CCI+ PHASE 1 – NEW ECVS

PERMAFROST

CCN1 & CCN2

ROCK GLACIER KINEMATICS AS NEW ASSOCIATED PARAMETER OF ECV PERMAFROST

D1.3 Data Access Requirement Document (DARD)

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Executive summary

Within the European Space Agency (ESA), the 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 user community. Permafrost has been selected as one of the Essential Climate Variables (ECVs) which 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 the primary variables that require climate-standard continuity as defined by 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 ingesting a set of global satellite data products (Land Surface Temperature LST, Snow Water Equivalent SWE, and Landover) 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 1km 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. CCN1 and CCN2 options 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 area. 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 regions, 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 variable related to rock glacier kinematics through the two products (i) regional rock glacier inventories and (ii) kinematical time series of selected rock glacier. Actually, inventories and monitoring of rock glaciers are not explicitly mentioned as being an ECV associated parameter. However, rock glacier monitoring builds up a unique validation dataset of climate models for mountain regions, where direct permafrost (thermal state) measurements are very scarce or even totally lacking. Therefore, proper rock glacier monitoring adapted to climate issues could be integrated as a new associated parameter to the ECV permafrost. The international initiative IPA (International Permafrost Association) Action Group *Rock glacier inventories and kinematics*, gathering about one hundred members, also supports this integration and CCN2 is working closely with this Action Group [RD-4]. Specific user requirements for the development of remote sensing-based mountain permafrost products that include (i) regional rock glacier inventories, (ii) kinematical time series for selected rock glaciers and (iii) a permafrost distribution model, have been compiled in the URD.

This Data Access Requirement Document (DARD) identifies all required input data, including satellite, aerial and in-situ data, for product generation and validation. The DARD also describes the conditions under which these data are made accessible. Accordingly, each data description contains information on key technical characteristics, about data availability and coverage (time-scale, geographic, temporal). For the regional kinematical inventories, the required input data for the proposed work mainly include freely available Sentinel-1 satellite SAR data. Complementary SAR

images include free archives (ERS-1/2, ENVISAT) and additional SAR collections available at partner institutions (JERS-1, ALOS-1/2 PALSAR-1/2, Radarsat-1/2, TerraSAR-X, Cosmo-Skymed). Optical imagery available from Sentinel-2, Landsat-7/8 and very high-resolution satellite and aerial acquisitions will also be used as a complement. In-situ data (GNSS campaigns, permanent GNSS station, solifluction stations) and local-scale ground-based and aerial remote sensing (laser scanning, terrestrial radar and unmanned aircraft) at selected sites will be used for validation of remote sensing products.

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

1 Introduction

1.1 Purpose of the document

The parameters required for mountain permafrost regions include (i) regional rock glaciers inventories, (ii) kinematical time series of selected rock glaciers, and (iii) a permafrost distribution model described in the PSD. This document details the requirements towards global satellite products as well as other datasets needed for product generation, model parameterization and validation. It provides all the necessary data needed by permafrost algorithm developers and users to write and read the permafrost products respectively.

1.2 Structure of the document

In Section 1.7, this document contains a glossary of terms specific to mountain permafrost. Section 2 provides information on the data that are required as input for the product generation. Section 3 gives an overview on the validation data that are available. A summary of the attributes of the data required to generate and validate the Permafrost_cci products is provided in Section 4.

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, 1 Nov 2009, 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., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onacu, A., Kroisleitner, C., Strozzi, T. 2019. ESA CCI+ Permafrost User Requirements Document, v1.0.

[RD-2] Bartsch, A., Westermann, Strozzi, T., Wiesmann, A., Kroisleitner, C. 2019. ESA CCI+ Permafrost Product Specifications Document, v1.0.

[RD-3] 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).

[RD-4] IPA Action Group Rock glacier inventories and kinematics. 2019. Towards standard guidelines for inventorying rock glaciers. Baseline concepts, v3.0.

1.5 Bibliography

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

1.6 Acronyms

A list of acronyms is provided in section 5.2.

1.7 Glossary

The list below provides a selection of terms relevant for the parameters addressed in Permafrost_cci [RD-3]. A comprehensive glossary is available as part of the Product Specifications Document [RD-2].

active layer

The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

In the zone of continuous permafrost the active layer generally reaches the permafrost table; in the zone of discontinuous permafrost it often does not. The active layer includes the uppermost part of the permafrost wherever either the salinity or clay content of the permafrost allows it to thaw and refreeze annually, even though the material remains cryotic (T < 0°C).

The active layer is sometimes referred to as the "active zone"; the term "zone," however, should be reserved for the zones of discontinuous and continuous permafrost.

In Russian and Chinese literature, the term active layer covers two distinct types: (1) the seasonally thawed layer overlying permafrost, and (2) the seasonally frozen layer overlying unfrozen ground inside or outside permafrost areas.

REFERENCES: Muller, 1943; Williams, 1965; Brown, 1971; van Everdingen, 1985.

active-layer thickness

The thickness of the layer of the ground that is subject to annual thawing and freezing in areas underlain by permafrost.

The thickness of the active layer depends on such factors as the ambient air temperature, vegetation, drainage, soil or rock type and total water content, snowcover, and degree and orientation of slope. As a rule, the active layer is thin in the High Arctic (it can be less than 15 cm) and becomes thicker farther south (1 m or more).

The thickness of the active layer can vary from year to year, primarily due to variations in the mean annual air temperature, distribution of soil moisture, and snowcover.

The thickness of the active layer includes the uppermost part of the permafrost wherever either the salinity or clay content of the permafrost allows it to thaw and refreeze annually, even though the material remains cryotic (T < 0°C).

Use of the term "depth to permafrost" as a synonym for the thickness of the active layer is misleading, especially in areas where the active layer is separated from the permafrost by a residual thaw layer, that is, by a thawed or noncryotic (T> 0°C) layer of ground.
REFERENCES: Muller, 1943; Williams, 1965; van Everdingen, 1985

ground ice

A general term referring to all types of ice contained in freezing and frozen ground.
Ground ice occurs in pores, cavities, voids or other openings in soil or rock and includes massive ice. It generally excludes buried ice, except in Russian usage. Ground ice may be epigenetic or syngeneic, contemporaneous or relict, aggrading or degrading, perennial or seasonal. It may occur as lenses, wedges, veins, sheets, seams, irregular masses, or as individual crystals or coatings on mineral or organic particles. Perennial ground ice can only occur within permafrost bodies.
REFERENCES: Mackay, 1972b; Pollard and French, 1980.

ice content

The amount of ice contained in frozen or partially frozen soil or rock.
Ice content is normally expressed in one of two ways:
1. on a dry-weight basis (gravimetric), as the ratio of the mass of the ice in a sample to the mass of the dry sample, expressed as a percentage, or
2. on a volume basis (volumetric), as the ratio of the volume of ice in a sample to the volume of the whole sample, expressed as a fraction.
The volumetric ice content cannot exceed unity whereas the gravimetric ice content can greatly exceed 100 percent.
REFERENCES: Penner, 1970; Anderson and Morgenstern, 1973; Johnston, 1981.

