CCI+ PHASE 1 – NEW ECVS
PERMAFROST

CCN1 & CCN2
ROCK GLACIER KINEMATICS AS NEW ASSOCIATED PARAMETER OF ECV PERMAFROST

D2.5 Product Validation Plan (PVP)

VERSION 1.0

30 APRIL 2020

PREPARED BY

Document Status Sheet

Issue	Date	Details	Authors
0.1	31.01.2020	Template based on [RD-5] & [RD-9]	L. Rouyet
0.2	09.03.2020	First draft to co-authors	L. Rouyet
0.3	13.03.2020	New version after feedback	L. Rouyet, C. Barboux, A. Bartsch
0.4	27.03.2020	New version after feedback	L. Rouyet, C. Barboux, A. Onaca, F. Sirbu
0.5	19.04.2020	New version after feedback	L. Rouyet, A. Kääb, H.H. Christiansen
1.0	30.04.2020	Final version	L. Rouyet, C. Barboux, A. Bartsch

Author team

Line Rouyet and Tom Rune Lauknes, NORCE

Chloé Barboux, Aldo Bertone and Reynald Delaloye, UNIFR

Andreas Kääb, GUIO

Hanne H. Christiansen, UNIS

Alexandru Onaca and Flavius Sirbu, WUT

Valentin Poncos, TERRASIGNA

Tazio Strozzi, GAMMA

Annett Bartsch, B.GEOS

ESA Technical Officer:

Frank Martin Seifert

EUROPEAN SPACE AGENCY CONTRACT REPORT

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The European Space Agency (ESA) Climate Change Initiative (CCI) is a global monitoring program that aims to provide long-term satellite-based products to serve the climate modelling and climate data user community. Permafrost has been selected as one of the Essential Climate Variables (ECVs) that are elaborated during Phase 1 of CCI+ (2018-2021). As part of the Permafrost_cci baseline project, ground temperature and active layer thickness were considered to be the primary variables that require climate-standard continuity as defined by the Global Climate Observing System (GCOS). Permafrost extent and zonation are secondary parameters, but of high interest to users. The ultimate objective of Permafrost_cci is to develop and deliver permafrost maps as ECV products primarily derived from satellite measurements. Algorithms have been identified, which can provide these parameters by ingesting a set of global satellite data products (Land Surface Temperature LST, Snow Water Equivalent SWE, and Landcover) in a permafrost model scheme that computes the ground thermal regime. Annual averages of ground temperature and annual maxima of thaw depth (active layer thickness) were provided at 1 km spatial resolution during Year 1 of Permafrost_cci. The data sets were created from the analysis of lower level data, resulting in gridded, gap-free products.

In periglacial mountain environments, the permafrost occurrence is patchy, and the preservation of permafrost is controlled by site-specific conditions. Three options initiated within CCN1 and CCN2 address the need for additional regional cases in cooperation with dedicated users in characterizing mountain permafrost as local indicator for climate change and direct impact on the society in mountainous areas. Started in October 2018, CCN1 is led by a Romanian team focusing on case studies in the Carpathians. The specific objective of CCN1 is to develop and deliver maps and products for mountain permafrost, such as (i) rock glacier inventories, (ii) kinematical time series of selected rock glaciers and (iii) a permafrost distribution model, primarily derived from satellite measurements. Started in September 2019, CCN2 consists of two options led by Swiss and Norwegian teams focusing on the investigation and definition of a new associated ECV Permafrost product related to rock glacier kinematics. Early 2020, Rock Glacier Kinematics (RGK) has been proposed as a new product to the ECV Permafrost for the next GCOS implementation plan (IP). It would consist of a global dataset of surface velocity time series measured/computed on single rock glacier units. A proper rock glacier kinematics monitoring network, adapted to climate research needs, builds up a unique validation dataset of climate models for mountain regions, where direct permafrost (thermal state) measurements are very scarce or even lacking totally. The international Action Group *Rock glacier inventories and kinematics*, under the IPA (International Permafrost Association), gathering about one hundred members, supports this integration and CCN2 is working closely with this Action Group [RD-10 to RD-13]. Following the recommendations of this IPA Action Group, the overall goal of CCN2 is achieved through the development of two products: (i) regional rock glacier inventories and (ii) kinematical time series of selected rock glacier. User Requirements, Product Specifications and Data Access Requirements are described in D1.1-1.3 of CCN 1&2 [RD-6 to RD-8].

This Product Validation Plan (PVP) defines the rules for unbiased validation and the criteria applied for the three products of CCN 1&2. It described the planned validation activities and lists the available datasets at the different study sites. It presents the timeline related to the validation documents and endorsement.

1 INTRODUCTION

1.1 Purpose of the document

The products required within CCN1 and CCN2 of the ESA Permafrost_cci project for mountain permafrost regions include (i) regional rock glaciers inventories, including a kinematical attribute (RGI), (ii) kinematical time series (KTS) on selected rock glaciers, and (iii) a mountain permafrost distribution model (MPDM) in the Carpathians. The Product Validation Plan (PVP) describes the planning for the validation of the products, as introduced in the PSD [RD-7].

1.2 Structure of the document

- Section 1 provides information about the purpose and background of this document.
- Section 2 defines the rules for unbiased validation and the validation criteria.
- Section 3 describes the planned validation activities and recalls the justification of the selected algorithms.
- Section 4 provides an overview of validation documents and endorsement.

1.3 Applicable documents

[AD-1] ESA. 2017. Climate Change Initiative Extension (CCI+) Phase 1 – New Essential Climate Variables - Statement of Work. ESA-CCI-PRGM-EOPS-SW-17-0032.

[AD-2] Requirements for monitoring of permafrost in polar regions - A community white paper in response to the WMO Polar Space Task Group (PSTG), Version 4, 2014-10-09. Austrian Polar Research Institute, Vienna, Austria, 20 pp.

[AD-3] ECV 9 Permafrost: assessment report on available methodological standards and guides. 2019-11-01. GTOS-62.

