permafrost
cci

CCI+ PHASE 2
PERMAFROST

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

D1.1 User Requirement Document (URD)

VERSION 1.0

15 FEBRUARY 2023

PREPARED BY

b·geos

GAMMA REMOTE SENSING

UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

West University of Timisoara

TERRASIGNA

NORCE

UiO : University of Oslo

Document status sheet

Issue	Date	Details	Authors
0.0	30.11.2019	Final version CCN2 D1.1	C. Barboux, A. Bertone, R. Delaloye, L. Rouyet, A. Kääb, H. H. Christiansen, A. Onaca, F. Ardelean, V. Poncos, T. Strozzi, A. Bartsch
0.1	30.01.2023	First draft CCN4 D1.1	L. Rouyet
0.2	06.02.2023	Updated version CCN4 D1.1	C. Pellet, T. Strozzi, L. Rouyet
1.0	15.02.2023	Final version CCN4 D1.1	L. Rouyet, C. Pellet, R. Delaloye, A. Onaca, F. Sirbu, V. Poncos, A. Kääb, T. Strozzi, N. Jones, A. Bartsch

Author team

Line Rouyet, Cécile Pellet and Reynald Delaloye, UNIFR

Alexandru Onaca and Flavius Sirbu, WUT

Valentin Poncos, Terrasigna

Francesco Brardinoni, University of Bologna

Line Rouyet, NORCE

Andreas M. Kääb, UiO

Tazio Strozzi and Nina Jones, GAMMA

Annett Bartsch, BGEOS

ESA Technical Officer

Frank Martin Seifert

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.

TABLE OF CONTENTS

1 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, 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 is largely influenced by climatic factors. There are 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. It 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 even totally 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 technique 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 of 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 collaborative work of the IPA Action Group RGIK. The Action Group had extensive discussions and agreements during two workshops in 2019 and 2020, followed by several rounds of consultation, commenting and corrections of consensus-based international guidelines [RD-6 to RD-10]. The listed User Requirements (URq) are therefore an updated version of the initial Phase 1 URq, corrected based on recent RGIK community agreements.

1 Introduction

1.1 Purpose of the document

The User Requirement Document (URD) summarizes the user requirements of the mountain permafrost products: Rock Glacier Inventories (RoGIs) 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. 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-16].

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**] 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] 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. D1.2 Product Specification Document (PSD), v1.0. European Space Agency.

[RD-3] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onaca, A., Kroisleitner, C., Strozzi, T. 2020. ESA CCI+ Permafrost Phase 1. D1.1 User Requirement Document (URD), v2.0. European Space Agency.

[RD-4] Bartsch, A., Westermann, S., Strozzi, T., Wiesmann, A., Kroisleitner, C. 2020. ESA CCI+ Permafrost Phase 1. D1.2 Product Specification Document (PSD), v3.0. European Space Agency.

[RD-5] 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-6] 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-7] 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-8] 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-9] RGIK. 2020. Rock glacier inventory using InSAR (kinematic approach) (version 3.0.2). IPA Action Group Rock glacier inventories and kinematics, 40 pp.

[RD-10] RGIK 2022. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.1). IPA Action Group Rock glacier inventories and kinematics, 12 pp.

[RD-11] 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-12] 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-13] 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-14] Pellet, C., X., Bodin, D., Cusicanqui, R., Delaloye, A., Kääb, V., Kaufmann, J., Noetzli, E., Thibert and A. Kellerer-Pirklbauer. 2022. Rock Glacier Velocity. In Bull. Amer. Soc. Vol. 103(8), State of the Climate in 2021, pp. 43-45. https://doi.org/10.1175/2022BAMSStateoftheClimate.1.

[RD-15] 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-16] 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

3.1 Applications and users of the rock glacier products

In mountainous terrain, permafrost is occurring 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 because of the extreme variability of both the topographical setting and ground constitution. The combination of both gravity and steep topography makes the frozen ground susceptible to gradual downslope deformation (creep). Permafrost creep shapes 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-6].

Initiatives have risen for decades 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 glaciers, their key morpho-kinematic characteristics and their interannual velocity changes are therefore relevant for a wide range of users. Rock Glacier Inventories (RoGI) and Rock Glacier Velocity (RGV) time series can be 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 related hazards in particular**.