isolated patches of permafrost

Permafrost underlying less than 10 percent of the exposed land sur-face.
Individual areas of permafrost are of limited areal extent, widely separated, and are completely surrounded by unfrozen ground.
SYNONYMS: (not recommended) insular permafrost; island permafrost; scattered permafrost.
REFERENCES: Heginbottom and Radburn, 1992.

mean annual ground-surface temperature (MAGST)

Mean annual temperature of the surface of the ground.
Permafrost exists if the mean annual ground-surface temperature is perennially below 0°C. Although the mean annual surface temperature may be below 0°C, the surface temperature will fluctuate during the year, causing a layer of ground immediately beneath the surface to thaw in the summer and freeze in the winter (the active layer). Small changes in the annual range of surface temperature and in the mean annual surface temperature from year to year, or over a period of a few years, may cause a layer of ground between the bottom of the active layer and the permafrost table to remain at a temperature above 0°C, creating a talik or residual thaw layer. [RD-1]

mean annual ground temperature (MAGT)

Mean annual temperature of the ground at a particular depth.

The mean annual temperature of the ground usually increases with depth below the surface. In some northern areas, however, it is not un-common to find that the mean annual ground temperature decreases in the upper 50 to 100 meters below the ground surface as a result of past changes in surface and climate conditions. Below that depth, it will increase as a result of the geothermal heat flux from the interior of the earth. The mean annual ground temperature at the depth of zero annual amplitude is often used to assess the thermal regime of the ground at various locations [RD-1]

mountain permafrost

Mountain permafrost is simply permafrost in mountain areas. It can be situated at low or at high latitudes and in the Arctic or Antarctic – we define mountain permafrost based on the influence that mountain topography has on its properties. Many other terms that are commonly used to classify certain types of permafrost, such as Arctic, Antarctic, polar, or plateau, can be applicable at the same time. The dominating characteristic of mountain areas and mountain permafrost is their extreme spatial variability with respect to nearly all surface and near-surface characteristics and properties

REFERENCES: Gruber and Haeberli, 2009

periglacial environments

Those environments in which cold, non glacial processes dominate.

Frost action and either seasonally or perennially frozen ground dominate in these environments. Around 20% of the Earth`s land surface currently experiences periglacial conditions.

SYNONYMS: (not recommended): cold, non glacial processes

REFERENCES: French, 2007

permafrost

Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

Permafrost is synonymous with perennially cryotic ground: it is defined on the basis of temperature. It is not necessarily frozen, because the freezing point of the included water may be depressed several degrees below 0°C; moisture in the form of water or ice may or may not be present. In other words, whereas all perennially frozen ground is permafrost, not all permafrost is perennially frozen. Permafrost should not be regarded as permanent, because natural or man-made changes in the climate or terrain may cause the temperature of the ground to rise above 0°C.

Permafrost includes perennial ground ice, but not glacier ice or icings, or bodies of surface water with temperatures perennially below 0°C; it does include man-made perennially frozen ground around or below chilled pipelines, hockey arenas, etc.

Russian usage requires the continuous existence of temperatures below 0°C for at least three years, and also the presence of at least some ice.

SYNONYMS: perennially frozen ground, perennially cryotic ground and (not recommended) biennially frozen ground, climafrost, cryic layer, permanently frozen ground.

REFERENCES: Muller, 1943; van Everdingen, 1985; Kudryavtsev, 1978.

permafrost degradation

A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost.

Permafrost degradation may be caused by climatic warming or by changes in terrain conditions, such as disturbance or removal of an insulating vegetation layer by fire, or by flooding caused by a landslide-blocked stream, or by human activity. It may be expressed as a thickening of the active layer, a lowering of the permafrost table, a raising of the permafrost base, or a reduction in the areal extent or the complete disappearance of permafrost. [RD-1]

rock glaciers

Rock glaciers are cryo-conditioned landforms. They are the visible expression of former or current cumulative deformation by long-term gravity-driven creep of ice/debris mixtures under permafrost conditions, often characterized by a distinctive surface topography of transversal and longitudinal ridges and furrows.

They have been described either as periglacial features resulting from the downslope creep of rock-ice matrix, but some authors state that the deforming ice in within rock glaciers may be of glacial origin. These outstanding landforms are common features in alpine environments and their specific characteristics enable conclusions to be drawn about past and present environmental conditions in high mountain ranges.

REFERENCES: Barsch, 1996; Haeberli, 1985, Bertling 2011.

2 Data required for product generation

2.1 Satellite SAR data

To get a complete overview over 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. weekly, monthly and yearly on at least 2 consecutive years) and a small spatial baseline for both orbital geometries (i.e. ascending and descending orbits) (Barboux et al. 2014). The major obstacle limiting a successful use of SAR derived products in an Alpine environment is the presence of (wet) snow. Selected SAR images have to be acquired during the late summer period (e.g. in the period August–October for European Alps) to avoid reduced SAR coherence due to snow-cover. SAR scenes with a short time interval can also be used in the wintertime, when the snow is still cold and dry. In order to highlight the current situation when deriving regional rock glacier inventories, Sentinel-1 SAR Interferometric Wide Swath Mode scenes will be used at least for the period 2018-2020 at all sites. Where available, complementary SAR data (ALOS-1/2 PALSAR-1/2, Radarsat-1/2, TerraSAR-X, Cosmo-Skymed) will be used. Regarding kinematical time series of selected rock glacier product, complementary satellite SAR archives have to be used to investigating in the past as much as possible.

The required input data includes Sentinel-1 IWS images, and other archives or recent datasets available at partner institutions (ERS-1/2, ENVISAT, JERS-1, ALOS-1 PALSAR-1, ALOS-2 PALSAR-2, Radarsat-1/2, TerraSAR-X, Cosmo-Skymed).

2.1.1 Carpathians sites

A series of ALOS-2 PALSAR-2 data of the ascending orbit is available over the two areas of interest. We considered images acquired during the snow-free period for 2014.09.08, 2015.09.07, 2016.09.05, 2017.09.04, 2018.04.30 and 2018.06.25. These data were provided by JAXA and are courtesy of RA6-3016 (P.I. T. Strozzi). Because the quota for this project is used up, no data for the summer of 2018 could be ordered.

Sentinel-1 IWS images are acquired frequently on descending track (#80) and ascending track (#29) since 2014. The repeat interval for Sentinel 1 images in the study area is 6 days/track. There are 839 available images for the study area on 4 different tracks.

2.1.2 European Alpine sites

a) Switzerland, Western Swiss Alps

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms is already available for the period 2014-2017 (ESA GlobPermafrost). The continuation will be provided up to 2019.

