permafrost
cci

CCI+ PHASE 2
PERMAFROST

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

D2.4 Algorithm Development Plan (ADP)

VERSION 2.0

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EUROPEAN SPACE AGENCY CONTRACT REPORT
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Executive summary

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

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

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

This Algorithm Development Plan (ADP) describes the development planned in the second iteration of CCN4 (2024–2025), according to the initial proposal and in synergy with the future plans of the RGIK international community. This is an updated version (version 2.0) including minor corrections and updates.

1 Introduction

1.1 Purpose of the document

The mountain permafrost component of Permafrost_cci Phase 2 focuses on the generation of two products: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). The Algorithm Development Plan (ADP) suggested idea for future developments in the extension phase of Permafrost_cci (2025–2026) and at longer-term, via the CLIMATE-SPACE programme.

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 describes the algorithm development plan. A list of acronyms is provided in Section 3. A glossary of the commonly accepted permafrost terminology can be found in [RD-18].

1.3 Applicable documents

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

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

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

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

1.4 Reference Documents

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

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

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

[RD-4] RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2). IPA Action Group Rock glacier inventories and kinematics, 13 pp.

[RD-5] RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0). IPA Action Group Rock glacier inventories and kinematics, 10 pp.

[RD-6] RGIK. 2022. Optional kinematic attribute in standardized rock glacier inventories (version 3.0.1). IPA Action Group Rock glacier inventories and kinematics, 8 pp.

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

[RD-8] RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories. Practical InSAR guidelines (version 4.0). IPA Action Group Rock glacier inventories and kinematics, 33 pp.

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

[RD-10] RGIK 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: practical concepts (version 1.2). IPA Action Group Rock glacier inventories and kinematics, 17 pp.

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

[RD-12] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2020. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.2 Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.

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

[RD-14] Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Christiansen, H. H., Darrow, M. M., Delaloye, R., Etzelmüller, B., Humlum, O, Lambiel, C., Lilleøren, K. S., Mair, V., Pellegrinon, G., Rouyet, L., Ruiz, L., Strozzi, T. 2022. Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide. The Cryosphere. 16, 2769–2792. https://doi.org/10.5194/tc-16-2769-2022.

[RD-15] Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D3.2 Climate Research Data Package (CRDP), v1.0. European Space Agency.

[RD-16] Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Kääb, A., Kaufmann, V., Thibert E., Vivero, S. and Kellerer-Pirklbauer, A. 2023. Rock Glacier Velocity. In Bull. Amer. Soc. Vol. 105(8), State of the Climate in 2023, pp. 43–45. https://doi.org/10.1175/2024BAMSStateoftheClimate.1

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

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

2 Algorithm Development Plan

2.1 General timeline and synergy with the RGIK community

Since Permafrost_cci Phase 1, the work on developing mountain permafrost products able to complement modelling products has been designed and performed in parallel to the activities of the **International Permafrost Association (IPA) Action Group on Rock Glacier Inventories and Kinematics (RGIK)**. The IPA Action Group RGIK was launched in 2018 with the objective to sustain the first steps toward the development of a network dedicated to rock glacier inventorying (mapping) and to promote the integration of the rock glacier velocity (RGV) as a new associated parameter to Essential Climate Variable (ECV) Permafrost to monitor the evolution of mountain permafrost at the global scale. RGIK currently consists of **a network of about 200 people from 25 countries**. Between 2018 and 2023, RGIK organized three workshops, released eight reference documents (baseline concepts and practical guidelines) to map and monitor rock glaciers. Webinars to discuss scientific advances in the field of mountain permafrost are organized each month. User-friendly exercise, flowchart and tutorial to explain and apply the guidelines have been released. The group has been a key actor to promote RGV as ECV parameter. In 2022, GCOS and GTN-P have accepted to add RGV as a third parameter to be complement GT and ALT for the global monitoring of permafrost. There is no doubt that the initial objectives of the group have been fulfilled.

The IPA Action Group RGIK formally ended in 2023. The European Conference on Permafrost (EUCOP) in Puigcerdà (Spain) hosted the last workshop of RGIK as Action Group. In total 55 people participated (40 people on-site, 15 people online). One important objective of the workshop was to agree on the future structure and objectives of the group. It was concretized by the signature of the Puigcérda Commitment that stated the goal to transition into a permanent structure. In 2024, RGIK bylaws were approved, and an Executive Committee was elected by the members. A formal request to become an IPA Standing Committee was sent to the IPA Council, which unanimously approved the proposition at its meeting in June 2024 (Whitehorse, Canada). From a phase of network building, standard definition and promotion, **RGIK is now moving toward a more operational phase.** RGIK aims to provide the necessary **framework for the systematic production** of RoGI and RGV and act as a reference group to **coordinate the effort on detailed requirements, product generation, data management/sharing and outreach**.

