CCI+ PHASE 1 – NEW ECVS
PERMAFROST

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

D2.1 Product Validation and Algorithm Selection Report (PVASR)

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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 glaciers. User Requirements, Product Specifications and Data Access Requirements are described in D1.1-1.3 of CCN1-2 [RD-6 to RD-8].

This Product Validation and Algorithm Selection Report (PVASR) summarizes and discusses the process leading to the definition of standards for production of rock glacier inventories and kinematical time series, and the selection of a model for the permafrost distribution in the Carpathians. For the CCN1 mountain permafrost distribution product, the PVASR presents the available models, discusses their differences and justifies the selection of an empirical approach based on a machine-

learning model with a random forest classifier, with respect to the user requirements. For CCN2 products, this document presents the available techniques able to measure rock glacier kinematics and key criteria that need to be standardized in order to provide comparable products. Challenges for standardization and risk of discrepancies are identified and analyzed to enable the selection of the most appropriate standards, with respect to the user requirements.

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 glacier 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 Product Validation and Algorithm Selection Report (PVASR) documents the selection of standards (for RGI and KTS) and the model required (for MPDM) to provide 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 gives an overview on the user requirements (from CCN 1&2 URD [RD-6]) related to each product (from CCN 1&2 PSD [RD-7]) and how it determines the selection of the standards and the model.
- Section 3 introduces the available techniques for measuring rock glacier kinematics, describes the key criteria that need to be standardized to generate RGI and KTS products, and lists the available models for MPDM.
- Section 4 provides an analysis and intercomparison of the results and identifies the challenges for standardization and risk for discrepancies between operators when generating RGI and KTS products. It compares the available models for MPDM.
- Section 5 summarizes the conclusion of the analysis and presents the chosen methodology, selected standards and the model, which allow meeting the user requirements.

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 6.1.

1.6 Acronyms

A list of acronyms is provided in Section 6.2.

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 CONTEXT OF THE ALGORITHMS AND ACCURACY DETERMINATION

2.1 Context of the algorithms

The objective of the Permafrost_cci CCN1 and CCN2 options is to develop specific products for mountain permafrost areas. As defined in the 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)

For each product, 23 user requirements based on surveys have been determined, as presented in the CCN 1&2 URD [RD-6]. The Tables 1-3 thereafter summarize these requirements. These user requirements demonstrate the need for upscaling location specific investigations and monitoring of mountain permafrost in general. The common element for all products is that a large coverage is required (regional to global scale for RGI; sufficient rock glaciers representative for a defined regional context for KTS, Southern Carpathians for MPDM). For this reason, the present document focuses on <u>remote sensing techniques able to provide the three defined products at a regional to global scale.</u>

For RGI and KTS products, the project takes advantage of the synergy with the IPA Action Group *Rock glacier inventories and kinematics* (2018-2022), aiming to define standards for the development of consistent and comparable rock glacier inventories and kinematics monitoring strategies. CCN2 is meant to support this Action Group on integrating rock glacier kinematics in GTN-P (Global Terrestrial Network for Permafrost) as a new associated parameter of the Essential Climate Variable (ECV) Permafrost in the framework of GCOS, characterizing the evolution of mountain permafrost. The IPA Action Group organized two workshops in September 2019 and February 2020, respectively, which discussed standards for RGI and KTS. The identified challenges for standardization and risks for discrepancies are analyzed in Section 3, the key criteria necessary to be defined to provide a standardized methodology are discussed in Section 3 and 4 and the recommended international standards are summarized in Tables 9-10.

The Southern Carpathians in Romania (CCN1), located in a marginal periglacial environment where permafrost occurrence is patchy and the existing database incomplete, includes in addition a mountain permafrost distribution model (MPDM).

2.1.1 User requirements for regional rock glacier inventories, incl. kinematics (RGI)

User requirements for RGI related to coverage, sampling, resolution, attributes and error/uncertainty are summarized in Table 1.

Regarding the preparation of the inventories, the baseline concepts from the IPA Action Group *Rock glacier inventories and kinematics* (following the Workshop I in September 2019) [RD-10] defines the standards for which landforms have to be considered in the inventory (technical definition of rock glaciers) and for which attributes have to be documented (connection to upslope unit, activity, etc.). This is further discussed in Section 3.2.

The threshold requirement for geographical coverage and sampling (URq_01) is a regional coverage of selected mountain ranges, while the target requirement is a global coverage. According to users, specific attributes can remain undefined for up to 30% of rock glaciers in an inventory, which means that rock glaciers can be included with center coordinates only (indicating their presence, URq_10). URq_01 and URq_10 highlight the need to focus on techniques that allow for measurements at regional to global scale. There are uncertainties and discrepancies in the answers e.g. related to the way to delineate and classify moving areas and assign a kinematical attribute to individual rock glacier units. This is discussed in Section 3.2 in relation to the results from the IPA Action Group workshop II (February 2020) [RD-11].

Table 1: User requirements for RGI (from CCN URD, RD-6)

	Threshold requirement	**Target requirement**
Geographical coverage and sampling [URq_01]	European Alps and Andes on the basis of a mountain range whatever the national boundary.	Global coverage on the basis of a mountain range whatever the national boundary.
Time frame and temporal extend [URq_02]	Current year	Assessed over 5-10 years and investigation in the past
Rock glacier identification [URq_03]	By a point	By its geomorphological footprint
Multi-unit differentiation [URq_04]	Different generations or different dynamics	Different dynamics, different generations and different connection to the upper slope
Update [URq_5]	10 years	10 years
Rock glacier activity [URq_06]	-	Extended classification [RD-10]
Rock glacier destabilization [URq_07]	Optional	Useful
Kinematics [URq_08]	Qualitative value (tbd)	Quantitative value (tbd)
Moving areas [URq_09]	Optional. Classification (tbd)	Useful. Classification (tbd)
Precision & accuracy [URq_10]	-	Up to 30% of rock glaciers in an inventory could be left undefined

2.1.2 User requirements for kinematical time series on selected rock glaciers (KTS)

User requirements for KTS related to coverage, sampling, resolution and error/uncertainty are summarized in Table 2.

Regarding the kinematical time series, the users require that at least 30% of rock glaciers (optimal goal) should be selected in a regional context for deriving kinematical time series with a time step of one year. There are uncertainties and discrepancies in the answers by users, e.g. related to the requested position of velocity measurement over the landform. This is discussed in Section 3.4 in relation to the results from the IPA Action Group workshop II (February 2020) [RD-12] and the recently published response to the GCOS ECV review [RD-13].

Table 2: User requirements for KTS (from CCN URD, RD-6)

	Threshold requirement	**Target requirement**
Geographical coverage [URq_11]	European Alps	Global coverage
Geographical sampling [URq_12]	Sufficient rock glaciers to be representative in a defined regional context	At least 30% of representative rock glaciers in a defined regional context
Update [URq_13]	5 years	1 year

Time resolution [URq_14]	Yearly or seasonally with an annual time step	Yearly or seasonally with an annual time step
Temporal extent [URq_15]	Past 5-10 years	As far as possible back in time
Velocity value [URq_16]	Semi-quantitative value	Exact value
Horizontal resolution [URq_17]	tbd	tbd
Precision & accuracy [URq_18]	< 5 cm/yr	< 1 cm/yr

2.1.3 User requirements for mountain permafrost distribution model in Southern Carpathians (MPDM)

Specific user requirements for the MPDM in the Southern Carpathians related to coverage, temporal extent, resolution and accuracy are summarized in Table 3.

The ultimate objective of Permafrost_cci is to develop and deliver permafrost maps as ECV products primarily derived from satellite measurements. The required associated parameters by GCOS for the ECV Permafrost are "Depth of active layer (m)" and "Permafrost temperature (K)". 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 [RD-1].

The Southern Carpathians in Romania are, however, located in a marginal periglacial mountain environment, where 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 demand 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]. Models to estimate permafrost distribution taking into account these criteria are discussed in Section 3.4.

