CCI+ PHASE 1 – NEW ECVS
PERMAFROST

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

D2.2 Algorithm Theoretical Basis Document (ATBD)

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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 CCN1-2 [RD-6 to RD-8].

The present Algorithm Theoretical Basis Document (ATBD) specifies the theoretical background of the methods used to develop the CCN products and describes the processing lines. For the RGI product, the methodology to update existing or implement new rock glacier inventories is summarized, the guidelines to delineate moving areas based on InSAR and then rules to assign the kinematical attribute to the rock glacier units are presented in detail. For the KTS product, the processing steps based on InSAR, SAR offset tracking and feature tracking on repeat optical airphotos are presented and the standards to provide comparable time series are summarized. For the MPDM product, the steps of the statistical modeling, including the preparation of the predictors and training data, building, running and validation of the model, are described. Required input data and output products are summarized and practical considerations for the implementation are discussed.

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 on selected rock glaciers (KTS), and (iii) a mountain permafrost distribution model in the Carpathians (MPDM). The Algorithm Theoretical Basis Document (ATBD) specifies the theoretical background of the methods used to develop the products described in the CCN 1&2 PSD, with respect to the user requirements described in the CCN 1&2 URD.

1.2 Structure of the document

- Section 1 provides information about the purpose and background of this document.
- Section 2 summarizes the scientific background related to the monitoring of mountain permafrost and reminds the justification of the selected methods.
- Section 3 describes the processing lines.
- Sections 4 and 5 describe the required input data and the properties of the output products, respectively.
- Section 6 gives some practical considerations for the implementation.

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.

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 7.1.

1.6 Acronyms

A list of acronyms is provided in Section 7.2.

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 SCIENTIFIC BACKGROUND AND SELECTED ALGORITHMS

2.1 Monitoring of mountain permafrost

On a global scale, the evolution of mountain permafrost is scarcely observed by temperature monitoring in a few boreholes, whose long-term maintenance is particularly challenging (Haeberli et al., 2010; Harris et al., 2001). A large majority of periglacial mountain areas worldwide are thus lacking permafrost monitoring data. While Arctic permafrost is typically continuous or discontinuous and covers extended areas of land, mountain permafrost is usually sporadic or isolated and its spatial distribution is complex and hard to determine by direct measurements (Levavasseur et al., 2011). Permafrost preservation is controlled by site-specific conditions. Monitoring networks are typically difficult to set up in a systematic way, and the spatially very variable permafrost conditions are challenging to investigate based on global-scale permafrost products. Therefore, the response of mountain permafrost to ongoing climate evolution cannot be directly precisely assessed in most regions on Earth.

Recent studies have shown that the overall magnitude of the effect of micro-climatic and topographic conditions on the MAGST can be as high as 15°C within less than 1 km distance (Haeberli et al., 2010). These spatial variations are linked to the main factors controlling the GST regime, which are the incoming solar radiation, the presence or absence of coarse blocks along with the snow cover characteristics (Brenning et al., 2005; Luetschg et al., 2008). The main problem is that all these controlling factors show a strong lateral heterogeneity, mainly due to variable topography, causing important variations of GST values on short distance (Nelson et al., 1998). Therefore, the GST reactions to environmental changes are likewise extremely heterogeneous in space. Particular sites with favorable conditions for permafrost preservation are expected to have little or even reverse reaction to air temperature rise, while other sites can have fast and intense reactions (Gisnås et al., 2014).

Mountain permafrost plays a different role than lowland circumpolar permafrost. It is largely affecting slope stability in high mountains and permafrost degradation promotes geohazards; thawing mountain permafrost may lead for instance to rock and glacier slides. Mountain permafrost covers large areas and is typically close to human settlements, not least in Europe. Therefore, climate change impacts on mountain permafrost affect people directly and on short-term scale due to its – typically – close proximity to the thawing point.

2.1.1 Rock glacier inventories and kinematics

Scientific motivations for producing and/or for exploiting an exhaustive rock glacier inventory, at various scales, can be summarized as follows [RD-10]:

- *Geomorphological mapping*: Rock glaciers are identified and mapped as active (functional), relict (fossil/inherited) or transitional landforms of the geomorphological landscape: they are part of the mountain sediment cascade and as such, contribute to control the pace of the periglacial mountain landscape evolution. Enhancing the value of natural heritage of geomorphological landforms could also be the main motivation to realize a rock glacier inventory.
- *Proxy for permafrost occurrence*: Active rock glaciers are geomorphological direct indicators of the occurrence of permafrost. Even if it is accepted that active rock glaciers may export perennially

frozen ground outside of a permafrost area, they can be used for approximating the regional lower limit of the mountain permafrost and to validate spatial models of permafrost extent, whereas relict rock glaciers are reflecting former permafrost extents. It must be carefully taken into consideration that active rock glaciers show the occurrence of permafrost at depth, but with regards to the ongoing climate change, may gradually no longer attest that the surface conditions are still favourable for permafrost occurrence.

- *Paleo-permafrost studies*: Relict rock glaciers in particular can be used as proxies for various paleo-permafrost extents. The distinction between a active and a relict state can be difficult to assess, particularly in case of coalescent landforms, making a strict delimitation between what should be inventoried or not very difficult to set, and thus the integration of relict landforms in a global inventory indispensable.
- *Climate relevant variable*: Rock glacier movement is particularly sensitive to changing permafrost temperature. Repeating (updating) inventories of active rock glaciers, which include a temporally well-defined kinematical information, can be used to regionally assess the impact of ongoing climate change on the mountain periglacial environment.
- *Hydrological significance*: Active rock glaciers are, by nature, ice (and water) storage features, which may play a role in the hydrological regime of river/stream catchments, especially in dry areas. Rock glacier inventories have been set up and/or used in particular for estimating their regional water-equivalent significance. In addition to being ice storage features, rock glaciers can affect water transit time and water chemistry in a catchment.
- *Geohazards*: Active rock glaciers may be the source of direct or indirect geohazard phenomena (e.g. destabilization, conveying of loose debris into a debris flow prone gully) that may be a risk for human activities and/or facilities (e.g. transport infrastructures, buildings, livelihoods). Rock glacier inventories and related kinematic data can be used to locate and assess some potential geohazards at local to regional scales. It must be noted that in the context of infrastructure construction/maintenance, using a rock glacier inventory will not be sufficient to fully understand the issues related to permafrost degradation. However, it may provide an important clue for assessing the occurrence (or absence) of permafrost in the study area.

Two main approaches have been commonly used for compiling a regional rock glacier inventory: *the* g*eomorphological approach* (rock glacier features are recognized by a systematic visual inspection of the (imaged) landscape and DEM-derived products, as well as locally based on field visits) and *the kinematical approach* (moving areas are detected using multi-temporal remotely sensed data and rock glacier discrimination performed by the recognition of the association of a moving area to a rock glacier feature on optical images). While these two approaches yield different resulting inventories, they are complementary. The work performed within the IPA Action Group *Rock glacier inventories and kinematics*, as well as CCN1 and CCN2 of Permafrost_cci will ensure to make them as compatible as possible. For instance, one attribute that is important to document in rock glacier inventories is the activity (active, transitional and relict, as defined in [RD-10]). Primarily based on the visual observation of morphological (e.g. front slope angle) and vegetation-related indicators, we can also take advantage of kinematical information. When kinematics data is available, it can be integrated as a supplementary attribute in inventories and must be considered to assign the category of activity.

2.1.2 Kinematical time series on rock glaciers

Several studies, conducted in particular in the European Alps for the last two decades, have shown that rock glacier interannual behavior is dependent on permafrost temperature, the latter impacting in particular the rheological and hydrological properties of the frozen ground (Delaloye et al., 2010; Ikeda et al., 2008; Kääb et al., 2007; Kellerer-Pirklbauer & Kaufmann, 2012; Kenner & Magnusson, 2017; Roer et al., 2005). It has been observed that rock glaciers tend to accelerate on an interannual basis under warmer climatic conditions. So far the permafrost degradation has not become too severe to prevent this response.

Rock glaciers tend to display a similar regional behavior (pluri-)annual to (pluri-)decennial time scale. Interannual acceleration and deceleration are occurring at almost the same time and in the same proportion in a given region, whatever the activity rate and the morphological characteristics of the rock glaciers. Finally, continuous or seasonal monitoring has shown that the observed rock glaciers develop a landform-specific but repetitive intra-annual behavior, whose inter-annual variations are usually not altering the pluri-annual trends in a significant manner. The evidence of a relation between rock glacier kinematics and climate variables, as well as their similar regional behaviors makes the development of regional indexes possible, which can be used as a new associated product of the ECV Permafrost [RD-13]. The objective is to set up a global dataset of rock glacier surface velocity time series, which would permit assessing the regional/global reaction of mountain permafrost creep to climate change [RD-12].

2.1.3 Permafrost distribution model in a marginal periglacial mountain environment

The Southern Carpathians in Romania are located in a marginal periglacial mountain environment, the permafrost occurrence is patchy, and the preservation of permafrost is controlled by site-specific conditions. Specific user requirements for ground temperature and active layer thickness in the Southern Carpathians have been compiled in [RD-6]. They require a regional geographical coverage (regional permafrost extent Southern Carpathians, 14,000 km²), high temporal resolution (monthly data), high spatial resolution (target resolution 0.1 km) including representation of sub-grid variability, and long temporal coverage (one to several decades back in time). These requirements go considerably beyond the state-of-the-art in remote permafrost ECV assessment, based on published studies and recently demonstrated progress [RD-1] [RD-2] and require the development of algorithms especially designed for mountainous permafrost, where lateral heterogeneity due to micro-climatic and topographic conditions have to be accounted for.

2.2 Justification of the selected algorithms

CCN 1&2 D2.1 PVASR presented the selected standardized methodology and key criteria to provide comparable products, as described in the CCN 1&2 PSD [RD-6], with respect to the user requirements described in the CCN 1&2 URD [RD-7].

Regarding rock glacier kinematics, PVASR shows that there are several techniques available to fulfill the large-scale requirements [URq_1] [URq_10-12]. They are complementary and able to provide similar products in accordance with the objectives of the project. The basic concepts aim to be technology independent. The focus has thus been placed on the analysis of the key criteria that needed to be defined in order to standardize the outputs. Criteria allowing for the standardization of rock glacier inventories (RGI), including a kinematical attribute and the production of comparable kinematical time series (KTS), have been defined in synergy with the work of the IPA Action Group *Rock glacier inventories and kinematics* [RD-11] [RD-12] [RD-13]. The selected methods fulfill the user requirements [RD-7] and contribute to answer to the challenges and risk for discrepancies between operators identified in the CCN 1&2 D2.1 PVASR.