The climate research community also benefit from RoGI and RGV products to calibrate or validate models in mountain regions, where direct permafrost measurements are very scarce or even totally lacking, leading to large uncertainties in climate change projection [RD-14]. Rock glaciers are often moving at a rate closely depending on the temperature profile between the permafrost table and the main shear horizon at depth. RGV time series documenting the interannual changes of permafrost creep rates can be used as indicator of climatic change in mountains [RD-13]. In 2022, GCOS has decided to add **RGV as new product associated to the ECV Permafrost** [AD-02]. The general requirements for producing such time series have been defined [AD-03], but further work is still needed to develop 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.

3.1 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 remotely sensed images, the number of dedicated rock glacier studies with a regional-global perspective keeps increasing. However, these studies often rely on different methodologies based on the unequal availability of source datasets and on variable local skills and institutional support. With the objective to define standard inventorying and monitoring rules and generate comparable RoGI and RGV worldwide, the international initiative IPA Action Group on *Rock glacier inventories and kinematics* (RGIK) was launched in 2018 [RD-5]. In parallel,

the activities of Permafrost_cci Phase 1 supported the objectives of the IPA Action Group RGIK and applied the international guidelines to develop pilot RoGI and RGV results, primarily based on satellite remote sensing products [RD-11] [RD-12]. The generation of RoGI in 12 regions involved six external partner institutions, in addition to the Permafrost_cci partners.

In the first iteration of Permafrost_cci Phase 2 (15.11.22 – 15.05.24), it is intended to:

- For RoGI: perform a cross-check exercise with multiple operators to evaluate the RoGIs in selected subareas from the initial regions of Permafrost_cci Phase 1 (Table 1, upper part), refine the inventorying procedure and consolidate the initial RoGIs.
- For RGV: further define the procedure to convert initial InSAR time series into RGV and generate pilot ECV products for selected RGs.

In the second iteration of Permafrost_cci Phase 2 (15.05.24 – 15.11.25), it is intended to:

- For RoGI: revise the 12 initial regions based on the conclusions from the first iteration, compile inventories in six new regions (Table 1, lower part) and explore possibilities of the using RoGI as training data for automated inventorying solution (machine learning).
- For RGV: evaluate the chosen procedure with a multi-institution round robin, potentially adjust the procedure and generalize the production (generation for more landforms in more regions).

As for Phase 1, **external partners** will be involved in the consolidation of the initial RoGI and the generation of new RoGI in additional regions. The work will focus on 18 regions in collaboration with 16 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 different continents are represented. The regions are further described in the PSD.

The shared responsibility of the RoGI consolidation and 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 considered 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: 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 landforms and unstable rock slopes.
- The national meteorological institutes conducting monitoring programmes and research in climatology and permafrost-climate interactions in the Earth System.
- A large public (e.g. mountaineers, local community) having an interest in mountain stability issues and relations with climate change.

In addition, the project will follow the simultaneous developments occurring within the IPA Action Group RGIK, which involves a constantly growing pool of people from the international mountain permafrost community. The IPA Action Group RGIK represent a wide range of backgrounds, perspectives and applications, from different institutions all around the World. **In January 2023, the RGIK community counted 195 members from 25 countries.** RGIK consensus-based decisions regarding the RoGI and RGV recommendations and associated guidelines are used for the definition of the Permafrost_cci User Requirements (URq) in the following sections.

Table 1: *Permafrost_cci Phase 2 regions and responsible institutions*

RoGI consolidation (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)	Option 8 Proposal
Finnmark (Norway)	NORCE Norwegian Research Centre (Norway)	Option 8 Proposal
Nordenskiöld Land (Svalbard)	NORCE Norwegian Research Centre (Norway)	Option 8 Proposal
Southern Venosta (Italy)	University of Bologna (Italy)	CCN4 Option 9
Carpathians (Romania)	WUT and Terrasigna (Romania)	CCN4 Option 9
Vanoise Massif (France)	University of Savoie / University Grenoble Alps (France)	External partner
Brooks Range (Alaska)	University of Alaska Fairbanks (USA)	External partner
Central Andes (Argentina)	IANIGLA (Argentina)	External partner
Tien Shan (Kazakhstan/Kirghizistan)	University of St. Andrews (UK) / TU Graz (Austria)	External partner
Southern Alps (New Zealand)	University of Lausanne (Switzerland)	External partner
Proposed RoGI in new regions (Permafrost_cci Phase 2 Phase 2 second iteration)		
RoGI region	**Responsible institution**	**CCI affiliation**
Goms – Binntal (Switzerland)	University of Fribourg (Switzerland)	CCN4 Baseline
Northern Vensota (Italy)	University of Bologna (Italy)	CCN4 Option 9
Rila and Pirin Mts (Bulgaria)	WUT and Terrasigna (Romania)	CCN4 Option 9
To be defined	The Chinese University of Hong Kong (China)	External partner
To be defined	Queen's University (Canada)	External partner
Tsengel Khairkhan	Mongolian Academy of Sciences (Mongolia)	External partner

