CCI+ PHASE 1 – NEW ECVS
PERMAFROST

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

D1.2 Product Specification Document (PSD)

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Executive summary

Within the European Space Agency (ESA), the Climate Change Initiative (CCI) is a global monitoring program which 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 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 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 characterising 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 for climate models over 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. 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 Product Specification Document (PSD) describes the product specifications for the generation of the three mountain permafrost products specified above. Standard guidelines to produce homogeneous regional rock glacier inventories and kinematical time series of selected rock glaciers will be developed thanks to the close collaboration with the IPA Action Group (CCN2). Both of these products will be provided for selected regional cases proposed by options CCN1 and CCN2. In addition, a further specific permafrost product was determined and specified in the URD, i.e. a

regional permafrost distribution model and will be delivered for selected site located in Southern Carpathians (CCN1).

This PSD also includes a glossary of permafrost relevant terms, the product specifications and formats, including the requirements related to the metadata.

1 Introduction

1.1 Purpose of the document

This document describes in detail the product specifications in order to obtain mountain permafrost products that are consistent, robust and error-characterised. The purpose of this document is to present the structure, syntax and file naming conventions used to describe the different permafrost products.

1.2 Structure of the document

In Section 1.7, this document contains a glossary of terms specific to mountain permafrost. Section 2 describes the areas covered for the services as well as regions of interest for evaluation. The remaining sections detail the product specifications and format.

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, the Global Observing System for Climate: Implementation Needs (2016 GCOS Implementation Plan, 2015.

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 4.1.

1.6 Acronyms

A list of acronyms is provided in section 4.2.

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 con-tent, 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 syngenetic, 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 surface.

Individual areas of permafrost are of limited areal extent, widely separated, and are completely surrounded by unfrozen ground.

SYNONYMS: (not recommended) insular permafrost; island perma-frost; 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 metres 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 Key regions for study

2.1 Introduction

CCN1 and CCN2 options address the need for additional regional cases in cooperation with dedicated users in order to characterise mountain permafrost as local indicator for climate change and direct impact on societies in mountainous areas. It is intended to develop the options in different climatic regions, namely: Carpathians sites, European Alpine sites, European subarctic/arctic sites as well as Extra-European sites.

2.2 Carpathians sites (CCN1)

The Southern Carpathians represent the highest part of the Romanian Carpathians (2544 m) and occupy approximately 14 000 km^2. They are located at 45^{0}N latitude, exactly in the median part of the temperate zone. Around 15% of the entire surface of the Southern Carpathians lies above the treeline, in the alpine periglacial environment. The highest concentration of rock glaciers is found in the central part of the Retezat and Parâng Mountains. Within these mountain ranges two study sites were delineated, covering around 60 km^2 each (see Fig. 1).

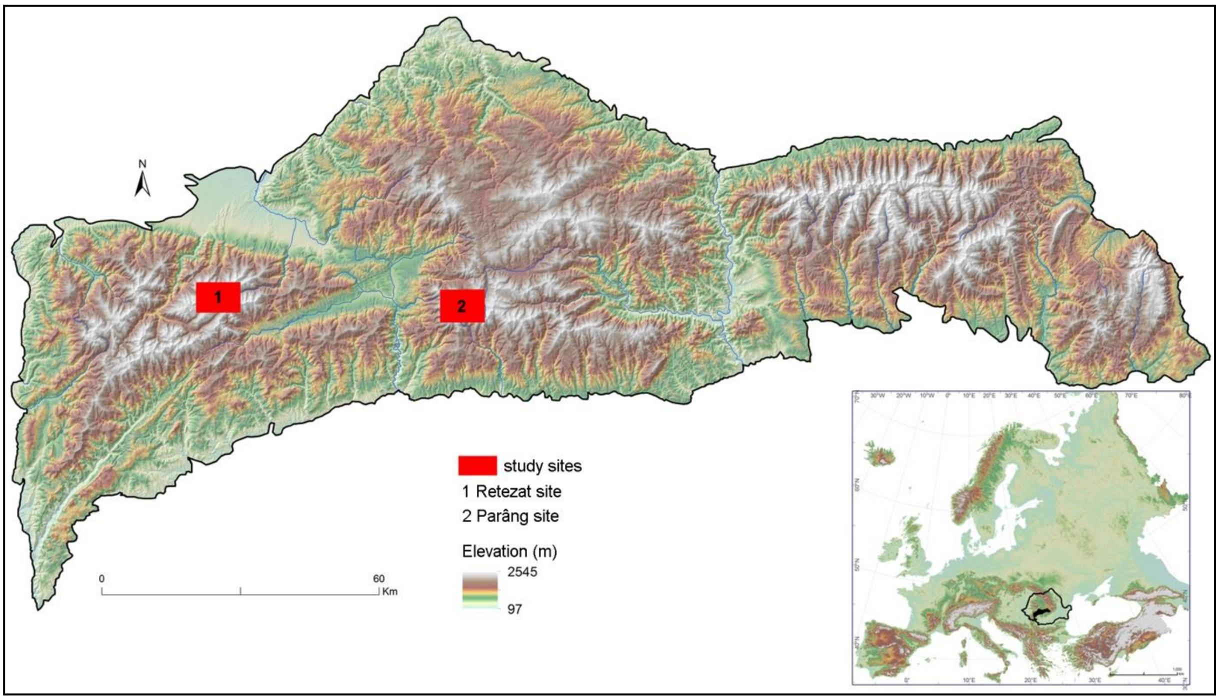

Figure 1. *Location of the study sites in the Southern Carpathians. The insert map highlights the location of Romania (outline) and the study site (black fill) in Europe.*

Compared to the Alps, the climate of the Southern Carpathians is characterized by a more pronounced continentality. The closest meteorological station at high altitude is Ţarcu (2180 m, 45^{0}16'50" N, 22^{0}32'00" E), whereas the highest altitude meteorological station in Romania is Omu (2505 m, 45^{0}26'45" N, 25^{0}27'22" E). The alpine climate of the mid-latitude mountains (French, 1996), characterized by high daily and annually amplitudes, is typical of the highest ridges of the Carpathians (see Fig. 2).

The mean multiannual air temperature at Țarcu meteorological station is -0.4^0 C, whereas at Omu the mean annual temperature is -2.3^0 C. The mean annual precipitation varies between 900 and 1000 mm at both meteorological stations. This mountainous region is predominantly under the influence of western air-mass circulation.

The long-term evolution of mean annual air temperature at high elevation in the Southern Carpathians reveals an evident increase in air temperatures in the last two decades (see Fig. 3). It is widely accepted that permafrost is very sensitive to air temperature rising and its degradation generates irreversible changes to the environment.

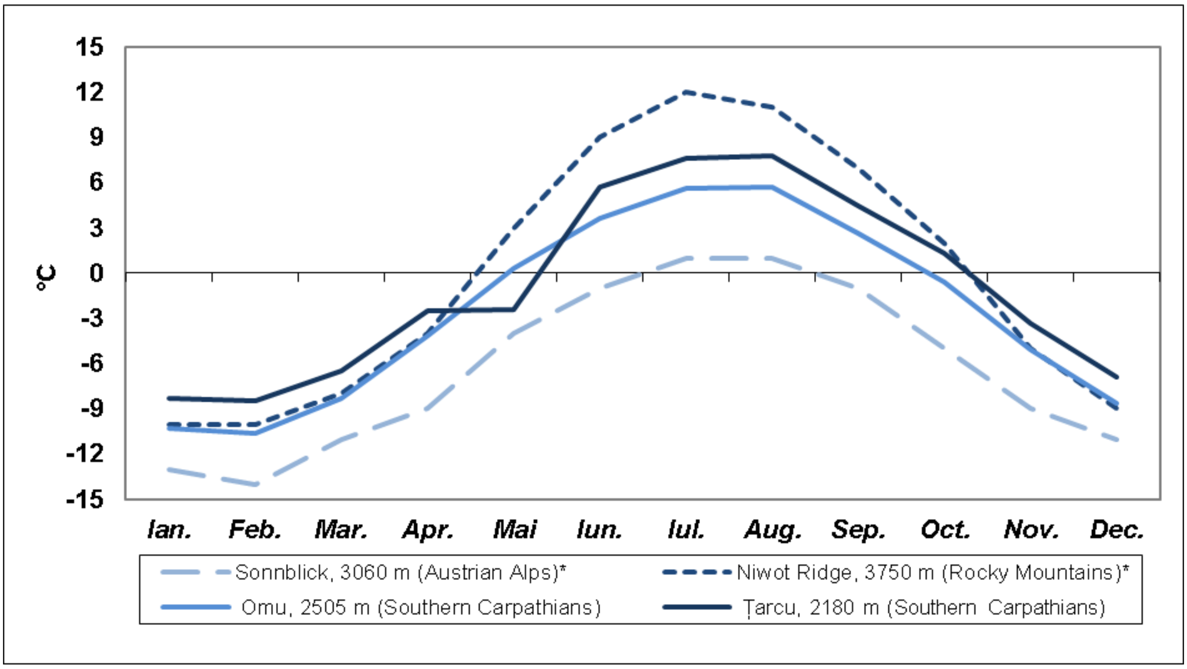

Figure 2. *Air temperature regimes in 3 different periglacial mountain regions: Austrian Alps, Rocky Mountains and Southern Carpathians (* data from French, 1996).*