[AD-4] GCOS-200. 2016. The Global Observing System for Climate: Implementation Needs. GCOS Implementation Plan, WMO.

[AD-5] GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO) protocols 3-4

[AD-6] ESA Climate Change Initiative. CCI Project Guidelines. EOP-DTEX-EOPS-SW-10-0002

1.4 Reference Documents

[RD-1] Bartsch, A., Westermann, S., Strozzi, T. 2019. ESA CCI+ Permafrost. D2.1 Product Validation and Algorithm Selection Report (PVASR), v2.0.

[RD-2] Westermann, S., Bartsch, A., Strozzi, T. 2019. ESA CCI+ Permafrost. D2.2 Algorithm Theoretical Basis Document (ATBD), v2.0.

[RD-3] Westermann, S., Bartsch, A., Heim, B., A., Strozzi, T. 2019. ESA CCI+ Permafrost. D2.3 End-to-End ECV Uncertainty Budget (E3UB), v2.0.

[RD-4] Westermann, S., Bartsch, A., Heim, B., A., Strozzi, T. 2019. ESA CCI+ Permafrost. D2.4 Algorithm Development Plan (ADP), v2.0.

[RD-5] Heim, B., Wieczorek, M., Pellet, C., Delaloye, R., Barboux, C., Westermann, S., Bartsch, A., Strozzi, T. 2019. ESA CCI+ Permafrost. D2.5 Product Validation Plan (PVP), v2.0.

[RD-6] 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. CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D1.1 User Requirement Document (URD), v1.0.

[RD-7] 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. CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D1.2 Product Specification Document (PSD), v1.0.

[RD-8] 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. CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D1.3 Data Access Requirement Document (DARD), v1.0.

[RD-9] Strozzi, T., Sîrbu, F., Onaca, A, Ardelean, F., Poncos, V., Bartsch, A. 2019. ESA CCI+ Permafrost. CCN1 Rock Glacier Kinematics in the Carpathians (Romania). D2. Algorithm Development Document, v1.0.

[RD-10] IPA Action Group Rock glacier inventories and kinematics. 2020. Towards standard guidelines for inventorying rock glaciers. Baseline concepts. Last version available on: https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/IPA/CurrentVersion/Current_Baseline_Concepts_Inventorying_Rock_Glaciers.pdf

[RD-11] IPA Action Group Rock glacier inventories and kinematics. 2020. Kinematics as an optional attribute of standardized rock glacier inventories. Last version available on: https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/IPA/CurrentVersion/Current_KinematicalAttribute.pdf

[RD-12] IPA Action Group Rock glacier inventories and kinematics. 2020. Rock glaciers kinematics as an associated parameter of ECV Permafrost. Last version available on: https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/IPA/CurrentVersion/Current_RockGlacierKinematics.pdf

[RD-13] IPA Action Group Rock glacier inventories and kinematics. 2020. Response to GCOS ECV review – ECV Permafrost. ECV Product: Rock Glacier Kinematics. Available on: https://gcos.wmo.int/en/ecv-review-2020.

[RD-14] van Everdingen, Robert, ed. 1998 (revised 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/; accessed 23.09.2009).

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 5.1.

1.6 Acronyms

A list of acronyms is provided in Section 5.2.

1.7 Glossary

A comprehensive glossary of terms relevant for the parameters addressed in Permafrost_cci is available as part of the Reference Documents of the baseline project [RD-1 to RD-5] and of CCN 1-2 [RD-6 to RD-9], as well as in [RD-14].

2 RULES FOR UNBIASED VALIDATION AND VALIDATION CRITERIA

As for the baseline project [RD-5], the project team shall ensure independency for the validation implying that the assessment of the Permafrost_cci products, as well as its uncertainties, are established with independent data sets and suitable statistical approaches [AD-1, 5, 6]. The standardized methodology for rock glacier kinematics is proposed by the IPA Action Group. The validation needs to be carried out by teams not involved in the product generation. The validation in CCN1 and CCN2 Permafrost_cci will be based on independent validation datasets which differ from those used for the product generation and will be performed by regional experts not involved in the product generation.

The validation team consists of:

- For the option 1 of CCN2 (Swiss team): Cécile Pellet (Permos), Reynald Delaloye (Unifr, leader of the IPA Action Group), Aldo Bertone (Unifr, evaluation of products from external partners)
- For the option 4 of CCN2 (Norwegian team): Hanne H. Christiansen (UNIS, President of the IPA), Andreas M. Kääb (UiO), Bernd Etzelmüller (UiO), Karianne S. Lilleøren (UiO)
- For CCN1 (Romanian team): Flavius Sirbu (WTU), Alexandru Onaca (WTU)

Independent assessment is also sought from individual members of the *IPA Rock glacier inventories and kinematics Action Group* (RGI and KTS products), the *IPA Permafrost mapping Action Group* (MPDM product) and the permafrost Climate Research Group (CRG).

2.1 Regional rock glacier inventories, incl. kinematics (RGI)

The geomorphological elements of the inventories, i.e. the identification of the rock glaciers, the definition of the units/systems, the delineations of the landforms, the attributes “spatial connection of the rock glacier to the upslope unit” and the attribute “activity” will follow the recommended methodology and guidelines, developed by the IPA Action Group (see CCN 1&2 D2.1 PVASR and [RD-10]). During the production/update of the RGI, it will be recommended that at least two persons perform the work to reduce operator’s subjectivity and ensure the quality of the results. The standard products will be made available to the community and evaluated by experts in mountain permafrost. The feedback from the members of the IPA Action Group (over hundred people), as well as potential external contributors, will be used for the validation process. We plan to complement the communication of the products by a survey about the general utility of the datasets and ask for volunteers to contribute to the validation.

The kinematical elements of the inventories, i.e. the identified and characterized moving areas as well as the kinematical attribute and related characteristics (validity time frame, data used, spatial representativeness and reliability) of rock glacier units will follow the recommended methodology and guidelines developed by the IPA Action Group (see CCN 1&2 D2.1 PVASR and [RD-11]). The products will be evaluated and validated against in-situ or complementary remote sensing measurements when available, over the investigated sites (see available datasets in Section 3). Taking into account the different data properties (dimensionality, observation time window), the attributes are validated if the value determined based on remote sensing data (primarily InSAR, see CCN 1&2 D2.3 ATBD) falls into the correct category after comparison with available independent velocity measurements.