Due to the requirement of large coverage (regional-global), the focus is placed on aerial and spaceborne techniques. The standard products are technology independent and can be derived from a wide range of techniques listed in PVASR. For the production of RGI and KTS at the selected sites of CCN1 and CCN2, the project's partners have decided to primarily focus on Spaceborne Synthetic Aperture Radar Interferometry (InSAR) at regional scale, complemented by airborne feature tracking / photogrammetry and spaceborne SAR offset tracking in more restricted areas. The description of the processing line using these techniques is described in the current document (see Section 3).

The selected model for mountain permafrost distribution in the Southern Carpathians (MPDM) is an empirical approach based on a machine-learning model with a random forest (RF) classifier. An empirical approach is chosen instead of a process-based model due to the limitations of the available calibration and validation data and the complexity of the involved processes (Boeckli et al., 2012). A machine learning-empirical model with a random forest (RF) classifier is reported as best option in other mountain areas (Deluigi et al, 2017). In the Southern Carpathians, the model will benefit from an existing rock glacier inventory (Onaca et al., 2017) and other thermal and geophysical data used as evidences of permafrost occurrence (Onaca et al., 2013; Onaca et al., 2015; Popescu et al., 2015; Vespremeanu-Stroe et al., 2012). All these data are sufficient to support the fitting of the proposed model.

2.3 Background about Synthetic Aperture Radar Interferometry (InSAR)

Due to the regional-scale scale requirements of CCN 1&2, spaceborne Synthetic Aperture Radar (SAR) Interferometry (InSAR) is the primary technique used to generate the products related to rock glacier kinematics (see CCN 1&2 D2.1 PVASR). In this Section, we therefore summarize the background of the technique. For more theoretical background about InSAR, refer to Massonnet and Feigl (1998), Bamler and Hartl (1998), Rosen et al. (2000, Rocca et al. (2000), Hanssen (2001), Kampes (2006), and Ferretti (2014).

InSAR allows for the detection of surface deformation using pairs of SAR images acquired at different times over large areas. A pair of SAR images or interferogram is the result of the phase difference between two SAR acquisitions. It provides the observation of the 3D surface deformation component projected along the radar look direction (i.e. the Line Of Sight, LOS). A single SAR interferometric observation does therefore not allow fully determining the magnitude and direction of a surface deformation. The 3-dimensional displacement vector can be only computed if a displacement or "flow" direction is known, e.g. flowing along the steepest slope direction. Notice that the SAR measurement is not sensitive to the displacement if the flow and look directions are perpendicular to each other.

Current SAR satellites are polar orbiting and looking obliquely down, perpendicularly to the track direction. So, the LOS is roughly East or West and has an impact on which slopes are suited in mountainous terrain. North- and South-facing slopes, where deformations are often directed in the plane perpendicular to the LOS, can be difficult to analyze. Back-facing slopes (D to I, Fig. 1), defined as the western slope when viewing in descending mode or the eastern slope in ascending mode, are the most appropriate configuration: the local spatial resolution is less affected by geometric distortions and deformation orientation is more or less aligned with the LOS. The facing slopes (A-D, Fig. 1) are the opposite and are less favorable for an InSAR analysis. In addition, the slope steepness, along with the SAR incidence angle, has to be considered. A steep incidence angle (for instance 23° of ERS) reduces shadow effects observed in back-facing slopes but increases layover effects in facing slopes. Consequently, a good compromise has to be chosen to observe correctly the two sides of the valley in mountainous terrain.

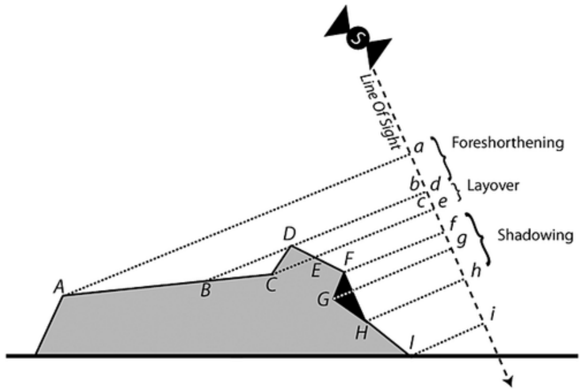

Figure 1. SAR acquisition geometry in the plane perpendicular to the orbit (Barboux et al., 2014).

The displacement can be evaluated through interferograms. The change of color in the resulting interferogram expresses the ground deformation projected into the LOS direction and the resulting fringe is equivalent to a change of half a wavelength in the LOS direction between two SAR images acquired at different times. The direction of the change can be interpreted using the key in Fig. 2. Looking at back-facing slopes, clockwise color changes mean that the radar beam has travelled further in the second acquisition and thus corresponds to a subsidence. In the opposite case, it will be interpreted as uplift.

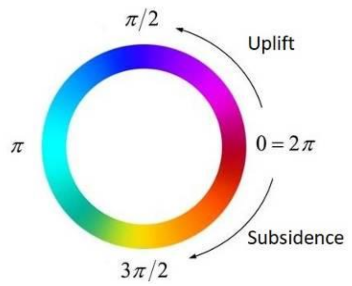

Figure 2: The difference in deformation rate between places having the same color is a multiple of λ/2. When the color turns in clockwise direction, the ground moves away from the satellite. In the opposite direction, the ground moves towards the satellite.

The rate of terrain movement that can be detected depends among others on the time interval, the spatial resolution, and on the wavelength (Fig. 3 and Tab. 1). The interferometric SAR signal will become ambiguous when the displacement gradient between adjacent pixels is higher than half of one fringe during the selected time interval. It will become decorrelated when the displacement gradient within a pixel is higher than half of the wavelength during the selected time interval. The time interval between the acquisitions must therefore be adjusted according to the excepted displacement rate. Temporal decorrelation can also be due to changes of surface properties (e.g. due to vegetation, snow, wetness).

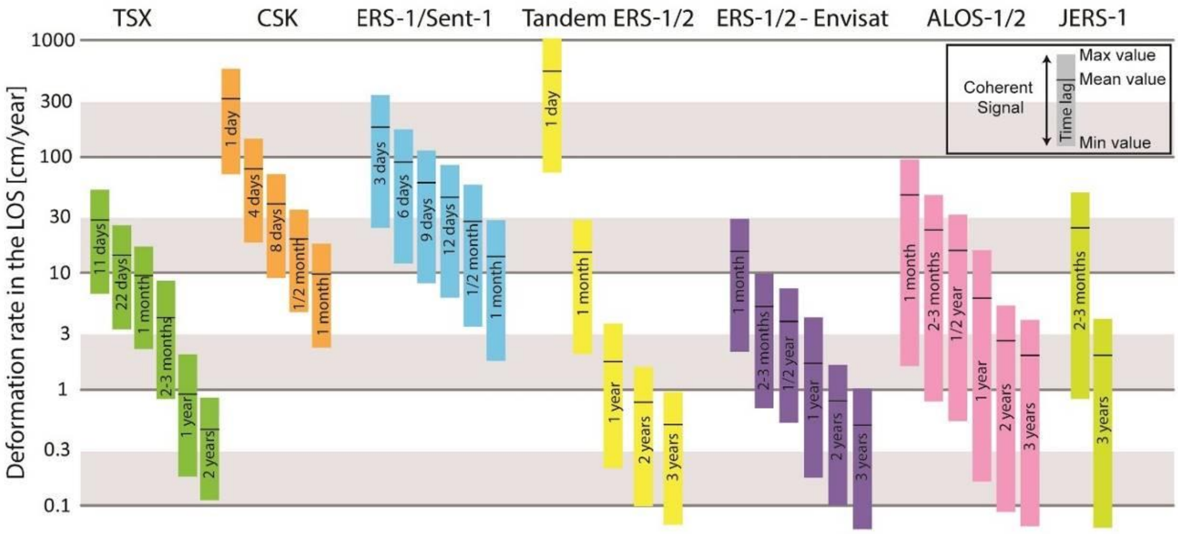

Figure 3: Deformation rate observed by SAR sensors for the most commonly used time interval. A bar defines the interval of deformation rate detected with a coherent signal on the interferogram of the selected time interval. For a specific time interval: a movement higher than the maximal value of deformation rate will be decorrelated on the interferogram, a movement lower than the minimal value is not detectable. The line in each bar defines the mean value of observable deformation rate. (source: Barboux et al., 2014)

To obtain a quantitative displacement information (e.g. cm), a particular step called phase unwrapping is required. This step allows to convert the periodic trend of the phase (that ranges between -π and +π), computing the absolute phase values, and then converting the phase into displacement according to the wavelength of the sensor. However, this step is often complicated, and introduces large errors especially over fast-moving areas and in mountainous regions, therefore results from this step should be interpreted carefully.

Different SAR sensors can be selected according to their availability and accessibility. To get a complete overview of slope movements in a given area and to prevent misinterpretation of detected mass wasting phenomena, it is essential to dispose of a large set of workable interferograms produced with various time intervals (e.g. daily, monthly and yearly) and a small spatial baseline. The major obstacle limiting a successful use of InSAR in an Alpine environment is the presence of (wet) snow. Usable SAR scenes must be, as much as possible, snow free (e.g. between June and October in the European Alps) (Barboux et al., 2014; 2015). SAR scenes with a short (daily) time interval can also be used in the wintertime when the snow is still cold. Estimating the occurrence of old or fresh snow and the weather conditions (rainy event) at or up to 2 days before each SAR image date on the basis of available meteorological data has proven to be a helpful step in evaluating the quality of an interferogram. Finally, phase noise and residual phase error terms remaining after InSAR processing (e.g. from atmospheric artifacts) must not be neglected when interpreting the interferogram (see CCN 1&2 D2.3 E3UB).