Complementary SAR interferograms datasets are also available:
- 2006-2010 ALOS1
- 2004-2007 ENVISAT
- 1991-2000 ERS-1/2

- 2008-2014 TerraSAR-X

b) Italy, Sud Val Venosta, Sudtirol

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms will be processed for the period 2017-2019.

c) France, Vanoise massif

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms is already available for the period 2016-2018. The continuation will be provided up to 2019.

2.1.3 European subarctic/arctic sites

InSAR in all Norwegian AOIs will be primarily based on Sentinel-1 IWS scenes in ascending and descending geometries acquired between 2015 and 2019. Note that for AOI3 in Svalbard, descending scenes were not available before early 2018.

The processing will be complemented by high-resolution SAR datasets:

- In parts of AOI1 (centered on Nordnesfjellet): 2009-2019 TerraSAR StripMap (30x50 km scene size) + Radarsat-2 F/UF (20x20 to 50x50 km scene size; shorter time period)
- In parts of AOI3 (centered on Adventdalen and Kapp Linné): 2009-2019 TerraSAR StripMap + Radarsat-2 F/UF (20x20 to 50x50 km scene size; shorter time period)

2.1.4 Extra European sites

a) Greenland, Disko Island

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms is already available for the period 2014-2016 (ESA GlobPermafrost). The continuation will be provided up to 2019.

b) Central Asia, Tien Shan

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms is already available for the period 2014-2016 (ESA GlobPermafrost). The continuation will be provided up to 2019.

c) Alaska, Brookes Range

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2016. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms is already available for the period 2014-2016 (ESA GlobPermafrost). The continuation will be provided up to 2019.

d) Argentina, Central Andes

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 6 days/track. A series of Sentinel-1 interferograms will be provided for the period 2017-2019.

e) New Zealand, Central part of the Southern Alps

Sentinel-1 IWS images are acquired frequently from descending and ascending orbits since 2014. The repeat interval for Sentinel 1 images is 12 days/track. A series of Sentinel-1 interferograms will be provided for the period 2017-2019.

2.2 Complementary required data

Complementary data required for product generation includes mainly orthoimages as well as Digital Elevation Models (DEMs).

2.2.1 Complementary data in Carpathian sites

- Orthophotos at 0.5 m spatial resolution:
  Orthorectified aerial images at 0.5 m resolution are provided by ANCPI (National Agency for Cadaster and Real Estate Advertising) and are available for 2006, 2009 and 2012.
- Digital elevation model (DEM) at a 10 m resolution:
  Digital elevation models at 10 m resolution are derived from topographic maps, scale 1:25000.
- SRTM 1 arcsec at 30 m resolution:
  SRTM DEM is used at 30 m resolution, with absolute vertical height accuracy of less than 16 meters (source: USGS).

2.2.2 Complementary data in European Alpine sites

a) Switzerland, Western Swiss Alps

- 0.25m Swissimages orthoimages over the whole Swiss Alps;
- SwissAlti3D: high resolution DEM at 2m resolution over the whole Swiss Alps;
- Aerial images from 1946 to 2019 of up to 0.15-0.20m spatial resolution for the newest ones over some specific rock glaciers (via search and scan order to Swisstopo);
- 0.5m Lidar-derived DEM over some specific rock glaciers (order to Swisstopo);
- ESA GlobPermafrost slope movement inventories (including rock glaciers)

b) Italy, Sud Val Venosta, Sudtirol

- Several WMS available from GeoCatalogo of Autonomous Province of Bolzano
- 2.5-m Lidar-derived DEM (taken in 2005) free download available from GeoCatalogo of Autonomous Province of Bolzano
- Morphological rock glacier inventory from University of Bologna & Geological Survey of the Autonomous Province of Bolzano, 1rst version in 2019.

c) France, Vanoise massif

- Multi-temporal high-resolution aerial imagery for the French Alps (IGN France)
- DEM at a 10 m resolution (TanDEM-X), BD-Alti at a 25m resolution (IGN France) and MNT RGE at a 5m resolution (IGN France)
- Morphological rock glacier inventory from Marcer et al. 2017

2.2.3 Complementary data in European subarctic/arctic sites

a) AOI1 Troms:

- Norgeibilder orthophotos at 0.1-1 m resolution (2001-2019)
- 10m Norwegian DEM (Norwegian Mapping Agency) and 2m ArcticDEM (US Polar GeoSpatial Center)
- Morphological inventory from Lilleøren and Etzelmüller, 2011 (and updated unpublished version based on higher resolution imagery)
- Aerial images from about the 1950s to 1960s on exist at lower resolution for complementary processing using aerial photogrammetry (via search and scan order to Norwegian Mapping Agency)

b) AOI2 Finnmark:

- Norgeibilder orthophotos at 0.25-0.5 m resolution (2008-2018)
- 10m Norwegian DEM (Norwegian Mapping Agency) and 2m ArcticDEM (US Polar GeoSpatial Center)
- Morphological rock glacier inventory from Lilleøren and Etzelmüller, 2011 (and updated unpublished version based on higher resolution imagery)
- Aerial images from about the 1950s to 1960s on exist at lower resolution for complementary processing using aerial photogrammetry

c) AOI3 Nordenskiöld Land:

- TopoSvalbard orthophotos at 0.2-0.4 m resolution (2009-2012)
- 20m Svalbard DEM (Norwegian Polar Institute)
- Morphological rock glacier inventory in Nordienskiöld Land (in development at UNIS)
- Aerial images from 1969 and 1990 at 0.2 m resolution for complementary processing using aerial photogrammetry

2.1.4 Complementary data in Extra European sites

a) Greenland, Disko Island

- Google Earth™ imagery
- DEM at a 10 m resolution (TanDEM-X)
- ESA GlobPermafrost slope movement inventories (including rock glaciers)

b) Central Asia, Tien Shan

- Orthorectified Landsat ETM+ data (1999-2002)
- ASTER scenes (2000-2019)
- Sentinel-2 images
- Google Earth™ imagery
- Aerial photographs and very high-resolution optical satellite data (~1m resolution) from the 1950s
- SRTM DEM (~30m resolution)
- DEM at 10 m resolution (TanDEM-X)
- ESA GlobPermafrost slope movement inventories (including rock glaciers)
- Morphological rock glacier inventory

c) Alaska, Brookes Range

- Google Earth™ imagery

- LiDAR coverage only along the Dalton Highway (high-resolution optical imagery for a broader area)
- DEM at 10 m resolution (TanDEM-X)
- ESA GlobPermafrost slope movement inventories (including rock glaciers)

d) Argentina, Central Andes.

