https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions

Incorporating kinematic attributes into rock glacier inventories exploiting InSAR data: preliminary results in eleven regions worldwide

Aldo Bertone[1,2*], Chloé Barboux[2], Xavier Bodin[3], Tobias Bolch[4], Francesco Brardinoni[1], Rafael Caduff[5], Hanne H. Christiansen[6], Margaret M. Darrow[7], Reynald Delaloye[2], Bernd Etzelmüller[8], Ole Humlum[6,8], Christophe Lambiel[9], Karianne S. Lilleøren[8], Volkmar Mair[10], Gabriel Pellegrinon[1], Line Rouyet[11], Lucas Ruiz[12], Tazio Strozzi[5]

[1] Department of Biological, Geological and Environmental Sciences, University of Bologna, Bologna, 40126, Italy
[2] Department of Geosciences, Geography, University of Fribourg, Fribourg, 1700, Switzerland
[3] Laboratoire EDYTEM, CNRS/Université Savoie Mont-Blanc, Le Bourget-du-Lac, 73370, France
[4] School of Geography & Sustainable Development, University of St Andrews, St Andrews, KY16 9AL, United Kingdom
[5] Gamma Remote Sensing, Gümligen, 3073, Switzerland
[6] Arctic Geology Department, The University Centre in Svalbard, Longyearbyen, 156 N-9171, Svalbard
[7] Department of Civil, Geological, and Environmental Engineering, University of Alaska Fairbanks, Fairbanks, Alaska, 99775-5900, USA
[8] Department of Geosciences, University of Oslo, Oslo, 0316, Norway
[9] Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, 1015, Switzerland
[10] Office for Geology and Building Materials Testing, Autonomous Province of Bolzano, Bolzano, 39100, Italy
[11] Department of Technology, NORCE Norwegian Research Centre AS, Troms, 9019, Norway
[12] Argentine Institute of Nivology, Glaciology and Environmental Sciences, CCT CONICET Mendoza, Mendoza, 5500, Argentina

Correspondence to: Aldo Bertone (aldo.bertone@unibo.it)

Abstract.

The dependence of rock glaciers on permafrost and thus their sensitivity to climatic parameters makes the spatial distribution of these landforms very important for hydrological and climate changes reasons. Inventories of rock glaciers have been produced for decades worldwide, often without an assessment of their kinematics; the availability of remote sensing data makes the inclusion of kinematic information potentially feasible, but the absence of a common methodology makes it challenging to create homogeneous inventories. In this context, the IPA Action Group on rock glacier inventories and kinematics (2018-2023), with the support of the ESA Permafrost_CCI project, is promoting the definition of standard guidelines for the inclusion of kinematic information within inventories. Here, we test the feasibility of applying common rules proposed by the Action Group in eleven regions worldwide. Satellite interferometry is used to characterize identifiable areas with slope movements related to rock glaciers; subsequently, these areas are used to assign kinematic information to rock glaciers in existing or newly compiled inventories. More than 5,000 slope movements and more than 3,600 rock glaciers are classified according to their kinematics. The analyzes conducted on the method and on the preliminary results show small irregularities related to the detection capacity of interferometry and to lack of rock glaciers without detectable

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

movements in some regions investigated. This is the first internationally coordinated effort of rock glacier inventories. We demonstrate the feasibility of applying common rules to implement kinematic attributes within inventories at a global scale, despite the various regions and intensive manual effort.

1 Introduction

Rock glaciers are creeping masses of frozen debris, detectable in the mountain periglacial landscape by the following morphologies: front, lateral margins, and optionally ridge-and-furrow surface topography (Barsch, 1996; Berthling, 2011; Haeberli et al., 2006). These landforms are frequently used as a proxy for permafrost occurrence in cold mountain regions (Boeckli et al., 2012; Haeberli, 1985; Marcer et al., 2017; Schmid et al., 2015; Scotti et al., 2017), and can important for ice (water) storage estimation (Azócar and Brenning, 2010; Bolch et al., 2009; Jones et al., 2018a), geohazard management (Delaloye et al., 2013; Kummert et al., 2018), as well as climate reconstruction (Kääb et al., 2007, 2021; Konrad et al., 1999).

The spatial distribution of rock glaciers is generally investigated with the support of geodatabases defined as inventories. Initiatives have risen for decades for inventorying rock glaciers in the main periglacial mountain regions of the world, such as in Asia (e.g., Blöthe et al., 2019; Bolch et al., 2019; Gorbunov et al., 1998; Jones et al., 2018b; Reinosch et al., 2021; Schmid et al., 2015; Wang et al., 2017), North America (e.g., Charbonneau and Smith, 2018; Liu et al., 2013; Munroe, 2018), South America (e.g., Barcaza et al., 2017; Falaschi et al., 2015; Rangecroft et al., 2014; Villarroel et al., 2018; Zalazar et al., 2020), New Zealand (e.g., Lambiel et al., 2019; Sattler et al., 2016), European Alps (e.g., Barboux et al., 2015; Colucci et al., 2016; Cremonese et al., 2011; Delaloye et al., 2010; Guglielmin and Smiraglia, 1998; Scotti et al., 2013; Seppi et al., 2012; Wagner et al., 2020), Carpathians (e.g., Necsoiu et al., 2016) and Scandinavia (e.g., Lilleøren and Etzelmüller, 2011; Lilleøren et al., 2013).

