial delivery from November 2023 (CRDP v.1.0) [RD-6]. RGV production is still at a pilot stage. Systematic RGV generation for a larger number of rock glaciers and the corresponding release of the final products are part of the second iteration of Permafrost_cci Phase 2.

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
MAGT	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
PERMOS	Swiss Permafrost Monitoring Network
PI	Principal Investigator
PM	Primary Marker
PSD	Product Specification Document
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RD	Reference Document
RG	Rock Glacier
RGIK	Rock Glacier Inventories and Kinematics
RGU	Rock Glacier Unit
RGV	Rock Glacier Velocity
RoGI	Rock Glacier Inventory
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
UiO	University of Oslo
UNIFR	University of Fribourg
URD	Users Requirement Document
URq	User Requirement
UTM	Universal Transverse Mercator
TR	Threshold Requirement
WUT	West University of Timisoara
WMO	World Meteorological Organization