Table 3: User requirements for MPDM (from CCN 1&2 URD, RD-6)

[URQ_23]	**Threshold requirement**	**Target requirement**
Geographical coverage	Southern Carpathians	Retezat and Parâng mountains
Temporal extent	Present	Present
Horizontal resolution	30 m	10 m
Accuracy	75%	90%

2.2 Accuracy determination

Validation and user assessment will be performed for the guidelines of remote sensing-based regional rock glacier inventories, the guidelines of remote sensing-based kinematical time series of selected rock glaciers, and the products for the selected sites (RGI, RTS and MPDM, see [RD-7]). The methodology for remote sensing-based rock glacier inventories is discussed in Section 4, using results of an exercise at the IPA Action Group workshop II and related discussions. Discrepancies between different producers were evaluated and guidelines for the production of RGI were refined accordingly. They provide the necessary basis for the inventories derived with a kinematical approach as well as an example of application through a practical exercise for a) the identification and characterization of moving areas on the basis of InSAR data and b) the assignment of a kinematical attribute to selected rock glacier units. External partners will be asked to perform a practical exercise in order to learn the standardized methodology and become familiar with the guidelines, as well as to observe and assess the homogeneity of their results. If needed, a webinar, technical support, etc. shall be provided. In this way, the delivered standardized regional rock glaciers inventories (consisting of an update of existing morphological rock glacier inventories and/or slope movement inventories) will rigorously follow the defined guidelines and ensure the homogeneity in the delivered RGI. Delivered kinematical time series of selected rock glaciers will be evaluated and validated against in-situ velocity measurements when available over the investigated sites. The permafrost distribution model in the Southern Carpathians will be evaluated and validated against in-situ ground temperature measurements and geophysical surveys.

With respect to the baseline activities of Permafrost_cci, the produced rock glacier inventories and kinematical time series constitute a unique validation dataset for climate models and permafrost indication maps for mountain regions, where direct permafrost (thermal state) measurements are very scarce or even totally lacking. The assessment of the data products by the Permafrost_cci Climate Research Group (CRG) and other users as well as outreach activities regarding publications and presentations will be summarized in the "Climate Assessment Report" (CCN 1&2 D5.1). It is planned to publish the standard guidelines for the inventorying of rock glaciers based on satellite SAR interferometry in a world class peer-reviewed scientific journal (CCN 1&2 D5.2). In addition, it is intended to publish the inventories of rock glaciers and the kinematical time series of selected rock glaciers in the various investigated regions.

3 ALGORITHMS AVAILABLE FOR CCN1&CCN2 PRODUCT GENERATION

The suitability and compatibility of the different types of product properties are evaluated and interpreted from a global perspective to define international standards. For this reason, the present document focuses on the definition of a standardized methodology (basic concepts and guidelines) able to fulfill the user requirements in case of RGI and KTS. The standards aim to be technology-independent, as long as the applied techniques are complying with the user requirements.

For sake of clarity, we define here several terms in the following

- Requirements: User requirements (from CCN 1&2 URD, RD-6) based on the results of user surveys. Relevant for RGI, KTS and MPDM products.
- Techniques: Available technologies able to provide kinematic measurements over rock glaciers (see Section 3.1), depending on the specificities of the sensor, platform and algorithm used for data processing. Relevant for RGI and KTS products.
- Key criteria: Main elements that are necessary to be defined to provide a standardized methodology. Relevant for RGI and KTS products.
- Standardized methodology: Recommended international standards (basic concepts and guidelines) for the production of rock glacier inventories and kinematical time series. Relevant for RGI and KTS products.
- Models: Available and selected modelling techniques for mountain permafrost distribution. Relevant for MPDM product.

Section 3.1 introduces the techniques available for measuring kinematics over rock glaciers. Sections 3.2 and 3.3 present the key criteria necessary to be defined in order to provide a standardized methodology for the production of rock glacier inventories, the assignment of a kinematical attribute, and the development of kinematical time series as Permafrost ECV product. Section 3.4 presents the available models for permafrost distribution in the Southern Carpathians (also available in [RD-9]).

3.1 Available techniques for rock glacier kinematic measurements

Table 4 summarizes properties of various techniques used for measuring kinematics over rock glaciers. Due to the requirement of large coverage (regional-global) (see Section 2, URq_01, URq_10-12), the focus is placed on aerial and spaceborne techniques (columns 6-10).

Table 4: Comparison of properties for different techniques to quantitatively characterize rock glaciers kinematics: 1.-5. Local scale; 6.-10. Regional-global scale.

	1.Terrestrial Survey	**2. GNSS**	**3. Terrestrial laser scanning**	**4. UAV-borne photogrammetry**	**5. Terrestrial Radar Interferometry**
Platform	Terrestrial: In-situ	Terrestrial: In-situ	Terrestrial: Remote	Aerial: Remote	Terrestrial: Remote
Coverage	Local	Local	Local	Local	Local
Resolution	Single point measurement	Single point measurement	cm	cm	m
Measured value	Direct 3D point coordinates of a	Direct 3D point coordinates of a	Direct 3D coordinates of	Direct 3D coordinates of	Indirect 3D coordinates of random

	single (clearly defined) point	single (clearly defined) point	random surface points	random surface points	surface points
Dimensions	3D displacement & rotation of an object	3D displacement & rotation of an object	2.5D Horizontal shift of a surface patch & ΔZ at defined location	2D horizontal shift of a surface patch	1D displacements along line-of-sight
Accuracy	mm	cm	cm	cm-dm	mm
Solar radiation	Independent	Independent	Independent	Dependent	Independent
Shadow effects	No influence	In steep terrain	Data gaps due to surface shadowing	In steep terrain	Data gaps due to surface shadowing
	6. Airborne laser scanning	**7. Airborne feature tracking / photogrammetry**	**8. Spaceborne photogrammetry**	**9. Spaceborne Synthetic Aperture Radar (SAR) Interferometry**	**10. Spaceborne SAR offset tracking**
Platform	Aerial: Remote	Aerial: Remote	Satellite: Remote	Satellite: Remote	Satellite: Remote
Coverage	Regional	Regional	Global	Global	Global
Resolution	dm-m	dm-m	>m	>m	>m
Measured value	Direct 3D coordinates of random surface points	Indirect 3D coordinates of random surface points	Indirect 3D coordinates of random surface points	Phase differences	SAR amplitude
Dimensions	2.5D Horizontal shift of a surface patch & ΔZ at defined location	2D horizontal shift of a surface patch	2D horizontal shift of a surface patch	1D displacements along line-of-sight	2D horizontal shift of a surface patch
Accuracy	dm	dm-m	dm-m	mm-cm	dm-m
Solar radiation	Independent	Dependent	Dependent	Independent	Independent
Shadow effects	No influence	In steep terrain	In steep terrain	If radar incidence angle > slope	If radar incidence angle > slope

For the production of RGI and KTS at the selected sites of CCN1 and CCN2, the project partners focus primarily on Spaceborne Synthetic Aperture Radar (SAR) Interferometry (InSAR) (column 9), airborne feature tracking / photogrammetry and spaceborne SAR offset tracking in more restricted areas (columns 7 and 10) (see CCN 1&2 D2.2 for details about the Algorithm Theoretical Basis).

3.2 Key criteria for regional rock glacier inventories, incl. kinematics (RGI)

Two main approaches have been commonly used for compiling a rock glacier inventory [RD-10]:

- **Geomorphological approach**: rock glacier features are recognized by a systematic visual inspection of the (imaged) landscape and DEM-derived products. Surface texture and morphometric analysis could also be used. This is the classical approach, also locally based on field visits. It allows the production of exhaustive inventories of presumed moving and non-moving landforms, whose discrimination (activity classes) is primarily based on morphological characteristics. Photogrammetry and LiDAR DEM surveys, when available, facilitate the identification of rock glaciers in particular in forested areas.
- **Kinematical approach**: moving areas are detected using multi-temporal remotely sensed data (e.g. SAR-derived products, multi-temporal airborne LiDAR, high resolution optical satellite and

aerial images). The typology assessment (rock glacier discrimination) is then mainly performed by relating a moving area to a rock glacier feature detected on optical images (geomorphological approach). This approach is limited to the non-exhaustive identification and delimitation of moving areas on rock glaciers, whereas non-moving rock glaciers, for instance, are missed. It provides quantitative data for evaluating the motion rate of rock glaciers. It allows also the identification of moving areas, which cannot be morphologically related to a rock glacier, but which, for some of them, can be driven by a permafrost creep process.

While these two approaches yield different resulting inventories, they are complementary and the IPA Action Group, as well as the CCN1 & CCN2 teams of the Permafrost_cci project will ensure adequate compatibility.

Beyond any controversy about rock glacier genesis, origin of ice, etc., the IPA Action Group agreed on a **technical definition of rock glaciers as debris landforms generated by a former or current gravity-driven creep of frozen ground (permafrost), detectable in the landscape with the following morphology: front, lateral margins and optionally ridge-and-furrow surface topography** [RD-10]. In a geomorphological slope sequence, rock glaciers are (or were) landforms conveying debris from an upslope area (called source area or rooting zone) towards their front. The debris grain size is not specified.