In 2018, Jones et al. (2018) provided an overview of available rock glacier inventories on a global scale, counting more than 130 inventories worldwide, of which over 90 % produced after the 2000s. The authors merged all these available inventories to create a global inventory, in order to provide a first-order approximation of volumetric ice content contained within rock glaciers. Their analyzes highlighted several limitations on the current inventories, namely the absence of an accessible open-access database, the heterogeneities/variabilities of the existing inventories (due to unequal availability of data sources and on variable local geomorphological skills and institutional support), and the subjectivity in the manual identification of rock glaciers, as also observed by Brardinoni et al. (2019). The authors noted that the main limitation is the absence of a common methodology to provide standardized inventories, making it challenging to create a homogeneous global inventory. Nowadays, the international cooperation of the scientific community represents the key element to solve these open questions.

The International Permafrost Association (IPA) Action Group on Rock Glacier Inventories and Kinematics, launched in 2018 (Delaloye et al., 2018), intends to sustain the establishment of widely accepted baseline concepts and standard guidelines for inventorying rock glaciers in mountain permafrost regions (IPA Action Group - baseline concepts, 2020). For the IPA community, a crucial element to include in standardized rock glacier inventories is the kinematic information. Indirect kinematic information - frequently imprecise because related to the operator's interpretations – are often derived from visual observation of morphological (e.g., front slope angle) and vegetation-related indicators (Barsch, 1992; Brardinoni et al., 2019). More precise and accurate approaches based on remote sensing data (e.g., satellite interferometry with Sentinel-1 images; Yague-Martinez et al., 2016) were developed in literature to characterize the rock glacier kinematics at a large-scale (Brencher et al., 2021; Necsoiu et al., 2016; Strozzi et al., 2020; Villarroel et al., 2018; Wang et al., 2017). These latter approaches are nevertheless based on different criteria and still lack standardized outputs (Brardinoni et al., 2019; Jones et al., 2018a), essential to integrate kinematic information in standardized rock glacier inventories. In this context, the ESA Permafrost_CCI project (https://climate.esa.int/en/projects/permafrost/; last access: 10 October 2021) – following the baseline concepts proposed by the IPA Action Group (IPA Action Group - baseline concepts, 2020) – developed specific guidelines (IPA Action Group - kinematic approach, 2020) to systematically integrate kinematic information within rock glacier inventories, exploiting spaceborne interferometric synthetic aperture radar (InSAR) data.

Here, our main aim is to present the developed guidelines (IPA Action Group - kinematic approach, 2020) and test the feasibility of an international cooperation to include kinematic information in rock glacier inventories (RoGI), applying the guidelines in eleven different periglacial regions of the world. The guidelines define common rules, intended at reducing subjectivity, which is a potential source of uncertainty and variability. To summarize the workflow, areas identified as slope movements are first delineated and characterized in terms of velocity class based on interferometric data. The inventoried slope movements are then used to assign kinematic information to rock glaciers. Existing rock glacier inventories or newly compiled inventories are exploited to circumscribe the identification of slope movements. Here we present a collection of products obtained in the investigated regions, including also analyzes aimed at studying irregularities and differences observed. A product validation is also conducted with independent measurements on some specific cases. Finally, we discuss the advantages and limitations of the guidelines – and their potential – to support the integration of kinematic information within inventories at a global scale.

2 Study areas and dataset

We investigate eleven periglacial regions with various environmental parameters distributed around the world (Fig. 1, Table 1), covering eight major mountain ranges over five continents. Their spatial extent ranges from 250 to 7200 km^2 (Table 1), with an approximate median of 1600 km^2. The study areas are in permafrost conditions, but in some places only in the higher parts of the landscape.

Three study sites are located in the European Alps: Western Swiss Alps (Switzerland), Southern Vinschgau/ Venosta Valley (Italy), Vanoise Massif (France); five study sites are located in the sub-Arctic to high Arctic regions: Troms and Finnmark (Northern Norway), Nordenskiöld Land (Svalbard), Disko Island (Greenland), Brooks Range (Alaska, USA); one site in

Central Asia: Northern Tien Shan (Kazakhstan); one site in South America: Central Andes (Argentina); one site in Oceania: Central Southern Alps (New Zealand).

In Nordenskiöld Land (Svalbard), an entirely new rock glacier inventory is generated. For the remaining ten regions, existing inventories or partial inventories are available. Detailed information on the geographical parameters of these investigated regions and references to the available rock glacier inventories are presented in Table 1. Additional information for each region is included in Supplementary material A "Description of study areas".