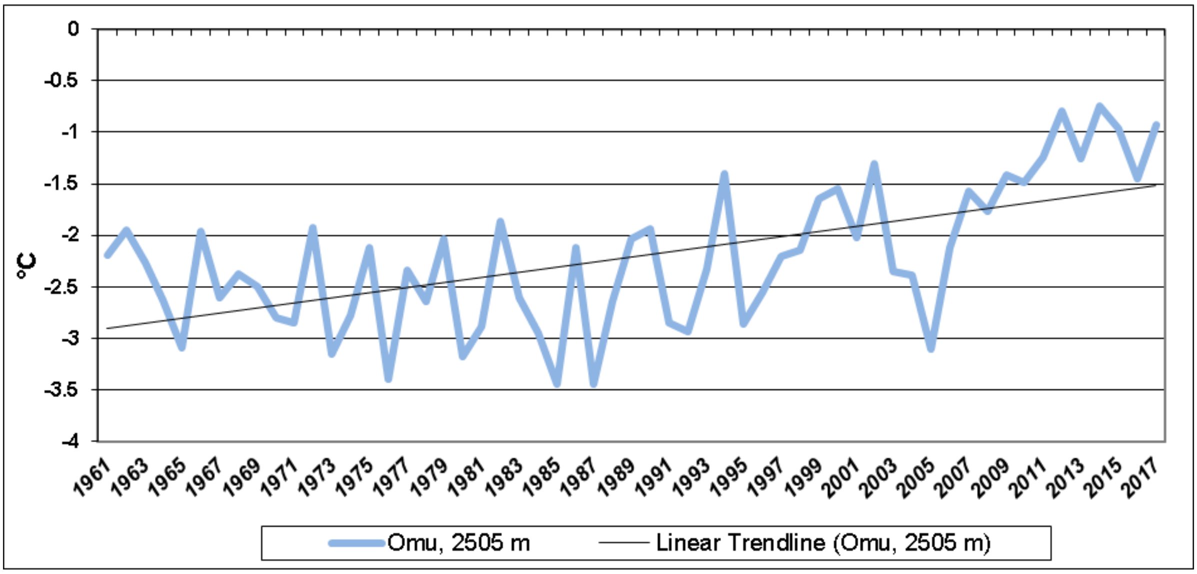

Figure 3. *Mean annual air temperature evolution between 1961 and 2017 at Omu meteorological station, in the Southern Carpathians.*

2.3 European Alpine sites (CCN2)

2.3.1 Switzerland, Western Swiss Alps

The Western Swiss Alps are located at approximately 7.5°E 46°N and cover an area of around 3000 km^2 of typical high-mountain terrain with predominantly continental climate. They consist of nine south-north catchments located on the orographic left side of the Rhône River with altitudes ranging between 500 m (Rhône Valley) and 4634 m a.s.l. (Dufourspitze). Along the suspended valleys, the vertical slope extend typically ranges between around 1250 m and more than 3000 m a.s.l. The periglacial belt – defined as the sparsely vegetated portion of the mountain slope in between the tree line up to the bottom of the glaciated area – ranges from approximately from 2300 m to 3000 m a.s.l. and is characterised by many different Alpine geomorphological processes (Barboux et al., 2015). Moving zones related to the creep of frozen debris (e.g. rock glaciers, push-moraines) and shallow to deep-seated landslides affecting frozen as well as unfrozen debris or rocks are widespread (see Fig.4).

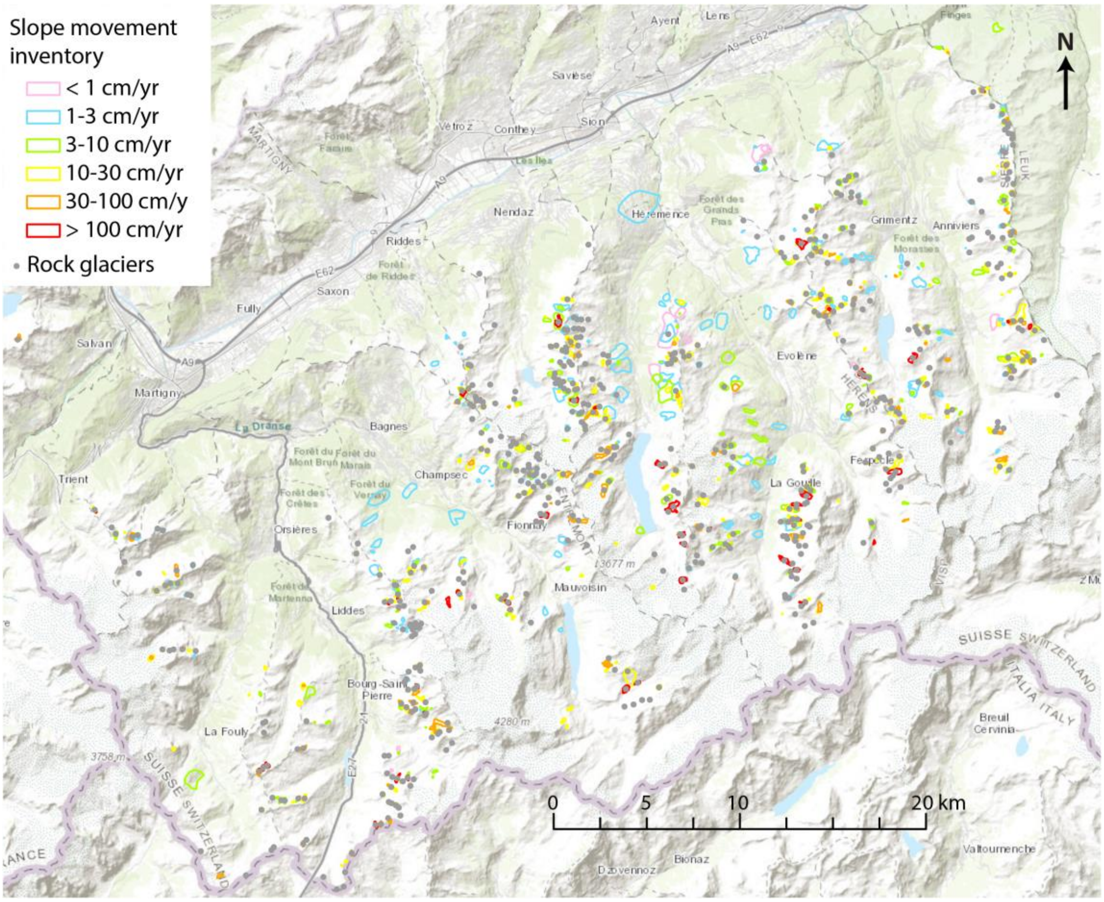

Figure 4*. Slope movement inventory (ESA GlobPermafrost) and identified rock glaciers in the Western Swiss Alps, Switzerland.*

In the Western Swiss Alps, the lower limit of discontinuous permafrost is estimated to be at an altitude of about 2400 m a.s.l. in north-facing slopes and 2700 m a.s.l. in southern exposures (Delaloye and Morand 1997; Lambiel and Reynard, 2003). The area encompasses about 800 active rock glaciers with typical velocities on the order of 0.1 to 2 m/yr. Among them, at least eleven rock glaciers have experienced over the last decades changes in their kinematics, geometry and/or topography (Delaloye et al., 2010b). These features, displaying exceptionally high velocities up to 10 m/yr and often showing distinct cracks as well as significant changes at their front, have been identified as destabilized. When located on steep slopes, they may be the source for gravitative movements such as rock falls or debris flows (Delaloye et al., 2010). Within the proposed study region, differential GNSS campaigns are systematically repeated twice per year, at the beginning and at the end of the summer season, for about fifteen active rock glaciers (Permos, 2019; Delaloye & Lambiel, 2017; Delaloye & Staub, 2016). In addition, permanent GNSS stations, allowing for the continuous measurement (hourly, daily, etc.) of the movement of a single point, are operated (Wirz et al., 2014; Permos 2016, Delaloye & Staub 2016). On the basis of these observations, results show that, although the creep velocities are measured at the different sites, a common general behaviour can be highlighted (see Fig. 5). Following the extraordinarily high horizontal velocities in 2003 and 2004, the creep velocities dropped until 2006 before increasing again until 2015. In 2015, new velocity records were reached at all sites. This new general velocity peak coincided with the absence of winter cooling due to an early development of the snow cover during the winter 2014/2015. Following the velocity peak, a general decrease of the surface velocity was observed in 2016 and 2017. The pronounced drop in velocity in 2017 can be linked to the observed general permafrost cooling caused by the extremely snow-poor winter 2016/2017 (Permos 2019). Moreover, seasonal variations are occurring on all monitored rock glaciers (See Fig. 6). The seasonal velocity pattern roughly resembles a sinusoidal curve and is characteristic for each rock glacier. An overall feature is a velocity minimum reached every year at the end of the winter (April-May), followed by an acceleration phase occurring during the snow melt season. Velocity maxima are reached on most rock glaciers every year in autumn or early winter (September-December), followed by a deceleration phase in the second half of the winter towards the velocity minimum at the end of the winter (Delaloye and Staub, 2016).

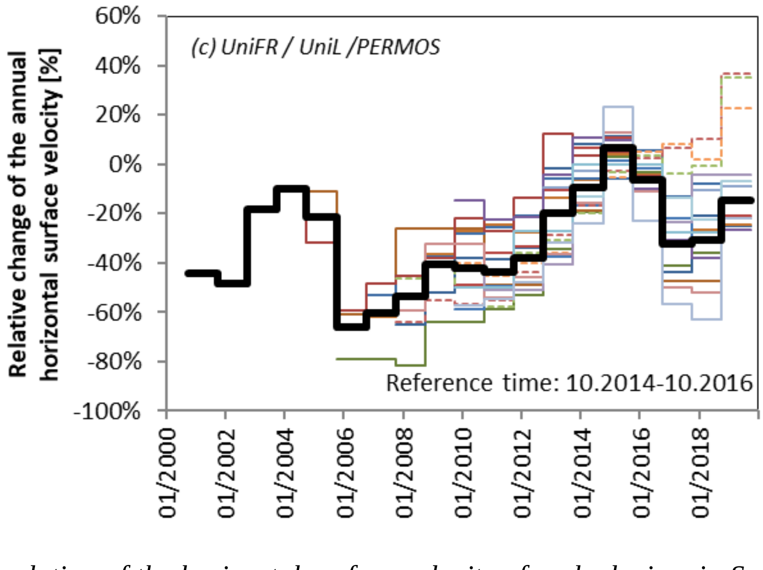

Figure 5. *Relative evolution of the horizontal surface velocity of rock glaciers in Swiss Alps based on annual terrestrial geodetic surveys. The bold line is the mean (n = 1 to 7 depending on the year).*

