CCI+ PHASE 1 – NEW ECVS
PERMAFROST

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

D2.5 Product Validation Plan (PVP)

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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-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


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).

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<th>Data type</th>
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<th>Repeat periodicity</th>
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<td>Switzerland</td>
<td>Since 2000 for the longest</td>
<td>Annually, Continuous</td>
<td>Available to consortium</td>
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<tr>
<td>RGI/KTS</td>
<td>Velocity measurements</td>
<td>UNIS, UiO, NORCE</td>
<td>Norway and Svalbard</td>
<td>Since 2005 for the longest</td>
<td>Seasonally, continuous</td>
<td>Available to consortium</td>
</tr>
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<td>RGI/KTS</td>
<td>Velocity measurements</td>
<td>WUT</td>
<td>Carpathians</td>
<td>Since 2019</td>
<td>2 times/year</td>
<td>Available to consortium</td>
</tr>
<tr>
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<td>Geophysical survey</td>
<td>WUT</td>
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<td>irregular</td>
<td>Single dates</td>
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<tr>
<td>MPDM</td>
<td>Ground and air measurements</td>
<td>WUT</td>
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<td>European Alpine sites</td>
<td>irregular</td>
<td>Single dates</td>
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#### 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 assess 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 Gámanjunní 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
Longyearbadalen. 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°C (-2°C), the mean annual ground surface temperature (MAGST) is lower than 0°C (1.5°C) and the ground freezing index (GFI) is greater than 600 (400) °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])

