CCI+ PERMAFROST

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

D1.1 User Requirement Document (URD)

VERSION 3.0

14 AUGUST 2026

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Document status sheet

Issue	Date	Details	Authors
1.0	15.02.2023	Final version CCN4 D1.1	L. Rouyet, C. Pellet, R. Delaloye, F. Sirbu, A. Onaca, V. Poncos, F. Brardinoni, A. Kääb, T. Strozzi, N. Jones, A. Bartsch
2.0	15.08.2024	Phase 2, iteration 2, D1.1. updates: RD updates, corrections typo errors, minor phrasing changes, updated information on users, RGIK community and external partners, new table 4 formatting.	L. Rouyet, C. Pellet, L. Schmid, T. Echelard, R. Delaloye, F. Brardinoni, F. Sirbu, A. Onaca, V. Poncos, A. Kääb, T. Strozzi, A. Bartsch
3.0	14.08.2026	CCN6 Legacy updates: RD updates, corrections of minor typo errors, phrasing adjustments, additional objectives of the current phase, updated information on background, users and partners.	L. Rouyet, C. Pellet, A. Milceva, R. Delaloye, F. Brardinoni, T. Echelard, F. Sirbu, A. Onaca, V. Poncos, T. R. Lauknes, A. Kääb, T. Strozzi, P. Bernhard, N. Jones, A. Bartsch

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EUROPEAN SPACE AGENCY CONTRACT REPORT
The work described in this report was done under ESA contract. Responsibility for the contents resides in the authors or organizations that prepared it.

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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) Quantities, using primarily satellite imagery. The two traditional Quantities associated to the ECV Permafrost, Ground Temperature (GT) and Active Layer Thickness (ALT), were the primary documented products during Permafrost_cci Phase 1 (2018–2021). In Permafrost_cci Phase 2 (2022–2025), GT and ALT were complemented by the third ECV Permafrost Quantity: Rock Glacier Velocity (RGV). Permafrost_cci Legacy (2026–2027) is a 14-month extension to foster and extend the production of the ECV Permafrost Quantities initiated in the previous phases [AD-1] [AD-2].

This document focuses on the mountain permafrost component of the Permafrost_cci project and the dedicated rock glacier products. In periglacial mountain environments, the 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. The interannual variations of the rock glacier creep rates are influenced by changing permafrost temperature, making RGV a key parameter for cryosphere monitoring in mountains.

Two mountain permafrost products are included in Permafrost_cci: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). RoGI is a valuable product to document past and present permafrost extent. It is a recommended first step to comprehensively characterise and select the rock glacier units (RGUs) to be used for RGV monitoring. RGV has been added by GCOS and Global Terrestrial Network for Permafrost (GTN-P) as ECV Permafrost Quantity [AD-3 to AD-5], following the recommendations suggested by the International Permafrost Association (IPA) Standing Committee on Rock Glacier Inventories and Kinematics (RGIK) (www.rgik.org). It is a valuable product to monitor changing mountain permafrost conditions. Together, RoGI and RGV products form a unique validation dataset for modelling in mountains, where direct permafrost measurements are scarce or even lacking. Using remote sensing, the generation of systematic RoGIs at the regional scale and the documentation of 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 by SAR offset tracking and spaceborne/airborne optical photogrammetry.

This User Requirement Document (URD) describes the User Requirements for RoGI and RGV products. The results from a user survey from 2019 served as basis for the URD document from Permafrost_cci Phase 1 [RD-1]. The present URD is an updated version that has been adjusted to the recent advances in the user-based RGIK collaborative work. RGIK had extensive discussions and agreements during two workshops in 2019 and 2020, followed by several rounds of consultations and corrections of consensus-based international guidelines [RD-6 to RD-7]. The listed User Requirements (URq) are therefore an updated version of the initial Phase 1 URq and have been corrected based on recent RGIK community agreements. Only minor corrections and updates have been implemented in the URD version 2.0 (Phase 2) and the URD version 3.0 (Legacy).

1 Introduction

1.1 Purpose of the document

The User Requirement Document (URD) summarises the User Requirements of the Permafrost_cci mountain permafrost products: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). The URD assesses the recommendations from relevant organisations from the climate research community and the international mountain permafrost community. The User Requirements are used to define the product specifications [RD-2]. A concise ID reference code 'URq_xx' is assigned to each User Requirement. This allows for cross-referencing and traceability between multiple Permafrost_cci documents.

1.2 Structure of the document

Section 2 describes the potential applications and related users of the Permafrost_cci mountain permafrost products. Adjusted User Requirements for both RoGI and RGV products are summarized in Section 3. Potential issues to fulfil these requirements are discussed in Section 4. A summary of the User Requirements is presented in Section 5. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 6.1. A list of acronyms is provided in Section 6.2. A glossary of the commonly accepted permafrost terminology can be found in RD-13.

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] ESA. 2025. CCN 6 – CCI PERMAFROST – Legacy. Change Request. ESA-EOP-SG-CCN-6.