The second iteration of Permafrost_cci contributes to the similar objectives. While the first iteration focuses on refining RoGI products, detailing the procedure for RGV production and generating test cases for InSAR-based RGV, the second iteration aims to generate the RoGI products in new regions, and to finalize and widely apply the InSAR-based procedure for RGV production. We plan to further this effort in the extension phase (2026), with a special focus placed on **the operationalisation of the RGV generation and the dissemination of the products to be used as climate change indicators**. In the long-term perspective, the products generated in the Permafrost_cci framework are meant to serve as examples to promote similar initiatives by different groups and in many regions all around the World.

2.2 Rock glacier inventory (RoGI)

For RoGI, the first iteration of Permafrost_cci Phase 2 (15.11.22 – 15.05.24) focused on performing a cross-check exercise with multiple operators (see ATBD) to evaluate the RoGIs in selected subareas from the initial regions of Permafrost_cci Phase 1 (*Table 1*, upper part; see also PSD), refine the inventorying procedure and consolidate the initial RoGIs.

In the second iteration of Permafrost_cci Phase 2 (15.05.24 – 15.11.25), we are working on:

- **Revising the rock glacier inventories in the 12 initial regions** based on the conclusions from the first iteration, i.e. the analyse of discrepancies between operators and the results of the consensus-based process (see E3UB);
- **Compiling rock glacier inventories in six new regions** (*Table 1*, lower part) to cover more comprehensively different parts of the world with diverse topo-climatic characteristics. The conclusions from the first iteration may allow for identifying unclear steps in the RoGI procedure, that lead to discrepancies between operators. In the second iteration, adjusted guidelines are used to generate RoGI in the new regions;
- **Exploring possibilities of using RoGI as training data for automated inventorying solution.** The automation of the RoGI procedure is designed and performed with third parties (partner institutions with expertise in machine learning). The activity is taking advantage of the large RGIK network to advertise the project and involve external partners willing to test machine learning algorithms for developing a RoGI-dedicated artificial intelligence.

During the extension phase (2026), support to extension and dissemination of RoGI products in new regions may continue but we envision that the main focus will be placed on RGV (see Section 2.3).

Table 1: *Permafrost_cci Phase 2 regions and responsible institutions. From PSD [RD-1].*

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)	West University of Timisoara and Terrasigna (Romania)	CCN4 Option 9
Manaslu (Nepal)	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

2.3 Rock glacier velocity (RGV)

For RGV, the first iteration of Permafrost_cci Phase 2 (15.11.22 – 15.05.24) focused on defining the procedure to convert initial InSAR time series into standard RGV products (see ATBD) and generate pilot ECV products for selected rock glaciers (see PSD).

In the second iteration of Permafrost_cci Phase 2 (15.05.24 – 15.11.25), we are working on:

- **Evaluating the procedure for InSAR-based RGV production using the conclusions of a multi-operators and multi-techniques RGV intercomparison exercise**. Three alpine rock glaciers with good data available (in-situ, optical and radar) have been selected. The operators are processing RGV based on the same data collection and following the RGIK guidelines [RD-9] [RD-10]. The results will be discussed during a workshop at the end of November 2024. The InSAR-RGV methodology described in the ATBD may be adjusted if the results of the intercomparison exercise highlight discrepancies and issues for general applicability.
- **To generalize the RGV production by generating similar products on many rock glaciers**. This is meant to be done in several previously inventoried regions (see Section 2.1; *Table 1*) but also for a large number of landforms within specific regions. The ultimate objective is to evaluate if the rock glaciers within specific regions have similar velocity trends and can serve the development of regional indices used as climate change indicators.

During the extension phase, we are planning to build on the results of the intercomparison exercise, finalise an operational production chain for InSAR-RGV and apply it on more landforms and more regions. **As ECV associated parameter, RGV production, dissemination and exploitation will be our priority in 2025 and beyond**

3 Acronyms

AD	Applicable Document
AI	Artificial Intelligence
ALT	Active Layer Thickness
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
BR	Breakthrough Requirement
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CCN	Contract Change Notice
CRDP	Climate Research Data Package
DEM	Digital Elevation Model
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
FT	Feature Tracking
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System
GR	Goal Requirement
GT	Ground Temperature
GTN-P	Global Climate Observing System
GTOS	Global Terrestrial Observing System
IANIGLA	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientale
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
KA	Kinematic Attribute
LOS	Line-of-sight
MA	Moving Area
MAGT	Mean Annual Ground Temperature
MAGT	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
OT	Offset Tracking
PERMOS	Swiss Permafrost Monitoring Network
PI	Principal Investigator
PM	Primary Marker
PSD	Product Specification Document
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RD	Reference Document
RG	Rock Glacier
RGIK	Rock Glacier Inventories and Kinematics

RGU	Rock Glacier Unit
RGV	Rock Glacier Velocity
RoGI	Rock Glacier Inventory
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SfM	Surface from Motion
TR	Threshold Requirement
UAV	Unmanned Aerial Vehicle
UiO	University of Oslo
UniBo	University of Bologna
UNIFR	University of Fribourg
URD	Users Requirement Document
URq	User Requirement
UTM	Universal Transverse Mercator
WUT	West University of Timisoara
WMO	World Meteorological Organization