Several elements have been identified as key criteria requiring to be standardized [RD-10]:

- Minimum size of inventoried rock glaciers (in relation with URq_03-04)
- Rock glacier morphological system and units (in relation with URq_03-04)
- Rock glacier outlines (in relation with URq_03-04)
- Spatial connection of the rock glacier to the upslope unit (in relation with URq_04)
- Rock glacier activity (in relation with URq_06)
- Rock glacier destabilization (in relation with URq_07)
- Time frame and update (in relation with URq_02 and URq_05)

The assignment of a semi-quantitative movement rate category (order of magnitude) to the optional kinematical attribute is treated separately (in relation with URq_08 and URq_09). **Kinematics is defined here as the surface movement rate related to the permafrost creep of the inventoried rock glaciers**. Fig. 1 shows an example of kinematics characterization over a Swiss rock glacier using InSAR data. The following elements have been identified as key criteria requiring standardization [RD-11]:

- Definition of moving area (extent and uniformity)
- Velocity classes of moving areas
- Semi-quantitative categories of a kinematical attribute (order of magnitude) of rock glacier units
- Temporal representativness of the kinematical attribute
- Spatial representativness of the kinematical attribute

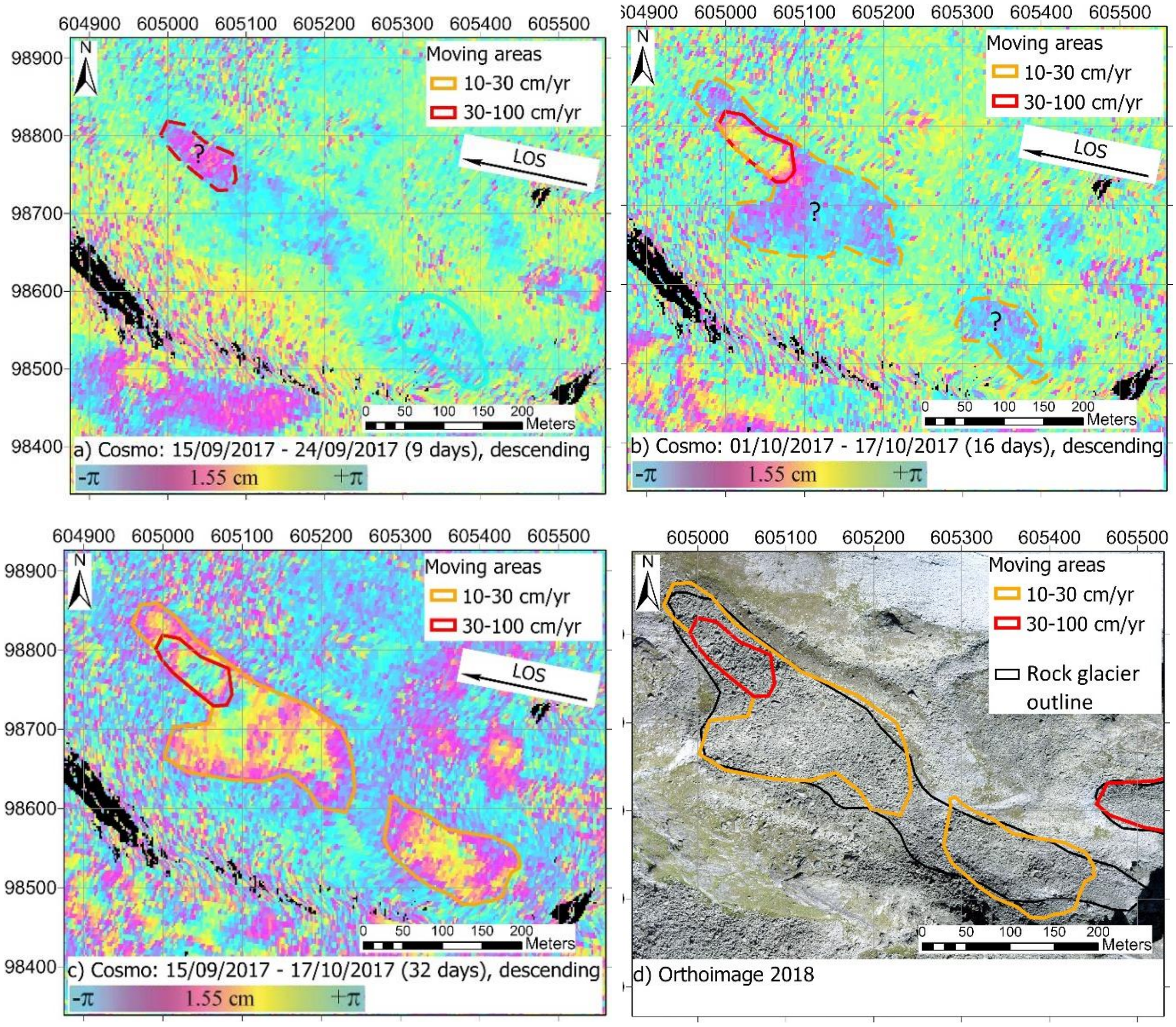

Figure 1: Rock glacier detection using Cosmo-SkyMed data. A large set of valid combinations of interferograms with different time intervals is required to increase the relevance of detected polygons. (a) A small red-outlined signal could be detected on the 9-day interferogram. (b) Using a 16-day time 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 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 (black line: restricted geomorphological footprint). Three moving areas have been drawn and classified in terms of the deformation rate as moving in the order of 30-100cm/yr within the red outline, and in the order of 10-30 cm/yr within the orange outlines. However, other not outlined moving areas are visible in these figures.

3.3 Key criteria for kinematical time series on selected rock glaciers (KTS)

Rock glaciers are the best geomorphological expression of the creep of mountain permafrost and constitute a prevalent heritage of the mountain periglacial landscape. Observing changes in rock glacier kinematics provides information about climate impact on mountain permafrost and has the potential to become a key parameter of cryosphere monitoring in mountain regions. Several studies conducted in particular in the European Alps for the last two decades, have shown that there is dependency of rock glacier interannual behavior to 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 climate conditions; so far, the permafrost degradation has not become too severe to prevent this response. The temporal evolution of rock glacier kinematics depends, among others, on the altering of the temperature profile between the permafrost table and the main shearing horizon: the closer to 0°C it is rising, the faster the rock glacier tends to become.

Rock glaciers tend to display a similar regional behavior at (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 behavior makes the development of regional indexes possible, which can be used as 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 to assess the regional/global reaction of mountain permafrost creep to climate change [RD-12].

Kinematical time series and regional index are defined by the IPA Action Group [RD-12] as followed:

- **First-level data** consist of individual kinematical time series having an annual and pluri-annual resolution expressing a velocity (Fig. 2);
- **Second-level data** consist of individual kinematical time series having an annual or pluri-annual resolution expressing a relative velocity with respect to a reference time;
- **A regional index** is an assemblage (e.g. mean) of selected relative time series (Fig. 3).

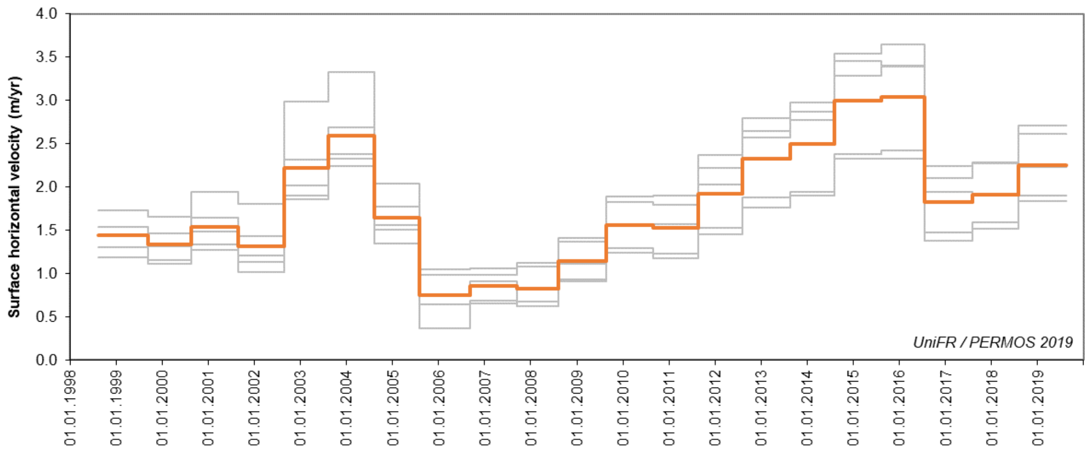

Figure 2: Long time series of an individual rock glacier (Gemmi-Furggentälti rock glacier; data source: University of Fribourg, PERMOS). Represented in the figure: the mean annual velocity of 5 points (orange), and the annual velocity of each point (grey). Annual measurement interval by total station until 2013, then by GNSS survey.