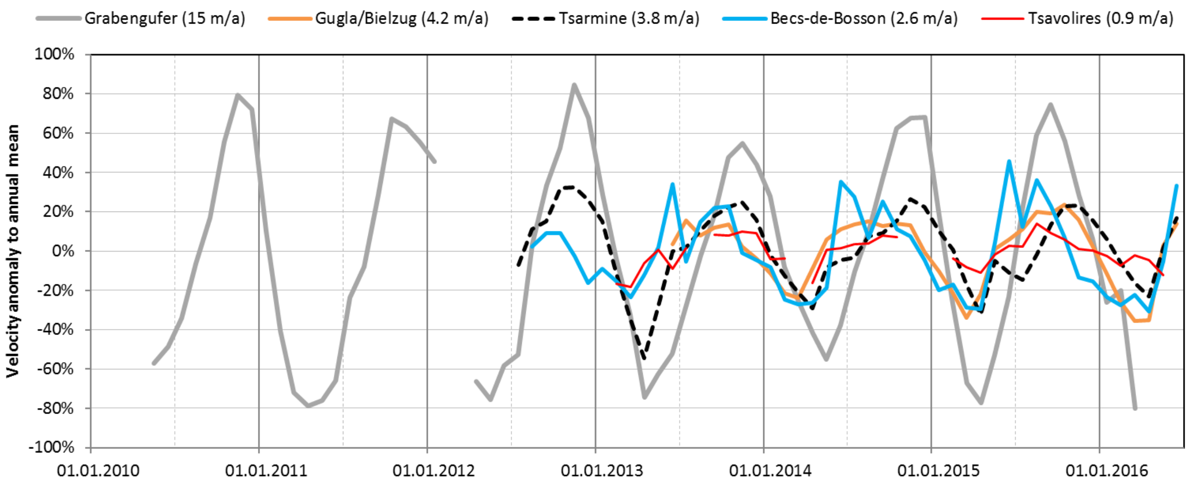

Figure 6. *Various types of year-round surface velocity anomalies observed at 4 rock glaciers in the Western Swiss Alps. Illustrated values are anomalies of the monthly velocity relative to the annual mean, which is given at the top of the figure.*

2.3.2 Italy, Sud Val Venosta, Sudtirol

The study area occupies the north-eastern portion of Ortles-Cevedale massif in South Tyrol, Central-Eastern Italian Alps (46°31' N, 10°50' E). It extends over about 970 km2 and includes the southern side of the lower Vinschgau (Val Venosta) as well as five tributary valleys: Ultental (Val d'Ultimo), Martelltal (Val Martello), Laasertal (Val di Lasa), and Suldental (Val di Solda). Elevation ranges from 3905 m of Mount Ortles, down to about 500 m at Ultental outlet. Bedrock geology is dominated by metamorphic lithologies (chiefly paragneiss, micaschists, and orthogneiss), with granite outcropping locally in lower Martelltal, and limestones and dolostones in upper Suldental. Climate is dry, with mean annual precipitation ranging from less than 600 mm in Vinschgau valley floor (Schlanders station) to more than 1200 mm in upland cirque valleys (Weissbrunn station). According to Permanet modelling (www.permanet.eu) and field-based evidences, discontinuous mountain permafrost roughly occurs above threshold elevations varying between 2300 and 2700 m asl, depending on topographic (e.g., aspect) and microclimatic (site specific) conditions (Boeckli et al., 2012). In this context, rock glaciers are dominant geomorphic features above the present treeline. According to an unpublished regional inventory completed in September 2019, the study area hosts 781 rock glaciers, including 166 classified morphologically active, 152 inactive and 463 relict (see Fig. 7).

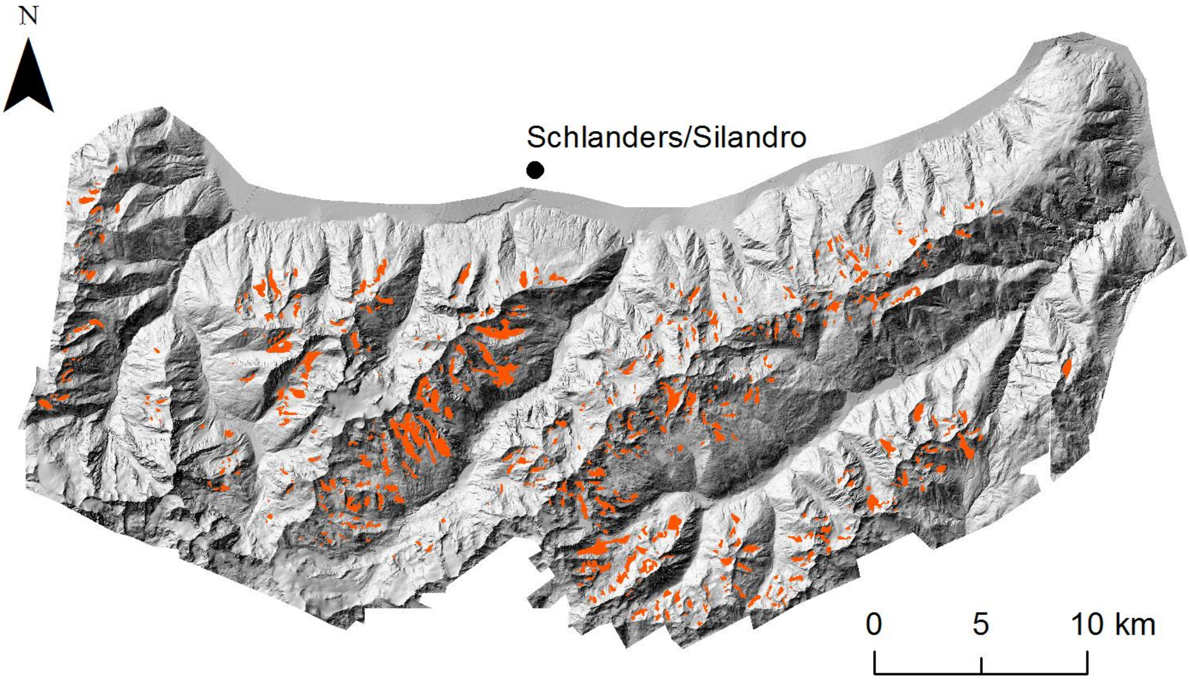

Figure 7. *Regional rock glacier inventory of the Sud Val Venosta, Sudtirol, Italy.*

2.3.3 France, Vanoise massif

The Vanoise massif is a mountain chain located between N 45.6° and N 45.2° in the French Alps, covering approximately 2000 km², and reaching 3855 m asl at its highest point (la Grande Casse). Though it has no strictly delimited boundaries, the massif is often confounded with the territory of the 'Parc national de la Vanoise' and it mostly includes the highest parts of the Arc and Isère watersheds. The mean elevation of the massif is 2325 m asl, and about 60 % of the terrain are above 2500 m asl, and about 4 % are covered by glaciers (Gardent et al., 2015).

Because of its topographical and climatic settings, permafrost is largely present (Marcer et al., 2017) in the region, as testified by abundant rock glaciers (n = 518, 38 km², fig. 8). These landforms are mostly located in valleys above 2400 m asl (Monnier, 2004), and more than half of them (n = 357) most probably contain ice (Marcer et al., 2017). Among the actively creeping rock glaciers of the Vanoise massif, 24 landforms presently show evidences of destabilization, such as extensional cracks, crevasses and scarps (Marcer et al., 2019).

Thanks to multi-temporal orthophotographs analysis (Marcer et al., 2019), it is possible to evaluate the evolution of the Vanoise rock glaciers surface velocity: between the first available measurement period (1950 – 2000) and the next one (2000 – 2010), an increase of 157 % was observed, whereas the speed-up is only 38 % between 2000 – 2010 and 2010 – 2015. The mean/maximal velocities shifted, respectively, from 0.3/1.5 m/yr to 0.9/7.3 m/yr between the first and the last period, depicting a significative acceleration of rock glaciers, similar to what is observed in other regions of the Alps (Kellerer et al., 2018).