<table>
<thead>
<tr>
<th>Site for validation</th>
<th>Coordinates of the site</th>
<th>Measurement method</th>
<th>Measurement time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland, Western Swiss Alps</td>
<td>Petit-Vélan rock glacier 45°54'54.66&quot;N, 7°14'0.30&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2005 – ongoing</td>
</tr>
<tr>
<td>Location</td>
<td>Coordinates</td>
<td>Survey Type</td>
<td>Dates</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------------------</td>
<td>-------------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Aget rock glacier (push-moraine)</td>
<td>46°03'2.77&quot;N, 7°14'19.09&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2001 – ongoing</td>
</tr>
<tr>
<td>Mille rock glacier</td>
<td>46°12'1.55&quot;N, 7°12'14.47&quot;E</td>
<td>2-yr geodetic survey (DGNSS)</td>
<td>2003 – ongoing</td>
</tr>
<tr>
<td>Gemmi-Furggentälti rock glacier</td>
<td>46°24'25.35&quot;N, 7°37'52.63&quot;E</td>
<td>Annual geodetic survey (DGNSS) + permanent GNSS station</td>
<td>1994 – ongoing + 2017 – ongoing</td>
</tr>
<tr>
<td>Lapires rock glacier</td>
<td>46°6'15.42&quot;N, 7°1'1.73&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2007 – ongoing</td>
</tr>
<tr>
<td>Becs-de-Bosson rock glacier</td>
<td>46°10'25.31&quot;N, 7°30'39.19&quot;E</td>
<td>Annual geodetic survey (DGNSS) + permanent GNSS stations</td>
<td>2001 – ongoing + 2012 – ongoing</td>
</tr>
<tr>
<td>Tsavolire rock glacier</td>
<td>46°9'57.50&quot;N, 7°30'27.83&quot;E</td>
<td>Permanent GNSS station</td>
<td>2012 – ongoing</td>
</tr>
<tr>
<td>Perroc rock glacier</td>
<td>46°2'26.47&quot;N, 7°30'12.22&quot;E</td>
<td>Permanent GNSS station</td>
<td>2016 – ongoing</td>
</tr>
<tr>
<td>Perroc landslide</td>
<td>46°2'42.51&quot;N, 7°30'15.89&quot;E</td>
<td>Permanent GNSS station</td>
<td>2016 – ongoing</td>
</tr>
<tr>
<td>Tsarmine rock glacier</td>
<td>46°2'46.77&quot;N, 7°30'23.36&quot;E</td>
<td>Bi-annual geodetic survey (DGNSS) + permanent GNSS stations</td>
<td>2004 – ongoing + 2012 – ongoing</td>
</tr>
<tr>
<td>Bonnard (Péternay) rock glacier</td>
<td>46°8'4.09&quot;N, 7°39'25.97&quot;E</td>
<td>Annual or multi-annual geodetic survey (DGNSS) + permanent GNSS stations</td>
<td>2006 – ongoing + 2012 – ongoing</td>
</tr>
<tr>
<td>Grosse Grabe rock glacier (and landslide)</td>
<td>46°9'2.96&quot;N, 7°49'24.02&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2007 – ongoing</td>
</tr>
<tr>
<td>Gänder rock glacier</td>
<td>46°4'52.67&quot;N, 7°48'30.11&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2009 – ongoing</td>
</tr>
<tr>
<td>Chessi rock glacier</td>
<td>46°5'0.67&quot;N, 7°48'40.19&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2009 – ongoing</td>
</tr>
<tr>
<td>Jegi rock glacier (and landslide)</td>
<td>46°9'5.02&quot;N, 7°5'16.16&quot;E</td>
<td>Bi-annual geodetic survey (DGNSS) + permanent GNSS station</td>
<td>2009 – ongoing + 2014 – ongoing</td>
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<tr>
<td>Grosses Gufir rock glacier</td>
<td>46°25'35.22&quot;N, 8°45'0.68&quot;E</td>
<td>Annual geodetic survey (DGNSS) + permanent GNSS station</td>
<td>2007 – ongoing + 2018 – ongoing</td>
</tr>
<tr>
<td>Klein Furkahorn rock glacier</td>
<td>46°35'0.20&quot;N, 8°24'54.30&quot;E</td>
<td>2-yr geodetic survey (DGNSS)</td>
<td>2009 – ongoing</td>
</tr>
<tr>
<td>Gaetsch rock glacier</td>
<td>46°39'35.99&quot;N, 8°37'2.56&quot;E</td>
<td>2-yr geodetic survey (DGNSS)</td>
<td>2009 – ongoing</td>
</tr>
<tr>
<td>Monte Prosa rock glaciers</td>
<td>46°33'55.07&quot;N, 8°34'44.49&quot;E</td>
<td>Bi-annual geodetic survey (DGNSS) + permanent GNSS station</td>
<td>2009 – ongoing + 2017 – ongoing</td>
</tr>
<tr>
<td>Dirru rock glacier</td>
<td>46°7'18.25&quot;N, 7°49'0.33&quot;E</td>
<td>Bi-annual geodetic survey (DGNSS)</td>
<td>2007 – ongoing</td>
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<tr>
<td>Gugla rock glacier</td>
<td>46°8'20.19&quot;N, 7°49'2.78&quot;E</td>
<td>Bi-annual geodetic survey (DGNSS) + permanent GNSS station</td>
<td>2007 – ongoing</td>
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<tr>
<td>Grabengufer rock</td>
<td>46°5'44.25&quot;N, 7°17'1.73&quot;E</td>
<td>2-month geodetic</td>
<td>2009 – ongoing</td>
</tr>
<tr>
<td>Glacier</td>
<td>Coordinates</td>
<td>Survey Type</td>
<td>Start Year</td>
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<tr>
<td>---------</td>
<td>-------------</td>
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<td>------------</td>
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<tr>
<td>Yettes Condjà rock glaciers</td>
<td>46°5’49.33&quot;N, 7°17’12.14&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2000 – ongoing</td>
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<tr>
<td>Hugerlitállí rock glaciers</td>
<td>14°11’12.63&quot;N, 7°42’58.31&quot;E</td>
<td>Annual geodetic survey (total station)</td>
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<tr>
<td>Gruben rock glacier</td>
<td>46°10’18.33&quot;N, 7°57’42.76&quot;E</td>
<td>Annual geodetic survey (DGNSS) + permanent GNSS Station</td>
<td>2012 – ongoing + 2012 – ongoing</td>
</tr>
<tr>
<td>Corvatsch- Murtèl rock glacier</td>
<td>46°25’44.63&quot;N, 9°49’17.32&quot;E</td>
<td>Annual geodetic survey (total station) + permanent GNSS Station</td>
<td>2009 – ongoing + 2015 – ongoing</td>
</tr>
<tr>
<td>Largario rock glacier</td>
<td>46°28’40.79&quot;N, 8°59’9.42&quot;E</td>
<td>Annual geodetic survey (DGNSS) + permanent GNSS station</td>
<td>2009 – ongoing + 2014 – ongoing</td>
</tr>
<tr>
<td>Muragl rock glacier</td>
<td>46°30’25.47&quot;N, 9°33’18.04&quot;E</td>
<td>Annual geodetic survey (total station) + permanent GNSS station</td>
<td>2009 – ongoing + 2012 –ongoing</td>
</tr>
<tr>
<td>Sceru rock glacier</td>
<td>46°27’4.02&quot;N, 9°14’17.61&quot;E</td>
<td>Annual geodetic survey (DGNSS)</td>
<td>2009 – ongoing</td>
</tr>
</tbody>
</table>

**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 |
- Ádjet 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 |
- 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 Permafrost_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)

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

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).

<table>
<thead>
<tr>
<th>Deliv. No.</th>
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<th>Date</th>
<th>Comment</th>
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<tr>
<td>D1</td>
<td>User Requirement, Product Specifications, and Data Access Requirements Document</td>
<td>15 February 2019</td>
<td>Describes data accessibility</td>
</tr>
<tr>
<td>D4</td>
<td>Product Validation and Intercomparison Report and Product User Guide</td>
<td>April 2020</td>
<td>Provides a summary on quality and uncertainty of CCI products and describes the delivered CCI products</td>
</tr>
<tr>
<td>D5</td>
<td>Climate Assessment Report</td>
<td>August 2020</td>
<td>Climate science study cases using the CCI products and user’s feedback</td>
</tr>
</tbody>
</table>
5 REFERENCES

5.1 Bibliography


### 5.2 Acronyms

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