Synthetic aperture radar (SAR) data from the Sentinel-1 (S1) and ALOS-2 satellites used in the present work (Table 1) are collected in both SAR geometries (i.e., ascending and descending) to ensure the best line-of-sight (LOS) orientation (Barboux et al., 2014; Liu et al., 2013). As snow cover is a severe limitation for InSAR (Klees and Massonnet, 1998), only snow-free periods are considered. Sentinel-1 images are acquired in Interferometric Wide swath mode with a 250 km swath at 5 m (range) by 20 m (azimuth) spatial resolution. ALOS-2 images are collected in Fine mode with a swath width of 70 km and spatial resolution of about 10 m (both range and azimuth). The information on the satellite data used and the time intervals considered for the investigated regions are presented in Table 1.

Depending on availability in each region, additional data such as aerial orthoimages, digital terrain models (DTMs) and DTM-derived products (e.g., hillshade) are included. The complete list of data used for each investigated region is included in Supplementary material A "Description of study areas". Additional kinematic measurements from differential global navigation satellite system (DGNSS) available for 17 rock glaciers in the Western Swiss Alps (Delaloye and Staub, 2016; Kummert and Delaloye, 2018; Noetzli et al., 2019; Strozzi et al., 2020), Vanoise (Marcer et al., 2020), Nordenskiöld Land (Matsuoka et al., 2019), Central Andes (Blöthe et al., 2021), Central Southern Alps regions, and for four frozen debris lobes (FDLs) in the Brooks Range (Darrow et al., 2016) are used for qualitative validations. For the purposes of this study, measurements of FDLs are not differentiated from rock glaciers for the Brooks Range study area. Feature tracking measurements on optical aerial photographs are also conducted for nine rock glaciers in the Troms (Eriksen et al., 2018), Nordenskiöld Land, and Northern Tien Shan (Bolch and Strel, 2018; Kääb et al., 2021) regions.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

Table 1. Descriptions of geographic settings, rock glacier inventory (RoGI) references and InSAR data used for each investigated region.

Western Swiss Alps, Switzerland	Extent [km^2]	1100
46°N 7.5°E	Altitude range [m a.s.l.]	1250 – 4600
	Annual Precipitation range [mm]	1100-1700
	Reference RoGI	(Barboux et al., 2015)
	InSAR data used (time intervals)	S1 (2018-2019)
Southern Venosta, Italy	Extent [km^2]	970
46.5°N 10.9°E	Altitude range [m a.s.l.]	500-3900
	Annual Precipitation range [mm]	600-1200
	Reference RoGI	(Mair et al., 2008)
	InSAR data used (time intervals)	S1 (2018-2019)
Vanoise, France	Extent [km^2]	2000
45.4°N 6.9°E	Altitude range [m a.s.l.]	700-3900
	Annual Precipitation range [mm]	1000-1600
	Reference RoGI	(Marcer et al., 2017)
	InSAR data used (time intervals)	S1 (2016-2019)
Troms, Norway	Extent [km^2]	4400
69.5°N 20°E	Altitude range [m a.s.l.]	0-1800
	Annual Precipitation range [mm]	700-1300
	Reference RoGI	(Lilleøren and Etzelmüller, 2011)
	InSAR data used (time intervals)	S1 (2015-2019)
Finnmark, Norway	Extent [km^2]	2600
70.7°N 27.9E	Altitude range [m a.s.l.]	0-700
	Annual Precipitation range [mm]	500-900
	Reference RoGI	(Lilleøren and Etzelmüller, 2011)
	InSAR data used (time intervals)	S1 (2015-2020)
Nordenskiöld Land, Svalbard	Extent [km^2]	4100
78°N 15.5°E	Altitude range [m a.s.l.]	0-1200
	Annual Precipitation range [mm]	400-1000
	Reference RoGI	New
	InSAR data used (time intervals)	S1 (2015-2020)
Disko Island, Greenland	Extent [km^2]	7200
70°N 53°W	Altitude range [m a.s.l.]	900-1900
	Annual Precipitation range [mm]	300-500
	Reference RoGI	(Humlum, 1982)
	InSAR data used (time intervals)	S1 (2015-2019), ALOS-2 (2015-2017)
Brooks Range, Alaska	Extent [km^2]	1250
68°N 150°W	Altitude range [m a.s.l.]	900-2400
	Annual Precipitation range [mm]	200-400
	Reference RoGI	(Ellis and Calkin, 1979)
	InSAR data used (time intervals)	S1 (2016-2019), ALOS-2 (2015-2016)
Northern Tien Shan, Kazakhstan	Extent [km^2]	250
43°N 77°W	Altitude range [m a.s.l.]	1000-5000
	Annual Precipitation range [mm]	800-1300
	Reference RoGI	(Bolch and Gorbunov, 2014)
	InSAR data used (time intervals)	S1 (2018-2019), ALOS-2 (2015-2016)
Central Andes, Argentina	Extent [km^2]	2900
33°S 69.6W	Altitude range [m a.s.l.]	2000-6000
	Annual Precipitation range [mm]	400-500
	Reference RoGI	(Zalazar et al., 2020)
	InSAR data used (time intervals)	S1 (2018-2020), ALOS-2 (2016-2019)
Central Southern Alps, New Zealand	Extent [km^2]	4800
43°S 170°E	Altitude range [m a.s.l.]	500-3700
	Annual Precipitation range [mm]	1000-14000
	Reference RoGI	(Sattler et al., 2016)
	InSAR data used (time intervals)	S1 (2018-2019)