2.2 Kinematical time series on selected rock glaciers (KTS)

The retrieval of kinematical time series will follow the recommended methodology and guidelines developed by the IPA Action Group (see CCN 1&2 D2.1 PVASR, [RD-12] and [RD-13]). The products will be evaluated and validated against in-situ or complementary independent remote sensing velocity measurements when available over the investigated sites (see available datasets in Section 3). As defined in the GCOS ECV recommendations from the IPA Action Group, the required measurement uncertainty depends on the applied methodology (uncertainty of position or displacement measurement), on the procedure (for instance aggregation) as well as on the observation time window used to measure and compute the annual velocity value for the selected rock glacier unit. The uncertainty has to be converted into m/yr for each annual velocity value. The ratio in between this uncertainty and the considered annual velocity value has to be lower than 20% (threshold value). The comparison between KTS and complementary datasets has to show a difference below the accepted uncertainty threshold to be considered as valid.

2.3 Mountain permafrost distribution model in the Southern Carpathians (MPDM)

For the validation of the permafrost distribution model at a regional scale in the Romanian Carpathians independent validation data sets will be used. The data considered here are represented by in-situ observations and measurements regarding permafrost detection owned by the WUT. The datasets include both thermal and geophysical measurements that were not considered for the permafrost training model. A relevant thermal parameter for permafrost detection is the basal temperature of snow cover (BTS) in late winter. For several rock glaciers in the study area, BTS data are available for different years.

Ground surface temperatures recorded by data-loggers are typically used to determine if the microclimatic conditions at the surface are suitable for hosting permafrost. An accurate determination of the small-scale GST regime is needed in order to fully understand near surface energy exchange fluxes and snow/permafrost/atmosphere interactions within high mountain regions. In this matter there are a considerable number of recent studies that have used miniature temperature data loggers to record and analyze GST regimes over time. Because different physical parameters record obvious changes when the water in the substrate reaches the freezing point geophysical techniques are frequently used to map permafrost occurrence. In the Southern Carpathians the applied geophysical methods consist of electrical resistivity tomography (ERT) and ground penetrating radar (GPR).

For validation, the rock glacier inventory will be used with information related the activity status of the rock glaciers, which will be developed within CCN 1. For the Retezat Mountains the existing empirical-statistical permafrost model by Ardelean et al. (2015) will be also considered for comparisons and validation.

Because there are no boreholes in the Romanian Carpathians in the area with isolated permafrost, we will use as parameters for validation mainly BTS measurements, GST records and geophysical data. The geophysical measurements allow to detect the internal structure of periglacial deposits (e.g. rock glaciers) and thus to estimate the active layer thickness. As the variability of permafrost conditions displays a strong spatial variability, which might be finer than the resolution of the model, we will calculate the permafrost fraction within each pixel. Thus, the validation will be point-wise and pixel-based.

Regarding the permafrost distribution model, using random forest as a classifier, the classification accuracy usually improves because of the randomly selected inputs as a combination to construct multiple trees. Using random forest there is no need for a cross-validation / separate validation set to get an unbiased estimate of the training set error. Although the RF permafrost prediction will be coded -1/+1 as absence/presence, we also can obtain as output the probability to belong to a certain class. The Receiver Operating Characteristics curve (ROC) (Fawcett, 2006), will be used as a tool to measure the quality of the model prediction by plotting the true and false positive classified values on a 2-dimensional graph. The range is between 0.5 and 1, with values larger than 0.8 indicating a model with good predicting performance (Swets, 1988).

3 PLANNED VALIDATION ACTIVITIES

Validation and user assessment will be performed for the recommended methodology and guidelines for regional rock glacier inventories (RGI), the kinematical time series of selected rock glaciers (KTS), and the products for the selected sites (see PSD, [RD-7]). The performance of the methodology for remote sensing-based rock glacier inventories using dedicated guidelines has been discussed in an exercise in a workshop in February 2020 where discrepancies between different producers have been evaluated and the guidelines refined accordingly (see CCN 1&2 D2.1 PVASR). Delivered standardized regional rock glacier inventories will rigorously follow these guidelines to ensure the homogeneity in the delivered RGI [RD-10, RD-11]. Delivered kinematical time series of selected rock glaciers will follow guidelines for the production of comparable individual time series [RD-12]. The order of magnitude for the kinematical attributes in a RGI and the KTS will be evaluated and validated against in-situ velocity measurements when available over investigated sites, as well as additional aerial and high-resolution satellite optical feature tracking at selected sites. The permafrost modelling produced in the Southern Carpathian sites will be evaluated and validated against in-situ ground temperature measurements and geophysical surveys. Due to the time frame of the project, the validation is based on existing datasets, monitoring networks and local field observations/acquisitions at single dates. No additional data collection is foreseen during the duration of the CCN 1&2 projects. A summary of the validation data according to the DARD [RD-8] is presented in Table 1. The data availability varies depending on the sites and is summarized in the following sections (3.2-3.3).