Table 1. Radar characteristics of the SAR systems commonly used in interferometry

Satellite	*TerraSAR-X*	*Cosmo-SkyMed*	*Sentinel-1*	*Radarsat-2*	*ALOS-2*
Date	from 2007	from 2007[2]	from 2014	from 2007	from 2014
Agency	DLR	ASI	ESA	CSA	JAXA
Wavelength (cm)	3.1	3.1	5.5	5.6	24.3
Band	X	X	C	C	L
Incidence angle (°)	20-45	25-45	20-45	35	30-40
Range resolution (m)[1]	1-16	1-100	5-25	3-100	3-60
Azimuth resolution (m)[1]	1-16	1-3-100	5-40	3-100	3-60
Scene width (km)	10-100	10-200	80-400	50-500	70
Repeat cycle (day)	11	1-4-8-16	(6)-12[3]	24	14

[1] *The resolution in range and azimuth and the scene width depend on the image acquisition mode. The most common modes are Interferometric Wide (IW) for Sentinel-1, Extra-Fine (XF) for Radarsat-2 and StripMap for the other sensors.*

[2] *Constellation of small Satellites for Mediterranean basin Observation (1st and 2nd satellites launched in 2007, 3rd in 2008 and 4th in 2010)*

[3] *With both satellites Sentinel-1A and Sentinel-1B operating, the repeat cycle is 6 days.*

3 PROCESSING LINE

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

We aim to provide standardized regional rock glacier inventories mostly based on previously existing inventories (InSAR polygons from GlobPermafrost and/or existing morphological rock glacier inventories). The update/upgrade will follow the general procedure given in Figure 4 and will follow the selected standards described in the CCN 1&2 D2.1 PVASR and [RD-10]. Two outputs will be provided: the moving areas related to rock glacier units (Section 3.1.1) and the rock glacier units themselves (Section 3.1.2).

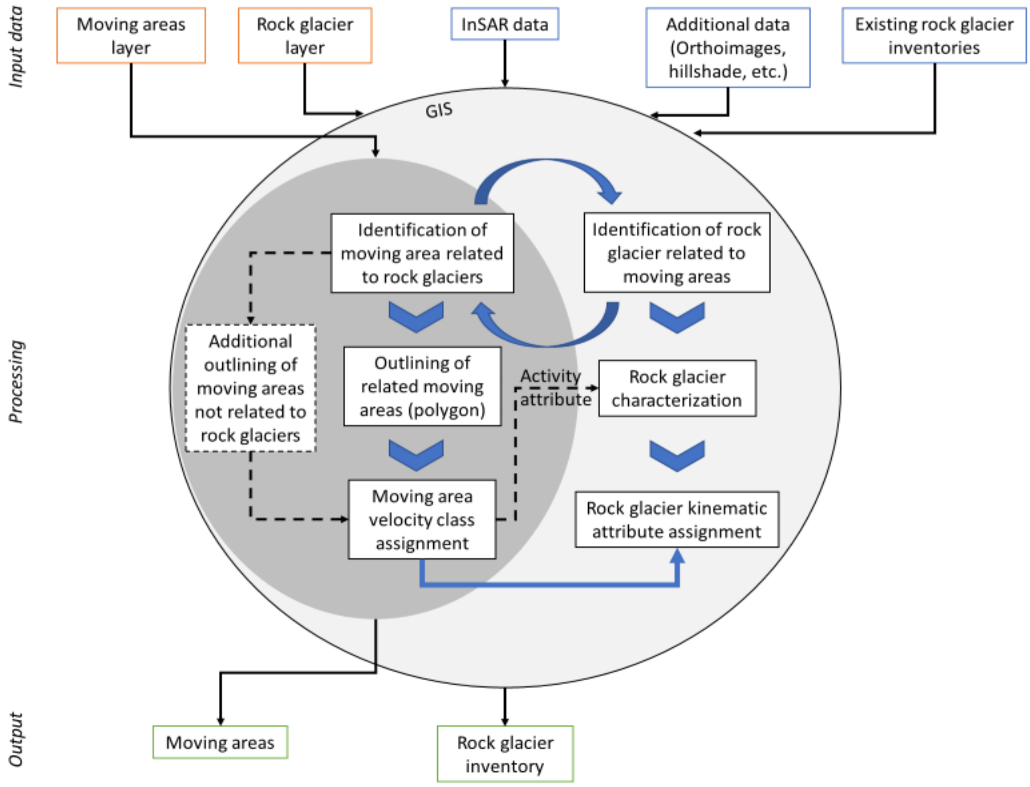

Figure 4: Procedure for the proposed standardization of rock glacier inventory using InSAR data. The analysis is performed in GIS software

3.1.1 Identification and characterization of moving areas

The identification and characterization of moving areas is a recommended first step to be able to assign later a kinematical attribute to a rock glacier unit. In principle, all moving areas related to rock glacier unit only should be compiled in the final product. However, a level 0 layer containing the whole identified moving areas irrespective of size, type or other factors could be useful. This layer is not mandatory; it is under the responsibility and must fit the needs of the operator.

a) Visual identification of moving areas using InSAR

The detection is performed by looking at the textural features from the interferometric phase image according to three InSAR signal patterns: (1) no change defined by a plain pattern, (2) smooth change characterized by a (partly) fringe pattern and (3) decorrelated signal expressed by a noisy pattern (Fig. 4) (Barboux et al., 2014; 2015). The texture is evaluated around the considered pixel related to the size of the landforms that have to be detected. The minimal size of detectable targets is consequently limited by the spatial resolution of the interferogram as well as by the filtering applied to reduce noise. However, a moving area can be identified if at least 20-30 pixels show a fringe pattern.

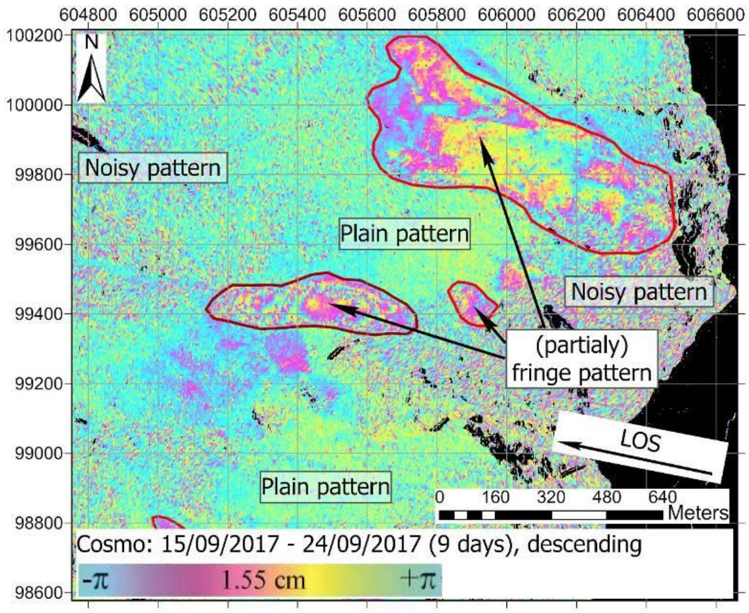

Figure 4: InSAR signal patterns. Arolla area (Western Swiss Alps). Data where layover and shadowing are masked (black)

The methodology to detect a moving area using InSAR is developed on the basis of the visual signal interpretation from a set of valid wrapped interferograms. Valid means that the error sources (e.g. due to processing, atmospheric artefacts, etc.) are as low as possible to make the resulting data confidently exploitable. This procedure allows for the systematical detection and characterization of moving areas related to mass wasting processes, rock glaciers in particular. The combined visualization of wrapped interferograms allows to prevent the presence of single artifacts due e.g. to atmosphere or snow, identifiable with a noisy pattern or, sometimes, with a fringe pattern extended over very large areas. In fact, atmosphere or snow artifacts occur only on few (or single) interferograms, and therefore can be discriminated from moving areas. Noise patterns related to vegetation or glaciated area, persistent over all interferograms, have to be interpreted correctly.

An estimation (magnitude order) of the related displacement rate (velocity) along the LOS is possible when the moving area is characterized by a (partly) fringe pattern (see part 3.1.1.c). When a moving area is characterized by noise patterns (i.e. the rate of terrain movement is too fast for the selected time interval and the signal became decorrelated), the identification of the position, the extent and the contour of rapid displacements is still possible. Slow movement rates (velocities slower than 3 cm/yr) are detectable but often difficult to be assessed with enough precision.

The detected InSAR-derived moving areas can be compared to their related geomorphological landforms using topographical maps, orthophotos and/or existing rock glacier inventories. This step permits on the one hand to evaluate the reliability (or the degree of confidence) of the detected moving areas, and on the other hand, to discriminate moving areas related to rock glaciers.

b) Moving area outlining

The detected moving area is indicated using a polygon that is manually drawn around the detected InSAR pattern. A polygon describes an area where a given InSAR signal is detected for most of available interferograms.

Moving areas have to be outlined according to the following requirements (an example of moving area outlining is shown in Fig. 5):

- Outlines should be drawn starting from interferograms with lower time intervals (and smaller wavelengths). After which, by increasing the time intervals, the drawn outlines can be refined, and additional outlines (with lower velocities) can be identified and drawn. As the extent of a moving area could partly vary depending on the observation time and the velocity behavior, the final outline should delineate a moving area with homogeneous velocity, and the velocity range within a moving area should fit the class of velocity defined in part 3.1.1.c.
- The outline does not necessarily fit the morphological outline of the rock glacier unit but has to fit the detected InSAR pattern.
- A moving area can override the geomorphological limits of a rock glacier unit (e.g. when two overlying rock glacier units are moving at rates, which are not significantly different).
- Several polygons can be related to the same landform, and several moving areas can be overlying, a slower moving area always embedding a faster one (an area where only little movement is identified must be differentiated to parts where a movement rate is higher).
- The minimum extent of a moving area depends on the spatial resolution of the data inputs and the size of the landform, based on operator’s judgment. However, interferograms with high spatial resolution allow for higher details when drawing outlines. It is recommended that a fixed precision of the drawn outline is applied (e.g. the drawn line should fit the size of one or two image pixels of the highest resolution InSAR data available).
- Isolated movements, unreliable areas and unrepresentative parts have to be avoided.

In addition, one has to note that:

- The border of a moving area is often non-sharp, depending also on the detection capability of the used technique, making a precise delineation possibly difficult to obtain.
- Areas outside of any delineated moving area refer either to the absence of movement, to a movement which may be under the detection limit, or to unreliable data.