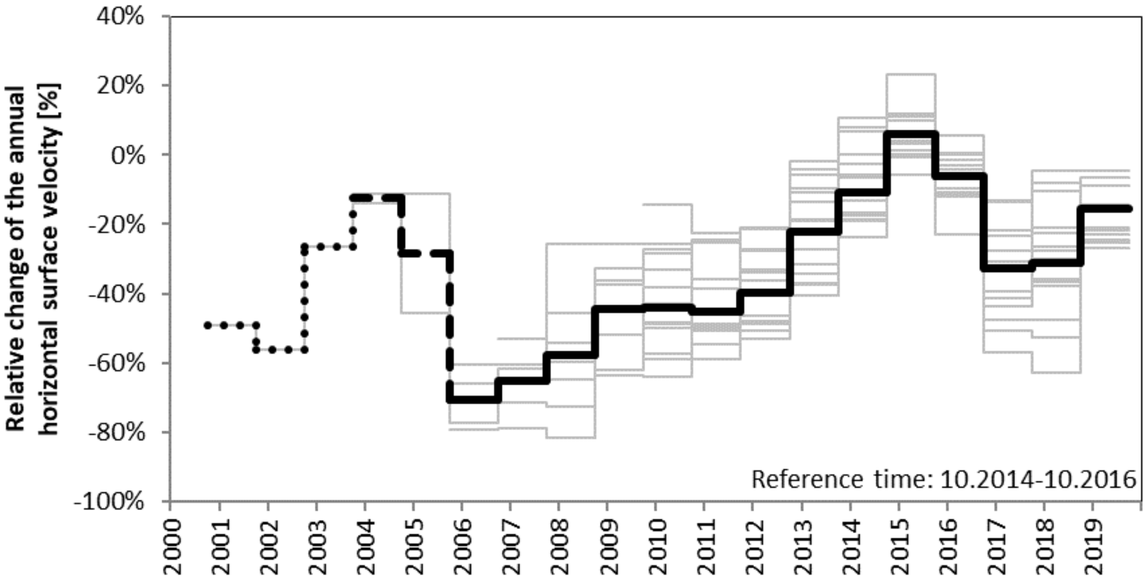

Figure 3: Relative change of the rock glacier surface velocity in the western Swiss Alps (data source: University of Fribourg, University of Lausanne, PERMOS): the regional index (black line) is the mean of selected individual rock glacier time series (n = 1 to 14 according on years), which are derived from aggregated horizontal velocities based on annual GNSS multi-point surveys. Scale in % of change to a reference time. Measurement and calculation interval: 1 yr. The regional index is less significant when n is small, here drawn by small dots when n=1 and larger dots when n=2.

The following elements have been identified as **key criteria requiring to be standardized in order to propose rock glacier kinematics as a new GCOS ECV Permafrost product** [RD-12, RD-13]:

- Horizontal resolution, i.e. spatial distribution of selected rock glaciers (in relation with URq_12)
- Horizontal resolution (2), i.e. surface velocity value (in relation with URq_16-17)
- Time resolution: frequency and observation time window (in relation with URq_13-15)
- Timeliness, i.e. time needed for data processing
- Required measurement uncertainty of the velocity values (in relation with URq_18)
- Stability, i.e. consistency over time

3.4 Available schemes for mountain permafrost distribution modelling in the Southern Carpathians (MPDM)

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 (Levavasseur et al., 2011) and hard to determine by direct measurements. It requires the development of algorithms especially designed for mountainous permafrost, where lateral heterogeneity due to micro-climatic and topographic conditions have to be accounted for (Haeberli et al., 2010; Nelson et al., 1998). A considerable number of models for mountain permafrost distribution have been published in the last two decades for different mountain areas around the world (e.g. Azócar et al., 2017; Deluigi et al., 2017; Gruber and Hoelzle, 2001; Sattler et al., 2016; Westermann et al., 2013).

a) Process-based models:

Process-based models are complex models that use a more detailed understanding of the energy fluxes between the atmosphere and permafrost, and require a large amount of accurate measured input data (Harris et al., 2009).

b) Empirical models based on statistical equations:

The first models developed for the Alps used the relation of permafrost occurrence with geomorphometric parameters as altitude, slope gradient and slope aspect (Haeberli, 1973). These factors were further used to develop models for permafrost occurrence that were based on simple approaches as linear regression (e.g. Avian and Kellerer-Pirklbauer, 2012; Ebohon and Schrott, 2008; Fraunfelder et al., 1998; Keller, 1992).

In these approaches the permafrost is modelled as presence/absence using thresholds based on a restricted number of topographic and climatic parameters (Deluigi et al., 2017).

For regional-scale distribution of permafrost in mountain areas, empirical models are frequently based on rock glacier activity status and temperature data, rock glaciers being considered as permafrost indicators in alpine environments (e.g. Haeberli et al., 2006).

c) Empirical models based on machine learning algorithms:

A relatively recent alternative for permafrost distribution modelling includes the machine learning algorithms resulting in a binary classification of samples produced by learning dependencies between the studied phenomenon and other variables (Vapnik, 1998), generically called 'training samples datasets' (Deluigi et al., 2012).

c1) Using Support Vector Machine classifier

SVM is a machine-learning algorithm based on the theoretical background developed by Vapnik, (1998). It utilizes structural risk minimization in order to reduce training errors and to improve generalization of the model. It is an algorithm that performs very well in classifying non-linear variables like landslides (Pawluszek et al., 2018), soil mapping (Levi, 2017) and mountain permafrost (Deluigi et al., 2017).

c2) Using Random Forest classifier

Random forest (RF) is a robust classification algorithm suited for use on non-linear classifications. A model based on RF was produced for mountain permafrost by Deluigi et al. (2017) for the Western Valais Alps (Switzerland) where it outperforms a model based on SVM and one based on logistic regression.

4 ANALYSIS AND INTERCOMPARISON OF RESULTS

Regarding kinematics, Section 3.1 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 is thus placed here on the analysis of the key criteria that needed to be defined in order to standardize the outputs.

4.1 Challenges for standardization and risk for discrepancies for regional rock glacier inventories, incl. kinematics (RGI)

Table 5 summarizes the results of the discussions at the IPA Action Group workshop I (September 2019) identifying the challenges for standardization and risk for discrepancies between operators when producing rock glacier inventories.

Table 5: Analysis of key criteria for rock glacier inventories (RGI): Identified challenges for standardization and risk for discrepancies between operators

Minimum size of inventoried rock glaciers	URq_03	The minimal detectable size varies according to the input data and technical limitations. It also depends on the purpose and scale of the inventory.
Rock glacier morphological system and units	URq_04	Rock glaciers with complex morphology (e.g. multiple generations, multiple lobes, coalescent lobes, and heterogeneous dynamics) are common and difficult to characterize unequivocally. The variable spatial resolution and quality of input data may have an unwanted impact on the results of the morphological system and units' definition.
Rock glacier outlines	URq_03	Technically defining a rock glacier as a landform implies an outlining task, and for various practical issues (e.g. area calculation) it has to be a closed polygon, but this operation retains some degree of subjectivity, in particular regarding the upper limit of the rock glacier (see following point).
Spatial connection of the rock glacier to the upslope unit	URq_04	The geomorphological unit located directly upslope of a rock glacier system can hold implications on the characterization of the latter (e.g. internal structure and composition, ice origin, ice content), as well as the designation of attributes (e.g. landform outlining, definition of the rooting zone). The term "derived" has to be avoided because it implies an interpretation on the origin of both debris and/or ice.
Rock glacier activity	URq_06	Rock glaciers have been most commonly classified into the following categories of activity: Intact (active/inactive) and relict. The classical categorization was considering the activity rate of rock glaciers as almost constant over the long term (decades to centuries). Observations of the rock glacier kinematical behavior, in particular in the European Alps, have shown that an acceleration by a factor of 2 to 10 of the surface velocities between the 1980s and the 2010s has been a common feature at many investigated sites, probably in response to increased permafrost temperature resulting from warmer air temperatures. Whereas a significant majority of the monitored rock glaciers follows this regional trend, some features manifest singular behaviors (e.g. reactivation, rapid acceleration, destabilization or decrease in velocity). In cold permafrost regions (e.g. Arctic or high altitude Andes), rock glaciers, which are almost not moving or only very slowly, may accelerate in response to warming. These scientific observations have revealed the need of redefining and/or refining the categorization of rock glacier activity.