- Google Earth™ imagery
- National orthoimages
- 30m DEM (combining SRTM and ALOS DEM).
- Morphological rock glacier inventory (IANIGLA)

e) New Zealand, Central part of the Southern Alps

- New Zealand aerial images (LINZ data service)
- 8m Digital Elevation Model (originally created by Geographx (geographx.co.nz) from January 2012 LINZ Topo50 20m contours)
- Rock glacier inventory of Sattler et al. (2016). Only points available, no outlines.

3 Product validation

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 in the selected sites (rock glacier inventories, kinematical time series of selected rock glacier, and permafrost modelling, see PSD). Especially, the performance of the methodology for remote sensing-based rock glacier inventories using dedicated guidelines will be assessed in a "round-robin" exercise in a workshop in February 2020 where discrepancies between different producers will be evaluated. Guidelines will be refined accordingly. Delivered standardized regional rock glaciers inventories (consisting of an update of existing morphological rock glacier inventories and/or slope movement inventories) will rigorously follow these guidelines. Delivered kinematical time series of selected rock glaciers will be evaluated and validated against in-situ velocity measurements when available over sites investigated. The permafrost modelling produced in the Southern Carpathians sites will be evaluated and validated against in-situ ground temperature measurements and geophysical surveys.

On the other hand, the produced rock glacier inventories and kinematical time series builds up a unique validation dataset for climate models and permafrost indication maps for mountain regions, where direct permafrost (thermal state) measurements are very scarce or even totally lacking. The assessment of the data products by the permafrost Climate Research Group (CRG) and other users as well as outreach activities regarding publications and presentations will be summarized in the "Climate Assessment Report" (D5.1). 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 (D5.2). In addition, we also intend to publish the inventories of rock glaciers and the kinematical time series of selected rock glaciers for the various investigated regions.

3.1 Velocity measurements

3.1.1 Western Swiss Alps

In Switzerland an increasing number of landforms (currently about 30 between rock glaciers, moraines and landslides) are being surveyed regularly by field measurements (e.g. DGNSS, LIDAR, terrestrial radar interferometry, webcams). Especially, continuous long-term data series of permafrost creep are currently available at several rock glacier sites in order to provide a basis for the understanding and investigation of ongoing processes and dynamics. Some of them are part of the national data-services PERMOS in Switzerland (PERMOS 2019, Figure 1). The kinematic monitoring strategy follows a landform-based approach. Seasonal, inter-annual and long-term variations in rock glacier kinematics (see e.g. Delaloye et al. 2010, PERMOS 2019) may be captured using a combination of aerial survey (AS) and terrestrial geodetic surveys (TGS, by total station or differential GNSS). Changes in geometry (i.e. horizontal velocities and vertical changes) are analyzed in detail to quantify permafrost creep and to detect signs of potential permafrost degradation such as vertical thinning due to ice melt or rock glacier destabilization. Surveys are performed at least once a year at the same time in the season (usually in late summer) for a number of selected boulders on each rock glacier (10–100 points). The measured coordinates (x, y) and elevation (z) are used to quantify the horizontal (Δxy) and vertical (Δz, ratio of slope) changes of each point. Trajectories and flow fields are then generated and creep rate time series for single measurement points and/or representative zones of the rock glacier are determined. The relative mean annual horizontal surface velocity (in %) can be then derived for the region (Figure 2).