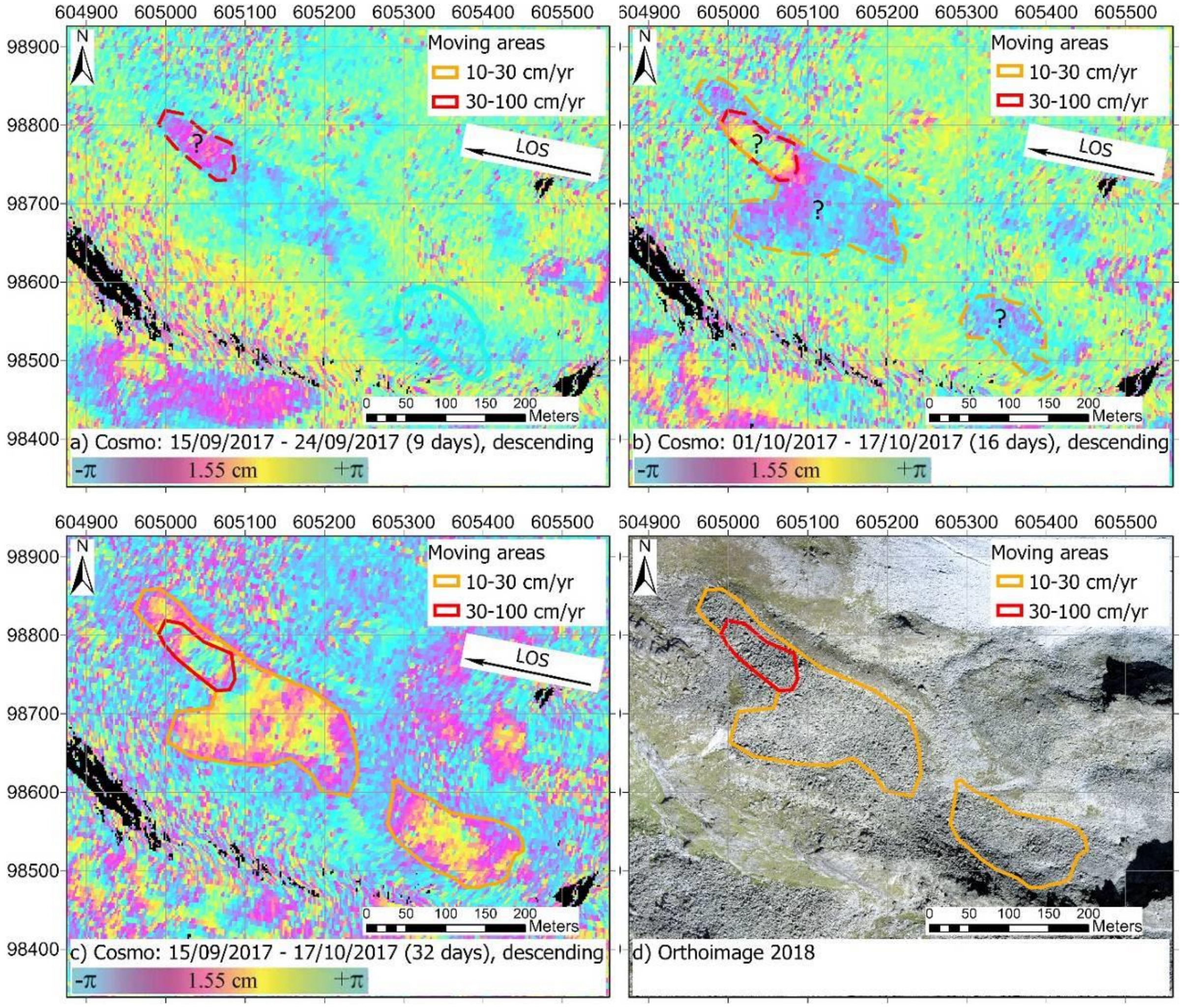

Figure 5: Rock glacier detection using Cosmo-SkyMed data. A large set of valid combinations of interferograms with different time intervals is required to increase the relevance of detected polygons. (a) A small red signal could be detected on the 9-day interferogram. (b) Using a 16-day time interval, a signal could again be seen on the frontal part and around two parts of the whole landform. (c) The frontal and upper parts are now well detected on the 32-day interferogram whereas a signal appears around two parts of the rock glacier. The frontal part becomes partially decorrelated. (d) The entire rock glacier is visible on the orthoimage. Three moving areas have been drawn and classified in terms of the deformation rate as moving in the order of 30-100cm/yr in red and of 10-30 cm/yr in orange.

c) Velocity class of a moving area

A velocity classification of moving areas is recommended to be able to assign later a kinematical attribute to a rock glacier unit. The use of velocity classes is intending to facilitate the assignment of a more homogeneous, but simplified velocity information to moving areas. It also permits an assignment, which is based on operator’s judgment.

The velocity class of InSAR-derived moving areas refers, as far as possible, to the 1D LOS InSAR measurements performed on back facing slopes (the local spatial resolution is less affected by geometric distortions and deformation orientation is more or less aligned with the LOS).

It is strictly stamped by time characteristics:

- The observation time window, i.e. period during which the detection and characterization is computed/measured (e.g. multi-annual, annual, intra-annual). The minimal required duration is one month (several months are preferable) within the snow free period.
- The temporal frame, i.e. the duration during which the periodic computations/measurements are repeated and aggregated for defining the moving area (i.e. during which year(s)).

The velocity class should reflect somehow a spatio-temporal mean movement rate, but neither a single intra-annual variation nor an extreme. Thus, when moving areas are detected/characterized using time intervals shorter than 1 month (e.g. 6 days for Sentinel InSAR data), several pairs should be used in order to cover the minimal observation time window of one month (e.g. at least two 6-day pairs spaced by 18 days). When periodic measurements are available during a temporal frame of several years (consecutive years are preferable), the same observation time window must be applied (e.g. always August-September in 2018 and 2019).

For InSAR-derived moving areas, the following half an order magnitude classification of 1D LOS velocity are recommended:

0. Undefined
1. < 1 cm/yr
2. 1-3 cm/yr
3. 3-10 cm/yr
4. 10-30 cm/yr
5. 30-100 cm/yr
6. > 100 cm/yr *
7. Other (velocity can be then expressed in a field "Remarks")

* Optional. If the sensor has the detection capability, the velocity class should be set at *7. Other* and the following classes can be indicated in a field "Remarks":

- 100-300 cm/yr
- > 300 cm/yr

The categorization of the velocity is performed:

- Either by estimating the velocity value by comparing the phase signal inside and outside a detected moving area at different time intervals. This is done by two steps: first, by counting the entire fringe cycles from a point assumed to be stable to the detected moving area (exploiting Fig. 2); second, by converting the fringe cycle into velocity per year.
- Or by the categorization related to the time intervals at which a moving feature is detected by a coherent, respectively a decorrelated, signal. This is done by comparing the signal of each interferogram with the respective bar of Fig. 3 (i.e. the bar with the same sensor and time interval): a decorrelated pattern means that the displacement is greater than the maximum detectable limit with that interferogram (i.e. the displacement exceed the upper limit of the bar); no visible fringe pattern means that the displacement is less than the minimum detectable limit with that specific interferogram (i.e. displacement lower than the lower limit of the bar); a visible

fringe pattern means that the displacement is detectable with that specific interferogram and the bar provides a velocity value.

d) Reliability of moving area identification and characterization

The reliability (or the degree of confidence) *of the detected moving area* has to be qualitatively assessed (low, medium, high) in accordance with the quality of both the detection and the velocity classification.

<u>Categories:</u>

0. Low: signal interpretation (velocity estimation) <u>and</u> outline are uncertain but there is something to consider.
1. Medium: signal interpretation (velocity estimation) <u>or</u> outline are uncertain.
2. High: obvious signal, best appropriate configuration (back-facing slope).

When looking N-S facing slope, or if the number of interferograms is low, the reliability of the detection decreases. When the reliability in classifying velocity is low due to specific technical limitations, the velocity class has to be set as “undefined”.

When available, the comparison can be performed with other available kinematical data (e.g. in-situ measurements). This analysis allows for consolidating the assignment of the velocity class of the moving areas and later the reliability of the rock glacier kinematics characterization.

Additional multi-temporal InSAR techniques have been developed over the last decades to overcome some limitations of the single interferogram approach (e.g. to reduce the effects of irrelevant phase components such as atmospheric effects) and retrieve time series. Outputs from these techniques can also be used to identify moving areas and are described in more detail in Section 3.2.1. The classification of the velocity based on multi-temporal InSAR methods can follow the same semi-quantitative classes as previously described.

The detection of moving areas can be also complemented at more local scale by SAR offset tracking of SAR or feature tracking on repeat optical airphotos. These techniques are particularly useful for fast moving landforms when the reliability of InSAR data is not ensured. The classification of the velocity based on feature-tracking methods can follow the same semi-quantitative classes as previously described. These techniques are described in more detail in Sections 3.2.2 and 3.2.3.

3.1.2 Rock glacier units

In principle, all rock glacier units should be compiled irrespective of size, type or other factors.

a) Rock glacier identification

According to the IPA Action Group, a rock glacier unit (i.e. a single rock glacier landform that can be unambiguously discerned from other rock glacier units) is differentiated from a rock glacier system (i.e. landform identified as rock glacier, which is composed of either a single or multiple rock glacier units that are spatially connected either in a toposequence or in coalescence).

The recommendation is to use **a point feature** manually positioned on the landform, **able to identify the rock glacier units location, and discriminate it clearly from other rock glacier units without ambiguity**; the positioning of the point on the rock glacier unit should avoid, as far as possible, any (frequent) temporal updating. It is recommended that 0.01 km² is used as the minimum size of a rock glacier unit to be registered when conditions permit.

When rock glacier inventories are not previously available over the region of interest, the typology of the landform (geomorphologic process) related to each moving area must be evaluated on satellite or airborne optical images or by field visits. Rock glaciers units can be discriminated using the technical definition proposed by the IPA Action Group and compiled.

When rock glacier inventories are available over the region of interest, they can be used to discriminate rock glacier units. However, it is recommended to evaluate the remaining detected moving areas that can be related to missed rock glaciers.

Basic attributes recommended by the IPA Action Group have to be documented (unit morphology, spatial connection to the upslope unit and destabilization attributes). As kinematical data are available from moving areas which have been previously inventoried, they must be considered in order to assign the category of the activity attribute.

For further details regarding the technical definition and standardized attributes of rock glacier, see [RD-10].

b) Kinematical attribute definition

As defined in CCN 1&2 D2.1 PVASR and [RD-11], the kinematical attribute is a semi-quantitative (order of magnitude) optional information, which must be representative of the overall multi-annual downslope movement rate of an inventoried rock glacier unit. It is a refinement of the activity categorization, which reflects somehow the mean kinematical behavior of the rock glacier unit of concern. It is basically determined by the exploitation of the characteristics (extent, velocity class, time specificities) of the moving area(s), which have been identified at the surface of the rock glacier unit. The attribute must be spatially representative of the rock glacier unit for a given multi-annual validity **time frame** (snapshot) **of at least 2 years**. The exploited data, the applied method and their related time characteristics (observation time window and temporal frame) of all supporting data have to be documented.