Rock glacier destabilization	URq_07	The motion rate of some rock glaciers may be characterized by a drastic acceleration that can bring the landform, or a part of it, to behave abnormally fast (i.e. not following the regional trend anymore) for several years at least. The term destabilization has been progressively used since the 2000s to refer to rock glaciers with obvious signals of abnormally fast behavior but is misleading if considered in a geotechnical sense.
Time frame and update	URq_02 and URq_05	Different times of production of rock glacier inventories (observation time window and time frame) can lead to products that are not fully comparable. Updates are recommended but pragmatic temporality has to be considered.

Table 6 summarizes the results of the discussions at the IPA Action Group workshop II (February 2020) identifying the challenges and risk for discrepancies between operators when assigning a kinematical attribute to inventoried rock glacier. These discussions take the results of the exercise performed the 11th of February by 16 workshop's participants into account. The tasks were a) to identify and characterize moving areas using InSAR data and b) to characterize the kinematics of rock glacier units in the Swiss Alps based on the previously delineated InSAR moving areas. The participants had no specific training related to InSAR technology; the aim of the exercise was primarily that they face various challenges related to the integration of kinematics as an optional attribute of standardized rock glacier inventories, in order to discuss and define relevant standards. The results of the exercise were also used as a basis for the development of the practical guidelines for including a kinematical attribute in rock glacier inventories, and the implementation of a training plan for the CCN2 external partners.

Table 6: Analysis of key criteria for kinematical attribute in rock glacier inventories (RGI): Identified challenges for standardization and risk for discrepancies between operators

	URq	Challenges for standardization / risk for discrepancies
Definition of moving area (extent and uniformity)	URq_08 and URq_09	The level of details varies depending on the operator. Isolated movement or unreliable areas can lead to an unrepresentative delineation of moving areas. The definition of uniformity or spatial consistency of the movement is partly subjective. The detected signal can be related to different processes, not only permafrost creep.
Velocity classes of moving areas	URq_08 and URq_09	The detection capability and the dimensionality (one- to three- dimensional displacement measurements) depend on the technology. Moving areas should be defined in accordance with the methodology used. Using 1D InSAR data, the downslope velocity can be significantly underestimated if the movement direction deviates significantly from the line-of-sight. The reliability (or degree of confidence) needs to be documented. There is a subjectivity of the class attribution when the detected movement is close to the limits between classes.
Semi-quantitative categories of kinematical attribute (order of magnitude)	URq_08 and URq_09	There is a subjectivity involved in the choice of a category/order of magnitude. The use of absolute velocity values would be valuable but pragmatically problematic to integrate for measurements from different techniques. An order of a magnitude estimate is enough to be used to assess the activity of a rock glacier unit (as a complement to morphological evidences) but is still also affected by subjectivity if the detected movement is close to the limits between categories. There is a risk for subjectivity in the choice of a category/order of magnitude and thus a need for explicit rules to transfer velocity classes observed from

		InSAR moving area to the category of the kinematical attribute of the rock glacier unit.
Temporal representativness of kinematical attribute	URq_08 and URq_09	Some techniques allow for the observation of displacement during summertime only, and not from one summer to the next, making that the velocity value cannot be measured over an annual time interval. Other techniques allow for the measurement of annual velocity or multi-annual velocity only. Kinematical measurements representing single infra-annual variation have to be avoided and when the technique allows for a minimum observation time window lower or equal to one year, the temporal frame should be at least 2 years.
Spatial representativness of kinematical attribute	URq_08 and URq_09	Isolated movement, unreliable areas and unrepresentative moving parts can lead to misleading documentation of kinematics. Incomplete coverage can be problematic, e.g. when using single point measurements that are not representative for larger moving areas.

4.2 Challenges for standardization and risk for discrepancies for kinematical time series on selected rock glaciers (KTS)

Table 7 summarizes the results of the discussions at the IPA Action Group workshop I (September 2019) identifying the challenges and risk for discrepancies between operators when producing kinematical time series on selected rock glaciers.

Table 7: Analysis of key criteria for kinematical time series on selected rock glaciers (KTS): Identified challenges for standardization and risk for discrepancies between operators

	URq	Challenges for standardization / risk for discrepancies
Horizontal resolution, i.e. spatial distribution of select rock glaciers	URq_12	The objective of developing regional indexes requires the integration of a significant amount of representative rock glaciers in a region. The number of sites allowing for the definition of a regional trend has to be defined.
Horizontal resolution (2), i.e. surface velocity value	URq_16 and URq_17	The dimensionality (one- to three- dimensional displacement measurements) varies depending on the technology. Depending on the technology, the time series can be based on point or areal measurements. The spatial representativness of the selected point/area on a rock glacier is challenging. Considerations related to spatial representativness of kinematical attributes in Table 6 apply also here.
Time resolution, i.e. frequency and observation time window	URq_13, URq_14 and URq_15	Depending on the applied technique, this velocity value might only be obtained for a shorter observation time window than an annual one (e.g. snow-free summer period for InSAR). The consistency of the series can be affected if the observation time window is modified from one year to another. If we aim for including past data, it might be difficult to require an annual frequency due to data gaps.
Timeliness, i.e. time needed for data processing	-	Time needed for data processing has to be considered to set up a monitoring strategy.
Required measurement uncertainty of the velocity value	URq_18	The uncertainty is given by the specificities of the sensor/platform and the algorithm used in the data processing. Depending on the observed velocity, different techniques can be better suitable than others. Documenting a relative measurement uncertainty may ensure technology-independent standards.
Stability, i.e. consistency	-	The velocity value is an annualized displacement rate derived from methodologies allowing either for displacement measurement (i.e. from

over time		permanent location, point or area with always the same coordinates, e.g. photogrammetry) or for position measurements (i.e. from moving position, e.g. GNSS). On the long term, the stability is not ensured in the case of a displacement measurement, as the location of this measurement is constant over time whereas the creeping mass is moving. Likewise, in the case of position measurement, the stability is not ensured on the long term since the location is moving over time and the creeping mass is subject to change of topography, for instance.

4.3 Comparison of models for mountain permafrost distribution in Southern Carpathians (MPDM)

The following table (Table 8) summarizes the main aspects that are important for the model that will be used to create the spatial distribution of permafrost in the Southern Carpathians. The empirical models based on machine-learning are further divided based on the algorithm they use, SVM and RF. If possible, the expected performance of a model is characterized by - bad, 0 satisfactory, + good. The proposed algorithm for Permafrost_CCI is shaded in grey.

Table 8: Respective advantages and disadvantages of the mountain permafrost distribution models (a: Process-based models; b: Empirical models; c1: Support Vector Machine classifier; c2: Random Forest classifier). Expected performance of the models: - bad, 0 satisfactory, + good (NO: the model do not allow the recommendations to be fulfilled)

Method (see 3.4)	a	b	c1	c2
Uses available input data	NO	+	+	+
Low computational cost	NO	+	0	+
High pixel resolution	NO	+	+	+
Transferability to different areas	+	-	0	0
Accuracy assessment	+	+	+	+
Uncertainty map	+	NO	0	+
Predictor importance ranking	+	+	NO	+

5 DISCUSSION AND ALGORITHM SELECTION

This Section describes the selected standardized methodology to fulfill the user requirements related to each product defined in the PSD [RD-7]. Sections 5.1 and 5.2 present the chosen criteria allowing for the standardization of rock glacier inventories, including a kinematical attribute and the production of the comparable kinematical time series. The standards are technology independent, allowing for a similar exploitation of kinematical information from various sources. Section 5.3 presents the conclusion of the comparison between models able to provide permafrost distribution in the Southern Carpathians.

5.1 Selected standards for regional rock glacier inventories, incl. kinematics (RGI)

Table 9 and Table 10 summarize the standards selected for the key criteria for inventorying rock glaciers, following the user requirements and the results of the analysis (identified challenges and risk for discrepancies between operators, see Section 4). More detailed versions of the standards are available in the baseline document [RD-10] [RD-11].