[AD-3] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-4] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

[AD-5] 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**] Barboux, C., Bertone, A., Delaloye, R., Onaca, A., Ardelean, F., Poncos, V., Kääb, A., Rouyet, L., Christiansen, H. H., Strozzi, T., Bartsch, A. 2019. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D1.1 User Requirement Document (URD), v1.0. European Space Agency.

[RD-2] Rouyet, L., Pellet, C., Delaloye, R., Brardinoni, F., Echelard, T., Sirbu, F., Onaca, A., Poncos, V., Lauknes, T. R., Kääb, A., Strozzi, T., Bernhard, P., Jones, N., Bartsch, A. 2026. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier Inventories (RoGI) and Rock Glacier Velocity Products (RGV). D2.1 Product Specification Document (PSD), v3.0. 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. 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-5] RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories (version 4.0). IPA Action Group Rock Glacier Inventories and Kinematics, 33 pp.

[RD-6] 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, 13 pp.

[RD-7] 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-8] 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-9] 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-10] 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-11] Rouyet, L., Pellet, C., Echelard, T., Schmid, L., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Lauknes, T. R., Wendt, L., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2025. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier Inventory (RoGI) and Rock glacier Velocity (RGV) Products. D3.2 Climate Research Data Package (CRDP), v2.0. European Space Agency.

[RD-12] 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-13] 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 Users of the rock glacier products and involvement of the community

2.1 Applications and users of the rock glacier products

In mountainous terrain, permafrost occurs above an altitude rising from the sea level in polar regions to > 4'500 m a.s.l. in the intertropical zone. The regional lower altitudinal limit of the so-called discontinuous permafrost belt is heterogeneous over short distances due to the large variability of the topographical setting and the ground constitution. The combination of both gravity and steep topography makes the frozen ground susceptible to gradual downslope deformation (creep). Permafrost creep forms typically lobate landforms called rock glaciers, detectable in the landscape with the following morphologies: front, lateral margins and optionally ridge-and-furrow surface topography [RD-4] (Brardinoni et al., 2025).

For decades, initiatives have arisen in many high-altitude regions for inventorying and monitoring rock glaciers as a **proxy for permafrost occurrence**, but also in the perspective of **climate reconstruction, geohazards management and/or ice (water) storage estimation**. Rock glaciers provide information on the transfer rates of sediments along mountain slopes and on the impact of climate change on the slope stability and the water cycle. Products documenting the regional distribution of rock glacier units (RGUs), their key morpho-kinematic characteristics and their interannual velocity changes are therefore relevant for a wide range of users. Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV) products can have direct **operational value for the local communities**. Stakeholders involved in the assessment and monitoring of mass wasting processes in cold mountain environments are typically targeted by Permafrost_cci rock glacier products. In general, providing tools and standards for monitoring rock glaciers will serve **any instance involved with the management of cold mountain slopes and their related hazards**.

The climate research community also benefits from RoGI and RGV products to calibrate or validate models in mountain regions, where direct permafrost measurements are very scarce or even lacking, leading to large uncertainties in climate change projection [RD-12]. Rock glaciers often move at a rate closely depending on the temperature profile between the permafrost table and the main shear horizon at depth. RGV products documenting the interannual changes of permafrost creep rates can be used as an indicator of climate change in mountains (Hu et al., 2025). In 2022, GCOS decided to add **RGV as a new Quantity associated to the ECV Permafrost** [AD-03]. The general requirements for producing such time series have been defined in the GTN-P Strategy and Implement Plan [AD-04], in agreement with the recommendations compiled by RGIK [RD-6] [RD-7]. RGV is included in the annual update of the State of the Climate published by the Bulletin of the American Meteorology Society (BAMS) (Pellet et al., 2025). Despite the recent improvement of reference documents and data compilation, further work is still needed to refine the practical guidelines to systematically identify, characterise and monitor rock glaciers, implement the defined requirements, and build up an operational database of RGV products as climate change indicators.

2.2 Involvement of the mountain permafrost community in the Permafrost_cci project

Mapping rock glaciers and observing their interannual velocity changes over many landforms in large regions is feasible using multi-temporal satellite remote sensing. In a context of constant improvement of the coverage, accessibility and quality of satellite images, the number of dedicated rock glacier studies with a regional perspective keeps increasing. However, these studies often rely on different methodologies based on the unequal availability of source datasets, as well as the variable local

priorities, expertise and institutional support. With the objective to define standard inventorying and monitoring rules and generate comparable RoGI and RGV products worldwide, the International Permafrost Association (IPA) Action Group on **Rock Glacier Inventories and Kinematics (RGIK)** was launched in 2018 [RD-3]. In 2024, RGIK submitted a proposal to become a Standing Committee, a permanent structure under the umbrella of the IPA. On June 16th 2024, in Whitehorse, Canada, the proposal was unanimously accepted by the IPA Council. Since then, RGIK keeps working on extending its guidelines and tools for enhancing the worldwide production of RoGI and RGV products. In parallel, the Permafrost_cci activities support RGIK objectives and apply the international guidelines to generate RoGI and RGV, primarily based on remote sensing products. During Permafrost_cci Phase 1 (2018–2022), the generation of RoGIs in 12 regions involved six external partner institutions, in addition to the Permafrost_cci partners [RD-8] [RD-9] (Bertone et al., 2022).