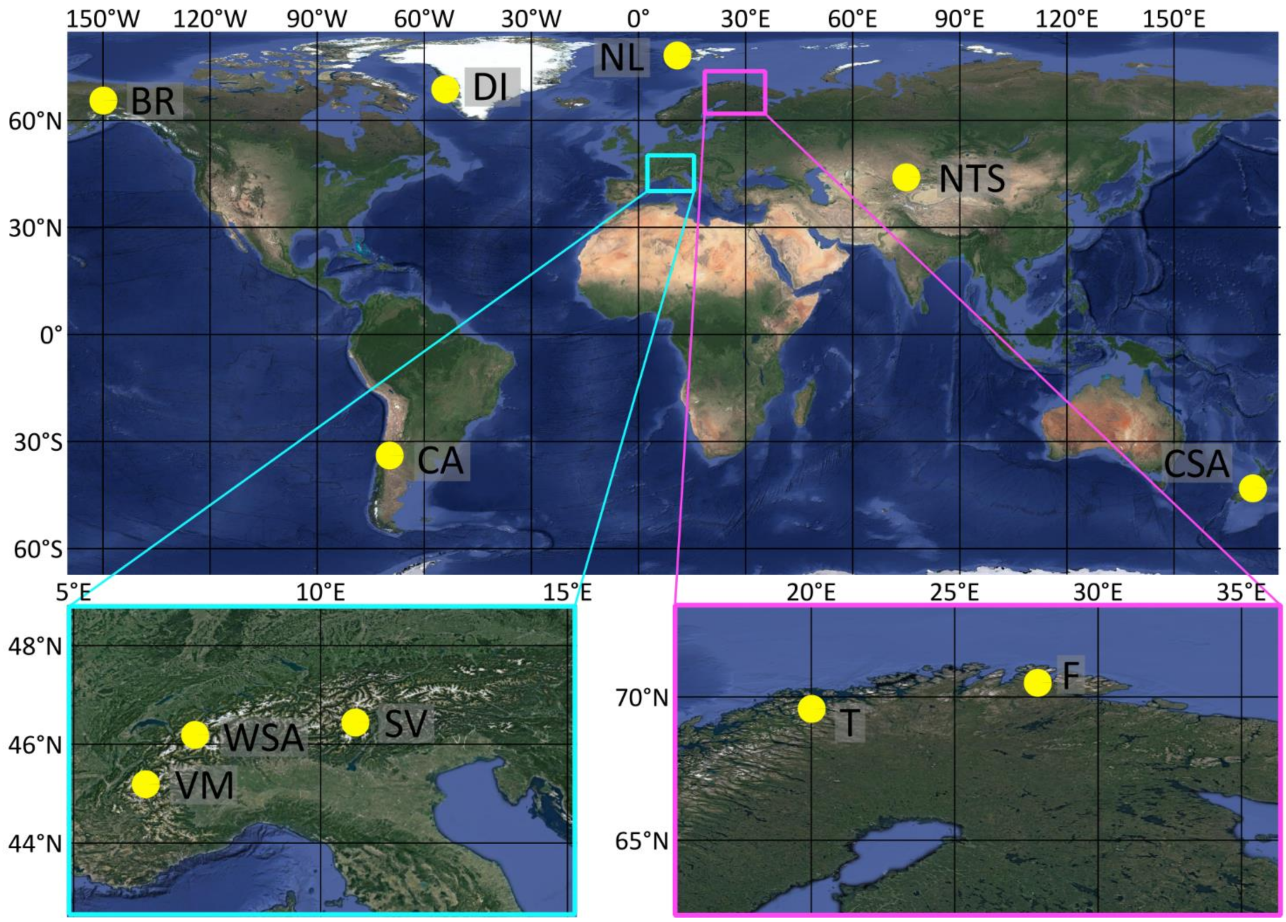


Figure 1. Location of the eleven investigated regions (yellow dots): Nordenskiöld Land (NL), Disko Island (DI), Brooks Range (BR), Northern Tien Shan (NTS), Central Andes (CA) and Central Southern Alps (CSA); Western Swiss Alps (WSA), Southern Venosta (SV), Vanoise Massif (VM), Troms (T) and Finnmark (F) are visible in two enlarged panels. Orthoimages from © Google Earth 2019.

3 Methods

3.1 Workflow and input data

The technical aspects related to rock glaciers and presented below are contained in the baseline concepts documents of the IPA Action Group (IPA Action Group - baseline concepts, 2020). The baseline concepts are constantly discussed and updated by the scientific community, and are therefore susceptible to changes, evolutions and improvements. This work refers to the version of the baseline concepts produced in May 2020. A rock glacier inventory consists of a geodatabase, containing the rock glaciers' locations as points and additional information such as activity rates and geomorphological parameters. Optional information, such as the geomorphological delineations with polygons, can be included. A rock glacier – and precisely a rock glacier unit (RG) – is defined as a single lobate structure that can be unambiguously discerned

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

according to morphologic evidence such as frontal slope, lateral margins, and ridge-and-furrow topography. The spatial connection from other (adjacent or overlapping) rock glacier units can be determined by distinguishing different generations of landforms (e.g., overlapping lobes), different connections to the upslope unit, or specific activity rates. A rock glacier "unit" is differentiated from a rock glacier "system" (i.e., a landform identified as a rock glacier), which is composed of either one single or multiple rock glacier "units" that are spatially connected either in a toposequence or in coalescence. Because of practical and technical limitations, the minimum size of a considered rock glacier unit is 0.01 km^2.