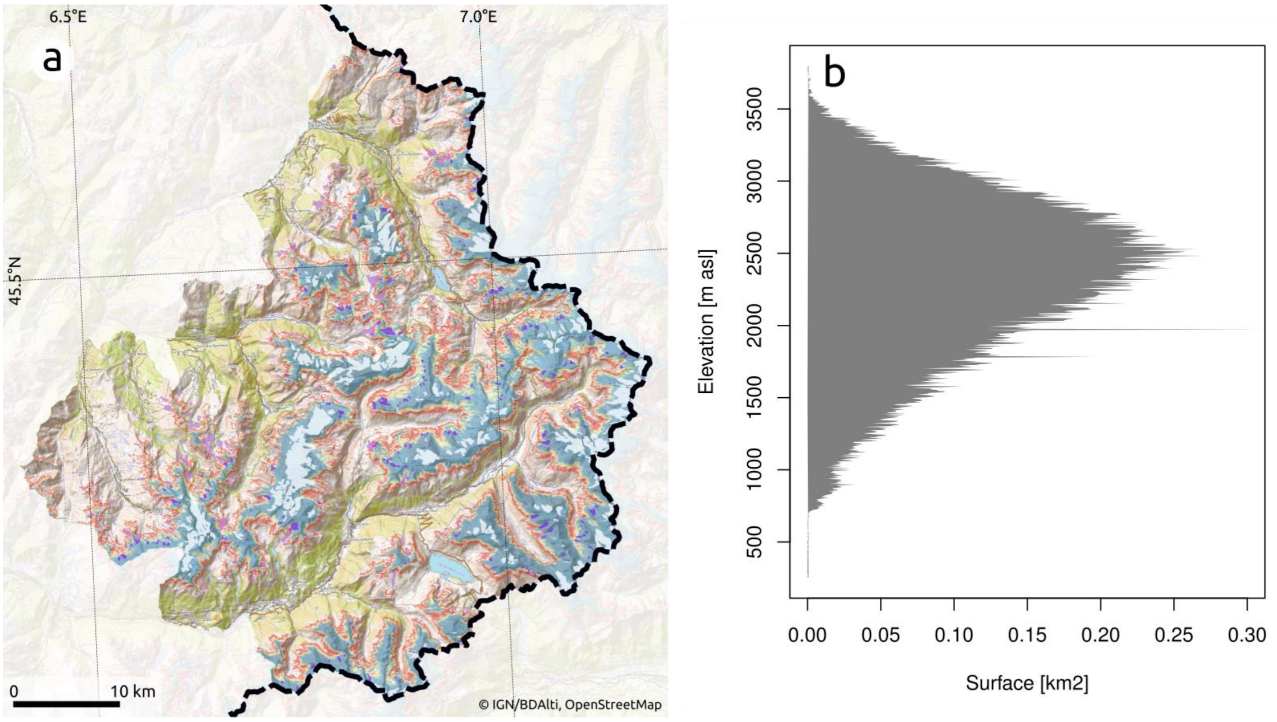

***Figure 8**: Geographical context (a) and hypsometry (b) of the Vanoise massif.*

2.4 European Subarctic/Arctic sites (CCN2)

2.4.1 Norway and Svalbard

CCN2 Permafrost_cci research in Norway considers the continuous, discontinuous and sporadic permafrost zones in Northern Norway and Svalbard. Observations and models show that this subartic-arctic region is highly affected by climate change (NCCS, 2017; NCCS; 2019). The three selected areas of interest (AOIs, see Fig. 9) are in Troms County and Finnmark County in Northern Norway and Nordenskiöld Land in Svalbard. AOI1 in Troms County covers Kåfjord, Lyngen and Storfjord municipalities and the south-eastern part of Tromsø municipality and corresponds to a total area of approx. 4’400 km^2 (see Fig. 10). AOI2 in Finnmark County covers parts of Gamvik, Berlevåg and Tana municipalities and corresponds to a total area of approx. 2’600 km^2 (see Fig. 10). AOI3 in Nordenskiöld Land covers the land area in central Svalbard between Isfjorden and Van Mijenfjorden and corresponds to a total area of approx. 4’100 km^2 (see Fig. 11). These AOIs have been selected to encompass a wide range of climatic, topographical, geological and periglacial contexts.

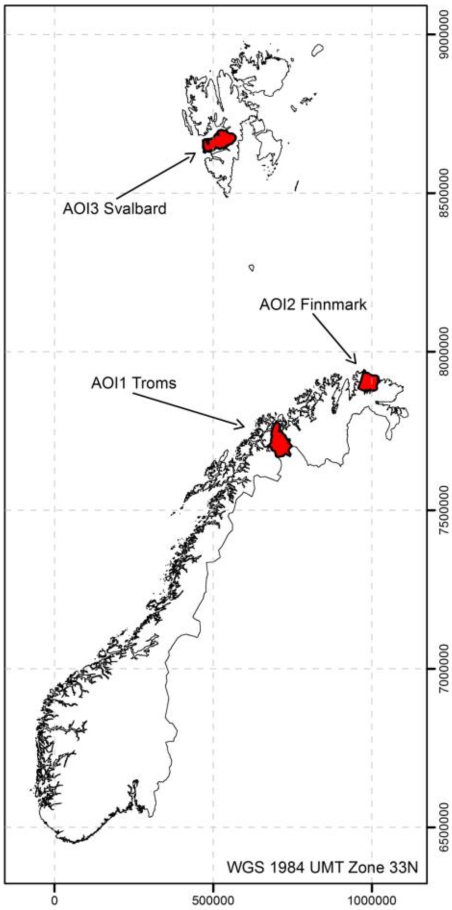

Figure 9*: Location of the areas of interest for CCN2 in Northern Norway and Svalbard.*

In Northern Norway, rock glacier inventories exist (Lilleøren & Etzelmüller, 2011; Sollid & Sørbel, 1992) and ground temperature has been measured at several locations (Blikra & Christiansen, 2014; Christiansen et al., 2010; Farbrot et al., 2013; Isaksen et al., 2007). High resolution SAR data from TerraSAR-X and Radarsat-2 have been acquired by NORCE since 2009. Previous studies have applied InSAR for measuring ground displacements (Lauknes et al., 2010; Eckerstorfer et al., 2018, Eriksen et al., 2017) and Sentinel-1 InSAR is now publicly available through the InSAR Norway mapping service (insar.ngu.no). A recent study of the Ádjet rock glacier in Troms county show acceleration in a context of climate change (in AOI 1, Eriksen et al., 2018). Many sites are investigated by the Geological Survey of Norway (NGU) and monitored by the Norwegian Water Resources and Energy Directorate (NVE) due to geohazards, providing valuable in-situ datasets for validation and comparison. Several rock glaciers are studied by UiO (e.g. Ivarsfjord/Hopsfjorden).

In Svalbard, intensive permafrost research is performed by UNIS. Monitoring of the permafrost ECV (temperature, active layer thickness) is performed at several landforms in Nordenskiöld Land (AOI 3). Long data series are available e.g. in Adventdalen, Longyeardalen, Endalen and Kapp Linné and contribute to study the variability of periglacial conditions in the Nordic area (Christiansen et al., 2010; Sollid & Sørbel, 1992) and the impact of meteorological variability on periglacial landforms (Christiansen et al., 2013). Several rock glaciers have been studied (Berthling et al., 1998; Berthling et al., 2000; Isaksen et al., 2000). In-situ monitoring of ground displacements is performed e.g. in the Huset rock glacier and in the Endalen and Kapp Line solifluction sheet stations and can valuably be used for validation and comparison. High resolution SAR data from TerraSAR-X and Radarsat-2 have been acquired by NORCE since 2009, and InSAR in relation with permafrost studies has already been performed around Adventdalen using Sentinel-1 (Rouyet et al., 2019).

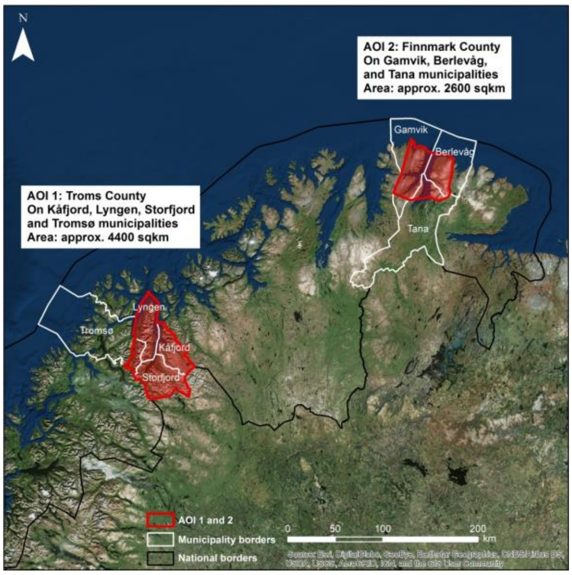

Figure 10: *Location of the areas of interest in Northern Norway.*

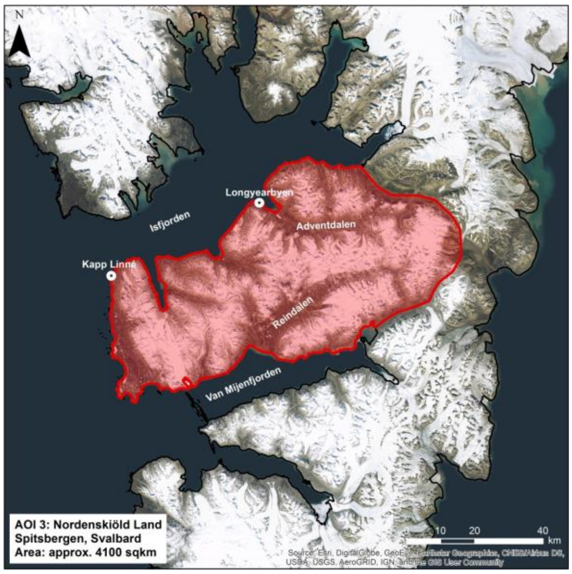

Figure 11: *Location of the area of interest on Svalbard.*

2.5 Extra-European sites (CCN2)

2.5.1 Greenland, Disko Island

Disko Island is located off the central West Coast of Greenland at approximately 53°W 70°N. It is the largest island in Greenland covering approx. 8575 km2 and has a high relief landscape with steep slopes rising up to 900-1200 m a.s.l. and large glaciers covering up to 20% of the total land area (Yde and Knudsen, 2007). The island is located in the zone of continuous permafrost, and rock glaciers are common on the island both inland and especially along its eastern shores as well as on the mainland shores in Disko Bugt (Disko Bay). Rock glaciers in typically occur in three forms: lobate (width-to-length ratio ≥1), tongue-shaped (width-to-length ratio <1) or spatulate (also termed piedmont type, these are tongue-shaped with a broadened terminus); depending on topography, several rock glaciers can merge or separate (Humlum, 1982; Martin and Whalley, 1987). The activity of rock glaciers cannot be determined easily using field observations or photographs only as rock glaciers may be composed of several superimposed rock glaciers of different generations and activity levels and thus render a complex topography. Remote sensing techniques are thus key to better understand rock glacier kinematics and permafrost development.

Rock glaciers on Disko Island strongly vary in length and thickness. Lobate rock glaciers are typically talus-derived and ice-cemented and collectively estimated as 30-300 m long and 10-30 m thick, with a general surface slope of only 5-25° while the frontal lobe slope may be inclined up to 35-50° (Humlum, 1982; Humlum, 1996). Furrows and ridges may form a relief up to 5 m on large rock glaciers and less than 2 m on smaller ones. According to Humlum (1982), lobate rock glaciers are predominant on north-facing valley wall slopes and are rare on south-facing slopes. Tongue-shaped rock glaciers reach greater lengths of 500-6000 m with a thickness of 20-75 m. Frontal slopes are similarly inclined as lobate rock glaciers. A main difference is the presence of glaciers at the upper end of the majority of tongue-shaped rock glaciers, suggesting a glacial origin and ice-cored interior (Humlum, 1982). These generally form in steeper terrain and below cirque headwalls. Ridge and furrow topography is equally observed, however, appears to occur mainly towards the downstream end of rock glaciers. Spatulate rock glaciers are less frequent on Disko Island. They are largely tongue-shaped rock glaciers, but with a much broader, spatulate-like front, which forms when the rock glacier flows onto a less constrained so-called 'trunk' valley and spreads laterally (Humlum, 1982; Martin and Whalley, 1987). This may often result in the formation of two distinct lobes or tongues.