In Permafrost_cci Phase 2 first iteration (15.11.2022–15.05.2024), the main objectives were to:

- **For RoGI:** perform a multi-operator exercise following a consensus-based RoGI procedure to identify discrepancies, agree on common solutions and improve the quality of the products in 12 areas (*Table 1*, upper part), and refine the RoGI instructions and GIS tools.
- **For RGV:** define the procedure to convert initial InSAR time series into RGV, and generate pilot RGV products for selected rock glaciers.

In Permafrost_cci Phase 2 second iteration (15.05.2024–15.11.2025), the main objectives were to:

- **For RoGI:** publish the results of the multi-operator exercise from the first iteration (Rouyet et al., 2025), support RoGI compilation in eight new regions (*Table 1*, middle part), and explore possibilities to use the generated RoGI products as training data for machine learning.
- **For RGV:** evaluate and refine the InSAR-RGV procedure developed during the first iteration with a multi-operator and multi-technique intercomparison exercise, and implement the adjusted procedure and extend the production to more landforms.

In Permafrost_cci Legacy (15.04.2026–15.06.2027), our priorities are to:

- **For RoGI:** finalise the work in the eight new regions of Permafrost_cci Phase 2 (*Table 1*, middle part), release the data in an open-access database, publish main findings in scientific articles, update the kinematic attributes in Italy and Romania, and initiate RoGI work in six new regions (*Table 1*, lower part).
- **For RGV:** release the recommended InSAR-RGV procedure as part of the merged RGV international guidelines from RGIK, finalise and publish the InSAR-RGV results covering alpine landforms, and extend the production to other regions.

As for Phase 1, **external partners** are involved in the generation of new RoGIs in additional regions. In total, Permafrost_cci includes **22 regions involving 15 partner institutions** (*Table 1*). The selected regions encompass a wide range of climatic, topographical and periglacial conditions, within continuous, discontinuous, and sporadic permafrost zones. Various mountain ranges located at diverse latitudes, altitudes and in all continents are represented. The regions covered by Permafrost_cci Phase 2 and Legacy are further described in the Product Specification Document (PSD) [RD_2].

The shared responsibility of the RoGI generation led by institutions with strong background and experience in their respective region(s) ensure a **close dialog with local, regional and national stakeholders**. In each study area, the RoGI and RGV products will be valuable for dedicated users within the permafrost, geohazard and climate communities:

- **Research and education institutions** involved in geoscience and climate programmes, such as universities and research institutes/centres.

- **National and local authorities** (e.g. geological surveys, environmental and geohazard management agencies, road and rail authorities, municipalities, counties, etc.) interested in the identification of destabilized and potentially hazardous rock glaciers, and the relation between permafrost, unstable rock slopes and water management.
- **The national meteorological institutes** conducting monitoring programmes and research in climatology and permafrost-climate interactions in the Earth System.
- **A large public body** (e.g. mountaineers, local community) interested in mountain stability issues and relations with climate change.

In addition, the project will follow the simultaneous developments of the RGIK initiative, which involves a constantly growing pool of people from the international mountain permafrost community. RGIK represents a wide range of backgrounds, perspectives and applications, from different institutions all around the world. **In 2026, the RGIK community counts 268 members from 33 countries.** In Permafrost_cci Phase 2, we reached out to this community to involve **41 operators in the RoGI exercise**. Since 2024, we are also involving **22 RGIK members in the RGV intercomparison working group**. This group had several digital meetings since 2024 and two physical workshops in November 2024 and December 2025. The collaboration will continue until the end of CCI Legacy and beyond. RGIK consensus-based decisions regarding the RoGI and RGV recommendations and associated guidelines have been used for the definition of the Permafrost_cci User Requirements (URq) in the following sections. At the same time, Permafrost_cci contributes to improve the RGIK standards by supplying actual results that help refining and extending the guidelines.