Table 1: Summary of the in-situ validation data for RGI, KTS and MPDM (based on [RD-8])

Product	Data type	Source	Spatial coverage	Temporal coverage	Repeat periodicity	Availability
RGI/KTS	Velocity measurements	PERMOS, UniFR	Switzerland	Since 2000 for the longest	Seasonally Annually Continuous	Available to consortium
RGI/KTS	Velocity measurements	UNIS, UiO, NORCE	Norway and Svalbard	Since 2005 for the longest	Seasonally, annually, continuous	Available to consortium
RGI/KTS	Velocity measurements	WUT	Carpathians	Since 2019	2 times/year	Available to consortium
MPDM	Geophysical survey	WUT	Carpathians	irregular	Single dates	Available to consortium
MPDM	Ground and air measurements	WUT	Carpathians	irregular	Single dates	Available to consortium
RGI/KTS	Field visits	mixed	European Alpine sites Brookes Range	irregular	Single dates	N/A

3.1 Regional rock glacier inventories, incl. kinematics (RGI)

The aim is to provide homogeneous RGI products mostly based on previously existing inventories (InSAR polygons from GlobPermafrost and/or regional rock glacier inventories). External partners have been asked to perform a practical exercise in order to learn the standardized methodology and to get familiar with the guidelines. Results of this practice will be analyzed in order to asses the inventorying homogeneity between partners. If needed, a webinar, technical support, etc. will be provided. In this way, the delivered standardized regional rock glaciers inventories will rigorously follow the defined guidelines and ensure the homogeneity.

The external validation of the geomorphological elements of the inventories is based on expert evaluation and will follow the timeline of the tasks 4 and 5 of the project (see Section 4).

When possible, RGI products, especially the kinematical attribute, will be compared with available field data recorded at (or around) the same temporal frame. Pre-existing inventories of slope movements (landslide and/or rock glaciers), terrestrial geodetic survey data (DGPS, total station, Lidar, etc.), as well as airborne photogrammetry data are, for instance, precious sources of validation. They will be used to assess the quality of the results. The available datasets for each region are presented in Sections 3.1.1 to 3.1.4.

3.1.1 Carpathians sites (CCN1)

In Romania, there is a lack of continuous long-term measurements on rock glacier kinematics. Within CCN1 we started to survey two rock glaciers in the Retezat Mountains using repeated differential GNSS measurements. Ground displacements were measured two times/year in 2019 (August and October) for a number of selected points. For each point the coordinates and elevation were recorded and possible horizontal/vertical changes between consecutive measurements were quantified to express the inter-annual kinematics of these rock glaciers. In the next years the measurements will be repeated at least once per/year to quantify permafrost creep. For the validation of the CCI products, available velocity measurements between 2012 and 2014 for three rock glaciers in the Retezat Mountains from geodetic surveys (by total station) will be also used (Popescu, 2015).

Since in the Romanian Carpathians permafrost is marginal and its occurrence is limited to sites where particular favorable conditions for permafrost preservation exist, expected rock glaciers kinematics are lower compared with other alpine regions (Necsoiu et al., 2016). Existing geophysical measurements (electrical resistivity tomography and ground penetrating radar) reveal the patchy distribution of permafrost within four rock glaciers in the Retezat Mountains and will be also used to confirm that the ground displacement is due to permafrost creep and not due to other processes (e.g. solifluction, frost heaving, rockfalls etc.). Existing ground surface temperature data on six rock glaciers in the Retezat Mountains will serve to assess the relation between local climatic conditions and rock glacier kinematics.

Validation of CCI products against these data, available since 2012 for the longest time series, will be summarized in the Product Validation and Intercomparison Report (CCN 1&2 D4.1 PVIR).

3.1.2 European Alpine sites (CCN2)

In Switzerland, an increasing number of landforms (currently about 30 between rock glaciers, moraines and landslides) are being surveyed regularly by field measurements (e.g. DGNSS, LIDAR, terrestrial radar interferometry, webcams). Especially, continuous long-term data series of permafrost creep are currently available at several rock glacier sites in order to provide a basis for the understanding and investigation of ongoing processes and dynamics. Some of them are part of the national data-service PERMOS in Switzerland (PERMOS, 2019). The kinematic monitoring strategy follows a landform-based approach. Seasonal, inter-annual and long-term variations in rock glacier kinematics (see e.g. Delaloye et al., 2010; PERMOS, 2019) may be captured using a combination of aerial survey (AS) and terrestrial geodetic surveys (TGS, by total station or differential GNSS). Changes in geometry (i.e. horizontal velocities and vertical changes) are analyzed in detail to quantify permafrost creep and to detect signs of potential permafrost degradation such as vertical thinning due to ice melt or rock glacier destabilization. Surveys are performed at least once a year at the same time in the season (usually in late summer) for a number of selected boulders on each rock glacier (10–100 points). The measured coordinates (x, y) and elevation (z) are used to quantify the horizontal (Δxy) and vertical (Δz, ratio of slope) changes of each point. Trajectories and flow fields are then generated and creep rate time series for single measurement points and/or representative zones of the rock glacier are determined. The relative mean annual horizontal surface velocity (in %) can be then derived for the region.

Validation of CCI products against these data, available since 2000 for the longest time series, will be summarized in the Product Validation and Intercomparison Report (CCN 1&2 D4.1 PVIR).

3.1.3 European Subarctic/Arctic sites (CCN2)

In Norway, in-situ and landform-scale remote sensing datasets at selected sites will be exploited for comparison and validation with the CCI kinematical products:

In the AOI1 (Troms), intensive in-situ networks are continuously monitoring ground displacements at the location of three high-risk rockslides (since 2007 on Jettan and Indre Nordnes on Nordnesfjellet and since 2016 on Gámanjunni3 in Manndalen). The rockslide section of the Norwegian Water Resources and Energy Directorate (NVE) is responsible for the management of a large set of instrumentation: GNSS, extensometers, laser-reflectors, tiltmeters, ground-based radar, corner reflectors for using InSAR the entire year, etc. (Blikra & Christiansen, 2014; Böhme et al., 2016; Nordvik et al., 2010). Even if not directly related to the processes studied in the Permafrost_cci CCN2 project, these networks are documenting landforms moving at the same order of magnitude (cm/yr) and are located close to identified rock glaciers. They will be thus valuable for validation. In addition, the Ádjet rock glacier complex in Skibotndalen has been studied by NORCE and The Arctic University of Norway in Tromsø (UiT). A combination of InSAR, SAR offset-tracking, aerial feature tracking, terrestrial radar interferometry and periodic GPS measurements has highlighted very high velocities (several m/yr) and an accelerating trend during the recent decades (Eriksen et al., 2018). The existing dataset will be compared with the CCI new products and will also be used to discuss the limitations of InSAR over very fast-moving rock glaciers.