2.5.2 Tien Shan

The mountain ranges Ile Alatau (former names Zailijskij or Transili Alatau) and Kungöj Ala-Too (Kungej Alatau, 42°30' to 43°30'N, 75° to 79°E) of the northern Tien Shan are located at the border between Kazakhstan and Kyrgyzstan, and rise to nearly 5000 m asl (see Fig. 12).

The ranges originated from the Caledonian orogenesis but are still affected by compression and are slightly uplifting. Predominantly WSW-ENE-striking faults are characteristic (Chedija, 1986). Several major earthquakes have occurred and thousands of smaller seismic events have been recorded since the end of the 19th century (Yadav and Kulieshhius, 1992; Lukk et al., 1995; Delevaux et al., 2001). The mountains are formed mainly of granites of Devonian, Silurian and Carboniferous age. Cambrian gneisses occur in the Kungöj Ala-Too.

Because of the topography, the continental climate is locally variable. At altitudes of about 3000 m asl, precipitation can exceed 1000 mm/yr on windward northern slopes or be less than 800 mm/yr in a leeward valley south of the main mountain ridges. Precipitation minima occur in all areas in winter. Mean annual air temperature (MAAT) at the Tuyuksu glacier station (3434 m asl), located slightly lower than the glacier terminus, was -3.7 °C for the period 1972–2000. Hence, the glaciers in the study area are probably polythermal and permafrost is very likely to occur in the surroundings, even for the lowermost parts of most glacier tongues. The northern Tien Shan has a pronounced periglacial zone that is characterised by frequent diurnal freeze-thaw cycles (Marchenko, 2003a; Marchenko et al., 2007). Existing investigations indicate that permafrost is extremely rare below 2700 m asl, likely above 3200 m asl and very likely above 3500 m asl (Gorbunov et al., 1996). The thickness of the permafrost varies between 10 and 80 m (Marchenko, 2003b). Geothermal observations indicate warming of the permafrost by 0.3–0.6 °C from 1974 to 2004, while the lower boundary of permafrost has shifted upward about 150–200 m since the beginning of the 20th century and the area of permafrost decreased by ~18 per cent (Marchenko et al., 2007).

Many active rock glaciers occur in Ile and Kungöj Alatau. Based on aerial photography and field investigations, 429 active and 75 inactive rock glaciers in Ile and 422 active and 108 inactive rock glaciers in Kungöj Ala-Too were identified, which cover a total area of 90.3 km2 (Gorbunov et al., 1998). Active rock glaciers were classified into two main types: moraine (n= 321) and talus (n = 530). Whereas the latter are more numerous, the former cover a larger area (54.8 to 35.5 km2, respectively; Gorbunov and Titkov, 1989). The majority of the rock glaciers are located in the elevation range of 3000 to 3800 m asl, with an average elevation of ~3400 m asl (Gorbunov and Titkov, 1989). The lowest elevation of an active rock glacier front is about 2500 m asl, which is even below the treeline (Gorbunov, 1983). Several rock glaciers have areas of more than 1 km2 and the largest covers more than 2 km2. Some of the most impressive rock glaciers are the active moraine-type rock glaciers Gorodetzkij and Morrenij in the Ulken Alamty (Bolshaja Almatinka) valley (see Fig. 13). These rock glaciers have an average slope of 15–20° and a steep front of 40–45°. They are up to 1.3 km long, up to 1 km wide and have a thickness at the front of 20–50 m (Glazovskiy, 1978; Gorbunov and Titkov, 1989).

Measured annual displacement rates of the rock glacier surfaces range from less than 1 m to about 11 m (Gorbunov and Titkov, 1989; Gorbunov et al., 1992). The average surface velocity rates of the rock glaciers in northern Tien Shan are higher in comparison to the majority of the rock glaciers in the Alps (Kääb et al., 1997; Roer et al., 2005) or the Rocky Mountains (Janke, 2005), where the rates are usually some decimetres per year. However, there are also some fast-moving rock glaciers situated on steep slopes in the Alps (Roer et al., 2008; Delaloye et al., 2013).

Figure 12: *Location map of the study area. The detailed study area is indicated by the black rectangle.*

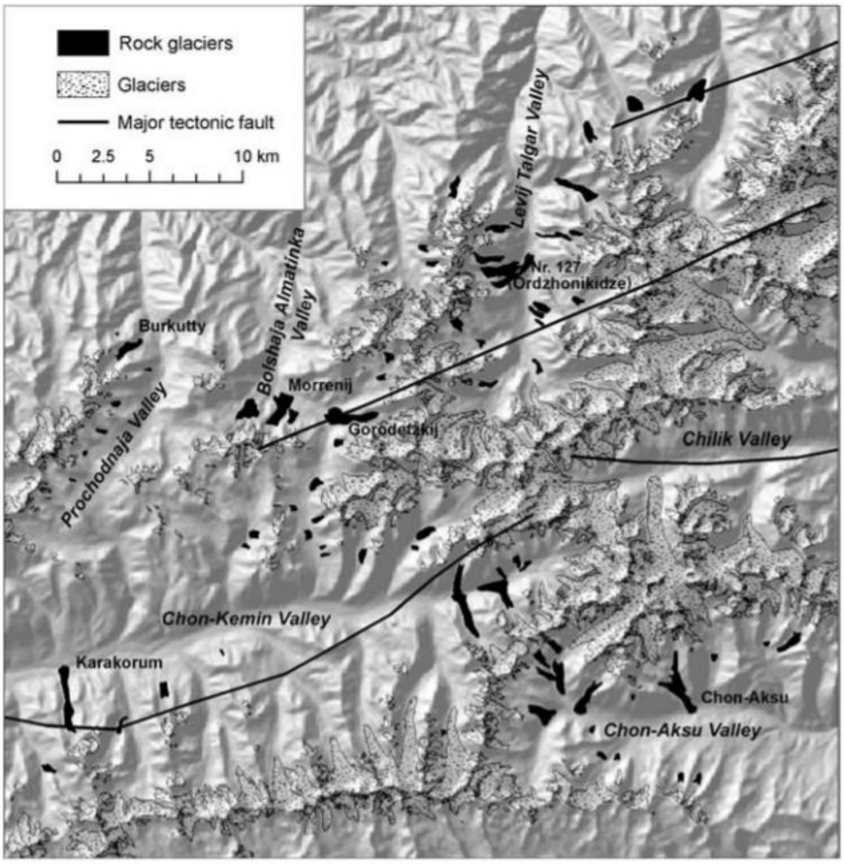

Figure 13*: Map of the investigated rock glaciers. Glacier extents are based on the Landsat scene from 1999 (Bolch, 2007). The tectonic faults are based on the Geological Map of the Kazakh SSR, scale 1:500 000.*

2.5.3. Alaska, Brookes Range

The Brooks Range of Alaska, centred at approximately 150°W 68°N, stretches approximately 1,000 km west to east into Yukon Territory, Canada, and ranges up to 300 km north to south. It is the northernmost extent of the North American Rocky Mountain system. The central and eastern Brooks Range consist of east-trending ridges that reach elevations up to 2,400 m (Warhaftig 1965). The climate ranges from sub-arctic on the south side to arctic on the north side of the range, characterized by exceptionally cold winters, warm to cool summers, low precipitation, and high winds (NPS 2018). All of the Brooks Range is in the continuous permafrost zone (Jorgenson et al. 2008), with measured permafrost depths ranging from 240 to 356 m. Treeline occurs on the south side of the Brooks Range (Viereck 1979), just south of the Continental Divide, which runs east-west through the Brooks Range.

Rock glaciers in the Brooks Range have received little attention, with previous mapping only by a handful of individuals, including Ellis and Calkin (1979), Ellis et al. (1984), Calkin et al. (1987), and Ikeda and Yoshikawa (2008). All of the rock glaciers are located between altitudes of 900 and 2,000 m (Ellis et al. 1984). Ellis and Calkin (1979) determined that the vast majority of the rock glaciers they mapped occur north of the Continental Divide, and can be divided into tongue-shaped and lobate rock glaciers. The tongue-shaped rock glaciers are typically supraglacial, whereas the lobate rock glaciers form below taluses and valley walls (Ellis and Calkin 1979). As of 1979, nearly all of the exposed glacier ice was north of the Continental Divide, correlating with the outcropping of the tougher, blocky-fracturing conglomerate and sandstone that also make up the tongue-shaped rock glaciers (Ellis and Calkin 1979). In general, the rock glaciers form below “resistant ridges of massive to thick-bedded sedimentary rocks interbedded with and underlain by thin-bedded politic rocks” (Calkin et al. 1987). Lichenometry and association with glacial moraines indicates that the rock glaciers in the Brooks Range formed after the Pleistocene, stabilizing during the early Holocene (Ellis et al. 1984). Ikeda and Yoshikawa (2009) investigated the internal composition of a few rock glaciers using DC resistivity, the results of which indicated that the ice content was relatively small, and varied little between the studied rock glaciers. Very few measurements of movement rates have been made on the Brooks Range rock glaciers. Rates measured on the central lobes of two rock glaciers in the early 1980s indicate rates of 0.4 and 0.1 m/yr (Calkin et al. 1987).

Other elongated, lobate features south of the Continental Divide were first identified by those mapping geologic hazards during the construction of the Trans Alaska Pipeline System and the Dalton Highway (Hamilton 1978, 1979, 1981; Krieg and Reger 1982; Brown and Krieg 1983). Termed frozen debris lobes (FDLs), these features consist of soil, rock, organic debris, and areas of infiltration ice. Research of these features began in earnest in 2008 with preliminary investigations of four FDLs (Daanen et al. 2012), followed by a subsurface investigation of FDL-A in 2012 (Simpson et al. 2016). In 2013, the research area was expanded to include a total of eight studied FDLs, and included drilling, sampling, and installing instrumentation within FDL-A; sampling soils and rocks to determine geotechnical properties; refining geologic maps of the catchment bedrock; analysing historic imagery to determine long-term movement rates; measuring subsurface ground temperature and displacement; measuring surface movement using a real-time kinetic global positioning system (RTK-GPS) unit; and performing remote sensing analysis using Light Detection and Ranging (LiDAR), Unmanned Aerial System (UAS), and Interferometric Synthetic Aperture Radar (InSAR) data (Darrow et al. 2016, 2017; Simpson et al. 2016; Gyswyt et al. 2017; Gong et al. 2019). The eight investigated FDLs range in elevation between 530 and 970 m. Mapping using freely-available high-resolution imagery indicates nearly 160 FDLs throughout the Brooks Range (Darrow et al. 2016); it must be noted, however, that this number may increase with additional available imagery. Annual movement rates from 2019 of the eight investigated FDLs range from 1.0 to 25.0 m/yr and have been increasing over the period of historic records (i.e., since 1955).