The kinematical attribute is basically determined by the exploitation of the characteristics (extent, velocity class, time specificities) of the moving area(s), which have been identified at the surface of the rock glacier unit. However, as dominant moving area(s) are only rarely covering a rock glacier unit in its whole and may be not reflecting a multi-annual displacement rate, a systematical translation of the velocity class to the kinematical attribute, highly dependent on the techniques, should carefully be performed. It must also be taken into consideration that the documented surface velocities may be faster than the effective rock glacier displacement rate and that intra-annual (usually summer) velocities may be faster the annual ones.

The categorization consists of semi-quantitative classes of the multi-annual downslope displacement rate of the entire rock glacier body (Table 2).

Table 2: Semi-quantitative classes of kinematical attribute

Category	Label	Comment	Related activity
0.	Undefined	Default category	
1.	< cm/yr	No or very little movement	Relict
2.	cm/yr	Order of magnitude ≈ 0.01 m/yr	Transitional
3.	cm/yr to dm/yr	Order of magnitude ≈ 0.05 m/yr	Transitional
4.	dm/y	Order of magnitude ≈ 0.1 m/yr	Active
5.	dm/yr to m/yr	Order of magnitude ≈ 0.5 m/yr	Active
6.	m/yr	Order of magnitude ≈ 1 m/yr	Active
7.	> m/yr	More than ≈ 3 m/yr	Active
8.	Other	Velocity can be then expressed in a field “Remarks”	

There is only one assigned category per rock glacier unit. In case of two partially dominant, but successive (e.g. 5-6) categories would occur on a rock glacier unit, the area closer to the front is favored for the attribution. In case of a larger heterogeneity of partially dominant categories on the same rock glacier unit, the median category should be retained, with a specific additional indication. A large heterogeneity can also indicate the need to affine/redefine the delineation of the initial morphological units (iterative process combining geomorphological and kinematical approaches).

The default category is *0. Undefined*. The rock glacier unit falls into this category when (i) no (reliable) kinematical information is available (e.g. N/S facing slopes), (ii) a dominant part of the rock glacier unit is characterized by a moving area of undefined velocity, (iii) the kinematical attribute could not be defined reliably.

For each rock glacier unit with assigned kinematical attribute, the following additional information has to be documented:

- Multi-year *validity time frame* of the kinematical attribute,
- *Data/technique(s) used* and related characteristics of all the supporting kinematical data including: sensor (e.g. Sent1), method (e.g. InSAR), observation time window (e.g. multi-annual, annual, intra-annual), temporal frame (e.g. which year(s)) and dimensionality (e.g. 1D),
- *Approximated spatial representativeness*: percentage of surface that is documented by supporting kinematical data (e.g. < 50%, 50-75%, > 75%). This is qualitatively estimated by comparing the total area of the moving areas inside the rock glacier unit and the total area of the rock glacier unit. The restricted geomorphological footprint method is recommended to delineate the rock glacier unit,

- *Reliability of the assignment* of the kinematical attribute (see part 3.1.2d).

c) Rules for the kinematical attribute assignment

The velocity information from moving areas should be transferred to the proper category of kinematical attributes in order to indicate the overall multi-annual rate of movement observed/estimated on a dominant part of the rock glacier surface. The assignment of kinematical attributes is based on the operator's judgment. Manual transfer from a velocity class of an InSAR-derived moving area to a kinematical attribute is recommended instead of automated procedures (e.g. automatic transfer using GIS software). Moreover, checking the original InSAR signal is sometimes helpful to assess the right categorization.

The two following cases a) and b) present recommendations based on two different observation time windows. They are proposed on the conditions that:

- 1D LOS InSAR measurements are performed on back facing slopes (the local spatial resolution is less affected by geometric distortions and deformation orientation is more or less aligned with the LOS),
- a dominant part of the rock glacier unit is depicted by a single moving area.

In case of several moving areas, the assigned category should represent the dominant velocity class of the rock glacier unit. For example, the median category should be used, with a specific additional indication of heterogeneity. However, if moving areas show a large heterogeneity over the unit (e.g. more than three moving areas with velocity classes falling into various categories), the category *0. Undefined* should be chosen.

An additional field named "remark" can be used to give more detail to the categorization (e.g.: half of the RG at class X, only upper part of the RG is moving, maybe faster, maybe slower, etc.)

<u>Case a: Annual or multi-annual observation time window</u>

A dominant part of the rock glacier unit is depicted by single moving area, whose associated velocity class is reliably characterized at <u>an annual or multi-annual observation time window</u>. Of concern are typically moving areas with a velocity class:

1. < 1 cm/yr (no movement up to some mm/yr)
2. 1-3 cm/yr (some cm/yr).

(nb: larger movements are decorrelated using annual interferograms)

The kinematical attribute of the considered rock glacier unit can be assigned as follows (only for back facing slope 1D LOS InSAR measurements):

<u>Velocity classes (annual)</u>	<u>Kinematical attribute</u>
1. < 1 cm/yr	1. < cm/yr
2. 1-3 cm/yr	2. cm/yr

Case b: Observation time window shorter than 1 year

A dominant part of the rock glacier unit is depicted by a single moving area, whose associated velocity class is reliably characterized at an observation time window shorter than 1 year (at least one month in snow free period). Of concern are typically moving areas with a velocity class of:

3. 3-10 cm/yr
4. 10-30 cm/yr (some dm/yr)
5. 30-100 cm/yr
6. > 100 cm/yr (m/yr and higher)

(nb: smaller movements are undetected using these time interval interferograms)

The order of magnitude of the rock glacier creep rate is estimated per default as 20% lower than the summer-time velocity. The kinematical attribute of the considered rock glacier unit can be assigned using Table 3 (only for back facing slope 1D LOS InSAR measurements).

Table 3: Assignment of the kinematical attribute rules

Velocity classes (based on summer season)	**Approx. annual velocity**	**Kinematical attribute**
< 1 cm/yr (no mov. up to mm/yr)	< 0.8 cm/yr	< cm/yr
1-3 cm/yr (some cm/yr)	0.8-2.4 cm/yr	cm/yr
3-10 cm/yr	2.4-8 cm/yr	cm/yr to dm/yr
10-30 cm/yr (some dm/yr)	8-24 cm/yr	dm/yr
30-100 cm/yr	24-80 cm/yr	dm/yr to m/yr
> 100 cm/yr (m/yr and higher)	> 80 cm/yr	Other*

**When it is possible to distinguish between the additional velocity classes '100-300 cm/yr' and '> 300 cm/yr', the kinematical attribute can be set at '6. m/yr' and '7. > m/yr' respectively. Otherwise, the category '8. Other' should be selected and the note 'm/yr or higher' should be indicated in the field 'Remark'.*

d) Reliability of the assigned kinematical attribute

The *reliability* (or the degree of confidence) *of the assigned kinematical attribute* ("Reliab" attribute) has to be qualitatively assessed (low, medium, high) according to the quality of the moving areas related to the rock glacier unit, and the certainty of the assigned kinematical attribute.

Value

0. Undefined: if the kinematical attribute is undefined
1. Low: low quality of the moving area(s).
2. Medium: medium or high quality of the moving area(s) but uncertain kinematical attribute assignment.
3. High: high quality of the moving area(s) and clear kinematical attribute assignment.

When available, the comparison can be performed with other available kinematical data (e.g. in-situ measurements). This analysis permits to consolidate the assignment of the kinematical attribute of the rock glacier unit.

3.1.4 Validation and consolidation with a second operator

More details about the validation strategy are described in CCN 1&2 D2.5 PVP

a) Consolidation of the results

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”, as well as the kinematical elements of the inventories, i.e. the velocity classes of the identified moving areas and the order of magnitude of the kinematical attribute have to follow the recommended methodology and guidelines, developed by the IPA action group [RD-10 and RD-11]. During production/update of the inventory, it is recommended that at least two persons perform the work to reduce operator’s subjectivity and to ensure the quality of the results.

Following this approach, moving areas and kinematical attributes are assigned by the first operator, who provides also the reliability degrees. Then the second operator checks the results of the first operator, confirming the results or modifying them. In addition, the first operator can also suggest supplementary checks at the second operator assignments for specific cases. The uncertainties are reduced by taking advantage of the knowledge of two different operators.

b) Assessment of the results

When possible, inventoried moving areas must be compared with available in-situ or complementary remote sensing measurements recorded at (or around) the same temporal frame. Terrestrial geodetic survey data (DGNSS, Total station, Lidar, etc.), as well as air-borne photogrammetry data are, for instance, precious sources of validation and can be used to assess the quality of the results. A comparison may be performed to verify that the kinematical attribute of the rock glacier unit falls into the correct category.

In the absence of terrestrial data, only the analysis of several interferograms and a good knowledge of the corresponding geomorphology allow for a good interpretation of the results. The presence of a clear signal on a long time interval, which confirms the activity of the landform, is an absolute prerequisite for attributing the signal to a change in the topography rather to noise. In any case, the interpretation of the dataset by a second operator is highly recommended in order to improve the validity of the inventory.

3.2 Kinematical time series on selected rock glaciers (KTS)

The processing line for KTS consists of the measurement of the InSAR time series on selected rock glaciers (Section 3.2.1), potentially complemented by time series from SAR offset tracking (Section 3.2.2), feature tracking on repeat optical airphotos (Section 3.2.3), and the development of standardized comparable products (Section 3.2.4).

3.2.1 *Kinematical time series from InSAR*

Kinematical time series can be produced using selected, co-registered, corrected and unwrapped interferograms (Strozzi et al., 2020). In general, initial preprocessing is performed on a reference image acquired in summer to ensure maximum coherence and the georeferencing uses an available Digital Elevation Model (DEM) in the area of interest. Subsequently, slave images are co-registered to the reference image using a geometrical approach, which includes the scene topography, followed for Sentinel-1 by a refinement of the transformation determined by a spectral diversity method (Wegmüller et al., 2016). Differential interferograms (DInSAR), including removal of the topographic phase using the DEM, are, then, created in series for variable time periods for the available sensors available, depending on the wavelengths and expected velocity (e.g. 6 to 24 days for Sentinel-1). Multi-looking (average of looks) is performed to improve the quality of the pixel statistics and provide final square pixels (e.g. 20m in range for Sentinel-1). Phase unwrapping to render absolute LOS movement values is achieved using a minimum cost flow (MCF) algorithm (Werner et al., 2000) and choosing a stable reference point close to the active rock glacier of interest. Atmospheric phase trend corrections with respect to height are, first, applied over the entire area covered by the image and, then, refined to particular smaller areas around the rock glaciers. Velocity and coherence data are then extracted for the rock glaciers of interest contained in a specified frame, and displayed for high coherence levels (e.g. >0.5). A vector representing the assumed direction of motion based on the slope and aspect of the filtered DEM and LOS vectors for each sensor is calculated and the total displacement determined.