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

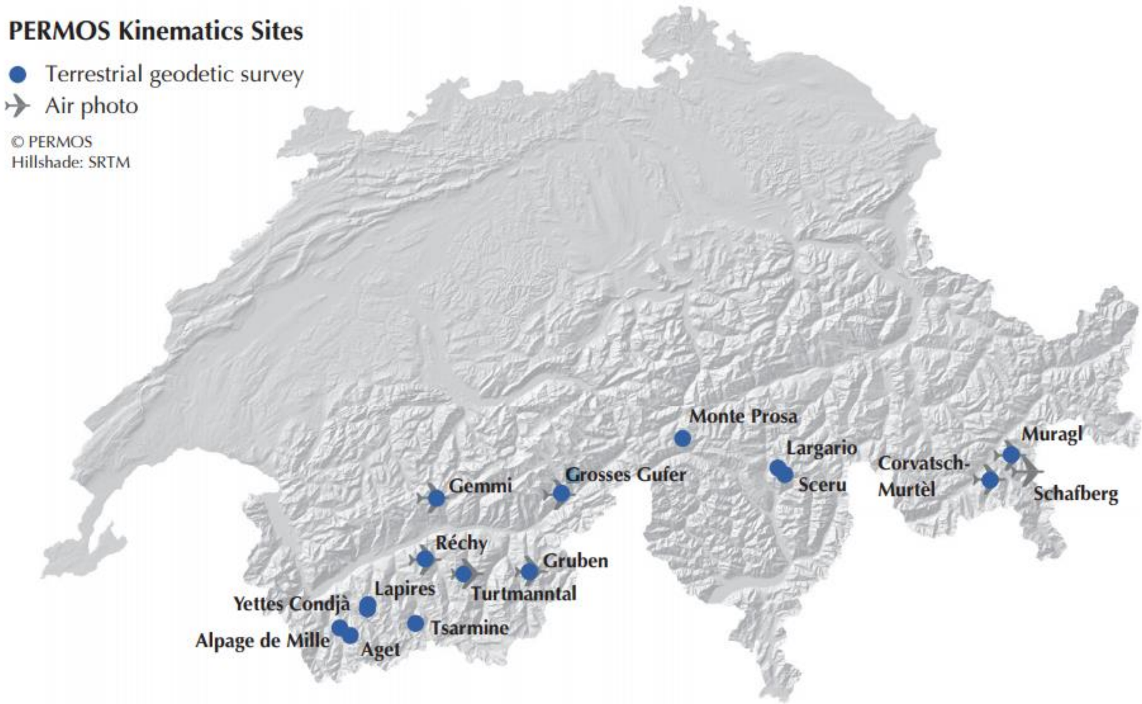

Figure 1: *PERMOS Kinematics sites (PERMOS 2019)*

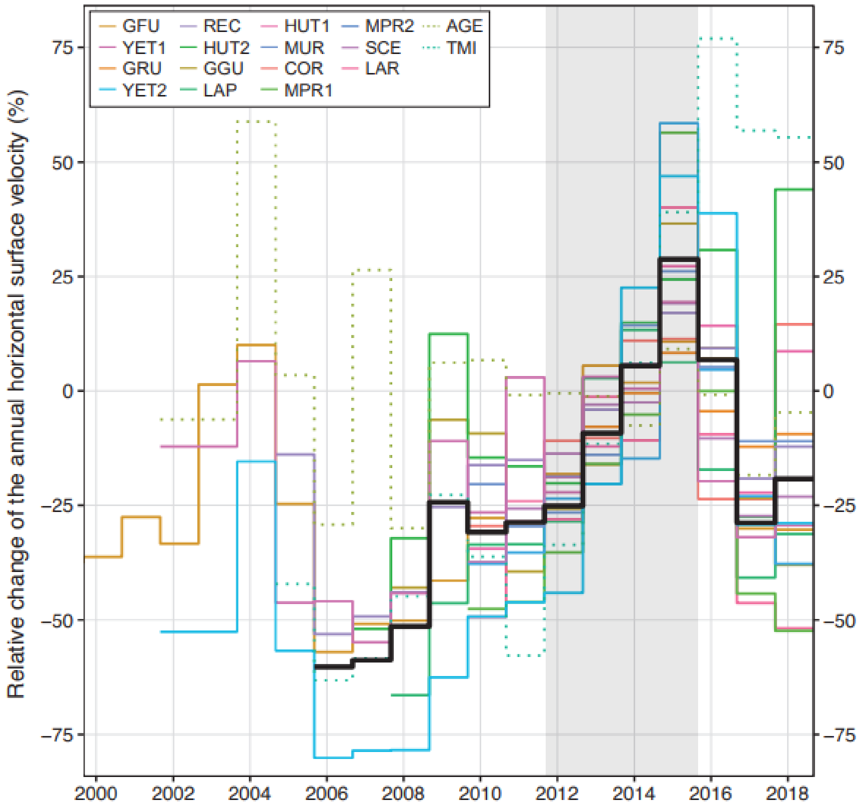

***Figure 2**: Mean annual horizontal surface velocity (in %) relative to the reference period 2012–2015 (grey area) at 17 rock glacier lobes from 2000 to 2018 derived from terrestrial geodetic surveys. Rock glaciers showing an atypical evolution are shown in dotted lines and the black line corresponds to the mean of the Swiss Alps (excluding the two atypical rock glaciers) (PERMOS 2019).*

3.2 Mountain permafrost sites located in European subarctic/arctic sites

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

In the AOI1 (Troms), intensive in-situ networks are continuously monitoring ground displacements at the location of three high-risk rockslides (since 2007 on Jettan and Indre Nordnes on Nordnesfjellet and since 2016 on Gámanjunni3 in Manndalen). The rockslide section of the Norwegian Water Resources and Energy Directorate (NVE) is responsible for the management of a large set of instrumentation: GNSS, extensometers, laser-reflectors, tiltmeters, ground-based radar, corner reflectors for using InSAR the entire year, etc. (Blikra & Christiansen, 2014; Böhme et al., 2016; Nordvik et al., 2010). Even if not directly related to the processes studied in the Permafrost_cci CCN2 project, these networks are documenting landforms moving at the same order of magnitude (cm/yr) and are located close to identified rock glaciers. They will be thus valuable for validation. In addition, the Ádjet rock glacier complex in Skibotndalen has been studied by NORCE and The Arctic University of Norway in Tromsø (UiT). A combination of InSAR, SAR offset-tracking, aerial feature tracking, terrestrial radar interferometry and periodic GPS measurements has highlighted very high velocities (several m/yr) and an accelerating trend these last decades (Eriksen et al., 2018, Figure 3).

The existing dataset will be compared with the new products and be also used to discuss the limitations of InSAR over very fast-moving rock glaciers.

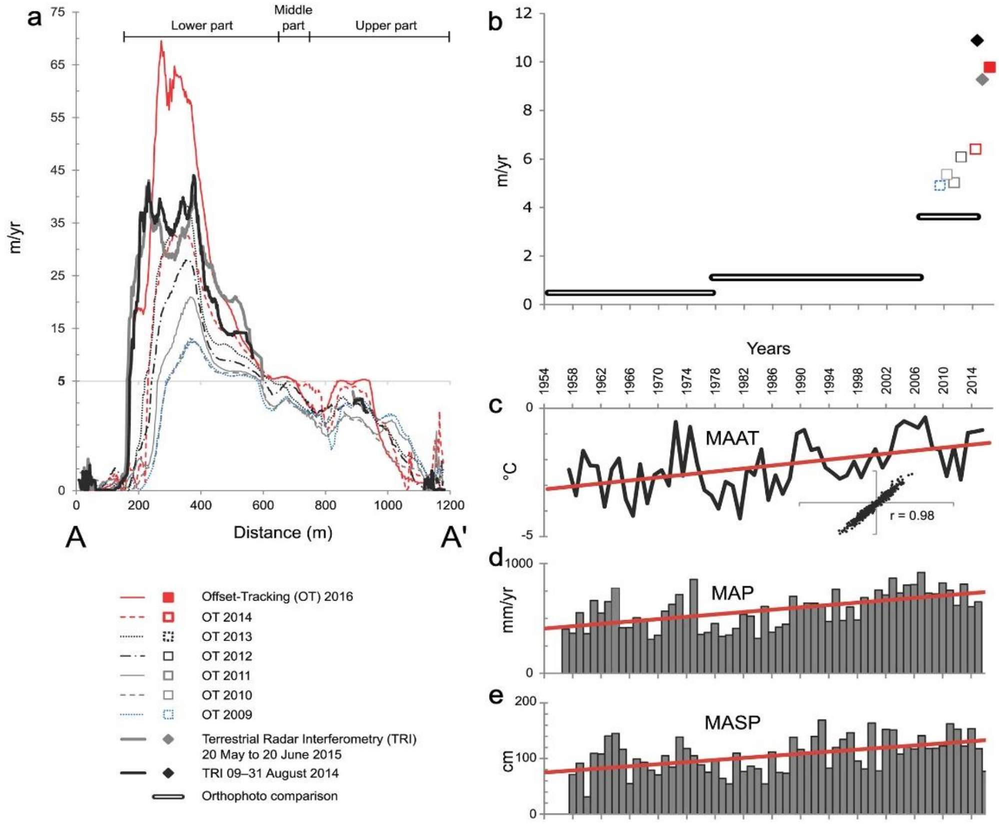

Figure 3. *Spatio-temporal variations of displacement rates on the main lobe of the Ádjet rock glacier complex (AOI1) based on SAR Offset-Tracking, Terrestrial Radar Interferometry and Aerial Feature Tracking. a) Variation of surface-parallel annual velocity along a profile. b) Evolution of the mean annual horizontal velocity since 1954 for an area in the middle part. c-e) Temperature, precipitation and snow depth based on modeled local climatic data (Eriksen et al., 2018).*

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

In AOI3 (Nordenskiöld Land), the University of Tsukuba (Japan) in collaboration with the University Centre in Svalbard (UNIS) have conducted 14 years (2005-2019) of annual Real Time Kinematic GPS Survey of surface benchmarks on a small valley-side rock glacier (Huset, in Longyeardalen). At this location, a borehole down to 15 m records temperature and deformation measurements (Matsuoka et al., 2019). In addition, two solifluction monitoring stations are measuring 2D displacements (normal and parallel to the ground surface) (Harris et al., 2007; 2011) in Endalen since 2005 and in Kapp Linné since 2008 (Figure 4). The monitoring is continuous but in some periods the stations have not been operational due to polar bear attacks and power problems. Like for the monitoring data from AOI1, the solifluction stations document different processes from the purpose of Permafrost_cci CCN2 project.