2.5.4 Argentina, Central Andes

The selected area is situated in the Central Andes of Mendoza, Argentina. The region corresponds to the most southern part of the Dry Andes, where there are extensive areas with permafrost conditions. Most of the selected area is represented by the Cordón del Plata mountain range, Cordillera Frontal, where the maximum height surpasses 6000 m, and the minimum altitude is 2000 m approximately. Furthermore, over this region it is possible to find permafrost occurrence from ~3600 m on upwards (Trombotto Liaudat, 2000; Ruiz and Trombotto Liaudat, 2012).

Cordón del Plata has the most extended active layer monitoring record in the area (continuously since 1999). One of the most studied rock glaciers of the Southern Andes, Morenas Coloradas rock glacier, is located there and some unique surface velocity measurements have been performed (Trombotto and Borzotta, 2009; Trombotto, 2014; Bodin and others, 2015; Trombotto-Liaudat and Bottegal, 2019).

Inside the study area, there is a real-time automatic weather station of the IANIGLA Network (http://estaciones.ianigla.mendoza-conicet.gob.ar/). The AWS called Morenas Coloradas (3400 m) is located at the front of the well-known rock glacier, and it has been operating since February of 2018. This network is complemented by seven other AWS, some of which, like Toscas or Horcanes, have been operating for almost 20 years. Previous and discontinuous weather data indicate that, in this region, the mean annual air temperature at 2500 m asl is around 6-7°C stations and total annual precipitation is around 400-500 mm.

The total area selected here (2900 km2) is one of the regions of the Central Andes, where more rock glaciers and debris-covered/rock glacier composites or transitional landforms are located. Almost 25% of the debris-covered and rock glaciers identified in the National Glacier Inventory of Argentina (IANIGLA and MAyDS, 2018) are located inside the selected area and due to the topography of Cordon the Plata, glaciers, rock-glaciers and transitional landforms area oriented to the East or West.

2.2.5 New Zealand, Central part of the Southern Alps

The Southern Alps of New Zealand is an elongated mountain range, ∼800 km long and 80 km wide, crossing almost all the South Island of New Zealand from north-east to south-west. The altitudes range between ~500 m a.s.l. and 3,724 m a.s.l. (Mount Cook). Many summits located along the central ridge, called the Main Divide, are higher than 2,500 m a.s.l., and 16 of them exceed 3,000 m a.s.l. The climate of the Southern Alps is temperate, with a strong maritime influence (Sturman and Wanner, 2001). Most of the atmospheric perturbations come from the West perpendicularly to the Southern Alps. This provokes a strong precipitation gradient across the mountain range, with annual rainfalls ranging from 3,000 mm on the West Coast, 14,000 mm at Mount Cook, to less than 1,000 mm further east (Henderson and Thompson, 1999). This has a strong influence of the altitude of the equilibrium line of glaciers, which is around 1,600 m a.s.l. on the West Coast and up to 2,200 m a.s.l. in the eastern catchments.

Sattler et al. (2016) identified 75 active and 88 inactive rock glaciers, as well as 220 relict landforms, based on aerial photograph analyses. All are located at the East side of the Main Divide, were glaciers are more reduced. From this, they assessed the permafrost lower limit at around 1,850 m a.s.l. in south-exposed slopes. Besides, only little attention has been paid to the dynamics and evolution of rock glaciers in the Southern Alps (e.g Brazier et al. 1998; Winkler & Lambiel 2018). Therefore, their rate of activity remains largely unknown.

The CCI – New Zealand study area is situated in the central part of the Southern Alps, between roughly 42°50’ S, 171°50’ E and 44°20’ S, 169°15’ E. This area comprises the highest elevations of the Southern Alps, and contains must of the rock glaciers of Sattler et al. (2016) inventory. The rock glaciers are mainly concentrated, from south-west to north-east in the Barrier Range, the Ben Ohau Range, the Liebig Range, the Two Thumb Range, as well as in the Lake Heron and Arthur’s pass regions.

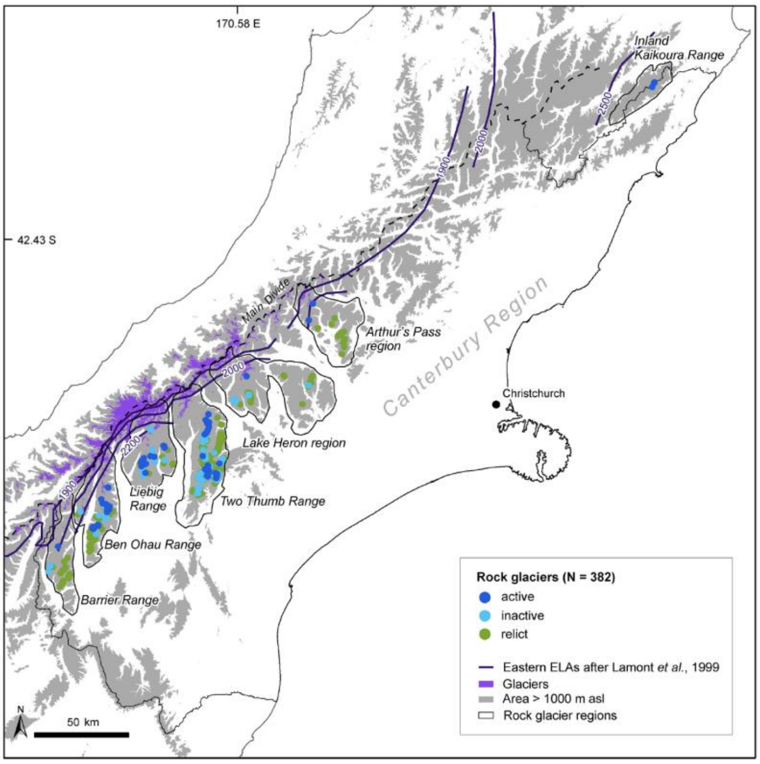

Figure 14. *Rock glacier inventory in the Southern Alps of New Zealand (Sattler et al. 2016)*

3 Products specifications and formats

3.1 Regional rock glacier inventories

Rock glaciers are the best visual expression of creeping mountain permafrost and constitute an essential geomorphological heritage of the mountain periglacial landscape. Their dynamics is largely depending on climatic factors and may locally interact with human activities (e.g. debris flow initiated from a rock glacier snout). Observing changes in rock glacier kinematics provides information about the climatic impact on mountain permafrost and has the potential to become a key parameter of the cryosphere monitoring in mountain regions.

Initiatives have risen for decades in many cold mountain regions for inventorying rock glaciers as a proxy for permafrost occurrence, but also for instance in the perspective of ice (water) storage estimation, geohazards management as well as climate reconstruction. However, these efforts often rely on different methodologies based on the unequal availability of source datasets and on variable local skills and institutional support. In a context where open access to high-quality remotely sensed data is constantly increasing, there is a need for the scientific community to promote international cooperation and develop standard guidelines.

The International Permafrost Association (IPA) Action Group on *Rock glacier inventories and kinematics* has been launched in 2018. At the time of writing this report (Nov. 2019), the Action Group is gathering 104 researchers supporting the idea of organizing and managing a network (open-access database) dedicated to rock glacier mapping (inventorying) and monitoring (kinematics) in all relevant mountain regions on Earth including the definition of the necessary standards. The Action Group activities are divided into three main tasks: 1) definition of widely accepted standard guidelines for inventorying (mapping) rock glaciers in mountain permafrost regions, including indications of kinematics; 2) preparation of products which could serve in the long run for monitoring rock glacier kinematics as a future associated parameter of the GCOS-defined ECV (Essential Climate Variable) Permafrost; 3) development of an operational database / web platform.

The task 1 (which is one of our concern) is currently running and basic concepts for inventorying rock glacier are under final review.

Two main approaches have been identified as commonly used for inventorying rock glaciers:

- Geomorphological approach: rock glacier landforms are mapped by 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 for the production of exhaustive inventories of moving and non-moving landforms, whose discrimination (activity classes) is primarily based on morphological characteristics. LIDAR-DEM surveys, upon availability, are facilitating the identification of (relict) rock glaciers in forested areas.
- Kinematical approach (more recent): Slope movements are detected and identified using remotely sensed derived products (e.g. SAR-derived products, multi-temporal airborne LIDAR, high resolution optical satellite and aerial images). The typology assessment and especially rock glacier discrimination is mainly performed by the identification of rock glacier features on optical images for each detected slope movement. If there are no existing rock

glacier inventories derived from a previous geomorphological approach, the present process may lead to some gaps in the resulting inventory due to undetected landforms (in areas that are not moving or not imaged for instance). However, the main advantages of this kinematical approach are to provide quantified data for the motion rate and an overview of slope processes in an area, both permafrost-related and not (Barboux et al., 2014).

While these two approaches yield different inventory types, both are complementary and practical inventorying guidelines, currently defined by the IPA Action Group, make them as far as possible compatible.

Based on these (futures) guidelines, regional standardized rock glacier inventories will, within the present project, be provided over different climatic regions of the globe (CCN1 & CCN2).

3.1.1 Product description

The product proposed here will be standardized for all selected sites. It needs to fit user requirements as presented in the URD and to be technology independent. The following specific product description is proposed as a basic requirement (the minimum required that will lead to efficient homogeneous inventories). Specific guidelines and algorithms to produce homogeneous remote sensing-based regional rock glacier inventories using InSAR data will be developed through close collaboration with the international IPA Action Group and will be documented in the Deliverables from Task 2 of CCN2 (Algorithm Theoretical Basis Document ATBD). Moreover, additional/optional information derived for specified sites due to further examination will be included to the respective final deliverables.