The systematic procedure contained in the guidelines (IPA Action Group - kinematic approach, 2020) follows the baseline concepts (IPA Action Group - baseline concepts, 2020) and consists of three phases described below and illustrated in Fig. 2. The aim of this procedure is to implement the kinematic information in the inventories, especially to the rock glaciers affected by movement, to reduce the subjectivity of operators' interpretations and thus have a more accurate and standardized classification.

The first phase consists of the identification of rock glaciers. For this purpose, existing rock glacier inventories or other forms of information such as from the literature are used. When inventories are not available over the investigated region (e.g., Nordenskiöld Land), the landform identification is performed following the baseline concepts proposed by the IPA Action Group (IPA Action Group - baseline concepts, 2020); systematic visual analysis of the landscape with satellite or airborne optical images (orthoimages and DTM-derived products), field visiting, or supervised/unsupervised methods that allow a systematic identification of rock glaciers can be used (Marcer, 2020; Robson et al., 2020). Within this work, the identified rock glaciers are distinguished using manually positioned dots on each landform, able to discriminate each rock glacier clearly without ambiguity (e.g., in the center of the lobe of the rock glacier unit). This initial phase is very important, because the greater the completeness of the rock glaciers identified, the greater the completeness of the products obtained in the following two phases.

The second phase consists in identifying, outlining, and assigning velocity classes to moving areas (MA) – i.e., areas identified as having slope movement with InSAR data – related to the previously identified rock glaciers. Moving area are included within inventories. This phase is conducted in parallel with the rock glacier identification, because additional landforms potentially missed can be identified when characterized by moving areas through an iterative process between the identifications of moving areas and rock glaciers.

The third phase consists in assigning kinematic attributes to rock glaciers by exploiting the velocity classes and extents of the moving areas that cover the rock glaciers. This information is then implemented within the inventory.

In this work, further phases of semi-quantitative assessments are conducted on specific rock glaciers to verify the correctly assigned kinematic categories, comparing the moving area velocity classes and the rock glacier kinematic attributes with independent measurements acquired during the same time frame. An additional effort adopted to further reduce the subjectivity, misclassifications, errors and increase the overall reliability of the products consists of multiple phases of correction and adjustment conducted by a second operator. In detail, the results produced by the first operator are checked by a second operator, thus exploiting the knowledge of two different operators. In order to optimize the work, operators with both interferometric- and geomorphological- backgrounds are involved, and study areas already known by the operators are considered to make the best use of the operators' knowledge.

Below in Sect. 3.2 we introduce the basic principles of InSAR. Subsequently in Sect. 3.3 we present the standards of moving areas and the interferometric methods used to produce the moving area inventories. The procedure to assign a kinematic attribute to rock glacier is described in Sect. 3.4. More details are further described in the practical guidelines (IPA Action Group - kinematic approach, 2020) and in Table B1 and B2.

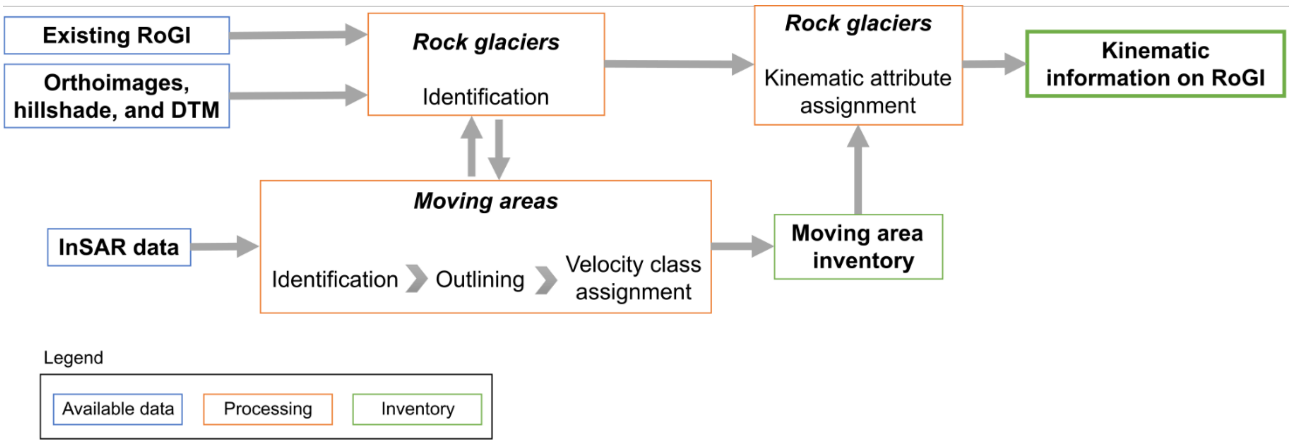


Figure 2. Conceptual diagram of the standardized method for producing a moving area inventory and a rock glacier inventory (RoGI) by including kinematics. The analysis is performed in a GIS environment.