Multi-Temporal InSAR techniques can also be applied to retrieve time series. They have been developed over the last decades to overcome some limitations of the single interferogram approach (to reduce the effects of irrelevant phase components such as atmospheric effects). They are generally divided into two main groups:

- Methods based on locating *Persistent Scatterers* (PSs), referred to as *Persistent Scatterer Interferometry* (PSI) methods (Ferretti et al., 2000; Ferretti et al., 2001; Colesanti et al, 2003; Kampes, 2006). A stack of interferograms is generated at full resolution using a single master scene. PSI has been used in Norway to map ground displacements over the whole country (insar.ngu.no). The method can contribute to the delineation of moving landforms at high resolution but is designed for linear and slow-moving features, and thus does not allow for correctly quantifying velocities higher than a few cm/year. For rock glaciers, PSI has thus to be complemented by single interferogram analysis and/or methods based on spatial correlation.
- Methods based on *spatial correlation* and *distributed scattering* (DS), referred to as *Stacking* and *Small BAseline Subset* (SBAS) methods (Berardino et al., 2002, Lauknes, et al. 2011, Peltzer et al., 2001; Pepe et al., 2011; Sandwell and Price, 1998). These methods incorporate a larger number of interferograms (multiple masters) and only interferograms below chosen spatial and temporal baseline thresholds (in relation with the wanted detection capability and expected velocity of the landforms) are selected in order to reduce geometric and temporal decorrelations. DS InSAR can be used to analyze the spatial distribution and temporal variations of permafrost landforms (Rouyet et al., 2019; Eriksen et al., 2017). The upper limit of detection of the rate of motion depends in particular on the chosen temporal baseline threshold. When only the shortest time-intervals are considered in series, this method corresponds to the above described one. When longer temporal baselines are incorporated, a higher accuracy is obtained for moderately fast landforms.

3.2.2 Kinematical time series from SAR offset tracking

The calculation of displacement fields with SAR data is also possible using offset tracking methods, largely adopted over glaciers in order to overcome InSAR signal decorrelation when using long time intervals or analyzing rapidly moving objects (Gray et al., 1998; Paul et al., 2017; Strozzi et al., 2002; Werner et al., 2005). Compared to glaciers, rock glaciers are rather small objects and offset tracking is feasible only with very high-resolution SAR images with a resolution of about 2 m. Using a normalized cross-correlation of chips in amplitude SAR images, offsets are measured with rectangular windows at a set of positions uniformly distributed over the image scene. In order to obtain an accurate subpixel precision estimate of the correlation peak, the correlation function values are fitted using a biquadratic polynomial surface. The time interval of the image pairs can be adjusted according to the expected maximum displacement over the rock glacier from a few months to several years. In general, late summer image pairs with short perpendicular baselines are preferably considered. Mismatches or blunders are filtered by applying a threshold to the correlation coefficient, by iteratively discarding spurious matches based on the angle and size of displacement vectors in the surrounding area, and by using a low-pass filter on the resulting fields (Paul et al., 2015). Finally, slant range and azimuth offset fields are transformed to 3D displacement along the terrain surface determined from the DEM (Strozzi et al., 2002) and geocoded.

3.2.3 Kinematical time series from feature tracking on repeat optical airphotos

Using feature tracking on repeat optical airphotos to measure rock glacier movement is highly complementary to the above SAR and InSAR methods. Optical feature tracking is in particular useful for three application scenarios:

- Very fast rock glacier motion (> 1m/yr), where InSAR typically fails to quantify the motion;
- Rock glacier motion time series back in time to when no suitable SAR data exist, i.e. at least pre-ERS era, or over gaps in the availability of suitable SAR data. In some countries first suitable airphotos date back to the middle of the 20th century, or even earlier;
- Validation/comparison to simultaneous InSAR-derived data (Strozzi et al. 2020) (Fig. 6).

Using cross-correlation techniques surface displacements are measured between two or more optical images (Fig. 7) (Kääb and Vollmer, 2000; Kääb et al., 2007). Digital photogrammetry benefits from a high degree of automation and this technique works actually particularly well over rock glaciers due to their good visual surface contrast (debris) and their slow and coherent deformation (due to the stress-transferring and cold ice content). The images to be matched have to be orthorectified. If they are not already orthorectified, this step is undertaken using the best DEM available to the consortium. Offsets between the orthophotos are then tracked using normalized cross-correlation. The raw results are then post-processed. This step contains for the most part the removal of outliers based on a combination of automatic and manual procedures, such as thresholding of correlation coefficients or visual inspection. For good image data, an accuracy of 1/5-1/10 pixels can be achieved. Limitations of the method come mostly from the availability of suitable imagery, bad image quality and resolution, and orthorectification errors. The final result of feature tracking on repeat optical airphotos are two-dimensional horizontal displacement vectors between the image acquisition dates.

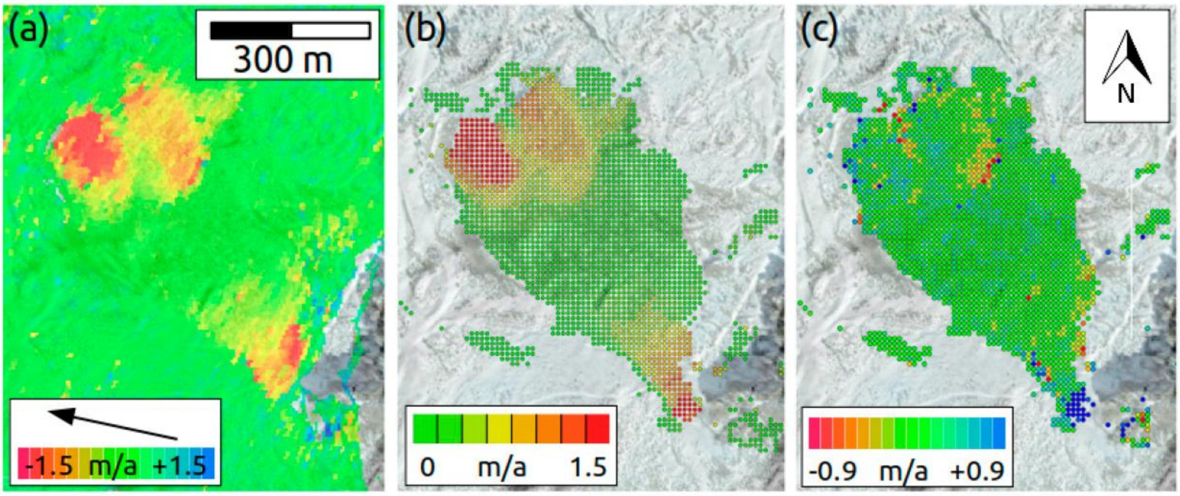

*Figure 6: Distelhorn rock glacier (Mattertal, Switzerland). (**a**) Sentinel-1 InSAR line-of-sight velocity map from 02.08.2018 to 08.08.2018; (**b**) Horizontal velocity map from matching of aerial optical images with a spatial resolution of 0.15 m acquired on 03.09.2014 and 21.09.2017; (**c**) Difference map between aerial photo matching and Sentinel-1 InSAR LOS velocities. From Strozzi et al. (2020).*

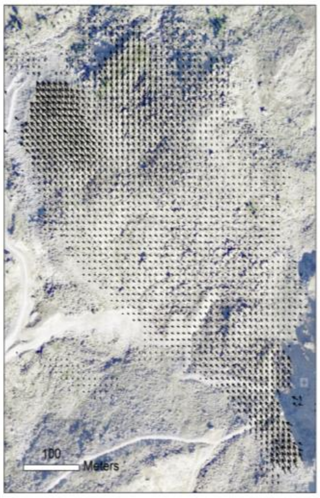

Figure 7: Original displacement measurements between repeat airphotos that are used for Fig. 6(b).

3.2.4 Standard time series

The methodology and key criteria for standardization of KTS are presented in CCN 1&2 D2.1 PVASR and described into details in [RD-12] and [RD-13].

We start from the first-level data (individual time series expressing a velocity at an annual and pluri-annual resolution) retrieved by following the procedure described in Sections 3.2.1 to 3.2.3. The standardization consists in transferring the first-level data into second-level data, used to develop regional indexes.

First-level data, second-level data and regional index are defined as followed:

- First-level data consist of individual kinematical time series having an annual and pluri-annual resolution expressing a velocity;

- Second-level data consist of individual kinematical time series having an annual or pluri-annual resolution expressing a relative velocity to a reference time;
- A regional index is an assemblage (e.g. mean) of selected relative time series.

The time series have to follow a series of key criteria defined in the submitted proposition of rock glacier kinematics as a new GCOS ECV Permafrost product [RD-13]:

- Horizontal resolution, i.e. spatial distribution of selected rock glaciers
- Horizontal resolution (2), i.e. surface velocity value
- Time resolution: frequency and observation time window
- Timeliness, i.e. time needed for data processing
- Required measurement uncertainty of the velocity values
- Stability, i.e. consistency over time

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

The Mountain Permafrost Distribution Model (MPDM) is a modeling product based on a RF classification algorithm that learns all the characteristics of the terrain and spectral data for the training area (for both the areas with permafrost and without permafrost) and searches for similar characteristics of the independent variables in the rest of the study area.

Random forest is a classification and regression algorithm that computes a number of individual classification trees and uses each classification in order to produce high accuracy results based on the majority "vote" of the classification trees. Because of the use of multiple sub-classifications, it is, in general, a robust tool that has a low sensitivity to outliers and errors in input data.

The RF classification algorithm can be run on a big set of predictor variables that can be extracted from both a DEM and satellite images. This is particularly important i) considering that different studies suggest the use of different predictor variables and ii) the model is run in an area where no distribution model has been used so far at a regional scale.

The MPDM is implemented in the open source software R, making it easy to use for any user.

Because the MPDM model can be computationally intensive for large regions when using high resolution input data, it has a built-in function that allows the division of the study area in smaller patches that can be independently classified and the merged to form the output. Using this function, the model can be run on a desktop computer, although the computation time increases significantly.