Table 1: *Permafrost_cci RoGI regions and responsible institutions*

RoGI – Permafrost_cci Phase 2 first iteration		
RoGI region	**Responsible institution**	**CCI affiliation**
Western Alps (Switzerland)	University of Fribourg (Switzerland)	CCN4 Baseline
Disko Island (Greenland)	Gamma Remote Sensing (Switzerland)	CCN4 Baseline
Troms (Norway)	NORCE Norwegian Research Centre (Norway)	CCN5 Option 8
Finnmark (Norway)	NORCE Norwegian Research Centre (Norway)	CCN5 Option 8
Nordenskiöld Land (Svalbard)	NORCE Norwegian Research Centre (Norway)	CCN5 Option 8
Southern Venosta (Italy)	University of Bologna (Italy)	CCN4 Option 9
Carpathians (Romania)	West University of Timisoara and Terrasigna (Romania)	CCN4 Option 9
Vanoise Massif (France)	University Grenoble Alpes and Université Savoie Mont-Blanc (France)	External partner
Brooks Range (Alaska)	University of Alaska Fairbanks (U.S.A)	External partner
Central Andes (Argentina)	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales IANIGLA (Argentina)	External partner
Tien Shan (Kazakhstan)	Graz University of Technology (Austria)	External partner
Southern Alps (New Zealand)	University of Lausanne (Switzerland)	External partner
RoGI – Permafrost_cci Phase 2 second iteration		
RoGI region	**Responsible institution**	**CCI affiliation**
Goms–Binntal (Switzerland)	University of Fribourg (Switzerland)	CCN4 Baseline
Northern Venosta (Italy)	University of Bologna (Italy)	CCN4 Option 9
Rila and Pirin Mts (Bulgaria)	West University of Timisoara and Terrasigna (Romania)	CCN4 Option 9
Manaslu (Nepal)	Université Grenoble Alpes (France) and The Chinese University of Hong Kong (China)	External partner
Sajama (Bolivia–Chile)	Université Grenoble Alpes and Université Savoie Mont-Blanc (France)	External partner
Tsengel Khairkhan (Mongolia)	Mongolian Academy of Sciences (Mongolia)	External partner
Baralacha La (India)	University of Bologna (Italy)	Side-project
Thana (Bhutan)	University of Fribourg (Switzerland)	Side-project
RoGI – Permafrost_cci Legacy		
Northwest Antarctic Peninsula (Antarctica)	University of Lisbon (Portugal)	External partner
Hazelton Mountains (Canada)	University of Ottawa (Canada)	External partner
North Cascades (USA)	University of Ottawa (Canada)	External partner
Făgăraș (Romania)	West University of Timisoara (Romania)	Side-project
Karakoram (Greater Kashmir)	University of Bologna (Italy)	Side-project
Ampato–Coropuna (Peru)	Université Grenoble Alpes (France)	Side-project

3 User Requirements

The present document is an updated version of the URD from Permafrost_cci Phase 1 [RD-1] that defined the main User Requirements (URq) based on a **user survey performed in 2019**. The results of this survey are briefly summarised in Section 3.1.

The URq have been **adjusted based on the recent work of the RGIK community since 2019**. The consensus-based decisions that were taken these past years are summarized in the latest versions of the RGIK guidelines [RD-4 to RD-7]. The RGIK community agreed on the following rock glacier definition: “Rock glaciers are debris landforms generated by the former or current creep of frozen ground (permafrost), detectable in the landscape with the following morphologies: front, lateral margins and optionally ridge-and-furrow surface topography. Rock glacier (or permafrost) creep has to be understood here as a generic term referring to the variable combination of both internal deformation within the crystalline structure of the frozen ground (creep stricto sensu) and shearing in one or several horizons at depth” [RD-4]. This definition is used to identify the landforms that are inventoried and monitored in Permafrost_cci.

RoGI and RGV URq are described separately in Section 3.2 and Section 3.3, according to three levels of requirements and following GCOS definitions [AD-04]:

- **Threshold requirement TR** (minimum: "must have"): The minimum requirement to be met to ensure that the data are useful.
- **Breakthrough requirement BR** (only documented for RGV product): An intermediate level between TR and GR, which – if achieved – would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specific uses within climate monitoring become possible.
- **Goal requirement GR** (optimal: "ideal to have"): The ideal requirement above which further improvements are not necessary.

3.1 Summary of the 2019 user survey and Permafrost_cci Phase 1 User Requirements

A user consultation was carried out during Permafrost_cci Phase 1. A comprehensive questionnaire was set-up by the project partners and posted online in 2019. In total, 32 international scientists working in mountain permafrost areas responded to the survey. They were mainly from research organisations and high education institutions.

For the RoGI product, the user survey showed the importance to have a global perspective when defining the product specifications for the inventories. The long-term objective should be to provide a database with a global coverage (GR). The extent of regional rock glacier inventories should follow the geography of the mountain ranges regardless of the national boundary (TR) [Phase1_URq_01]. The inventories should illustrate the present situation as a snapshot of the current year (TR) or based on the past 5–10 years, with potential investigation in the past (GR) [Phase1_URq_02]. A RoGI should identify each rock glacier at least by a point (TR). When possible, outlining the extended or restricted geomorphological footprint is recommended (GR) [Phase1_URq_03]. Multi-unit differentiation should represent different rock glacier generations or different dynamics (TR), and if possible different connections to the upper slope (GR) [Phase1_URq_04]. An update of a RoGI should be performed every 10 years (GR; TR was undefined) [Phase1_URq_05]. Qualitative information with defined classes of activity is required (GR; TR was undefined) [Phase1_URq_06]. The documentation of a potential destabilization is useful (GR) but should remain optional (TR) [Phase1_URq_07]. The

assignment of kinematic attributes based on identified moving areas is also useful (GR) but should remain optional (TR) [Phase1_URq_08] [Phase1_URq_09]. In 2019, the users indicated that up to 30% of rock glaciers in an inventory can remain undefined, i.e. if the units are identified without defined morpho-kinematic attributes (GR; TR was undefined) [Phase1_URq_10].