However, due to the same order of magnitude (cm/yr) of the measured movement and the neighbouring locations of identified rock glaciers, these datasets will be valuable for validation.

Figure 4. *Endalen solifluction monitoring station (AOI3), 6 February 2007, automatic digital photography (UNIS).*

In addition to the in-situ datasets described above, at least one site per AOI will be selected to process complementary aerial optical photogrammetry (horizontal velocities using image matching; Kääb and Vollmer, 2000). For contemporary airphotos, the results at these locations will be used for cross-validation with InSAR-based products. For historical airphotos, they will be used to detect rock glacier long-term velocity changes. For a strandflat rock glacier at Nordenskiöldkysten (AOI3), geophysical soundings (DC resistivity, ground-penetrating radar) and aerophotogrammetric surveys exist (Kääb et al, 2002; Farbrot et al. 2005). Datasets from meteorological stations, ground surface and ground temperature loggers in boreholes are also available in the three AOIs to further investigate the relations with climate variables. In AOI3 for instance, permafrost boreholes operational since 2008-2009 are equipped for ground thermal monitoring in approx. 15 different sites representing the main periglacial landforms in this area (Christiansen et al., 2010).

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

3.3 Ground and air temperature

In the Southern Carpathians, ground and air temperatures are monitored on several rock glaciers at the study sites and will be used to evaluate and validate the regional permafrost distribution model. Validation with these datasets will be summarized in the Product Validation and Intercomparison Report (PVIR, D4.1).

3.3.1 Carpathian sites

Because of limited drilling possibilities, there are no boreholes in the rock glaciers of the Romanian Carpathians. The temperature of the ground is monitored only at the surface of the active layer in case of several rock glaciers at the selected test sites. Miniature temperature data loggers (MTD) are frequently used to monitor the thermal conditions and heat exchanges at the ground-atmosphere interface and to better understand the snow/permafrost/atmosphere interactions. The MTDs are generally placed at 5-30 cm beneath the surface of the rock glaciers and covered with small fragments of rocks and pebbles to avoid direct exposure to solar radiation. The thermal measurements are conducted with two different types of data loggers: iButton Digital Thermometers and UTL 3. The thermistors recorded the ground surface temperature every 2 or 4 hours between September 2012 and September 2018 and will measure the ground surface temperature for the next years too (Figure 5). In the Retezat site a miniature temperature data logger is also used to record the air temperature variation every 2 hours since 2012. This is installed in a wooden case and is located in the vicinity of one investigated rock glacier.

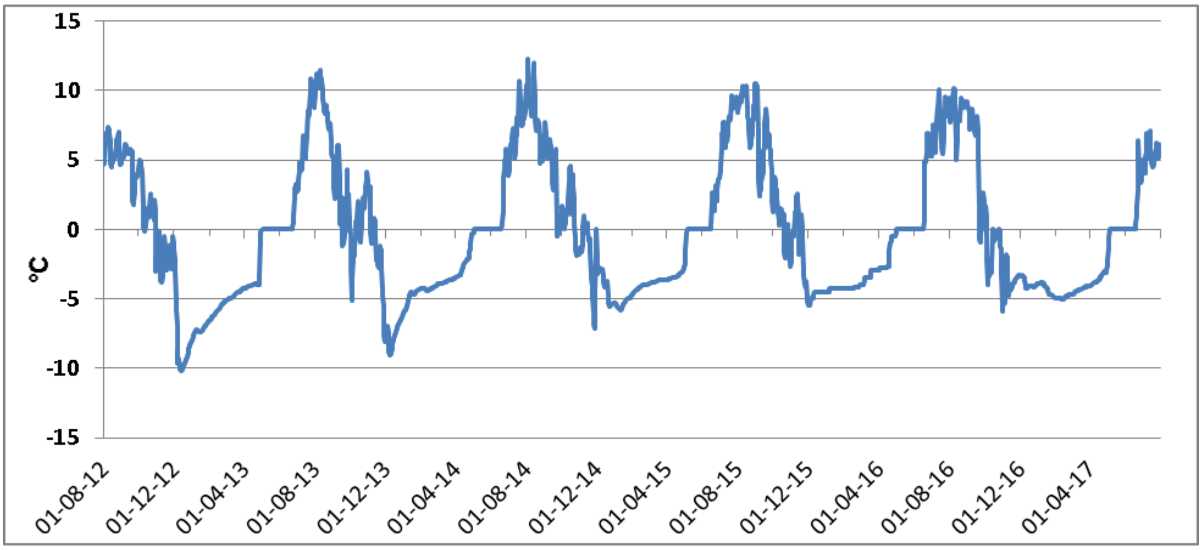

Figure 5. *Five years evolution (1.08.2012 – 31.07.2017) of mean-daily ground-surface temperature at one site in the Retezat Mountains.*

Within the selected sites, thermal measurements were performed in case of 9 rock glaciers in the Retezat Mountains and 5 in the Parâng Mountains (Figure 6). At some of these rock glaciers measurements of the bottom temperature of snow cover as well as geophysical surveys were also conducted.