The MPDM will be implemented in the following steps (Fig. 6):

a) Preparation of predictors
   - Selecting satellite image(s) that cover the entire area and are cloud free,
   - Deriving indexes from the satellite images that will be used as predictors along the four bands (R, G, B, NIR): NDVI, NDSI, NDWI,
   - Deriving predictors from DEM: Catchment Area, Channel Network, Aspect, Slope, Curvature, Plan curvature, Profile curvature, Channel network base level, Altitude above channel network, Catchment height, Catchment slope, Convergence index, Topographic Positioning Index, Terrain Roughness Index, Wetness Index, Valley Depth, Slope height, Standardize height, LS factor, Mid slope position, Direct potential solar radiation, Indirect potential solar radiation, Total potential solar radiation,
   - Test if predictors are correlated and remove highly correlated predictors.

b) Preparation of training data

- Build polygons with presence/absence of permafrost constructed based on ground surface temperature data from iButton data loggers, geophysical measurements and expert knowledge of the area

c) Building of the model as a script/tool
d) Running the model and production of the uncertainty map and predictor importance ranking
e) Evaluation of the uncertainty map for any positional bias and systematic errors
f) Evaluation of the predictor importance ranking and eliminate unnecessary predictors
g) If necessary, make adjustments to the model and/or input data, based on steps e) and f)
h) Run the model and produce all the model outputs: permafrost extension map, uncertainty map, accuracy assessment, predictor importance ranking
i) Validate results

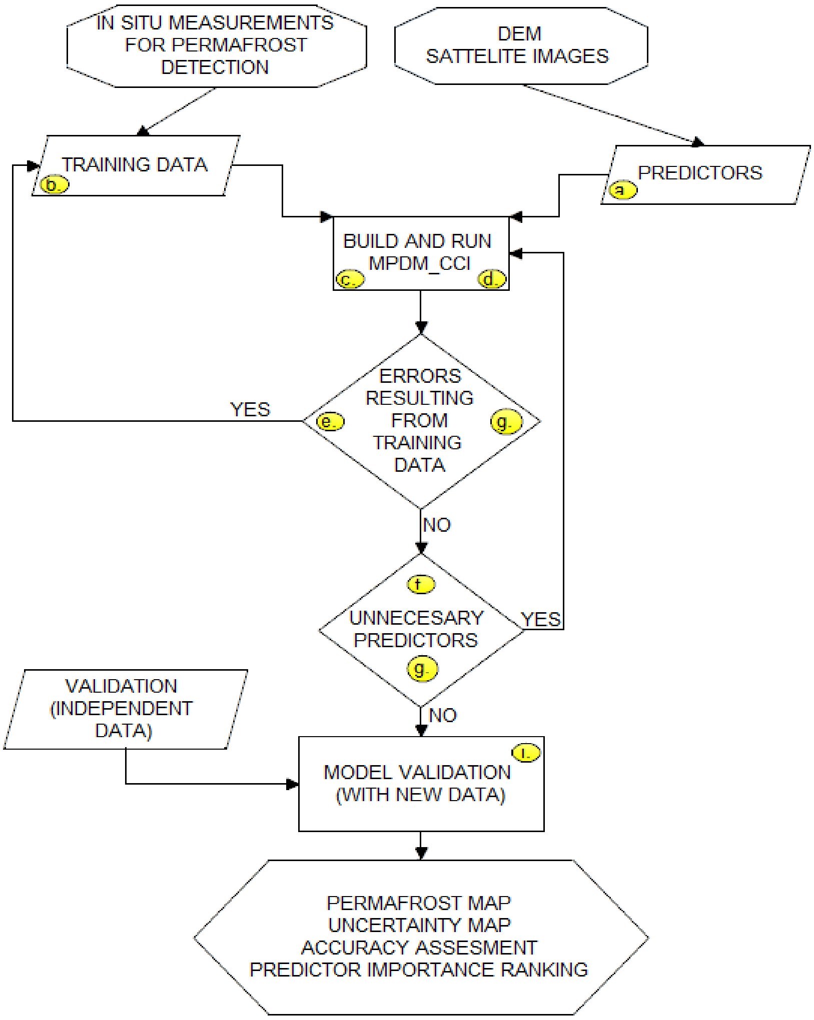

Figure 6: The workflow of the mountain permafrost distribution model in the Southern Carpathians (MDPM)

4 REQUIRED INPUT DATA

The required input data are presented in detail in the CCN 1&2 DARD [RD-8]. Elements related to the generation of the three products of the CCN1 and CCN2 are summarized in Table 3. Validation data are described in CCN 1&2 D2.5 PVP.

Table 3: Summary of required input elements for the development of the CCN 1 2 products

Data class	Data type	Source	Spatial coverage	Temporal coverage	Repeat periodicity	Availability
Production RGI/KTS	Sentinel-1 SAR data	ESA	All sites	2015-2019	6 days	Freely available, see DARD
Production RGI/KTS	Sentinel-1 SAR interferograms	CCI+ Permafrost	All sites	2015-2019	6 days to several years	CCI+ Permafrost consortium
Production RKI/KTS	Other SAR interferograms	ESA DUE GlobPermafrost	Swiss Alps, Disko Island, Tien Shan, Brookes Range	2016-2017	1 days to several year	PANGAEA
Production RGI/KTS	Complementary SAR data (TSX, CSK, ALOS1/2, JERS, ERS, ENVISAT)	Gamma/UniFR	Swiss Alps	1991-today	9 days to several years	CCI+ Permafrost consortium
Production RGI/KTS	Complementary SAR data (TSX, RSAT-2, ERS, ENVISAT)	NORCE	European subarctic/arctic sites	1991-today	11 days to several years	CCI+ Permafrost consortium
Production RGI/KTS	Complementary SAR data (ALOS-2)	Gamma/Terrasigna	Carpathian sites	2015-2019	Months to years	CCI+ Permafrost consortium
Production RGI/KTS	Complementary optical aerial imagery	UiO	European subarctic/arctic sites Tien Shan, Swiss Alps, Brookes Range	Depending on site, from 1950s – 1960s on	Irregular (few years – decades)	CCI+ Permafrost consortium
Production RGI/KTS	Complementary very high-resolution optical satellite imagery	UiO	Tien Shan	Depending on site, from about 2000-2010	Irregular (few years)	CCI+ Permafrost consortium
Production MPDM	Polygons with presence/ absence of permafrost	WUT	Carpathian sites	Based on ground surface temperature data from iButton data loggers, geophysical measurements and expert knowledge of the area (various coverage and periodicity)		CCI+ Permafrost consortium
Production MPDM	R, G, B and NIR bands from Landsat or Sentinel-2 satellite images.	WUT	Carpathian sites	Irregular	Single dates	Freely available, see DARD
Comple-mentary (required)	DEM	mixed	All sites	Irregular	Single dates	CCI+ Permafrost consortium
Comple-mentary (required)	Orthoimagery (satellite/aerial)	mixed	European Alpine sites European	Irregular	Single dates	CCI+ Permafrost consortium

			subarctic/arctic sites Tien Shan Brookes Range Central Andes New Yealand			
Comple-mentary (required)	Google Earth™/ Bing imagery	Google Earth	All sites	Irregular	Single dates	Freely available
Comple-mentary (required)	Morphological rock glacier inventories	mixed	Ultental Vanoise Tien Shan Central Andes Norway New Zealand	Irregular	Irregular	CCI+ Permafrost consortium
Comple-mentary (required)	ESA GlobPermafrost slope movement inventories	ESA DUE GlobPermafrost	Swiss Alps Disko Island Tien Shan Brookes Range	2016-2017	Single dates	CCI+ Permafrost consortium

5 OUTPUT PRODUCTS

As defined in the CCN1&2 PSD [RD-7], three products are considered in the options:

- Regional rock glacier inventories, including a kinematical attribute (RGI)
- Kinematical time series on selected rock glaciers (KTS)
- Mountain permafrost distribution model in the Southern Carpathians (MPDM)

Product specifications and formats are described in detail in CCN 1&2 PSD [RD-7] and will only be summarized here (Table 4).

Table 4: Properties of CCN output products

	RGI	KTS	MPDM
Spatial resolution	Minimum size of inventoried rock glacier is around 0.01 km^2. Moving areas based on Sentinel-1: 20-60m final resolution Complementary higher resolution TerraSAR-X: 3-10m. Complementary higher resolution optical feature tracking: 1-10m Input data is documented.	Spatial distribution of select rock glaciers: G: Regional coverage (at least 30% of the active talus-connected rock glaciers in a region) B: Multiple sites in a defined regional context T: Isolated site Surface velocity value: spatially representative of the surface velocity of the rock glacier unit, no restriction about the dimensionality but data property has to be documented and consistent over time. G: Flow field B: Few discrete point T: Velocity value at a point	The spatial resolution of potential permafrost distribution map is related to the resolution of the main input (the DEM) and will be generated at 30 m spatial resolution.
Temporal resolution	Rock glacier units are characterized for a multi-annual validity time frame (snapshot) of at least 2 years. Updates are recommended every 10 years. Observation time window and temporal frame of all the supporting kinematical data are documented.	The velocity value is computed at an annual frequency or a multiple of it. G: 1 yr: Measured/computed once a year. The observation time window is 1 year and consistent over time. B: 1 yr: Measured/computed once a year. The observation time window is shorter than 1 year. It should not be shorter than 1 month and must be consistent over time. T: 2-5 yr: Frequency limited by an observation time window of 2-5 yrs (admissible for optical images and reconstructions from archives)	The model represent a given current situation at documented time (snapshot).
Product attributes	Each inventoried rock glacier unit has the following attributes: ID, geographic location, morphological type (simple or complex unit), spatial connection	Reference rock glacier ID, Kinematical time series (velocity values)	The potential permafrost distribution map will store the probability values for permafrost absence-presence (0, 1).