3.2 Basic principles of Interferometric Synthetic Aperture Radar (InSAR)

InSAR is a powerful and consolidated techniques to detect and map ground movement at regional scale (Klees and Massonnet, 1998; Massonnet and Feigl, 1998). Systematic acquisitions and wide spatial coverage of the new generation of satellites such as Sentinel-1 make InSAR the most suitable tool for the global mapping objectives of this work (Yague-Martinez et al., 2016).

The interferometric processing consists of computing the interferometric phase differences (i.e., the interferograms) by combining pairs of images with different time intervals (from a few days up to annual) (Massonnet and Souyris, 2008; Yague-Martinez et al., 2016). After geometric, topographic, and atmospheric corrections, interferograms provide quantitative measurements of the superficial movements (Klees and Massonnet, 1998; Yague-Martinez et al., 2016).

Despite the potential of InSAR, some limitations apply. First, InSAR provides the observation of the 3D surface deformation component projected along the radar look direction (i.e., the line of sight, LOS), and the measurement is not sensitive to displacements directed perpendicular to the LOS orientation (Barboux et al., 2014; Liu et al., 2013; Strozzi et al., 2020). Therefore, displacements towards north or south are more affected by geometric distortions and the magnitude of the displacements might be largely underestimated (Klees and Massonnet, 1998; Liu et al., 2013). Second, steep terrain is masked by geometric distortions known as layover and shadow in mountainous areas (Barboux et al., 2014; Klees and Massonnet, 1998). To reduce the above limitations, both ascending and descending geometries are used in this work,

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions

allowing the selection of the best geometry according to the orientation of each rock glacier (Barboux et al., 2014; Strozzi et al., 2020). Third, the rate of terrain movement that can be detected depends on the time interval of the interferogram, the spatial resolution, and the wavelength of the satellite (Barboux et al., 2014; Massonnet and Feigl, 1998; Strozzi et al., 2020). Lastly, artefacts due to uncompensated atmospheric delays (Yu et al., 2018) and decorrelation or phase bias due to changes in physical properties of the surface (e.g., vegetation, snow, soil moisture; Klees and Massonnet, 1998; Zwieback et al., 2016) can mask the displacement measurements.

3.3 Moving area inventory with InSAR

A moving area is defined in the guidelines as an area at the surface of a rock glacier in which the observed flow field (direction and velocity) is uniform (spatially consistent and homogenous). The moving area represents the movement rate of the rock glacier or part of it, detected along the one-dimensional LOS. Each moving area is related to (i) a specific "observation time window" (e.g., summer or annual) during which the movement is measured and to (ii) a specific "temporal frame" (year(s)) during which the periodic measurements are repeated and aggregated. The minimal observation time window is one month during snow-free periods, detected within a temporal frame of at least two years. These time intervals are intended to average possible short, seasonal and multi-annual variations in the dynamics of rock glaciers (Kellerer-Pirklbauer et al., 2018; Wirz et al., 2016) that can distort the measurements. Observation time window and temporal frame are documented in the produced moving area inventories.

Moving areas are identified and outlined with polygons when the signal of movement is detectable for at least 20-30 pixels of InSAR data. A moving area does not necessarily fit the geomorphological outline of the rock glacier (Fig. 3); for instance, a moving area can override the geomorphological limits of a rock glacier, several polygons of moving areas can be related to the same landform, and a slower moving area that incorporates one or more faster areas can exist (Fig. 3).