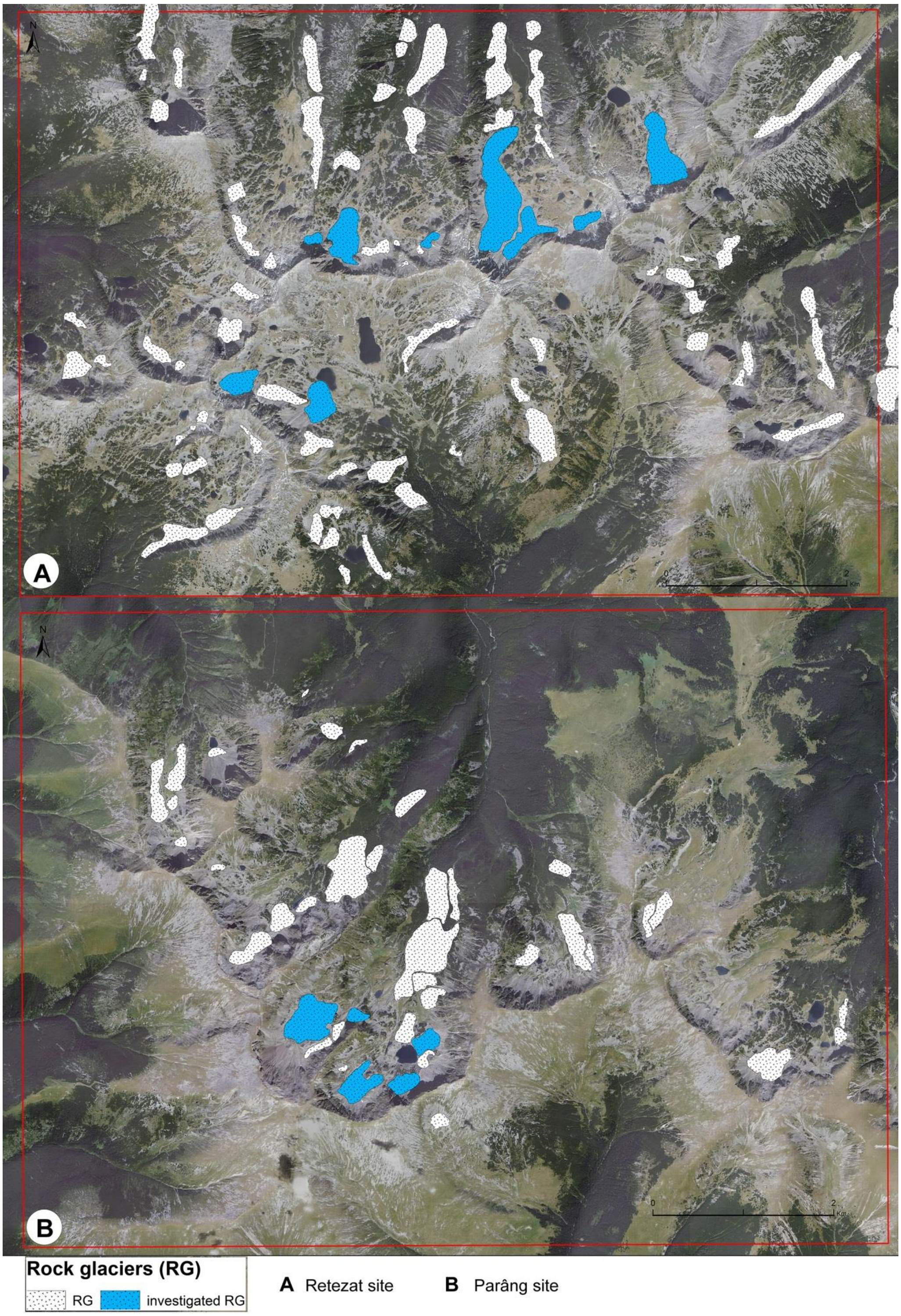

Figure 6. *Rock glaciers with existing ground temperature data in the selected sites.*

Based on previous thermal measurements permafrost is probable/possible to occur at those sites where the bottom temperature of the winter snow cover (BTS) is below -3^{0}C (-2^{0}C), the mean annual ground surface temperature (MAGST) is lower than 0^{0}C (1.5^{0}C) and the ground freezing index (GFI) is greater than 600 (400) ^{0}C days (Figure 7).

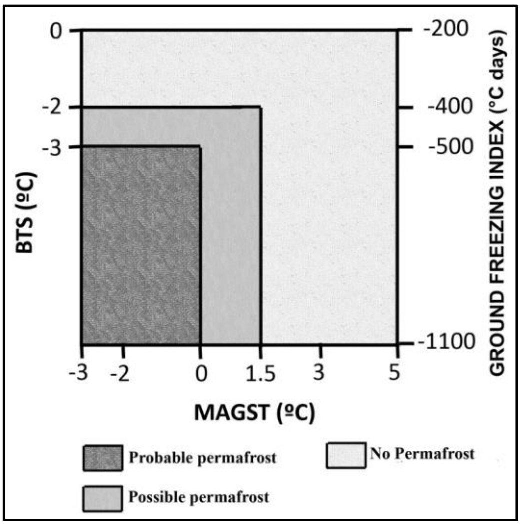

Figure 7. *MAGST versus BTS and GFI and the classification of the data loggers sites in the Southern Carpathians in the permafrost probable or no permafrost category (Onaca, 2017).*

3.4 Geophysical survey

Electrical resistivity tomography (ERT) and ground penetrating radar (GPR) surveys were conducted on several rock glaciers in Carpathians sites and will be used to evaluate and validate the regional permafrost distribution model. Validation with these data will be summarized in the Product Validation and Intercomparison Report (PVIR, D4.1).

3.4.1 Carpathians sites

Because several physical parameters of the substrate record remarkable changes when the water reaches the freezing point, geophysical techniques are preferred for permafrost detection, mapping, characterization and monitoring (Hauck, 2001). ERT is considered the most suitable geophysical method for mountain permafrost detection (Hauck et al., 2003) because the resistivity of frozen materials is very high and can reach 2000kΩm (Haeberli and Vonder Mühll, 1996). Based on the ERT surveys it is possible not only to estimate the thickness of the permafrost, but in some cases the ice content too, as well as the active layer thickness. Based on previous geophysical findings it was possible to show that in marginal periglacial environments, such as in the Romanian Carpathians, isolated patches of permafrost generally occur above 2000 m in north-facing rock glaciers. At the selected study sites the thickness of permafrost is approximately between 5 and 12 m (Onaca et al., 2013a, 2013b, Figure 8). Based on the previous findings (Vespreamnu-Stroe et al., 2012; Onaca et al., 2015; Popescu et al., 2015) permafrost in the Romanian Carpathians occurs at sites where the size of the boulders is large and consequently the porosity of the unconsolidated deposits is high allowing the cooling effect of coarse blocks to be very efficient. Another important factor controlling permafrost preservation within the rock glaciers in the Romanian Carpathians is the amount of solar radiation. At sites where permafrost is likely to occur, the reduced incoming of solar radiation allow the preservation of snow cover duration until July or August preventing the ground from heating up (Onaca et al., 2015).

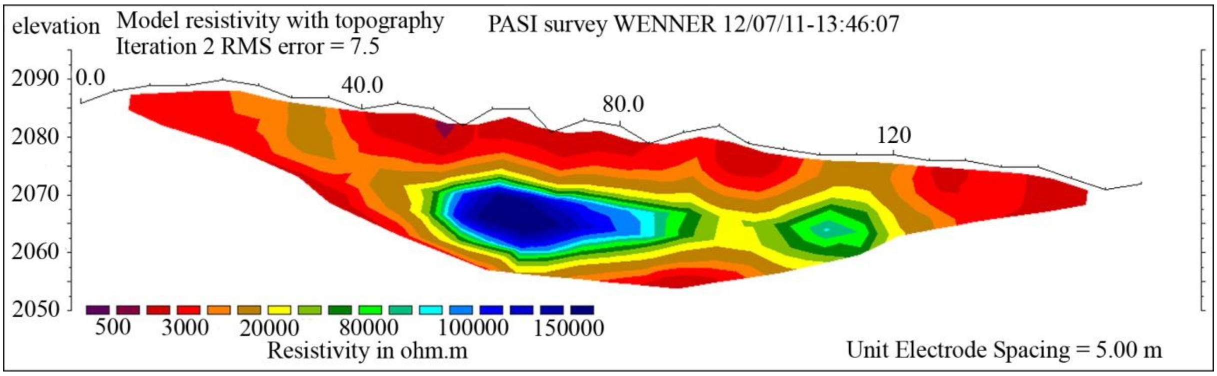

Figure 8. *Ice rich frozen debris in one rock glacier in the Parâng Mountains (Onaca et al., 2013b).*

Even if there are no boreholes in the rock glaciers of the Romanian Carpathians, it is possible to estimate the thickness of the active layer, using geophysical measurements. In case of several rock glaciers in the selected sites, electrical resistivity tomography (ERT) and ground penetrating radar (GPR) surveys were conducted (Figure 9). Typically, in marginal periglacial environments the active layer of rock glaciers is very thick (5-10 m) (Onaca et al., 2013a). An active layer thicker than 5 meters generally suggests permafrost degradation (Kneisel, 2010).