	to the upslope unit, activity, destabilization signs, kinematical attribute, validity time frame, data used, spatial representativeness, reliability and remarks Each inventoried rock glacier is linked to moving area(s) with the following attributes: ID, Reference rock glacier ID, velocity class, time characteristics, reliability and remarks		
Product accuracy	Minimum detectable velocity from Sentinel-1 InSAR: approx. 1/10 of a wavelength (i.e. around 5-6 mm) Maximum detectable velocity: approx. 1/2 wavelength (i.e. around 2.8 cm), i.e. 170-20 cm/yr for time intervals of 6-48 days respectively. Reliability (high, medium, low) is documented for the kinematical attribute and for each detected moving area	Documentation of the relative measurement uncertainty: G: 5%: Relative measurement uncertainty allowing for the reliable analysis of velocity trend over time (relative change). For fast moving rock glacier B: 10% T: 20%: Relative minimal measurement uncertainty allowing for the reliable analysis of velocity trend over time (relative change). For fast and slow moving rock glacier	MPDM outputs include an uncertainty map regarding the permafrost distribution map and an accuracy estimation of the modelling based on randomly extracted samples from the input data.
Data dissemi-nation	ESA CCI webpage, communicated to permafrost community via the IPA Rock Glacier Inventory and Kinematics Action Group, the IPA Permafrost Mapping Action Group, the CRG and international community relevant mailings lists, such as Permalist and Cryolist.		
Product project system	UTM based on the World Geodetic System 84 (WGS84) reference ellipsoid		
Metadata	Information about satellite scenes used (date, path, row, sensor, processing), additional kinematical used (used techniques, date acquisitions, points/areas measured, accuracy, precision), date/source/spatial resolution of the available DTM and orthoimages, available slope movement inventories and/or morphological rock glacier inventory as well as the name of the analysts and the date/region of the analysis. References, acknowledgments and any other important metainformation.	Technique used for deriving the kinematical time series (InSAR, optical, etc.) and the related accuracy. Additional information: velocity type (annual mean, snow-free period mean, maximum, seasonal), time period of measurement, producer and date of production.	Information about input data (predictors) and the predictor importance ranking
File formats	Shapefile and raster format, provided as different NetCDF files		Raster format, provided as different NetCDF files
Product file naming convention	ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-	ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional	ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional

s	<Additional Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc <Product String>: RGI	Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc <Product String>: KTS	Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc <Product String>: GTD: ground temperature, ALT: active layer thickness, PFR: permafrost extent (fraction), PFF: permafrost-free fraction, PFT: fraction underlain by talik, PZO: permafrost zone.

More specifically, RGI output will follow the format and structure presented in Table 5 and 6. KTS will follow criteria defined by GCOS ECV Permafrost.

Table 5: Rock glacier inventory: Attribute table of the inventoried rock glacier units

Name	*Definition*	*Values*
ID_CCI	A unique alpha-numerical identifier of the rock glacier unit	CCI-*ZZ-XXXX-UU* *ZZ*: Area number 05-Romania 06-Switzerland, Western Swiss Alps 07-Norway, Troms 08-Norway, Finnmark 09-Svalbard, Nordenskiöld 10-France, Vanoise 11-Italy, Ultental 12-Greenland, Disko Island 13-Tien Shan 14-Alaska, Brookes Range 15-Argentina, Central Andes 16-New Zealand, Central part of the Southern Alps *XXXX:* numerical code of the rock glacier (defined by the user) *UU*: numerical code of the rock glacier unit
Coord_X	X coordinate	WGS 84 coordinate system
Coord_Y	Y coordinate	WGS 84 coordinate system
Morph_Type	Unit morphology (see standards in the Baseline concepts document from the IPA Action Group)	0. Undefined 1. Simple 2. Complex
Spatia_Con	Spatial connection to the upslope unit (see standards in the Baseline concepts document from the IPA Action Group)	0. Undefined 1. Talus 2. Debris mantle 3. Landslide 4. Glacier 5. Glacier forefield 6. Poly
Activity	Efficiency of the sediment conveying (expressed by the surface movement) at the time of	0. Undefined 1. Active 2. Transitional

	observation (see standards in the [Baseline concepts document]() from the IPA Action Group)	3. Relict
Destabiliz	Signals of abnormally fast behavior, which can be expressed geomorphologically by the opening of large cracks and/or scarps (see standards in the [Baseline concepts document]() from the IPA Action Group)	0. Undefined 1. Yes 2. No
Kin_attrib	Kinematical attribute assigned to a rock glacier unit, based on the delineated moving areas. It indicates the overall multi-annual downslope movement rate of an inventoried rock glacier unit	0. Undefined 1. < cm/yr 2. cm/yr 3. cm/yr to dm/yr 4. dm/yr 5. dm/yr to m/yr 6. m/yr 7. > m/yr 8. Other (velocity can be then expressed in a field “Remarks”)
Val_time_frame	Multi-year *validity time frame* of the assigned Kin_attrib	Ya-Yb: between year Ya to year Yb (snapshot)
Data_used	Data type, observation time window, temporal frame and dimensionality	Text containing: DIMENSIONALITY-DATA-TYPE_ TIME-OBSERVATION-WINDOW_TEMPORAL-FRAME e.g: 1D InSAR S1 Summer Y1-Y2 (velocity observed with Sentinel1 InSAR in the LOS using a summer length observation time window each year in between year Y1 to year Y2) 1D InSAR TSX Summer Y1, Y2, … (velocity observed with TerraSAR-X InSAR in the LOS using a summer length observation time window at year Y1, year Y2, etc.) 3D permanent GNSS Y1-Y10 (velocity observed with permanent GNSS between year Y1 to year Y10)
Spatial_rep	Spatial representativeness: percentage of surface that is documented by supporting kinematical data	0. Undefined 1. < 50% 2. 50-75% 3. > 75%
Reliab	Reliability of the kinematical attribute	0. Undefined 1. Low 2. Medium 3. High
Remarks	If needed	Text

Table 6: Rock glacier inventory: attribute table of the inventoried moving areas related to rock glacier

Name	***Definition***	***Values***
ID_CCI	A unique alpha-numerical identifier of the moving area	CCI_*CodeRG_N* *CodeRG*: ID_CCI of the related rock glacier unit *N*: numerical code allowing the differentiation of each moving area related to a single rock glacier unit (defined by the user)
Vel_class	Velocity class: variable characterizing the surface displacement rate observed in the	0. Undefined 1. < 1 cm/yr 2. 1-3 cm/yr 3. 3-10 cm/yr

	LOS during the specified observation time window	4. 10-30 cm/yr 5. 30-100 cm/yr 6. > 100 cm/yr 7. Other (velocity can be then expressed in a field "Remarks") *Note:* - *when it is possible to distinguish in between the additional velocity classes 100-300 cm/yr and > 300 cm/yr, class 6 is chosen and the specific class can be indicated in the field "Remark".* - *when the reliability of the detected moving area is low due to specific technical limitation, the moving area has to be outlined and the velocity class has to be set as "undefined".*
Time	*Observation time window* (period during which the detection and characterization is computed/measured), and *temporal frame* (duration during which the periodic measurements/computations are repeated and aggregated for defining the moving area, i.e. during which year(s)). Sensor type used to perform the characterization is included here	Text containing: SENSOR(s)_OBSERVATION-TIME-WINDOW_TEMPORAL-FRAME e.g.: S1 Summer Y1-Y2 (velocity observed from Sentinel-1 with a summer length observation time window each year in between year Y1 to year Y2) TSX Summer Y1, Y2, … (velocity observed from TerraSAR-X with a summer length observation time window at year Y1, year Y2, etc.) CSK Annual Y1-Y2 (velocity observed from Cosmo-SkyMed with an annual length observation time window each year in between year Y1 to year Y2) ALOS 08-10 Y1-Y2 (velocity observed from ALOS with an observation time window centered in between August and October each year in between year Y1 and year Y2)
Reliability	Reliability of the detected moving areas	0. Low: signal interpretation (velocity estimation) and outline are uncertain, but there is something to consider. 1. Medium: signal interpretation (velocity estimation) and outline are uncertain 2. High: obvious signal, best appropriate configuration (back-facing slope) *Notes:* - *When looking N-S facing slope or the number of InSAR data allowing detection is low, the reliability of the detection decreases.*
REF_ID	ID_CCI of the related rock glacier unit	
Remarks	Notes related to the detection and characterization (if needed)	Text e.g.: N-S facing slopes, few data, noisy signal, faster velocity in the rooting zone, etc.

6 PRACTICAL CONSIDERATIONS FOR IMPLEMENTATION

The main basic concept behind the development of the RGI and KTS products, in line with the recommendations of the IPA action group, is to propose a methodology that is as far as possible technology-independent, allowing for upscaling the systematic investigation mountain permafrost and specifically the mapping and monitoring of rock glaciers by different research teams around the globe. Despite the standards presented in CCN 1&2 D2.1 PSVAR and the processing guidelines described in the present document, several challenges are identified and the CCN 1&2 team will keep discussing and assessing them all along the project. They can be summarized into four elements:

- The field knowledge and level of past or ongoing investigation vary for the different selected sites. For some areas, existing inventories will be used and updated according to the new standards. For other areas, the work for inventorying rock glaciers is starting during the Permafrost_cci sub-projects CCN 1&2 and will follow a geomorphological and/or a kinematical approach (see Section 3.1.1).
- The amount (e.g. every 6 or 12 days for Sentinel-1, availability of high-resolution SAR images) and properties (e.g. DEM and orthophoto resolution) of the input data vary depending on the study sites (see Section 4). In addition, the different regional contexts lead to various rock glacier distributions and activities (e.g. typically low velocity in the Carpathians vs. high velocity in the Alps), which may require to adapt the processing strategy to the specific needs.
- There is a variability in the InSAR basic knowledge between the external partners. A significant effort is placed on training the different teams to similar methodology (e.g. delineation of moving areas, see Section 3.1.2). Differences in terms of InSAR software and processing chains exist between the three options (using wrapped interferograms, multi-temporal InSAR techniques, complementary SAR offset tracking and feature tracking on repeat optical airphotos, see Sections 3.1.2, 3.2.1, 3.2.2, 3.2.3). It should not lead to different RGI and KTS outputs after standardization, but the difference between techniques have to be documented and respective limitations acknowledged.
- The work initiated in the Permafrost_cci sub-projects CCN 1&2, in synergy with the IPA action group, towards the integration of a new GCOS ECV Permafrost related to rock glacier kinematics, is promising and the consortium aims to start and continue remote sensing-based time series at several selected rock glaciers in the different study areas (see Sections 3.2.1, 3.2.2, 3.2.3). However, there is an unknown factor related to the ability of the different teams to perform a long-term monitoring of KTS, depending on the research funding and future projects.

These identified challenges and the risk for discrepancies in the final products will be assessed in the future CCN 1&2 deliverables, especially during the inter-comparison and validation of the results.

For the MPDM product, the main challenge identified is related to the limited input datasets to calibrate and validate the model. If the selected empirical approach overcomes the issue in the specific context of the Southern Carpathians, it has to be recalled that it applies for this region only. No assumption of transferability to other mountain ranges is made in the framework of the CCN 1&2 projects.

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7.2 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
LST	Land Surface Temperature
KTS	Kinematical Time Series
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
MPDM	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