In AOI2 (Finnmark), rock glaciers in Ivarsfjord have been intensively studied by the University of Oslo (UiO) during the recent years. Periodic GNSS measurements, Unmanned Aircraft Vehicle (UAS) imagery and Terrestrial Laser Scanning (TLS) have been performed during every summer field campaign since 2015. Repeated High Resolution Digital Elevation Models and GNSS ground displacement measurements will be valuable for validation of InSAR results (Aune, 2018).

In AOI3 (Nordenskiöld Land), the University of Tsukuba (Japan) in collaboration with the University Centre in Svalbard (UNIS) have conducted 14 years (2005-2019) of annual Real Time Kinematic GPS Survey of surface benchmarks on a small valley-side rock glacier (Huset rock glacier, in

Longyeardalen). At this location, a borehole down to 15 m records temperature and deformation measurements (Matsuoka et al., 2019). In addition, two solifluction monitoring stations are measuring 2D displacements (normal and parallel to the ground surface) (Harris et al., 2007; 2011) in Endalen since 2005 and in Kapp Linné since 2008. The monitoring is meant to be continuous but in some periods the stations have not been operational due to polar bear attacks and power problems. Like for the monitoring data from AOI1, the solifluction stations document different processes than considered in the Permafrost_cci CCN2 project. However, due to the same order of magnitude (cm/yr-dm/yr) of the measured movement and the neighbouring locations of identified rock glaciers, these datasets will be valuable for validation.

In addition to the datasets described above, at least one site per AOI will be selected to process complementary aerial optical feature tracking (horizontal velocities using image matching; Kääb and Vollmer, 2000). For contemporary aerial photographs, the results at these locations will be used for cross-validation with InSAR-based products. For historical aerial photographs, they will be used to detect rock glacier long-term velocity changes. For a strandflat rock glacier at Nordenskiöldkysten (AOI3), geophysical soundings (DC resistivity, ground-penetrating radar) and aerial photogrammetric surveys exist (Kääb et al., 2002; Farbrot et al. 2005). Velocity measurements from geodetic surveys are also available from Hjortfjellet and Birkafjellet rock glaciers (Isaksen et al., 2000).

Datasets from meteorological stations, ground surface and ground temperature loggers in boreholes are also available in the three AOIs to further investigate the relations with climate variables. In AOI3 for instance, permafrost boreholes operational since 2008-2009 are equipped for ground thermal monitoring in approx. 15 different sites representing the main periglacial landforms in this area (Christiansen et al., 2010).

Validation of CCI products against these data, available since 2005 for the longest time series, will be summarized in the Product Validation and Intercomparison Report (CCN 1&2 D4.1 PVIR).

3.1.4 Extra-European sites (CCN2)

Field visits may be performed by users at selected sites to validate the rock glacier inventories and assess the typology (e.g. at Brookes Range).

Aerial and high-resolution satellite optical feature tracking over four different rock glaciers is planned for the Tien Shan site (Kazakhstan-Kyrgyzstan). No other quantitative validation against velocity measurements is foreseen during the duration of the CCN project for the Extra-European sites.

3.2 Kinematical time series on selected rock glaciers (KTS)

This Section summarized the validation plan and related available datasets, as already introduced in the DARD [RD-8]. The production of KTS is not possible for all sites during the timeline of the CCN project and will focus on the region with complementary velocity data for validation (European Alpine and European Subarctic/Arctic sites). Table 2 summarizes the various validation sites.

3.3 Mountain permafrost distribution model in the Southern Carpathians (MPDM)

The MPDM will be validated using independent data points (not used in the training of the model) were the ground surface temperature was measured by BTS (basal temperature of snow cover) and/or miniature temperature data loggers (MTD). The metric used for model validation will be the AUC (area under the curve).

In the Southern Carpathians, datasets on air and ground surface temperature for the validation of terrestrial permafrost are managed by WUT and are available at no costs. They will be used to evaluate and validate the regional permafrost distribution model. Miniature temperature data loggers (MTD) or thermistors (iButton Digital Thermometers DS 1922L and UTL 3) were installed at the surface of different rock glaciers, rock walls, other periglacial landforms in the Romanian Carpathians to examine the near-surface thermal regime and to better understand the snow/permafrost/atmosphere interactions. The thermistors were used to register the ground surface temperature every 2 or 4 hours from September 2012. The thermistors were distributed at 5 to 30 cm beneath the surface of the rock glaciers and covered with pebbles to avoid direct exposure to solar radiation. Based on the recorded data from the ground-surface data loggers, the mean annual ground surface temperature, ground freezing index, insulating snow cover duration and zero-curtain interval (ZCI) were calculated. At the Retezat site, a miniature temperature data logger is also used to record the air temperature variation every 2 hours since 2012. It is installed in a wooden case located in the vicinity of one investigated rock glacier. Readings were recorded with a resolution of 0.065 °C with less than ±0.5 °C error and were indirectly calibrated at 0 °C using zero curtain intervals, because snowmelt causes isothermal conditions to occur at the ground surface.

Basal temperature of snow cover (BTS) is a reliable parameter for permafrost detection, measured in the late winter when the snow depth is thick enough (> ~80 cm) to insulate the ground surface from external air temperature fluctuations. The BTS values suggest the likely presence of permafrost when values lower than −2 °C are measured. Within the selected sites, thermal measurements were performed in case of 9 rock glaciers in the Retezat Mountains and 5 in the Parâng Mountains. Based on previous thermal measurements, permafrost is probable/possible to occur at those sites where the bottom temperature of the winter snow cover (BTS) is below -3^{0}C (-2^{0}C), the mean annual ground surface temperature (MAGST) is lower than 0^{0}C (1.5^{0}C) and the ground freezing index (GFI) is greater than 600 (400) ^{0}C days.

All the locations are visited once per year when the recorded temperatures are downloaded, and the functionality of the thermistors is verified. Ground temperature records will then be processed to monthly and yearly mean/min/max, including metadata information, which allows assessing the quality of each temperature value product.