For the RGV product, the initial survey again showed that the users had a global perspective and aimed at developing indicators representative of the evolution of rock glacier velocity at the regional scale (TR) and worldwide (GR) [Phase1_URq_11]. With the objective of generating regional indices as climate change indicators, the users indicated that RGV time series should be derived on several rock glaciers within a region (TR), ideally a minimum of 30% landforms to be representative of a defined regional context (GR) [Phase1_URq_12]. The RGV time series should be updated at least every 5 years (TR), ideally every year (GR) [Phase1_URq_13]. They meant that the time series should comprise mean annual velocity values with a 1-year time step (both TR and GR) [Phase1_URq_14]. The time series should document at least 5–10 years (TR), although it would ideally go as far back as possible (GR) [Phase1_URq_15]. The users requested at least velocity classes (TR), but ideally an exact velocity value (GR) [Phase1_URq_16]. Requirement regarding the horizontal resolution of the measurements remained undefined [Phase1_URq_17]. A precision/accuracy of at least 5 cm/yr, ideally 1 cm/yr (GR), was required [Phase1_URq_18].

3.2 Adjusted User Requirements for Rock Glacier Inventory (RoGI)

The current RGIK recommendations for RoGI have been used to adjust the Permafrost_cci Phase 2 and Legacy URq, summarised in *Table 2*. Some URq remain mostly the same as in Phase 1 and have simply been slightly rephrased to clarify their purpose and meaning [URq_01] [URq_02] [URq_05]. For the other URq, the RGIK guidelines added these past years more detailed recommendations regarding rock glacier identification and outlines [URq_03], optional attributes (morphology, spatial connection, activity, kinematics) [URq_04] [URq_06 to URq_09], and suggested strategies to document the reliability and the uncertainties [URq_10]. No completely new URq has been added from Permafrost_cci Phase 1. To better fit the steps related to the integration of a kinematic attribute in a RoGI, we have inversed the order of [URq_08] (moving areas) and [URq_09] (kinematics).

Table 2. *Permafrost_cci User Requirements (URq) for the RoGI products [RD-4].*

	Threshold Requirement[1]	**Goal Requirement[2]**
	Coverage and sampling	
Geographical coverage and sampling [URq_01]	Relevant geographical coverage at the local–regional scale (valley side, drainage basin, mountain range).	Global coverage, i.e. worldwide integration of comparable RoGIs for all mountain ranges regardless of the national boundary.
Time frame and temporal extent [URq_02]	Inventory based on datasets from the most recent year, at the time of production.	Inventory based on several recent datasets over a 5–10 years period, at the time of production.
	Resolution	
Rock glacier location [URq_03]	Identification by a primary marker (point named with a unique code / ID). [RD-4]	Identification by a primary marker (point) and rock glacier outline as a polygon following the extended and/or restricted geomorphological footprints. Each RGU is associated with one single rock glacier system. [RD-4]

Multi-unit differentiation [URq_04]	Differentiation of RGUs and mono-unit or multi-unit systems, based on distinct timing of formation, different connections to the upslope unit or distinct activities/kinematics. [RD-4]	-
Update [URq_5]	Mandatory documentation of the temporal properties (acquisition data, time frame/window) of the data sources used for RoGI generation, required for comparison and potential future updates.	Update every 10 years to account for changing rock glacier delineation, geomorphological and kinematic attributes.
	Attributes[3]	
Rock glacier activity [URq_06]	Optional attribute, only documented when geomorphological or kinematic evidence is available. [RD-4] [RD-5]	Updated activity categorization: active, transitional, or relict. Uncertainty between categories can be documented. [RD-4] [RD-5]
Rock glacier destabilization [URq_07]	Optional attribute, only documented when geomorphological or kinematic evidence is available. [RD-4]	Present (ongoing) or past (completed) evidence of destabilization. [RD-4]
Moving areas [URq_08]	Optional layer, only when reliable kinematic data (with sufficient spatial coverage) are available. [RD-4]	Semi-quantitative velocity classes, depending on the applied technique [RD-4] For InSAR: 1–3 cm/yr, 3–10 cm/yr, 10–30 cm/yr, 30–100 cm/yr, etc. [RD-5]
Kinematics [URq_09]	Optional attribute, only documented when reliable kinematic data are available. [RD-4] [RD-5]	Semi-quantitative 'half an order-of-magnitude' categories: cm–dm/yr, dm/yr, dm–m/yr, m/yr, etc. [RD-4] [RD-5]
	Error/Uncertainty	
Precision & accuracy [URq_10]	Optional attributes (e.g. kinematics and activity) that are too uncertain must remain 'Undefined'. [RD-4] [RD-5]	The data properties (data source, dimensionality, time window/frame) must be documented for all attributes. The reliability of the moving areas, kinematic attributes and outlines is qualitatively assessed (low, medium, high). [RD-4] [RD-5]

[1] Threshold Requirement (TR): The minimum requirement to be met to ensure that the data are useful [AD-03].
[2] Goal Requirement (GR): The ideal requirement above which further improvements are not necessary [AD-03].
[3] For the rock glacier morpho-kinematic attributes, TR is defined as the optional documentation of the attributes according to the RGIK guidelines. GR is the systematic documentation of the attributes according to the RGIK guidelines.