Table 9: Selected standards for regional rock glacier inventories (RGI) and related URq

Minimum size of inventoried rock glaciers	URq_03	It is recommended that the minimum rock glacier size applied for an inventory to be included into a global compilation should be **0.01 km^2**. Nevertheless, inventories at higher resolution are encouraged. The resolution of the input data has to be documented.
Rock glacier morphological system and units	URq_04	Solving the definition and delineation issues requires the use of an imbricated system of units. **A rock glacier system** is composed of either a single or multiple rock glacier units that are spatially connected either in a toposequence or in coalescence. **A rock glacier unit** is defined as single rock glacier landform that can be unambiguously discerned and, in case of spatial connection, can be differentiated from other rock glacier units based on morphological and land cover attributes suggesting a distinct generation of formation, discriminated connections to the upslope unit or different activity. A rock glacier unit is basically consisting of a single lobate structure, otherwise it is classified as **composite** (multiple lobes). Combining the geomorphological and kinematical approaches in an iterative way can contribute to affine the delineation of the units.
Rock glacier outlines	URq_03	Any rock glacier system and related unit(s) must be identified by a **primary marker**. The marker is **a point** associated with primary attributes. In addition, two ways of delineating rock glacier boundaries are recommended to be included as standards: the **extended geomorphological footprint (**the outline embeds the entire rock glacier body up to the rooting zone and includes the external parts (front and lateral margins) and the **restricted geomorphological footprint (**the outline embeds the entire rock glacier body up to the rooting zone and excludes the external parts**).**
Spatial connection of the rock glacier to the upslope unit	URq_04	The spatial connection of the rock glacier to an upslope unit does not necessarily mean that there is a dynamic and/or genetic connection. The focus is set on spatial (structural) connection because it is most of the time discernable on optical images. The recommended categories are: **Talus-connected, Debris-mantled slope-connected, Landslide-connected, Glacier-connected, Glacier forefield-connected, Other, Poly-connected.**
Rock glacier activity	URq_06	The categorization of rock glacier activity refers exclusively to the efficiency of the sediment conveying (expressed by the surface movement)

		at the time of observation and should not be used to infer about any ground ice content. The recommended categories are: **Active (**rock glacier moving downslope in most of its surface), **Transitional (**rock glacier with only low movement detectable by measurement or restricted to areas of non-dominant extent**), Relict (**rock glaciers with no detectable movement and no morphological evidence of recent movement and/or ice content), **Undefined** (inadequate data for discriminating between the activity classes). When kinematical data are available, they must be considered in order to assign the category of activity.
Rock glacier destabilization	URq_07	It is defined that in this context, destabilization is not used to describe slope failure in a geotechnical sense, but solely used to describe a temporal rock glacier deformation irregularity, i.e. **signals of abnormally fast behavior, which can be expressed geomorphologically by the opening of large cracks and/or scarps**. Rock glaciers experiencing an ongoing destabilization phase constitute a sub-category of active rock glaciers and must be inventoried as such.
Time frame and update	URq_02 and URq_05	**Rock glacier units are characterized for a multi-annual validity time frame (snapshot) of at least 2 years**. Any activity assessment must be dated and defined (i.e. based on geomorphological identifiers only or supported by kinematical data). **Updates are recommended every 10 years.**

Table 10: Selected standards for kinematical attribute in regional rock glacier inventories (RGI) and related URq

	URq	Summary standards
Definition of moving area (extent and uniformity)	URq_08 and URq_09	The identification and characterization of moving areas is a first step to be able to assign later a kinematical attribute to a rock glacier unit. It could be performed on the basis of any technique or combination of techniques providing areal (surface) displacement information. In the framework of a rock glacier inventory, **a moving area is defined as an area at the surface of a rock glacier in which the observed flow field (direction and velocity) is uniform (spatially consistent/homogenous) during a documented time. It has to represent the downslope movement rate of the rock glacier (permafrost creep).** The confusion with movement related to other processes (e.g. thaw subsidence or deep-seated landslide) has – as far as possible – to be avoided. **The velocity range within a moving area should not exceed a min/max velocity ratio of 1:5** (in the case of InSAR-derived moving areas, the final outline should delineate a moving area with homogeneous velocity, and the velocity range within a moving area should fit the defined class of velocity). The border of a moving area is often non-sharp, depending also on the detection capacity of the used technique, making a precise delineation difficult to obtain. The minimum extent of a moving area depends on the spatial resolution of the data inputs and the size of the landform, based on the operator’s judgment. Several moving areas can be overlying, a slower moving area embedding a faster one. A moving area can override the geomorphological limits of rock glacier units (e.g. when two overlying rock glacier units are moving at a rate, which is not significantly different). **Isolated movement, unreliable areas and unrepresentative parts have to be avoided.** A single point measurement is basically not a moving area, but the information it provides could be taken into consideration if it can be spatially attached to any moving area. Areas outside of any delineated

		moving area refer either to the absence of movement, or to a movement which may be under the detection limit, or to unreliable data. Areas where a movement rate is detected but difficult to be assessed with enough precision has to be outlined and classified as "undefined". The reliability (or the degree of confidence) of the detected moving area has to be at least qualitatively documented (low, medium, high) according to the quality of both the outline detection and the velocity class assignment.
Velocity classes of moving areas	URq_08 and URq_09	A velocity class assigned to a moving area is dependent on the technology and the conditions of observation. **It is mandatory to document the exploited data, the applied method and their related time characteristics (observation time window and temporal frame).** Some methodologies allow for the observation of displacement during summertime only, making that the velocity value cannot be measured a full annual time period. Others allow for the measurement of annual velocity or multi-annual velocity only. The dimensionality (one- to three-dimensional displacement measurements) also varies depending on the technology. Therefore, the definition of the classes of velocity as well as the rules for transferring information into kinematical information are dependent on the technology and should be specified for each of them. **The velocity 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). **The following half an order magnitude of 1D LOS velocity is 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 technique has the detection capability): - 100-300 cm/yr * - > 300 cm/yr * Moving areas where the reliability in classifying velocity is low due to specific technical limitations have to be classified as "undefined".
Semi-quantitative categories of kinematical attribute (order of magnitude)	URq_08 and URq_09	**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 the mean kinematical behavior of the rock glacier units. 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. A kinematical attribute can be assigned to a rock glacier unit, only when the latter is documented by consistent kinematical information on a significant part of its surface, based on the operator's judgment. 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 velocity class to kinematical attribute, highly dependent on the

		techniques, should be performed carefully. It must also be taken into consideration that the documented surface velocities may be faster than the effective rock glacier displacement rate (e.g. infra-annual (usually summer) velocities may be faster than the annual ones). The rules for using InSAR-derived moving areas for assigning a kinematical attribute to a rock glacier unit should be specified. **The categorization of the kinematical attribute** consists of semi-quantitative classes of the multi-annual downslope displacement rate of the entire 3D rock glacier body. The assignment is based on the operator's judgement (detailed rules in CCN 1&2 D2.2 ATBD). 0. Undefined (default category) 1. < cm/yr (no up to very few movement) 2. cm/yr (order of magnitude ≈ 0.01 m/yr) 3. cm/yr to dm/yr (order of magnitude ≈ 0.05 m/yr) 4. dm/yr (order of magnitude ≈ 0.1 m/yr) 5. dm/yr to m/yr (order of magnitude ≈ 0.5 m/yr) 6. m/yr (order of magnitude ≈ 1 m/yr) 7. > m/yr (more than ≈ 3 m/yr per year) The default category is 0 (undefined). The rock glacier unit falls into this category when no (reliable) kinematical information is available, or the kinematical information is derived from a single point survey which cannot be related to any moving area, or a dominant part of the rock glacier unit is characterized by a moving area of undefined velocity. **For each rock glacier unit with assigned kinematical attribute, the following information has to be documented:** - Multi-year validity time frame of the assigned category, - Data/technique(s) used, observation time window (e.g. multi-annual, annual, infra-annual), time frame and dimensionality of all the supporting kinematical data, - Approximated spatial representativeness: percentage of surface that is documented by supporting kinematical data (e.g. < 50%, 50-75%, > 75%), - Reliability of the assignment of the kinematical attribute (low, medium, high).
Temporal representativness of moving areas and kinematical attribute	URq_08 and URq_09	**A moving area is always strictly stamped with time:** - The observation time window, i.e. the duration during which the detection and characterization is computed/measured by the specific technique (e.g. multi-annual, annual, infra-annual). When the technique does not allow for a minimum of annual observation time window, the minimal length required is 1 month (can be obtained by an aggregation of several shortest time interval). - The temporal frame, i.e. the duration during which the measurements/computations are repeated and aggregated for defining the moving area (i.e. during which year(s)). When the technique allows for a minimum observation time window lower or equal to one year, the temporal frame should be at least 2 years. The velocity class of InSAR-derived moving areas refers to the **velocity observed in the LOS during an observation time window of at least one month** (several months are preferable) **in snow free periods with a temporal frame of at least 2 years** (consecutive years are preferable). **The kinematical attribute** is representative of the rock glacier unit for a

		multi-year validity time frame (snapshot) of at least 2 years. It should correspond to a multi-annual mean velocity. The exploited data, the applied method and the related time characteristics of all the supporting kinematical data must be documented.
Spatial representativness of the moving areas and kinematical attribute	URq_08 and URq_09	**A velocity class of a moving area** has to document the movement rate observed within a moving area. It means that a velocity class is reflecting a spatio-temporal mean movement rate in a moving area, not an extreme. Several velocity classes could be attributed to (almost) the same moving area with time. The velocity class must refer as far as possible to a displacement rate representative of a downslope creep movement. **The kinematical attribute** indicates the overall multi-annual rate of movement observed/estimated **on a dominant part of its surface**. The rock glacier unit has to be documented by **consistent kinematical information on a significant part of its surface**, based on the operator's judgment. There is only one assigned category per rock glacier unit. In case 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).