A geomorphological rock glacier inventory including kinematics will be proposed for the Southern Carpathians (CCN1). The existing rock glacier inventory contains 306 landforms (Onaca et al., 2017a) and will be updated using kinematics data derived from InSAR regarding activity status for the selected sites.

Kinematical rock glacier inventories will be derived for the European Alps, European Subarctic/Arctic and Extra-European sites (CCN2). Slope movements will be first detected on InSAR data. Rock glaciers will then be discriminated among them using the technical definition proposed by the IPA Action Group based on aerial imagery/high resolution satellite imagery [RD-4] or/and by comparing InSAR results with existing geomorphological rock glacier inventories. Finally, rock glaciers and their related moving area(s) will be spatially identified and characterized.

The performance of the methodology for the kinematical rock glacier inventory will be assessed in a “round-robin” exercise during a workshop in February 2020 where discrepancies between different producers will be evaluated and documented in the Product Validation and Algorithm Selection Report (PVASR). Guidelines will be refined accordingly. Automated approaches to detect and measure slope movements and update inventories will be proposed as far as possible.

3.1.2 Spatial resolution

The applied threshold for the minimum size of inventoried rock glacier is around 0.01 km^2. Rock glaciers will at least be identified by a point feature located within the landform perimeter.

Moving areas related to the inventoried rock glaciers will be outlined based on Sentinel-1 InSAR (20-60 m final resolution). Complementary higher resolution TerraSAR-X (3-10m final resolution) and/or optical aerial/satellite photogrammetry (1-10m final resolution, depending on image resolution) will also be used when available over the AOI.

Additional rock glacier outlines for the Carpathians sites and European subarctic/arctic sites:

Rock glaciers will be delineated based on existing inventories and complementary interpretation based on aerial/satellite imagery (0.2-0.5 m resolution) and digital elevation models (2-20 m resolution depending on the AOI).

3.1.3 Product accuracy

Regional rock glacier inventories will be exhaustive at least for the moving rock glaciers imaged by the Sentinel-1 InSAR data (undetected rock glaciers in areas that are not moving or not imaged). Minimum detectable displacement rates from Sentinel-1 InSAR are in the order of 1/10 of a wavelength (i.e. around 5-6 mm). For time intervals of 6-48 days this translates to minimum detectable rates of around 34-4 cm/yr, respectively. Slower displacements can be detected using annual or bi-annual temporal baseline. Maximum detectable displacement is limited by phase coherence loss due to high deformation and are on the order of 1/2 wavelength (i.e around 2.8 cm), i.e. 170-20 cm/yr for time intervals of 6-48 days, respectively. For a specific time interval, a movement higher than the maximal value of deformation rate will be decorrelated on the interferogram, that means it can be detected but not quantified (Barboux et al. 2014).

3.1.4 Product attributes

For each rock glacier in the study sites the following attributes will be recorded:

- ID,
- geographic location,
- morphological type (simple or complex unit),
- spatial connection to the upslope unit (talus, debris mantle, landslide, glacier, glacier forefield, poly, undefined),
- activity (active, transitional, relict, undefined),
- destabilization signs visible (yes, no, undefined).
- velocity class (m/yr)

Each rock glacier will be linked to moving area(s) whose following attributes will be recorded

- Reference rock glacier ID,
- InSAR velocity class (m/yr).

Additional attributes for Carpathians sites:

Slope aspect (°N), mean slope (°), minimum elevation (m), maximum elevation (m), mean elevation (m), area (km^2), length (m), width (m), contributing area (ha), bedrock lithology, degree of vegetation (%) will be indicated for each inventoried rock glacier.

Note: A standard to define the associate kinematics attribute that can be derived at global scale will be discussed during the next workshop of the IPA Action Group (February 2020). The defined standards will be used for the delivered rock glacier inventories.

3.1.5 Data documentation and dissemination

Data and documentation will be available on the ESA CCI webpage.

3.1.6 Product projection system

The Coordinate Reference System (CRS) used for the global permafrost products will be UTM based on the World Geodetic System 84 (WGS84) reference ellipsoid. The coordinates are specified in meters.

3.1.7 Metadata

Metadata should indicate the data used for deriving the regional rock glacier inventory (type, date, processing) as well as the chosen approach (kinematical, geomorphological, both). The producer and the date of production should be indicated.

3.1.8 File formats

All datasets will be provided in shapefile and raster format.

3.1.9 Product file naming conventions

ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc

<CCI Project>
PERMAFROST for Permafrost_cci

<Processing Level>
L3 for Level 3; Level 2 variables mapped on a defined grid with reduced requirements for ancillary data.

<Product String>
RGI, when the parameter is 'presence of a rock glacier' as part of the rock glacier inventory.

<Additional Segregator>
This should be AREA_<TILE_NUMBER> being the tile number the subset index: 5-Romania 6-Switzerland, Western Swiss Alps; 7-Norway, Troms; 8- Norway, Finnmark; 9-Svalbard, Nordenskiöld; 10-France, Vanoise; 11-Italy, Sud Val Venosta, Sudtirol; 12-Greenland, Disko Island; 13-Tien Shan; 14-Alaska, Brookes Range; 15-Argentina, Central Andes, 16-New Zealand, Central part of the Southern Alps

<Indicative Date>
The identifying date for this data set:
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. For monthly products DD=01. Annual averages are represented with year only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (That is 1 or more digits followed by optional . and another 1 or more digits). The most recent version is fv1.0 (released in May 2019).

<Layer>
In case that the individual layers of the vector/raster product are provided as different NetCDF files, the code of each layer will be detailed as follows:

- RG: layer 1, corresponding to the rock glacier inventories
- MA: layer 2, corresponding to the associated moving areas
- GO: layer 3, corresponding to the optional geomorphological outline of rock glaciers

Example:
ESACCI-PERMAFROST-L3-SENTINEL1-RGI-AREA6_RG-2003-fv01.0.shp

3.2 Kinematical times series on selected rock glaciers

The kinematics of active rock glaciers closely depends on the temperature profile between the surface and the main shearing horizon at depth: the closer to 0°C it is, the faster the rock glacier is moving in general. In the whole arc of the European Alps for instance, rapid and slow active rock glaciers have shown mostly a similar kind of annual velocity variations since 2000. Interannual variations of rock glacier dynamics appear so far—with probably a few exceptions—to be primarily related to external climatic factors rather than to the internal characteristics of the rock glaciers (Delaloye et al. 2008). They are mostly well related to variations in mean ground surface temperature over ~2.5 years with a time lag of 2-6 months reflecting the delay in propagation of corresponding anomalies deeper into permafrost. The relationship between relative variations of annual rock glacier velocities and anomalies in ground thermal state (proxy of the ground thermal evolution of permafrost) has been tested and clearly indicated that, within a decade, temperature changes at 10–30 m depth explain the largest part of inter-annual velocity variations (Staub et al. 2016, fig. 15). Seasonal factors may also play an important role. A lower intensity of winter ground freezing and/or a larger amount of winter (October–May) snowfall facilitate a higher rate of annual rock glaciers surface motion (PERMOS 2019). Finally, recent studies have observed that rock glaciers develop a landform-specific but repetitive intra-annual behavior displaying a ratio between minimal and maximal velocities ranging from close to 1:1 to 1:10 and have a concomitant regional behavior at the (pluri-)annual to (pluri-)decennial time scale (Delaloye & Staub 2016). Nevertheless, some rock glaciers may accelerate or decelerate abnormally. Therefore, it is important to use a relatively large set of rock glaciers for performing a regional trend analysis.

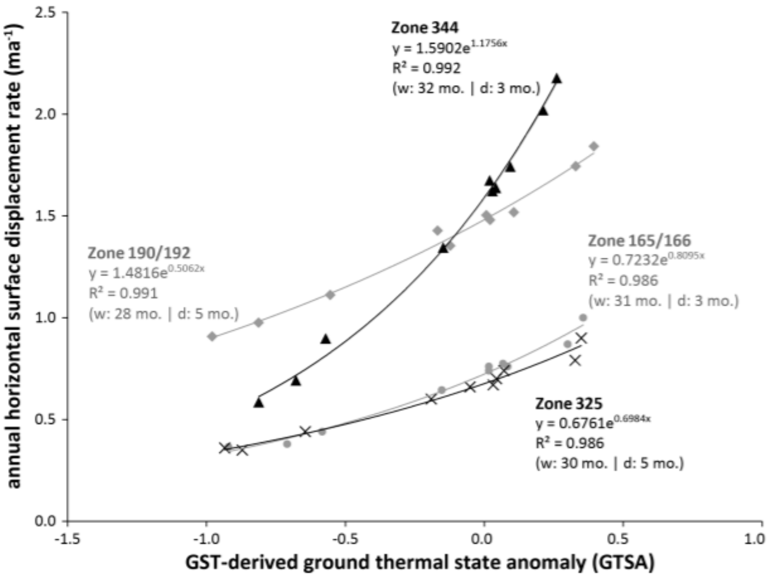

Figure 15*: The influence of the ground thermal state on mean annual permafrost creep velocities illustrated using GPS and ground surface temperature (GST) monitoring data from the Becs-de-Bosson rock glacier in the Valais Alps measured between 2004 and 2014 (Staub et al. 2016)*

Since the 1990s, in situ velocity monitoring activities have been substantially expanded but also institutionalized (e.g. Delaloye et al., 2010). In many cases, kinematic monitoring is carried out jointly with meteorological, hydrological and temperature monitoring in order to better understand the rock glacier-climate relationships and the reaction of rock glacier behaviour to climatic changes (e.g. Kellerer-Pirklbauer & Kaufmann, 2012).

Development in remote sensing technologies and the greater availability of appropriate satellite imagery have recently permitted to include more detailed kinematic information into rock glacier inventories. Observing or deriving a rock glacier kinematic variable at regional or even global scale seems technically feasible using remote sensing techniques.