Validation of CCI products against these data, available since 2012 for the longest time series, will be summarized in the Product Validation and Intercomparison Report (CCN 1&2 D4.1 PVIR).

Table 2: Summary of the validation data for RGI, KTS and MPDM (based on [RD-8])

	Site for validation	**Coordinates of the site**	**Measurement method**	**Measurement time period**
Switzerland, Western Swiss Alps	Petit-Vélan rock glacier	45°54'54.66"N, 7°14'0.30"E	Annual geodetic survey (DGNSS)	2005 – ongoing

	Aget rock glacier (push-moraine)	46° 0'32.77"N, 7°14'19.09"E	Annual geodetic survey (DGNSS)	2001 – ongoing
	Mille rock glacier	46° 1'21.55"N, 7°12'14.47"E	2-yr geodetic survey (DGNSS)	2003 – ongoing
	Gemmi-Furggentälti rock glacier	46°24'25.35"N, 7°37'52.63"E	Annual geodetic survey (DGNSS) + permanent GNSS station	1994 – ongoing + 2017 – ongoing
	Lapires rock glacier	46° 6'15.42"N, 7°17'1.73"E	Annual geodetic survey (DGNSS)	2007 – ongoing
	Becs-de-Bosson rock glacier	46°10'25.31"N, 7°30'39.19"E	Annual geodetic survey (DGNSS) + permanent GNSS stations	2001 – ongoing + 2012 – ongoing
	Tsavolire rock glacier	46° 9'57.50"N, 7°30'27.83"E	Permanent GNSS station	2012 – ongoing
	Perroc rock glacier	46° 2'26.47"N, 7°30'12.22"E	Permanent GNSS station	2016 – ongoing
	Perroc landslide	46° 2'42.51"N, 7°30'15.89"E	Permanent GNSS station	2016 – ongoing
	Tsarmine rock glacier	46° 2'46.77"N, 7°30'23.36"E	Bi-annual geodetic survey (DGNSS) + permanent GNSS stations	2004 – ongoing + 2012 – ongoing
	Bonnard (Péterey) rock glacier	46° 8'4.09"N, 7°39'25.97"E	Annual or multi-annual geodetic survey (DGNSS) + permanent GNSS stations	2006 – ongoing + 2012 – ongoing
	Grosse Grabe rock glacier (and landslide)	46° 9'2.96"N, 7°49'24.02"E	Annual geodetic survey (DGNSS)	2007 – ongoing
	Gänder rock glacier	46° 4'52.67"N, 7°48'30.11"E	Annual geodetic survey (DGNSS)	2009 – ongoing
	Chessi rock glacier	46° 5'0.67"N, 7°48'40.19"E	Annual geodetic survey (DGNSS)	2009 – ongoing
	Jegi rock glacier (and landslide)	46° 9'5.02"N, 7°57'16.16"E	Bi-annual geodetic survey (DGNSS) + permanent GNSS station	2009 – ongoing + 2014 – ongoing
	Grosses Gufer rock glacier	46°25'35.22"N, 8° 4'50.68"E	Annual geodetic survey (DGNSS) + permanent GNSS station	2007 – ongoing + 2018 – ongoing
	Klein Furkahorn rock glacier	46°35'0.20"N, 8°24'54.30"E	2-yr geodetic survey (DGNSS)	2009 – ongoing
	Guetsch rock glacier	46°39'35.99"N, 8°37'2.56"E	2-yr geodetic survey (DGNSS)	2009 – ongoing
	Monte Prosa rock glaciers	46°33'55.07"N, 8°34'44.49"E	Bi-annual geodetic survey (DGNSS) + permanent GNSS station	2009 – ongoing + 2017 – ongoing
	Dirru rock glacier	46° 7'18.25"N, 7°49'0.33"E	Bi-annual geodetic survey (DGNSS)	2007 – ongoing
	Gugla rock glacier	46° 8'20.19"N, 7°49'2.78"E	Bi-annual geodetic survey (DGNSS) + permanent GNSS station	2007 – ongoing
	Grabengufer rock	46° 5'44.25"N,	2-month geodetic	2009 – ongoing

	glacier	7°48'24.49"E	survey (total station)	
	Yettes Condjà rock glaciers	46°5'49.33 "N, 7°17'12.14"E	Annual geodetic survey (DGNSS)	2000 – ongoing
	Hugerlitälli rock glaciers	14°11'12.63"N, 7°42'58.31"E	Annual geodetic survey (total station)	2001 – ongoing
	Gruben rock glacier	46°10'18.33"N, 7°57'42.76"E	Annual geodetic survey (DGNSS) + permanent GNSS Station	2012 – ongoing + 2012 – ongoing
	Corvatsch- Murtèl rock glacier	46°25'44.63"N, 9°49'17.32"E	Annual geodetic survey (total station) + permanent GNSS Station	2009 – ongoing + 2015 – ongoing
	Largario rock glacier	46°28'40.79"N, 8°59'9.42"E	Annual geodetic survey (DGNSS) + permanent GNSS station	2009 – ongoing + 2014 – ongoing
	Muragl rock glacier	46°30'25.47"N, 9°55'38.04"E	Annual geodetic survey (total station) + permanent GNSS station	2009 – ongoing + 2012 –ongoing
	Sceru rock glacier	46°27'4.02"N, 9°0'14.61"E	Annual geodetic survey (DGNSS)	2009 – ongoing
Troms, Northern Norway	Gámanjunni3 rockslide and rock glacier	69°28'N 20°34'E	Permanent GPS stations	2016 – ongoing
	Nordnes rockslide and rock glacier	69°33'N 20°24'E	Permanent GPS stations	2007 – ongoing
	Àdjet rock glacier, Skibotndalen	69°21'N 20°24'E	SAR offset tracking (TerraSAR-X StripMap)	2009 – 2019
	TBD based on final InSAR products	TBD based on InSAR products	Aerial optical feature tracking	TBD based on available data
Finnmark, Northern Norway	Ivarsfjord rock glacier	70°49'N 28°02'E	GNSS, repeated HR DEMs from UAV and TLS	2015 – 2019
	TBD based on final InSAR products	TBD based on InSAR products	Aerial optical feature tracking	TBD based on available data
Nordenskiöld Land, Svalbard	Huset rock glacier, Longyeardalen	78°12'N 15°35'E	Annual RTK GPS Survey of surface benchmarks	2005 – ongoing
	Endalen solifluction station	78°11′N 15°44′E	Continuous 2D displacement measurements	2005 – ongoing
	Kapp Linné solifluction station	78°02′N 13°43′E	Discontinuous 2D displacement measurements	2008 – ongoing
	Hjortfjellet and Birkafjellet rock glaciers	78°15'N 15°47'E – 15°58'E	Geodetic survey	1994 – 1997
	Nordenskiöld kysten rock glacier	77° 54' N 13° 52' E	Aerial photogrammetry surveys	1969 – 1990
	TBD based on final InSAR products	TBD based on InSAR products	Aerial optical feature tracking	TBD based on available data
Tien Shan, Kazakhstan-Kyrgyzstan	4 different rock glacier sites	76° 51' – 77° 16' N 42° 50' – 43° 04' E	Aerial and high-res satellite optical feature tracking	1950 – 2018
Southern Carpathians	Central area of Retezat Mountains	45°20'N 22°49'E	Thermistors (GST measurements) and BTS	2012 – ongoing