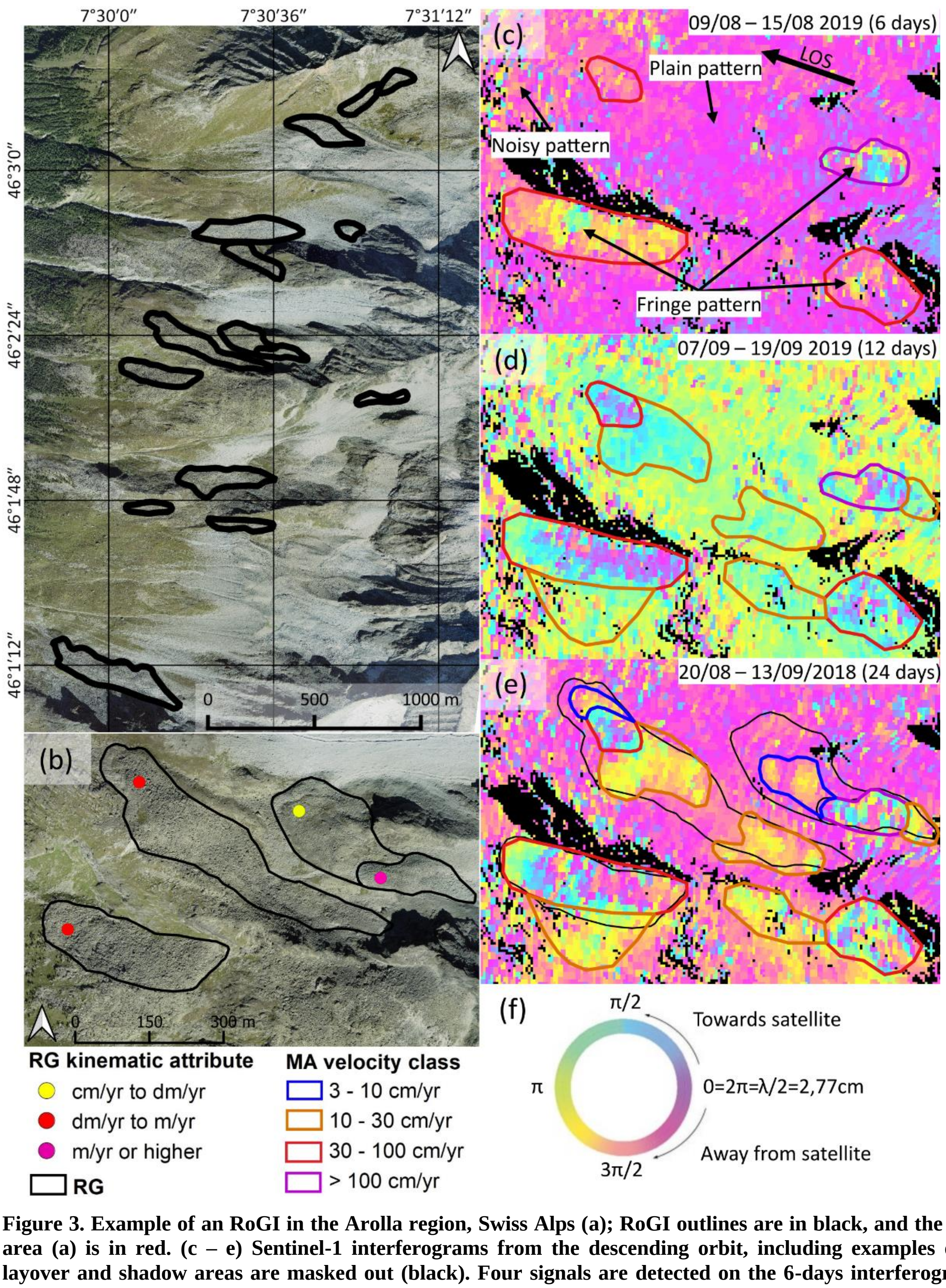
Standardized velocity classes are assigned to each moving area and are intended (i) to facilitate the subsequent assignment of kinematic attributes to the rock glaciers, and (ii) to reduce the greater degree of operator's subjectivity in assigning a specific velocity. According to recent studies (e.g., Barboux et al., 2014) the standardized velocity classes defined in the guidelines are respectively "Undefined" (velocity cannot be assessed reliably), "< 1 cm/yr," "1-3 cm/yr," "3-10 cm/yr," "10-30 cm/yr," "30-100 cm/yr," "> 100 cm/yr," and "Other" (if a more specific velocity can be expressed). These velocity classes reflect the spatio-temporal mean movement rate, but neither a single intra-annual variation nor an extreme value.

The production of moving area inventories can be accomplished following several approaches, such as manual interpretations of InSAR data (e.g., Barboux et al., 2014, 2015; Liu et al., 2013; Necsoiu et al., 2016; Villarroel et al., 2018), or supervised/unsupervised methods based on SAR images (e.g., Barboux et al., 2015; Rouyet et al., 2021). Below we describe the manual and semi-automated methods used in this work. The aim is not to compare the two methods, but to present and analyze the results obtained by establishing the standards described above.

With the manual approach we mainly considered wrapped differential interferograms, which can be computed using time intervals from a few days to a few years. Manual analyzes of geospatial data, although time-consuming, is a common approach in geomorphology and has the advantage of allowing interpretation of decorrelated regions (Barboux et al., 2014), which would be excluded in phase unwrapping. In addition, errors in phase unwrapping – which are inevitable in rough terrain with significant motion and not easily identified by the non-InSAR specialist - can bias the interpretation of fast-moving objects (Barboux et al., 2015). Nevertheless, weighted averaging (stacking; Sandwell and Price, 1998) of unwrapped 6/12 days Sentinel-1 interferograms are also computed to facilitate the interpretation of single-wrapped interferograms. Moving areas are identified by looking at the textural image features from interferograms, according to three typical InSAR signal patterns: (1) no change defined by a plain pattern, (2) smooth change characterized by a (partial) fringe pattern, and (3) a decorrelated signal expressed by a noisy pattern (Fig. 3c). The combined visualization of a large set of interferograms allows a user to draw fast moving area outlines from interferograms with shorter time intervals (e.g., 6 days for Sentinel-1) and shorter wavelengths; by increasing the time intervals, the drawn outlines are refined, and additional outlines (with lower velocities) are identified and drawn (Fig. 3d and 3e). The velocity classes are assigned by counting the number of fringe cycle(s) from a point assumed as stable (outside the moving area) to the detected moving area. The number of fringe cycle(s) is counted exploiting the change of color in the resulting interferograms, following Fig. 3f. A complete fringe is equivalent to a change of half a wavelength in the LOS direction between two SAR images acquired at different times. The displacement obtained by knowing the wavelength of the satellite and the number of fringe cycle(s) is converted to velocity by dividing by the time interval of the interferogram.