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 summarized in Section 3.1.

The URq have been **adjusted based on the recent work of the RGIK community in 2019–2022**. The consensus-based decisions that were taken these past years are summarized in the latest versions of the RGIK guidelines [RD-6 to RD-10]. 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-6]. This definition is used to identify the landforms inventoried and monitored in Permafrost_cci.

RoGI and RGV URq are described separately in Section 3.2 and 3.3, according to three levels of requirements, following GCOS definitions [AD-03]:

- **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 specified 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 until 31st of October 2019. In total, 32 international scientists working in mountain permafrost areas responded to the survey. They were mainly from research organizations and higher 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 whatever 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 5-10 past 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 (both TR and GR) [Phase1_URq_05]. Qualitative information with defined classes of activity is required (GR; TR was undefined) [Phase1_URq_06], while the documentation of a potential destabilization is useful (GR), but should remain optional (target requirement) [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 every 1 year (GR) to 5 years (TR) [Phase1_URq_13]. They meant that the RGV 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 (and ideally 1 cm/yr (GR) was required [Phase1_URq_18].

3.2 Adjusted User Requirements for Rock Glacier Inventories (RoGI)

The current RGIK recommendations for RoGI (status: January 2023) have been used to adjust the Permafrost_cci Phase 2 User Requirements, summarized in *Table 2*. Some URq remain mostly the same as in the Phase 1 and have simply been slightly rephrased to clarify their purpose/meaning [URq_01] [URq_02] [URq_05]. For the other URqs, the IPA Action Group 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 the RoGIs, we have inversed the order of [URq_08] (moving areas) and [URq_09] (kinematics).

Table 2. *Permafrost_cci Phase 2 User Requirements for rock glacier inventory (RoGI) products*

	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 RoGI for all mountain ranges whatever the national boundary.
Time frame and temporal extent [URq_02]	Inventory based on datasets one recent year, at the time of the production.	Inventory based on several recent datasets over a 5-10 years' period, at the time of the production.
	Resolution	
Rock glacier location [URq_03]	Identification by a primary marker (point named with a unique code / ID). [RD-7]	Identification by a primary marker (point) and rock glacier outline as a polygon following the extended and/or restricted geomorphological footprints). Each RGU must imperatively be associated with one

		single RGS. [RD-7]
Multi-unit differentiation [URq_04]	Differentiation of rock glacier units (RGU) and mono-unit or multi-unit systems (RGS), based on distinct timing of formation, different connections to the upslope unit or distinct activities/kinematics. [RD-6]	-
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 update.	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-6] [RD-7]	Updated activity categorization: active, transitional, or relict. Uncertainty between categories can be documented. [RD-6] [RD-7]
Rock glacier destabilization [URq_07]	Optional attribute, only documented when geomorphological or kinematic evidence is available. [RD-7]	Present (ongoing) or past (completed) evidence of destabilization. [RD-7]
Moving areas [URq_08]	Optional layer, only when reliable kinematic data (with sufficient spatial coverage) is available. [RD-8]	Semi-quantitative velocity classes, depending on the applied technique [RD-8] For InSAR: 1-3 cm/yr, 3-10 cm/yr, 10-30 cm/yr, 30-100 cm/yr, etc. [RD-9]
Kinematics [URq_09]	Optional attribute, only documented when reliable kinematic data is available. [RD-8]	Semi-quantitative 'half an order-of-magnitude' categories: cm-dm/yr, dm/yr, dm-m/yr, m/yr, etc. [RD-8]
	Error/Uncertainty	
Precision & accuracy [URq_10]	Optional attributes (e.g. kinematics and activity) that are too uncertain must remain 'Undefined'. [RD-7] [RD-8] [RD-9]	The data properties (data source, dimensionality, time window/frame) must be documented for all attributes. The reliability and spatial representativeness of moving areas and kinematic attributes must be qualitatively assessed (low, medium, high). [RD-7] [RD-8] [RD-9]

[1] Threshold requirement: The minimum requirement to be met to ensure that the data are useful. [AD-03].