A variable related to rock glacier kinematics has the potential to become a key parameter for the monitoring of the cryosphere in mountain regions (see fig. 5). It also provides a unique validation dataset for climate models, where direct permafrost (thermal state) measurements are mostly lacking. A proper rock glacier kinematics variable derived from Earth Observation (EO) products could be integrated as a new associated parameter to the Essential Climate Variable (ECV) permafrost in the monitoring strategy of international programs, in addition to the observation of the Thermal State of Permafrost and the Active Layer Thickness already available on the Global Terrestrial Network on Permafrost (GTN-P). This is one of the main objectives of the IPA Action Group Rock glacier inventories and kinematics (that we work with closely), which aims, in its second phase, to develop and define standards for EO products for the monitoring of the rock glacier-related ECV Permafrost.

3.2.1 Product description

The product proposed here will be standardized for the selected rock glaciers in the Carpathians sites, European arctic/subarctic sites and Western Swiss Alps. It needs to fit user requirements (URD) and to be technology independent. The following specific product description is proposed as a basic requirement (the minimum required that will lead to efficient kinematical time series that can be used to derive regional trend). However, specific standards to produce homogeneous kinematical time series of selected rock glaciers still need some refinements (see URD) and will be developed in close collaboration with the international IPA Action Group.

Especially, basic concepts will be defined during the Workshop 2 of the Action Group (February 2020) where the two main following points will be discussed/refined:

- Selection of rock glaciers representative within a region (rock glacier characteristics, rock glacier representativeness, methodology requirements, etc.)
- Kinematical value (spatial and temporal resolution, complementary remote-sensing techniques, etc.)

Algorithms for production of rock glaciers kinematical time series compliant with these standards will be documented in the Deliverables from Task 2 of CCN2 (Algorithm Theoretical Basis Document ATBD).

Additional/optional information derived for specified sites due to further examination will be included to the respective final deliverables.

3.2.2 Temporal resolution

Velocity values will be computed with biannual, annual or seasonal time steps. Especially annual or bi-annual mean velocity values will be computed for the slowest rock glaciers (1-3 cm/yr) using annual Sentinel-1 interferograms or multi-temporal InSAR techniques. Mean velocity value during the late snow-free period (August-October to avoid remnant late snow influence) will be computed using the acquisition time interval of Sentinel-1 of a multiple of 6 days for the fastest rock glaciers (3-100 cm/yr). The use of available repeat optical remote sensing data will be valuable for documenting velocities of very fast-moving rock glaciers, i.e. faster than around 1 m/yr. Such repeat optical aerial or satellite images are, however, only available with time intervals of a few years (in the optimal case) to one or even several decades, and for some areas not at all. Availability of suitable images varies strongly due to highly variable acquisitions and access to the data.

The time period selected to derive velocity value should be indicated and be consistent over time for the respective rock glacier.

The definition of standards for the temporal resolution of kinematical time series will be one of the main tasks of the next workshop of the IPA Action Group in February 2020. The delivered rock glacier kinematical time series in CCN1 and CCN2 will be compliant with these standards.

3.2.3 Spatial distribution and resolution

The definition of standards for the spatial distribution of the selected rock glacier and horizontal resolution of the velocity value will be one of the main tasks of the next workshop of the IPA Action Group (February 2020). The defined standards will be used for the delivered kinematical time series in CCN1 and CCN2. However, the selection of rock glaciers representative of the region will be dependant on data availability (rock glaciers which have a favourable configuration to be investigated with the selected remote sensing methods). Velocity measurements based on repeat optical images will typically cover only selected specific sites due to the much smaller swath width of aerial or very high-resolution satellite images compared to Sentinel-1.

3.2.4 Product accuracy

The URD indicates that the rmse should be at least below 5 cm/yr when deriving kinematical time series.

The expected accuracy of Sentinel-1 InSAR is 6 to 7 mm for every measurement for a single interferogram procedure and can go down to a mm accuracy using multi-temporal techniques. In order to derive trends in velocity over a region and to be able to detect associated changes, the accuracy will be kept to a maximum of 10% relatively to the measured velocity.

Under optimal conditions, displacements from repeat optical imagery can be measured with an accuracy of 1/10 of a pixel resolution. For images of lower quality and being affected by distortions, an accuracy around 1 pixel resolution is more realistic. Over a typical time interval of 10 years, these accuracies translate to accuracies for displacement rates of around 1-10 cm/yr for favourable and less favourable images available, respectively.

3.2.5 Product attributes

The following attributes will be recorded for each selected rock glacier:

- Reference rock glacier ID
- Kinematical time series (velocity values)

3.2.6 Data documentation and dissemination

Data and documentation will be available on the ESA CCI webpage.

3.2.7 Metadata

Metadata should indicate the methodology used for deriving the kinematical time series (InSAR, optical, etc.) and the related accuracy. Additional information regarding the velocity type (annual mean, snow-free period mean, maximum, seasonal), and the time period of measurement should be specified. The producer and the date of production should be indicated.

3.2.8 Product projection system

The Coordinate Reference System (CRS) used for the global permafrost products will be UTM based on the World Geodetic System 84 (WGS84) reference ellipsoid. The coordinates are specified in meters.

3.2.9 Product file naming conventions

The naming of the products follows the ECV naming convention.

The files for each parameter and month will be named as follows:

ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc

<CCI Project>
PERMAFROST for permafrost_cci

<Processing Level>
L3 for Level 3; Level 2 variables mapped on a defined grid with reduced requirements for ancillary data.

<Product String>
KTS, when the parameter is velocity.

<Additional Segregator>
This should be AREA_<TILE_NUMBER> being the tile number the subset index: 5-Romania 6-Switzerland, Western Swiss Alps; 7-Norway, Troms; 8-Norway, Finnmark; 9-Svalbard, Nordenskiöld; 10-France, Vanoise; 11-Italy, Sud Val Venosta, Sudtirol; 12-Greenland, Disko Island; 13-Tien Shan; 14-Alaska, Brookes Range; 15-Argentina, Central Andes, 16-New Zealand, Central part of the Southern Alps

<Indicative Date>
The identifying date for this data set:
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. For monthly products DD=01. Annual averages are represented with year only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (That is 1 or more digits followed by optional . and another 1 or more digits). The most recent version is fv1.0 (released in May 2019).

Example:
ESACCI-PERMAFROST-L3-SENTINEL1-KTS-AREA6-2003-fv01.0.shp

3.3 Permafrost distribution model in Southern Carpathians (CCN1)

3.3.1 Product description

So far, previous investigations focused on documenting new areas with permafrost in the Southern Carpathians, but no analyse of permafrost distribution at large scale was done yet. For the permafrost distribution model at the scale of the Southern Carpathians range, we will use a modelling methodology based on the Random Forest (RF) classification algorithm (Breiman, 2001). Recently, de Luigi et al. (2017) compared several machine learning algorithms to predict permafrost presence in mountain environments at the landform scale level. They revealed that random forest approach had the best performance and predicted with a very high accuracy the permafrost distribution. RF is a machine learning algorithm that learns all the characteristics of the independent variables for the training area (for both the areas with permafrost and without permafrost) and searches for similar characteristics of the independent variables in the rest of the study area. RF has several advantages among which the most important are: the input data can be both numerical and categorical; there is no need for the input data to have a specific distribution; it is not sensible to outliers in the input data; performs with a large number of independent variables. These characteristics allow the RF model to run on a big set of predictor variables that can be extracted from both a digital elevation model (DEM) and satellite images.

The input data for the model will be based on areas with known presence or absence of permafrost, respectively, as documented by previous studies. Because the extent of permafrost is limited to small patches, the input data should be split about 2/3 for areas without permafrost and 1/3 for area with permafrost, rather than an equal proportion. As predictor variables we will used many topographical variables derived from a 10 m resolution DEM and two land cover variables derived from Sentinel-2 satellite images. The model produces three outputs: the permafrost extent, the uncertainty associated with the permafrost extent output and the importance of the independent variables. The accuracy of the model will be tested using an error matrix and using the Area Under the receiver operating Curve (AUC).

3.3.2 Spatial resolution

The spatial resolution of potential permafrost distribution map is related to the resolution of the main input (the DEM) and will be generated at 30 m spatial resolution.

3.3.3 Pixel attributes

The potential permafrost distribution map will store the probability values for permafrost absence-presence (0, 1).

3.3.4 Data documentation and dissemination

Data and documentation will be available on the ESA CCI webpage.

3.3.5 Product projection system

The Coordinate Reference System (CRS) used for the global permafrost products will be UTM based on the World Geodetic System 84 (WGS84) reference ellipsoid. The coordinates are specified in meters.

3.3.6 Product file naming conventions

The naming of the products follows the ECV naming convention.

The files for each parameter and month will be named as follows:

ESACCI-<CCI Project>-<Processing Level>-<Data Type>-<Product String>[-<Additional Segregator>]-<Indicative Date>[<Indicative Time>]-fv<File version>.nc

<CCI Project>
PERMAFROST for permafrost_cci

<Processing Level>
L4 for Level 4; Data sets are created from the analysis of lower level data, resulting in gridded, gap-free products.

<Product String>
GTD, when the parameter is ground temperature at a certain depth, ALT, if the parameter is active layer thickness, PFR if the parameter is permafrost extent (fraction), PFF if the parameter is permafrost-free fraction, PFT if the parameter is fraction underlain by talik and PZO if the parameter is permafrost zone.

<Additional Segregator>
This should be AREA_<TILE_NUMBER> being the tile number the subset index: 1- global, 2-North America, 3-Eurasia, 4-Northern hemisphere, 5-Romania (CCN1)

<Indicative Date>
The identifying date for this data set:
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. For monthly products DD=01. Annual averages are represented with year only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (That is 1 or more digits followed by optional . and another 1 or more digits). The most recent version is fv1.0 (released in May 2019).

<Layer>
In case that the individual layers of the pixel product are provided as different NetCDF files, the code of each layer will be detailed as follows:

- PP: layer 1, corresponding to the Julian day, or day of the year of detection of the permafrost parameter.
- CL: layer 2, corresponding to the confidence level
- LC: layer 3, corresponding to the ground stratigraphy
- LS: layer 4, corresponding to the LST source.

Example:
ESACCI-PERMAFROST-L4-MODIS-ALT-AREA5_PP-2003-fv01.0.nc

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4.2 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