3.3 Adjusted User Requirements for Rock Glacier Velocity (RGV)

The RGV Phase1_URq have been modified to match the latest RGIK recommendations [RD-6] [RD-7] and the 2022 GCOS ECV requirements [AD-03]. Although the generation of regional indices based on multiple time series remain a final long-term goal, the RGIK community decided that the RGV requirements must first focus on the necessary criteria to generate RGV products on single landforms. RGV is defined as a time series of annualised surface velocity values expressed in m/yr and measured/computed on a RGU or a part of it [RD-6]. Any collection of velocity measurements over inventoried rock glaciers is encouraged especially if the landform meets the criteria for RGV monitoring, namely (1) the control of surface movement by permafrost creep processes and (2) the feasibility of long-term monitoring. The velocity value should be expressed in m/yr, and its quality

should be documented by the relative error of the velocity measurements, as well as a qualitative estimate of the consistency of the measurement procedure over time. The current Permafrost_cci Phase 2 URq are summarised in *Table 3*. Compared to Permafrost_cci Phase 1, one new URq has been added regarding RGV stability & consistency [URq_19]

Table 3. *Permafrost_cci User Requirements (URq) for the RGV products [RD-6] [RD-7] [AD-04].*

	Threshold requirement[1]	**Breakthrough requirement[2]**	**Goal Requirement[3]**
	Coverage and sampling		
Geographical coverage [URq_11]	Isolated site. Time series produced either from in situ measurements or remotely sensed measurements.	Multiple sites in a defined region, allowing for preliminary analysis of similar/dissimilar trends.	≥ 30% of the active rock glaciers in one or several region(s), allowing for analysis of regional trend(s). Based on remote sensing approaches.
Geographical sampling [URq_12]	Active or transitional rock glaciers with movement related to permafrost creep. Sites where long-term monitoring is feasible. RGUs are fully characterised following RoGI requirements.	-	-
	Resolution		
Temporal resolution (frequency) [URq_13]	Frequency < once a year. Max. observation time window 5 years.	-	1 year, i.e. measured or computed once a year.
Temporal resolution (observation time window) [URq_14]	Observation time window > 1 year (2–5 years). Longer intervals are admissible for reconstructions from archives.	Observation time window < 1 year (e.g. summer period only). At least 1 month and consistent over time (max. ±15 days of difference).	Observation time window = 1 year and consistent over time (max. ±15 days of difference).
Temporal extent [URq_15]	1 year (first year, when starting a series based on new data sources)	5–10 years	As long as possible (incl. past reconstruction if possible)
Velocity value [URq_16]	Annual mean velocity value. Unit: m/yr	-	-
Horizontal resolution [URq_17]	The velocity is measured/computed at one single point. The location should be consistent over time. It should refer to a consistent flow field representing the downslope movement of a RGU.	The velocity is aggregated from at least 3 points distributed referring to a consistent flow field representing the downslope movement of a RGU. The aggregation procedure should be consistent over time.	The velocity is aggregated from flow field or several discrete points referring to a consistent flow field representing the downslope movement of a RGU. The aggregation procedure should be consistent over time.
	Error/Uncertainty		
Precision & accuracy [URq_18]	Maximal relative error of the velocity data: 20%. If the error exceeds 20%, the	Intermediate relative error threshold: 5–20%. Specific attention should be paid in	Optimal relative error of the velocity data: < 5%. The technique is chosen in

	site must be discarded, or alternative techniques should be considered in accordance with the measured/computed absolute velocity of the selected rock glacier.	the future, especially if the velocity is decreasing. In that case, a change of the measurement technique or its temporal settings should be implemented.	accordance with the measured/computed absolute velocity of the selected rock glacier and allows analysis of the long-term RGV changes.
Stability & consistency [URq_19]	Problems occurred with the latest velocity data that imply major changes of the technique. The RGV consistency is not ensured. A new time series should start with adjusted technique and settings. A merging of the two time series is allowed only if they overlap for at least one (ideally several) year(s).	Problem(s) occurred with the latest velocity data that do(es) not imply major changes of the technique. The RGV consistency is ensured with medium confidence.	No problem with the latest velocity data. High consistency after the latest annual increment of velocity time series. The observation time window, horizontal resolution and procedure to measure/compute the velocity is consistent over time.

[1] Threshold Requirement (TR): The minimum requirement to be met to ensure that the data are useful [AD-03].
[2] Breakthrough Requirement (BR): An intermediate level between TR and GR, which, if achieved, would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specific uses within climate monitoring become possible [AD-03].
[3] Goal Requirement (GR): The ideal requirement above which further improvements are not necessary [AD-03].

4 User Requirements feasibility

The following sections highlight current knowledge gaps and challenges regarding the URq feasibility. The work performed as part of Permafrost_cci Legacy will hopefully contribute to solving these open questions, in synergy with the parallel activities of the RGIK IPA Standing Committee.