5.2 Selected standards for kinematical time series on selected rock glaciers (KTS)

Table 11 summarizes the standards selected for the key criteria for producing kinematical time series on selected rock glaciers, following the user requirements and the results of the analysis (identified challenges and risk for discrepancies between operators, see Section 4). More detailed versions of the standards are available in the baseline document [RD-12]. As a result of its second workshop (February 2020), the IPA Action Group has also formulated a proposition related to the ECV Permafrost product Rock Glacier Kinematics as part of the GCOS ECV review process [RD-13]. The following elements are based on this submitted proposition.

Table 11: Selected standards for kinematical time series on selected rock glaciers (KTS) and related URq. ECV requirements are presented according to the three GCOS ECV categories: Goal (G); Breakthrough (B) (not mandatory, more as one possible); Threshold (T)

	URq	Summary standards
Horizontal resolution, i.e. spatial distribution of select rock glaciers	URq_12	KTS focuses primarily on **talus-connected rock glaciers and debris-mantled slope-connected rock glaciers**, whereas glacier-connected and glacier forefield-connected rock glaciers, whose surface displacement rates can be significantly affected by other processes than permafrost creep, must be considered aside. KTS is defined for a single rock glacier unit that is expressed geomorphologically according to standards. Time series must be measured/computed separately if they come from different units, even within a unique rock glacier system. Several time series can be measured/computed on the same rock glacier unit when derived from different methodologies.

		ECV requirements: Unit: -, Metric: Spatial distribution of selected rock glaciers **G:** Regional coverage : At least 30% of the active talus-connected and/or debris-mantled slope-connected rock glaciers should be selected in a region, which is a part of a mountain range, in order to represent its climatic context. Only possible with remote sensing approaches. **B:** Multiple sites in a defined regional context: Allows the definition of a regional trend. **T:** Isolated site: Continuous time series produced either from in situ measurements or remotely sensed measurements.
Horizontal resolution (2), i.e. surface velocity value	URq_16 and URq_17	The location of the measurement has to be **spatially representative of the surface velocity of the rock glacier unit**. There is no restriction about the dimensionality of the measurement as the objective is to study relative trends. However, the data property has to be documented and for each time series, it has to be **consistent over time**. **ECV requirements:** Unit: m/yr. Metric: Surface velocity value, one value per selected rock glacier unit **G:** Flow field: Velocity is computed/measured by aggregation over a target area on a rock glacier unit. The aggregation procedure and the target area should be consistent over time. This allows for the best representation of the effective movement over the rock glacier unit. **B:** Few discrete points: Velocity is computed/measured as an aggregation of few measurement points over a target area on a rock glacier unit. The aggregation procedure and the target area should be consistent over time. This allows for a better representation of the effective movement over the rock glacier unit. **T:** Velocity value at a point: Velocity is computed/measured on a single point. The location should be consistent over time and be spatially representative of the rock glacier unit it is part of (i.e. located within a recognized moving area).
Time resolution, i.e. frequency and observation time window	URq_13, URq_14 and URq_15	The velocity value is computed at **an annual frequency or a multiple of it**. The velocity value is calculated on the basis of the effective displacement of a target (or an ensemble of targets) **over a year**. However, depending on the applied technique, this velocity value might only be obtained for **a shorter observation time window than an annual one**, but at an annual (or pluri-annual) frequency. **The observation time window should be documented, as constant as possible in time and long enough to avoid documenting single infra-annual variations.** The obtained velocity values may be seasonal, but the time series keeps an annual resolution. **ECV requirements:** Unit: yr, Metric: frequency and observation time window **G**: Frequency = 1 yr and observation time window = 1 yr: Measured/computed once a year. The observation time window is 1 year and consistent over time. **B:** Frequency = 1 yr and observation time window < 1 yr: Measured/computed once a year. The observation time window is shorter than 1 year (e.g. observation in summer period only). It should not be shorter than 1 month and must be consistent over time. Allows a better representation of the annual behavior. **T:** Frequency = 2-5 yrs and observation time window > 1 yr: Frequency

		limited by a observation time window of 2-5 yrs. This time period corresponds to the common periodicity for aerial image coverages, and can be adapted according to regional/national specificities. Longer intervals are admissible for optical images, as well as for reconstructions from archives.
Timeliness, i.e. time needed for data processing	-	**ECV requirements:** **G:** 3 months: Minimum time needed for data processing. **B:** – **T:** 1 year
Required measurement uncertainty of the velocity value	URq_18	The absolute uncertainty is given by the technology (specificities of the sensor/platform and the algorithm used in the data processing). Depending on the observed velocity, different techniques can be better suitable than others. Documenting a **relative measurement uncertainty** may ensure technology-independent standards. **ECV requirements:** Unit: %, Metric: Sensor/algorithm uncertainty **G:** 5%: Relative velocity uncertainty allowing for the reliable analysis of velocity trend over time (relative change of the RGK). Easily reachable for fast moving rock glacier whatever the technology and reachable using improved measurement techniques for slow moving rock glaciers. **B:** 10% **T:** 20%: Relative minimal velocity uncertainty allowing for the reliable analysis of a velocity trend over time (relative change of the RGK). Easily reachable for fast and slow moving rock glacier whatever the technology.
Stability, i.e. consistency over time	-	The only stability that has to be ensured is related to a change of methodology or procedure used to measure and compute velocity value, as well as the required parameters that need to be **consistent over time** (observation time window and horizontal resolution of the velocity value). If one of these elements is changing, two times series must be derived for the selected rock glacier unit. **The merging of these two time series can only be performed in the case of existing temporal overlap to enable cross-validation**. **ECV requirements:** Unit: - , metric: Overlapping **G:** With overlap of several yrs: Observation time window, horizontal resolution of the velocity value and methodologies/procedures used to measure/compute velocity value for a single time series must be consistent over time. If one of these elements is changing, two times series must be derived for the selected rock glacier unit. If these two time series have an overlap of several years ensuring consistency, they can be merged into a single time series. The merging procedure must be documented. **B:** With overlap of 1 yr: Observation time window, horizontal resolution of the velocity value and methodologies/procedures used to measure/compute velocity value for a single time series must be consistent over time. If one of these elements is changing, two time series must be derived for the selected rock glacier unit. If these two time series have an overlap of 1 year ensuring consistency, they can be merged into a single time series. The merging procedure must be documented. **T:** Without overlap: Observation time window, horizontal resolution of the velocity value and methodologies/procedures used to measure/compute velocity value for a single time series must be consistent over time. If one of these elements is changing without overlap, two time series must be derived

		for the selected rock glacier unit.

5.3 Selected model for mountain permafrost distribution in Southern Carpathians (MPDM)

The selected model for permafrost distribution in the Southern Carpathians is an empirical approach based on a machine-learning model with a random forest (RF) classifier (see Table 8, grey-filled column).

While much progress has been made in terms of physics-based modeling of mountain permafrost in recent years (Harris et al., 2009; Riseborough et al., 2008), also those methods are challenged in terms of their validation for diverse conditions. An important drawback in mountain permafrost modeling is the amount of available data for calibration and validation (Boeckli et al., 2012). Therefore, likewise in other mountain areas as the European Alps, we decided to use an empirical approach based on machine-learning algorithms instead of a process-based model because of the limitations of the available calibration and validation data and the complexity of the involved processes (Boeckli et al., 2012). For the Southern Carpathians, we choose to develop a machine learning-empirical model with a random forest (RF) classifier reported as best option in other mountain areas (Deluigi et al, 2017), in order to benefit from the existing rock glacier inventory from the Southern Carpathians (Onaca et al., 2017) and other thermal and geophysical data used as evidences for 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. Because in mountainous regions the conditions and factors controlling the energy balance at the ground surface show high spatial variability, the spatial resolution of the model should be high enough (i.e. 10-20 m), being dependent on the scale of variation in the area of implementation (Gisnås, 2016).