4 VALIDATION DOCUMENTS AND ENDORSEMENTS

Tables 3 and 4 provide an overview of the deliverables including information about product validation, intercomparison and assessment. Apart from these deliverables, we seek for documenting the methodology for RGI and KTS in baseline documents and guidelines co-authored by contributors of the *IPA Action Group Rock glacier inventories and kinematics.* It is also planned to publish the standard guidelines for the inventorying of rock glaciers based on satellite SAR interferometry in a world-class peer-reviewed scientific journal (D5.2). In addition, the products and main findings of CCN1 and CCN2 for the various investigated sites will be communicated in additional scientific peer-reviewed publications. The project deliverables will be prepared by the Permafrost_cci consortium, while the IPA Action Group publications and peer-reviewed papers will be prepared together with the involved mountain permafrost community and PI data providers of reference data sets. If the results of the validation, intercomparison and assessment of the individual Permafrost_cci products can be presented in form of publications and data publications, the largest possible endorsement is achieved.

The produced rock glacier inventories and kinematical time series build up a unique validation dataset for climate models and permafrost indication maps for mountain regions, where direct permafrost (thermal state) measurements are very scarce or even totally lacking. The assessment of the data products by the Permafrost_cci Climate Research Group (CRG) and other users as well as outreach activities regarding publications and presentations will be summarized in the "Climate Assessment Report" (D5.1).

We will seek for an open review process of all results achieved by informing the respective group of scientists and stakeholders such as the IPA, specifically with involvement of the IPA Rock Glacier Inventory and Kinematics Action Group (for RGI and KTS products), the IPA Permafrost Mapping Action Group (for MPDM products) and the CRG, when the deliverables, the products, the baseline documents, guidelines and other publications are available. We will also seek outreach via the international community relevant mailings lists, such as Permalist and Cryolist, to participate in the validation activities.

4.1 Regional rock glacier inventories, incl. kinematics (RGI) and kinematical time series on selected rock glaciers (KTS)

Table 3 provides an overview of the deliverables including information about product validation, intercomparison and assessment for RGI and KTS. These will be complemented with dedicated documentation by the IPA Action Group, i.e. the future accepted versions of [RD-10, RD-11, RD-12] and the related guidelines.

The Permaforst_cci CCN 1&2 sub-projects and the IPA Action Group aim to contribute to the GCOS' 4th assessment cycle (2019-2022), addressing the update of the Status Report and the Implementation Plan. Recommendations related to the integration of rock glacier kinematics as a new ECV Permafrost product have been published during the public review 2020 [RD-13]. The CCN team plans to follow the next steps of the assessment cycle and to provide inputs to the next public review in early 2021.

Table 3: Documents related to validation of the Permafrost_cci products of CCN2 (RGI and KTS)

Deliv. No.	Name	Date	Comment
D1.1-1.3	User Requirement, Product Specifications, and Data Access Requirements Document	30 November 2019	Describes data accessibility
D2.1	Product Validation and Algorithm Selection Report	30 April 2020	Documents the selection of the methods and criteria to provide standard products
D4.1	Product Validation and Intercomparison Report and Product User Guide	December 2020	Provides a summary on quality and uncertainty of CCI products and describes the delivered CCI products
D5.1	Climate Assessment Report	March 2021	Climate science study cases using the CCI products and user's feedback

4.2 Mountain permafrost distribution model in Southern Carpathians (MPDM)

Table 4 provides an overview of the deliverables including information about product validation, intercomparison and assessment for MPDM products in Southern Carpathians.

Table 4: Documents related to validation of the Permafrost_cci product of CCN1 (MPDM).

Deliv. No.	Name	Date	Comment
D1	User Requirement, Product Specifications, and Data Access Requirements Document	15 February 2019	Describes data accessibility
D4	Product Validation and Intercomparison Report and Product User Guide	April 2020	Provides a summary on quality and uncertainty of CCI products and describes the delivered CCI products
D5	Climate Assessment Report	August 2020	Climate science study cases using the CCI products and user's feedback

5 REFERENCES

5.1 Bibliography

Ardelean, A.C., Onaca, A.L., Urdea, P., Șerban, R.D., Sîrbu, F., 2015. A first estimate of permafrost distribution from BTS measurements in the Romanian Carpathians (Retezat Mountains). Géomorphologie: relief, processus, environnement, 2, 4, 297-312.

Aune, V., 2018. Active rock glaciers at sea level? - a case study of Ivarsfjord rock glacier in Finnmark, Northern Norway. Master thesis. University of Oslo (UiO).