[2] Goal requirement: The ideal requirement above which further improvements are not necessary [AD-03].

[3] Note that for the rock glacier morpho-kinematic attributes, the threshold requirement is defined as the optional definition of the attribute according to the RGIK guidelines. The Goal requirement is the Systematic definition of the attribute 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 recommendations of the IPA Action Group RGIK [RD-10] 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. 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 User Requirements are summarized 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 Phase 2 User Requirements for RGV products [RD-10] [AD-03].*

	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 analysing 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. Rock glacier units 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]	One 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 rock glacier unit.	The velocity is aggregated from at least 3 points distributed referring to a consistent flow field representing the downslope movement of a rock glacier unit. 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 rock glacier unit. 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 site must be discarded, or alternative techniques should be considered in accordance with the absolute velocity measured/computed of the selected rock glacier.	Intermediate relative error threshold: 5-20%. Specific attention should be paid in the future, especially if the velocity is decreasing. In that case, a change of the measurement technique or its temporal settings should be done.	Optimal relative error of the velocity data: <5%. The technique is chosen in accordance with the absolute velocity measured/computed of the selected rock glacier and allows the 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: The minimum requirement to be met to ensure that the data are useful [AD-03].

[2] Breakthrough requirement: An intermediate level between threshold and goal, which, if achieved, would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specified uses within climate monitoring become possible [AD-03].

[3] Goal requirement: 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 feasibility of the user requirements. The work that will be performed as part of Permafrost_cci Phase 2 will hopefully contribute solving these open questions, in synergy with the parallel activities of the IPA Action Group RGIK.

4.1 Rock glacier inventories (RoGI)

Since the start of the Phase 1 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 rock glacier units/systems remain optional, to avoid artificially documenting geomorphological or kinematic information when the uncertainty is too large or when reliable data is lacking.

All Threshold Requirements are expected to be met by the RoGI Phase 2 Permafrost_cci products. As the project focuses on the integration of kinematic information in the RoGI based on satellite remote sensing, we even expect to meet the Goal Requirements in several 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 RoGI will therefore be based on several recent datasets (multiple sources) over a 5-10 years' period, 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 rock glacier unit: an outline should be drawn only if sufficient geomorphological evidence is available. However, a comprehensive characterisation of 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 the Phase 1, we expect that most RoGI will include polygonal delineations corresponding to their extended 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 the IPA action group 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 not in a relict state, but that there is not sufficient evidence to distinguish between an "active" and 'transitional' state. 'Relict uncertain' can be used in case a rock glacier is 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 Phase 1 has contributed to the elaboration of practical guidelines for generating RoGI using InSAR. The procedure consists in 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 will remain the same in the 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 movement from InSAR to document rock glacier kinematics. The Goal Requirement will therefore be met in most cases: based on InSAR moving areas, we will assign a semi-quantitative 'half an order-of-magnitude' categories to the rock glacier units: 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 and spatial representativeness of moving areas and kinematic attributes will be 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) will therefore be documented for all attributes.

4.2 Rock glacier velocity time series (RGV)

Threshold Requirements are expected to be met by the RGV Phase 2 Permafrost_cci products. As the user requirements are generic and potentially applicable for a large range a measurement technique (e.g. in-situ point-based measurements), we expect to reach Breakthrough or Goal requirements in several cases, thanks to the temporal frequency and spatial coverage of InSAR:

- **Temporal resolution (frequency) [URq_13]:** The Threshold Requirement of 5 years of measurement frequency has been set to allow for using aerial images with variable periodicity depending on regional/national coverages, especially when considering historical archives. With InSAR data based on recent sensors such as Sentinel-1, velocity data computed once a year can be provided (Goal Requirement).
- **Temporal resolution (observation time window) [URq_14]:** The Breakthrough requirement can be reached using InSAR, as the observation time window is < 1 year in area with snow cover (data gaps). In the first iteration of Permafrost_cci Phase 2, we will select study areas where Sentinel-1 interferograms are available for at least 1 month/year. Technique to temporal aggregate the data and keep a consistent time window between years (max. ≈15 days of difference) will be developed.
- **Temporal extent [URq_15]:** The temporal extent of the primary data source of Permafrost_cci (i.e. Sentinel-1) is 5-10 years (Breakthrough Requirement).
- **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 (Goal requirement).