RF has been chosen instead of SVM mainly because of the additional output that it can provide. A ranking of predictors that can offer insights into permafrost conditions and can support further studies. It also provides an inset validation based on randomly selected samples that can offer a relatively good estimation of accuracy without the need of validation based on external data. This can be used as an intermediary step in modeling in order to fine tune the model.

6 REFERENCES

6.1 Bibliography

Avian, M. and Kellerer-Pirklbauer, A., 2012. Modelling of potential permafrost distribution during the Younger Dryas, the Little Ice Age and at present in the Reisseck Mountains, Hohe Tauern Range, Austria. Aust. J. Earth Sci. 105 (2), 140–153.

Azócar, G.F., Brenning, A. and Bodin, X., 2016. Permafrost distribution modeling in the semi-arid Chilean Andes. Cryosphere Discuss. 2016, 1–25.

Boeckli, L., Brenning, A., Gruber, S. and Noetzli, J., 2012. A statistical approach to modelling permafrost distribution in the European Alps or similar mountain ranges. Cryosphere 6 (1), 125–140.

Delaloye, R., Lambiel, C. and Gärtner-Roer, I., 2010. Overview of rock glacier kinematics research in the Swiss Alps. Geogr. Helv. 65, 135–145. http://dx.doi.org/10.5194/ gh-65-135-2010.

Deluigi, N., Lambiel, C. and Micheletti, N., 2012. A machine learning approach for alpine permafrost distribution modeling, Geophysical Research Abstracts Vol. 14, EGU2012-11290.

Deluigi, N., Lambiel, C. and Kanevski, M., 2017. Data-driven mapping of the potential mountain permafrost distribution. Science of The Total Environment, 590-591, 370-380.

Ebohon, B. and Schrott, L., 2008. Modeling Mountain Permafrost Distribution: A New Permafrost Map of Austria. In: Kane, D., Hinkel, K. (Eds.), Proceedings of the Ninth International Conference on Permafrost. pp. 397–402. Fairbanks, Alaska.

Frauenfelder, R., 1998. Rock Glaciers, Fletschhorn Area, Valais, Switzerland. International Permafrost Association, Data and Information Working Group, comp. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0. CD-ROM available from National Snow and Ice Data Center, nsidc@kryos.colorado.edu. Boulder, Colorado: NSIDC, University of Colorado at Boulder.

Gisnås, K., 2016. Permafrost modelling over different scales in arctic and high-mountain environments. Doctoral thesis, University of Oslo.

Gruber, S. and Hoelzle, M., 2001. Statistical modelling of mountain permafrost distribution: local calibration and incorporation of remotely sensed data. Permafrost and Periglacial Processes, 12(1), 69-77.

Haeberli, W., 1973. Die Basis Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost. Zeitschrift für Gletscherkunde und Glazialgeologie, 9, 221-227.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S. and Von der Mühll, D., 2006. Permafrost creep and rock glacier dynamics. Permafrost and Periglacial Processes 17 (3), 189–214.

Haeberli, W., Noetzli, J., Arenson, L., Delaloye, R., Gärtner-Roer, I., Gruber, S., Isaksen, K., Kneisel, C., Krautblatter, M. and Phillips, M., 2010. Mountain permafrost: development and challenges of a young research field. Journal of Glaciology, 56(200), 1043-1058.

Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M.A., Lehning, M., Matsuoka, N., Murton, J.B., Nötzli, J., Phillips, M., Ross, N., Seppälä, M., Springman, S.M., Vonder Mühll, D., 2009. Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. Earth-Science Reviews, 92(3), 117-171.

Ikeda, A., Matsuoka, N. and Kääb, A., 2008. Fast deformation of perennially frozen debris in a warm rock glacier in the Swiss Alps: An effect of liquid water. Journal of Geophysical Research: Earth Surface, 113(F1).

Keller, F., 1992. Automated mapping of mountain permafrost using the program PERMAKART within the geographical information system ARC/INFO. Permafrost and Periglacial Processes 3 (2), 133–138.

Kellerer-Pirklbauer, A. and Kaufmann, V., 2012. About the relationship between rock glacier velocity and climate parameters in central Austria. Austrian Journal of Earth Sciences, 105(2), pp.94-112.

Kenner, R. and Magnusson, J., 2017. Estimating the effect of different influencing factors on rock glacier development in two regions in the Swiss Alps. Permafrost and Periglacial Processes, 28(1), pp.195-208.

Kääb, A., Frauenfelder, R. and Roer, I., 2007. On the response of rockglacier creep to surface temperature increase. Global and Planetary Change, 56(1-2), pp.172-187.

Levavasseur, G., Vrac, M., Roche, D.M., Paillard, D., Martin, A. and Vandenberghe, J., 2011. Present and LGM permafrost from climate simulations: contribution of statistical downscaling. Climate of the Past Discussions, 7(3).

Levi, M.R., 2017. Neighborhood Size of Training Data Influences Soil Map Disaggregation. Soil Sci. Soc. Am. J., 81(2), 354-368.

Nelson, F.E., Outcalt, S.I., Brown, J., Shiklomanov, N.I. and Hinkel, K.M., 1998, June. Spatial and temporal attributes of the active layer thickness record, Barrow, Alaska, USA. In Proceedings of the Seventh International Conference on Permafrost, Yellowknife, NWT, 23-27 June 1998 (No. 57, pp. 797-802). Collection Nordiana.

Onaca, A., Urdea, P., Ardelean, A. and Şerban, R., 2013. Assessment of internal structure of periglacial landforms from Southern Carpathians (Romania) using dc resistivity tomography, Carpathian Journal of Earth and Environmental Sciences, 8 (2), 113-122.

Onaca, A., Ardelean, A. C., Urdea, P., Ardelean, F. and Sîrbu, F., 2015. Detection of mountain permafrost by combining conventional geophysical methods and thermal monitoring in the Retezat Mountains, Romania, Cold Regions Science and Technology, 119, 111-123

Onaca, A., Ardelean, F., Urdea, P. and Magori, B., 2017. Southern Carpathian rock glaciers: inventory, distribution and environmental controlling factors, Geomorphology. 293, 391-404

Pawluszek, K., Borkowski, A., Tarolli, P., 2018. Sensitivity analysis of automatic landslide mapping: numerical experiments towards the best solution. Landslides, 15(9), 1851-1865.

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

Riseborough, D., Shiklamonov, N.I., Etzelmuller, B., Gruber, S. and Marchengo, S., 2008. Recent advances in permafrost modeling. Permafrost and Periglacial Processes 19 (2), 137–156.

Roer, I., Avian, M., Delaloye, R., Lambiel, C., Dousse, J.P., Bodin, X., Thibert, E., Kääb, A., Kaufmann, V., Damm, B. and Langer, M., 2005. Rock glacier" speed-up" throughout European Alps-a climatic signal?. In Proceedings of the 2nd European Conference on Permafrost (pp. 101-102). Alfred-Wegener-Stiftung.

Sattler, K., Anderson, B., Mackintosh, A., Norton, K. and de Róiste, M., 2016. Estimating permafrost distribution in the maritime Southern Alps, New Zealand, based on climatic conditions at rock glacier sites. Front. Earth Sci. 4, 4.

Vapnik, V., 1998. Statistical Learning Theory. Wiley, New York.

Vespremeanu-Stroe, A., Urdea, P., Popescu, R. and Vasile, M., 2012. Rock Glacier Activity in the Retezat Mountains, Southern Carpathians, Romania. Permafrost and Periglacial Processes, 23(2), 127-137.

Westermann, S., Schuler, T.V., Gisnas, K. and Etzelmuller, B., 2013. Transient thermal modeling of permafrost conditions in Southern Norway. Cryosphere, 7(2), 719-739.

6.2 Acronyms

AD	Applicable Document
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
AUC	Area Under the Receiver Operating Curve
B.GEOS	b.geos GmbH
BTS	Bottom Temperature of Snow Cover
CCI	Climate Change Initiative
CCN	Contract Change Notice
CRS	Coordinate Reference System
DARD	Data Access Requirement Document
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ERT	Electrical Resistivity Tomography
ESA	European Space Agency
ESA DUE	ESA Data User Element
E3UB	End-to-End ECV Uncertainty Budget
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GFI	Ground Freezing Index
GPR	Ground Penetrating Radar
GST	Ground Surface Temperature
GT	Ground Temperature
GTOS	Global Terrestrial Observing System
GUIO	Department of Geosciences University of Oslo
INSAR	Synthetic Aperture Radar Interferometry
IPA	International Permafrost Association
KTS	Kinematical Time Series
LST	Land Surface Temperature
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
MPDM	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