4.1 Rock Glacier Inventory (RoGI)

Since the start of Permafrost_cci, the RGIK community has adjusted the recommendations with the pragmatic objective to be easily applicable by a large range of users. Several attributes that should ideally be characterised for all RGUs remain optional, to avoid artificially documenting geomorphological or kinematic information when the uncertainty is too large or when reliable data is lacking.

All TRs are expected to be met by the RoGI Permafrost_cci products. As the project focuses on the integration of kinematic information in the RoGIs based on satellite remote sensing, we even expect to meet the GRs in most cases:

- **Time frame and temporal extent [URq_02]:** The geomorphological attributes are based on all available datasets in the study areas (recent optical imagery, digital elevation models, topographical maps, geological maps, etc.). The kinematic attribute is primarily assigned using InSAR technology, based on Sentinel-1 images since 2015. The RoGIs will therefore be based on several recent datasets (multiple sources) over a period of 5–10 years, at the time of the production.
- **Rock glacier location [URq_03]:** If outlining is subject to too large uncertainty around most of the landform, it is recommended not to delineate the RGU: an outline should be drawn only if sufficient geomorphological evidence is available. However, a comprehensive characterisation of the rock glacier ideally implies outlining them, and for various practical issues (e.g. area calculation), this outline should be a polygon. Based on experience from Phase 1, we expect that most RoGIs will include polygonal delineations corresponding to their extended and/or restricted footprints.
- **Rock glacier activity [URq_06]:** Even if the activity is an optional attribute, we expect that most RoGIs will document the rock glacier activity according to the new RGIK categories (active, transitional, relict). Intermediate categories defined by RGIK can be used to document the uncertainty of the activity attribute. For instance, ‘active uncertain’ can be used in case a rock glacier is clearly not in a relict state, but there is not sufficient evidence to distinguish between an "active" and ‘transitional’ state. ‘Relict uncertain’ can be used in case a rock glacier is clearly not in an active state, but there is not sufficient evidence to distinguish between a ‘transitional’ and ‘relict" state.
- **Moving areas [URq_08]:** Permafrost_cci has contributed to the elaboration of practical guidelines for generating RoGIs using InSAR [RD-5]. The procedure consists of delineating moving areas based on the interpretation of several interferograms and attributing semi-quantitative velocity classes to the moving areas. The standard velocity classes have been defined in Phase 1 and remain the same in Phase 2: 1–3 cm/yr, 3–10 cm/yr, 10–30 cm/yr, 30–100 cm/yr, etc.

- **Kinematics [URq_09]:** One major objective of Permafrost_cci is to exploit remotely sensed ground movements from InSAR to document rock glacier kinematics. The GR will therefore be met in most cases: based on the InSAR moving areas, we can assign a semi-quantitative 'half an order-of-magnitude' category to the RGUs: cm–dm/yr, dm/yr, dm–m/yr, m/yr, etc.
- **Precision & accuracy [URq_10]:** In Permafrost_cci Phase 1, strategies to document the reliability of the attributes have been developed. The reliability of the moving areas, kinematic attributes and outlines are qualitatively assessed (low, medium, high). In addition, the users must be able to understand the limitations of the methods used to assign specific attributes, depending on the data sources. The data properties (data source, dimensionality, time window/frame) can therefore be documented in the RoGI attribute tables.

4.2 Rock Glacier Velocity (RGV)

All TRs are expected to be met by the RGV Permafrost_cci products. As the URq are generic and potentially applicable for a large range a measurement technique (e.g. in-situ point-based measurements), we expect to reach BR or GR in several cases, thanks to the temporal frequency and spatial coverage of InSAR:

- **Temporal resolution (frequency) [URq_13]:** Using aerial images, there is variable periodicity depending on regional/national coverages, especially when considering historical archives. In such cases, the minimal measurement frequency is set to 5 years (TR). With InSAR data based on recent sensors such as Sentinel-1, velocity data computed once a year can be provided (GR).
- **Temporal resolution (observation time window) [URq_14]:** Using InSAR, the observation time window is < 1 year in areas with snow cover (data gaps) (BR). In Permafrost_cci Phase 2, we have selected study areas where Sentinel-1 interferograms are available for at least 1 month per year. Methodologies to temporally aggregate the data and keep a consistent observation time window between years (max. ≈15 days of difference) are being developed.
- **Temporal extent [URq_15]:** The temporal extent of the primary Permafrost_cci data source (i.e. Sentinel-1) is 5–10 years (BR).
- **Horizontal resolution [URq_17]:** Although InSAR coverage can be limited by typical technical limitations (layover/shadow, loss of coherence, etc.), we expect availability of velocity time series over significant part of the rock glacier in most selected cases (GR).