Blikra, L.H. and Christiansen, H.H., 2014. A field-based model of permafrost-controlled rockslide deformation in northern Norway. Geomorphology, 208, pp.34-49.

Böhme, M., Bunkholt, H.S.S., Oppikofer, T., Dehls, J.F., Hermanns, R.L., Eriksen, H.Ø., Lauknes, T.R. and Eiken, T., 2016. June. Using 2D InSAR, dGNSS and structural field data to understand the deformation mechanism of the unstable rock slope Gamanjunni 3, northern Norway. In Landslides and Engineered Slopes: Experience, Theory and Practice: Proceedings of the 12th International Symposium on Landslides (Napoli, Italy, 12–19 June 2016): Rome, Associazione Geotecnica Italiana (pp. 443-449).

Christiansen, H.H, Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrot, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, L., Hjort, J, Holmlund, P., Sannel, A.B.K., Sigsgaard, C., Åkerman, H.J., Foged, N., Blikra, L.H., Pernosky, M.A. and Ødegård, R., 2010. The Thermal State of Permafrost in the Nordic area during the International Polar Year 2007-2009. Permafrost and Periglacial Processes, 21, 156-181.

Delaloye, R., Lambiel, C. and Gärtner-Roer, I., 2010. Overview of rock glacier kinematics research in the Swiss Alps: seasonal rhythm, interannual variations and trends over several decades. Geographica Helvetica, 65(2), 135–145.

Eriksen, H.Ø., Rouyet, L., Lauknes, T.R., Berthling, I., Isaksen, K., Hindberg, H., Larsen, Y. and Corner, G.D., 2018. Recent acceleration of a rock glacier complex, Ádjet, Norway, documented by 62 years of remote sensing observations. Geophysical Research Letters, 45(16), pp.8314-8323.

Farbrot H., Isaksen K., Eiken T., Kääb A. and Sollid J.L. 2005. Composition and internal structures of a rock glacier on the strandflat of western Spitsbergen, Svalbard. Norwegian Journal of Geography, 59, 139–148

Fawcett, T., 2006. An introduction to ROC analysis. Pattern recognition letters, 27(8), pp.861-874.

Harris, C., Luetschg, M., Davies, M.C.R., Smith, F., Christiansen, H.H. and Isaksen, K., 2007. Field Instrumentation for Real-time Monitoring of Periglacial Solifluction. Permafrost and Periglacial Processes, 18, 105-114.

Harris, C., Kern-Luetschg, M., Christiansen, H.H. and Smith, F., 2011. The role of interannual climate variability in controlling solifluction processes, Endalen, Svalbard. Permafrost and Periglacial Processes, 22(3), pp.239-253.

Isaksen, K., Ødegård, R.S., Eiken, T. and Sollid, J.L., 2000. Composition, flow and development of two tongue-shaped rock glaciers in the permafrost of Svalbard. Permafrost Periglac. Process., 11(3), 241–257. doi:10.1002/1099-1530(200007/09)11:3<241::AID-PPP358>3.0.CO;2-A.

Kääb, A. and Vollmer M., 2000. Surface geometry, thickness changes and flow fields on creeping mountain permafrost: automatic extraction by digital image analysis. Permafrost and Periglacial Processes,11, 315-326

Kääb, A., Isaksen, K., Eiken T. and Farbrot. H., 2002. Geometry and dynamics of two lobe-shaped rock glaciers in the permafrost of Svalbard. Norwegian Journal of Geography, 56, 152-160

Necsoiu, M., Onaca, A., Wigginton, S. and Urdea, P., 2016. Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery. Remote sensing of environment, 177, pp.21-36.

Nordvik, T., Blikra, L.H., Nyrnes, E. and Derron, M.H., 2010. Statistical analysis of seasonal displacements at the Nordnes rockslide, northern Norway. Engineering geology, 114(3-4), pp.228-237.

PERMOS, 2019. Permafrost in Switzerland 2014/2015 to 2017/2018. Noetzli, J., Pellet, C., and Staub, B. (eds.), Glaciological Report (Permafrost) No. 16-19 of the Cryospheric Commission of the Swiss Academy of Sciences, 104 pp, doi:10.13093/permos-rep-2019-16-19.

Popescu, R., Vespremeanu-Stroe, A., Onaca, A. and Cruceru, N., 2015. Permafrost in the granitic massifs of Southern Carpathians (Parâng Mountains). Zeitschrift für Geomorphologie, 59, 1, 1-20.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science, 240(4857), pp.1285-1293.

5.2 Acronyms

AD	Applicable Document
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
AUC	Area Under the Receiver Operating Curve
B.GEOS	b.geos GmbH
BTS	Bottom Temperature of Snow Cover
CCI	Climate Change Initiative
CCN	Contract Change Notice
CRS	Coordinate Reference System
DARD	Data Access Requirement Document
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ERT	Electrical Resistivity Tomography
ESA	European Space Agency
ESA DUE	ESA Data User Element
E3UB	End-to-End ECV Uncertainty Budget
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GFI	Ground Freezing Index
GPR	Ground Penetrating Radar
GST	Ground Surface Temperature

GT	Ground Temperature
GTOS	Global Terrestrial Observing System
GUIO	Department of Geosciences University of Oslo
INSAR	Synthetic Aperture Radar Interferometry
IPA	International Permafrost Association
KTS	Kinematical Time Series
LST	Land Surface Temperature
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
MPDM	Mountain Permafrost Distribution Model
MRI	Mountains Research Initiative
MTD	Miniature Temperature Data Loggers
NMA	National Meteorological Administration
NORCE	Norwegian Research Centre AS
NSIDC	National Snow and Ice Data Center
PSD	Product Specifications Document
PVASR	Product Validation and Algorithm Selection Report
PVP	Product Validation Plan
RF	Random Forest
RD	Reference Document
RGI	Rock Glacier Inventories
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
S4C	Science for the Carpathians
SWE	Snow Water Equivalent
T	Temperature
UNIFR	Department of Geosciences University of Fribourg
UNIS	University Centre in Svalbard
URD	Users Requirement Document
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WUT	West University of Timisoara