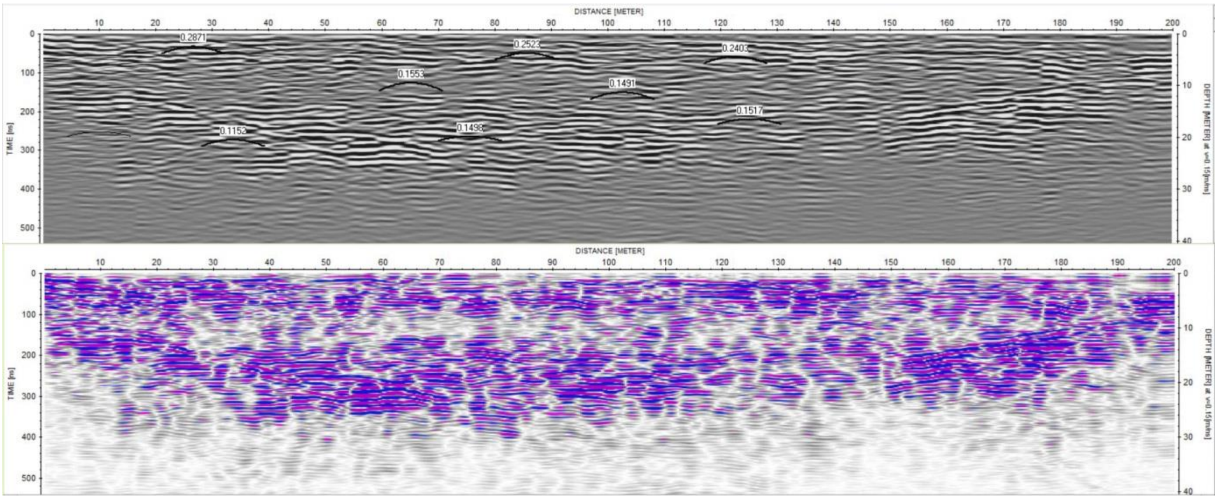

Figure 9. *Radargram of GPR profile performed on rock glacier in the Retezat Mountains with parabolas representing single objects smaller than the GPR footprint, whereas numbers represent propagation velocities in m ns-1.*

4 Summary

A summary of the attributes of the data required to generate and validate regional rock glacier inventories, kinematical time series of selected rock glaciers, and regional permafrost distribution models is given in Table below.

Data class	Data type	Source	Spatial coverage	Temporal coverage	Repeat periodicity	Availability
Production	Sentinel-1 SAR data	ESA	All sites	2015-2019	6 days	Freely available
Production	Sentinel-1 interferograms	ESA DUE GlobPermafrost	Swiss Alps, Disko Island, Tien Shan, Brookes Range	2016-2017	6 days to 1 year	PANGAEA
Production	Complementary SAR data (TSX, CSK, ALOS1/2, JERS, ERS, ENVISAT)	UniFR	Swiss Alps	1991-today	Irregular	Some freely available, others with restricted use, available to consortium
Production	Complementary SAR data (TSX, RSAT-2, ERS, ENVISAT)	NORCE	European subarctic/arctic sites	1991-today	Irregular	Some freely available, others with restricted use, available to consortium
Production	Complementary optical aerial imagery	UiO	European subarctic/arctic sites Tien Shan, Swiss Alps, Brookes Range	Depending on site, from 1950s – 1960s	Irregular (few years – decades)	Some freely available, others with restricted use, available to consortium
Production	Complementary very high-resolution optical satellite imagery	UiO	Tien Shan	Depending on site, from about 2000-2010	Irregular (few years)	Commercial, restricted use, available to the consortium
Complementary (required)	DEM	mixed	All sites	Irregular	Single dates	Some freely available, others with restricted use, available to consortium
Complementary (required)	Orthoimagery (satellite/aerial)	mixed	European Alpine sites European subarctic/arctic sites Tien Shan Brookes Range Central Andes New Yealand	Irregular	Single dates	Some freely available, others with restricted use, available to consortium
Complementary (required)	Google Earth™/ Bing imagery	Google Earth	All sites	Irregular	Single dates	Freely available
Complementary (required)	Morphological rock glacier inventories	mixed	Ultental Vanoise Tien Shan Central Andes Norway New Zealand	Irregular	Irregular	Some freely available, others with restricted use, available to consortium
Complementary (required)	ESA GlobPermafrost slope movement inventories	ESA DUE GlobPermafrost	Swiss Alps Disko Island Tien Shan Brookes Range	2016-2017	Single dates	Available to consortium

Validation	Velocity measurements	PERMOS, UniFR	Switzerland	Since 2000 for the longest	Seasonally Annually Continuous	Available to consortium
Validation	Velocity measurements	UNIS, UiO, NORCE	Norway and Svalbard	Since 2005 for the longest	Seasonally, annually, continuous	Available to consortium
Validation	Geophysical survey	WUT	Carpathians	irregular	Single dates	Available to consortium
Validation	Ground and air measurements	WUT	Carpathians	irregular	Single dates	Available to consortium
Validation	Field visits	mixed	European Alpine sites Brookes Range	irregular	Single dates	N/A

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5.2 Acronyms

AUC	Area Under the Receiver Operating Curve
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
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GFI	Ground Freezing Index
GPR	Ground Penetrating Radar
GST	Ground Surface Temperature
GTOS	Global Terrestrial Observing System
IPA	International Permafrost Association
MAGT	Mean Annual Ground Temperature
MAGT	Mean Annual Ground Surface Temperature
MRI	Mountains Research Initiative

MTD	Miniature Temperature Data Loggers
NMA	National Meteorological Administration
NSIDC	National Snow and Ice Data Center
PSD	Product Specifications Document
RF	Random Forest
RD	Reference Document
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
S4C	Science for the Carpathians
T	Temperature
URD	Users Requirement Document
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WUT	West University of Timisoara