Despite these assumptions, it should be noted that the standardized 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 IPA Action Group RGIK is ongoing. The first version of the RGV practical concepts is currently being finalized by the scientific committee and should be communicated to all members of the Action Group in March 2023. After round(s) of commenting, the objective is to an approved version in Summer 2023. It is therefore expected that the RGV user requirements will require a significant update for the URD of the second Permafrost_cci iteration.

5 Summary

Table 4 provides a summary of the user requirements organised by product type (RoGI and RGV). For each user requirement, the type of work it relates to is identified. We aim to meet as all the Threshold Requirements during the Phase 2 Permafrost_cci. When the Threshold requirements correspond to the expected properties of the Permafrost_cci products, the URq is shown in black. When we expect to meet the Breakthrough Requirement, the URq is shown in blue. When the goal requirement is expected to be reached, the URq is shown in green. The results of the first iteration will be evaluated against these objectives, and may contribute to adjust the work strategy for the second iteration.

Table 4. *Summary of user requirements for the Rock Glacier Inventories (RoGI) and the Rock Glacier Velocity (RGV) products. In the column 'Type', Background (BG) 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. The colours related to expected results of the Phase 2 of Permafrost_cci, as previously described in Section 4 (in black:* ***Threshold Requirement****; in blue:* ***Breakthrough Requirement****; in green:* ***Goal Requirement****).*

ID	PARAMETER	USER REQUIREMENTS	TYPE
URq_01	RoGI	Relevant geographical coverage at the local-regional scale (valley side, drainage basin, mountain range).	BG
URq_02	RoGI	Inventory based on several recent datasets over the 5-10 past years.	BG
URq_03	RoGI	Identification by a primary marker (point) and rock glacier outline as a polygon following the extended and/or restricted geomorphological footprints). Each RGU must imperatively be associated with one single RGS.	P
URq_04	RoGI	Differentiation of rock glacier units (RGU) and mono-unit or multi-unit systems (RGS), based on distinct timing of formation, different connections to the upslope unit or distinct activities/kinematics.	P
URq_05	RoGI	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	Updated activity categorization: active, transitional, or relict.	P
URq_07	RoGI	Optional attribute, only documented when geomorphological or kinematic evidence is available.	P
URq_08	RoGI	Semi-quantitative 'half an order-of-magnitude' categories: cm-dm/yr, dm/yr, dm-m/yr, m/yr, etc.	BG/P
URq_09	RoGI	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.	BG/P
URq_10	RoGI	The data properties (data source, dimensionality, time	E

		window/frame) must be documented for all attributes. The reliability and spatial representativeness of moving areas and kinematic attributes must be qualitatively assessed (low, medium, high).	
URq_11	RGV	Multiple sites in a defined region, allowing for preliminary analysis of similar/dissimilar trends.	BG
URq_12	RGV	Active or transitional rock glaciers with movement related to permafrost creep. Sites where long-term monitoring is feasible. Rock glacier units fully characterised following RoGI requirements.	BG
URq_13	RGV	1 year, i.e. measured or computed once a year.	BG/P
URq_14	RGV	Observation time window < 1 year (e.g. summer period only). At least 1 month and consistent over time (max. ≈15 days of difference).	BG/P
URq_15	RGV	Temporal extent: past 5-10 years	BG/P
URq_16	RGV	Annual mean velocity value. Unit: m/yr	P
URq_17	RGV	The velocity is aggregated from flow field or several discrete points covering a large part of the rock glacier unit. The aggregation procedure and the considered area should be consistent over time.	BG/P
URq_18	RGV	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 absolute velocity measured/computed of the selected rock glacier.	E
URq_19	RGV	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).	E

References

6.1 Bibliography

-

6.2 Acronyms

AD	Applicable Document
ALT	Active Layer Thickness
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
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
MAGT	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
PSD	Product Specification Document
RD	Reference Document
RG	Rock Glacier
RGIK	Rock Glacier Inventories and Kinematics
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