Despite these assumptions, it should be noted that the standardised guidelines and concrete experience of the community on how to produce systematic RGV products on a large amount of rock glaciers is still at an early stage. The work of the RGIK IPA Standing Committee is ongoing. The first version of the RGV practical concepts was finalised in 2023 [RD-7]. In 2024–2025, the current recommendations were tested by different operators using different techniques. A RGV intercomparison exercise was organised during Permafrost_cci Phase 2. The conclusions of the exercise contribute to define technical recommendations for RGV production. All guidelines are being merged and will be released before the end of Permafrost_cci Legacy.

5 Summary

Table 4 provides a summary of all URq organised by product type (RoGI and RGV). For each URq, the type of work it relates to is identified (B: Background, P: Production, E: Evaluation). The level of requirements (TR: Threshold Requirement, BR: Breakthrough Requirement, GR: Goal Requirement) we aim to achieve at the end of Permafrost_cci is indicated in the third column.

Table 4. *Summary of User Requirements (URq) for the Rock Glacier Inventories (RoGI) and the Rock Glacier Velocity (RGV) products. In the column 'Type', Background (**B**) means that the requirement relates to the initial selection of the study areas, data and/or methods. Production (**P**) means that the related requirements must be considered during the production phase. Evaluation (**E**) means that the requirements are related to the quality assessment of the products. We report here the level of requirement we aim to achieve at the end of Permafrost_cci (**TR**: Threshold Requirement, **BR**: Breakthrough Requirement, **GR**: Goal Requirement).*

ID	PARAMETER	USER REQUIREMENTS	TYPE
URq_01	RoGI	**TR**: Relevant geographical coverage at the local–regional scale (valley side, drainage basin, mountain range).	**B**
URq_02	RoGI	**GR**: Inventory based on several recent datasets over the past 5–10 years.	**B**
URq_03	RoGI	**GR**: Identification by a primary marker (point) and rock glacier outline as a polygon following the extended and/or restricted geomorphological footprints. Each RGU is associated with one single system.	**P**
URq_04	RoGI	**TR**: Differentiation of RGUs and mono-unit or multi-unit systems, based on distinct timing of formation, different connections to the upslope unit or distinct activities/kinematics.	**P**
URq_05	RoGI	**TR**: Mandatory documentation of the temporal properties (acquisition data, time frame/window) of the data sources used for RoGI generation, required for comparison and potential future update.	**P**
URq_06	RoGI	**GR**: Updated activity categorization: active, transitional, or relict. Uncertainty between categories can be documented.	**P**
URq_07	RoGI	**TR**: Optional attribute, only documented when geomorphological or kinematic evidence is available.	**P**
URq_08	RoGI	**GR**: Semi-quantitative velocity classes, depending on the applied technique. For InSAR: 1–3 cm/yr, 3–10 cm/yr, 10–30 cm/yr, 30–100 cm/yr, etc.	**B/P**
URq_09	RoGI	**GR**: Semi-quantitative 'half an order-of-magnitude' categories: cm–dm/yr, dm/yr, dm–m/yr, m/yr, etc.	**B/P**
URq_10	RoGI	**GR**: The data properties (data source, dimensionality, time window/frame) must be documented for all attributes. The reliability of the moving areas, kinematic attributes and outlines is qualitatively assessed (low, medium, high).	**E**
URq_11	RGV	**BR:** Multiple sites in a defined region, allowing for	**B**

		preliminary analysis of similar/dissimilar trends.	
URq_12	RGV	**TR:** Active or transitional rock glaciers with movement related to permafrost creep. Sites where long-term monitoring is feasible. RGUs are fully characterised following the RoGI requirements.	**B**
URq_13	RGV	**GR**: 1 year, i.e. measured or computed once a year.	**B/P**
URq_14	RGV	**BR:** Observation time window < 1 year (e.g. summer period only). At least 1 month and consistent over time (max. ≈15 days of difference).	**B/P**
URq_15	RGV	**BR:** Temporal extent: past 5–10 years.	**B/P**
URq_16	RGV	**TR**: Annual mean velocity value. Unit: m/yr	**P**
URq_17	RGV	**GR**: The velocity is aggregated from flow field or several discrete points covering a large part of the RGU. The aggregation procedure and the considered area should be consistent over time.	**P**
URq_18	RGV	**TR**: Maximal relative error of the velocity data: 20%. If the error exceeds 20%, the site must be discarded, or alternative techniques should be considered in accordance with the measured/computed absolute velocity of the selected rock glacier.	**E**
URq_19	RGV	**GR**: No problems with the latest velocity data. High consistency after the latest annual increment of velocity time series. The observation time window, horizontal resolution and procedure to measure/compute the velocity are consistent over time.	**E**

6 References

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6.2 Acronyms

AD	Applicable Document
ALT	Active Layer Thickness
B.GEOS	b.geos GmbH
BR	Breakthrough Requirement
CCI	Climate Change Initiative
CCN	Contract Change Notice
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
FT	Feature Tracking
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GR	Goal Requirement
GT	Ground Temperature

GTOS	Global Terrestrial Observing System
IANIGLA	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientale
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
OT	Offset Tracking
PSD	Product Specification Document
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
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
SfM	Surface from Motion
TR	Threshold Requirement
WUT	West University of Timisoara