For the Norway and Svalbard study regions, a semi-automated multiple temporal baseline InSAR stacking procedure is applied (Rouyet et al., 2021). The procedure aims to combine the strengths of the single interferogram analysis and multi-temporal InSAR techniques by stacking unwrapped interferograms with five complementary ranges of temporal intervals (336–396, 54–150, 18–49, 6–12 and 6 days) and complementing velocity information with mapping decorrelated signals associated with fast movement. The approach attempts to semi-automate the analysis to include a large number of interferograms (tens to hundreds for each stack) from both SAR geometries, and to combine complementary datasets with different detection capabilities, while avoiding large unwrapping errors for fast-moving landforms (Rouyet et al., 2021). The interpretation efforts are therefore reduced, but several time-consuming calibration tests are required.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022



260 **Figure 3. Example of an RoGI in the Arolla region, Swiss Alps (a); RoGI outlines are in black, and the location of an investigated area (a) is in red. (c – e) Sentinel-1 interferograms from the descending orbit, including examples of InSAR signal patterns; layover and shadow areas are masked out (black). Four signals are detected on the 6-days interferogram (c). Using 12- and 24-days, additional signals are visible (d and e). This is an example where the MAs outlines do not fully match the geomorphological outline of the RGs. A fringe pattern (SE-border) not related to RG is visible and mapped. Based on MAs, the kinematic attributes are assigned to RGs (b). Fringe cycle related to the change of color (f); a complete fringe cycle is equivalent to a change of half a wavelength (2,77 cm for Sentinel-1) in the LOS direction.**

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions
Open Access
EGU

3.4 Kinematics in the rock glacier inventory

A kinematic attribute is defined in the guidelines as semi-quantitative (order of magnitude) information, representative of the movement rate of an inventoried rock glacier. It is assigned only when spatially representative of the rock glacier, i.e., when the rock glacier is documented by consistent kinematic information on a significant part of its surface. Kinematic attributes refer to a multi-annual validity time frame of at least two years (same temporal frame from moving area inventory) to minimize the potentially large inter-annual variations of rock glacier movement rate (Kellerer-Pirklbauer et al., 2018; Wirz et al., 2016).

The characteristics (extent, velocity class, time intervals) of the moving area(s) identified at the surface of the rock glacier are used to assign the kinematic attributes (Table 2; IPA Action Group - kinematic approach, 2020). Only one kinematic category is assigned per rock glacier unit; however, a dominant moving area rarely covers a rock glacier as a whole. When two equally dominant, but directly adjoining categories occur on a rock glacier, the category of the most representative area (e.g., closest to the front) is favored for the attribution. In the case of a more extensive spread of equally dominant categories on the same rock glacier, the median category is retained. Heterogeneities of moving areas inside a rock glacier can also indicate the need to refine/redefine the delineation of the initial geomorphological units, following an iterative process between geomorphology and kinematics.

A manual transfer from velocity classes of moving areas to kinematic attributes of rock glaciers is done, depending on the observation time windows of the moving areas (IPA Action Group - kinematic approach, 2020). If the velocity class of a dominant moving area is characterized by an annual or multi-annual observation time window, a kinematic attribute "< cm/yr" or "cm/yr" is assigned with the respective velocity class of "< 1 cm/yr" and "1-3 cm/yr" (Table 2). The kinematic attribute "< cm/yr" is assigned even in the absence of detectable movement (i.e., without detected moving area(s)). If the velocity class of a dominant moving area is characterized by an observation time window shorter than one year (at least one month in the snow-free period), the kinematic attribute is assigned according to Table 2. The conversion from velocity classes to kinematic attributes considers the expected seasonal variations of rock glacier movement rate, generally higher during summer periods, with minimum velocity occurring in early spring, velocity peaks in late spring and maximum velocity in late autumn (Berger et al., 2004; Cicoira et al., 2019; Delaloye and Staub, 2016; Kenner et al., 2017; Wirz et al., 2016). The "undefined" category is chosen when (i) no (reliable) kinematic information is available (e.g., north/south-facing slopes, no data due to layover/shadow), (ii) the rock glacier is mainly characterized by a moving area of undefined velocity, or (iii) the heterogeneities of moving areas within rock glacier are too large.

For each rock glacier, additional information is documented, such as the multi-year validity time frame (i.e., the years to which the kinematic attributes apply) and the activity degree based on kinematic interpretation; according to the baseline concepts (IPA Action Group - baseline concepts, 2020), "active" is assigned with coherent movement over most of the rock glacier surface (displacement rate from decimeter to several meters per year), "transitional" with little to no movement over most of the rock glacier surface (displacement rate less than decimeter per year in an annual mean), and "relict" without

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

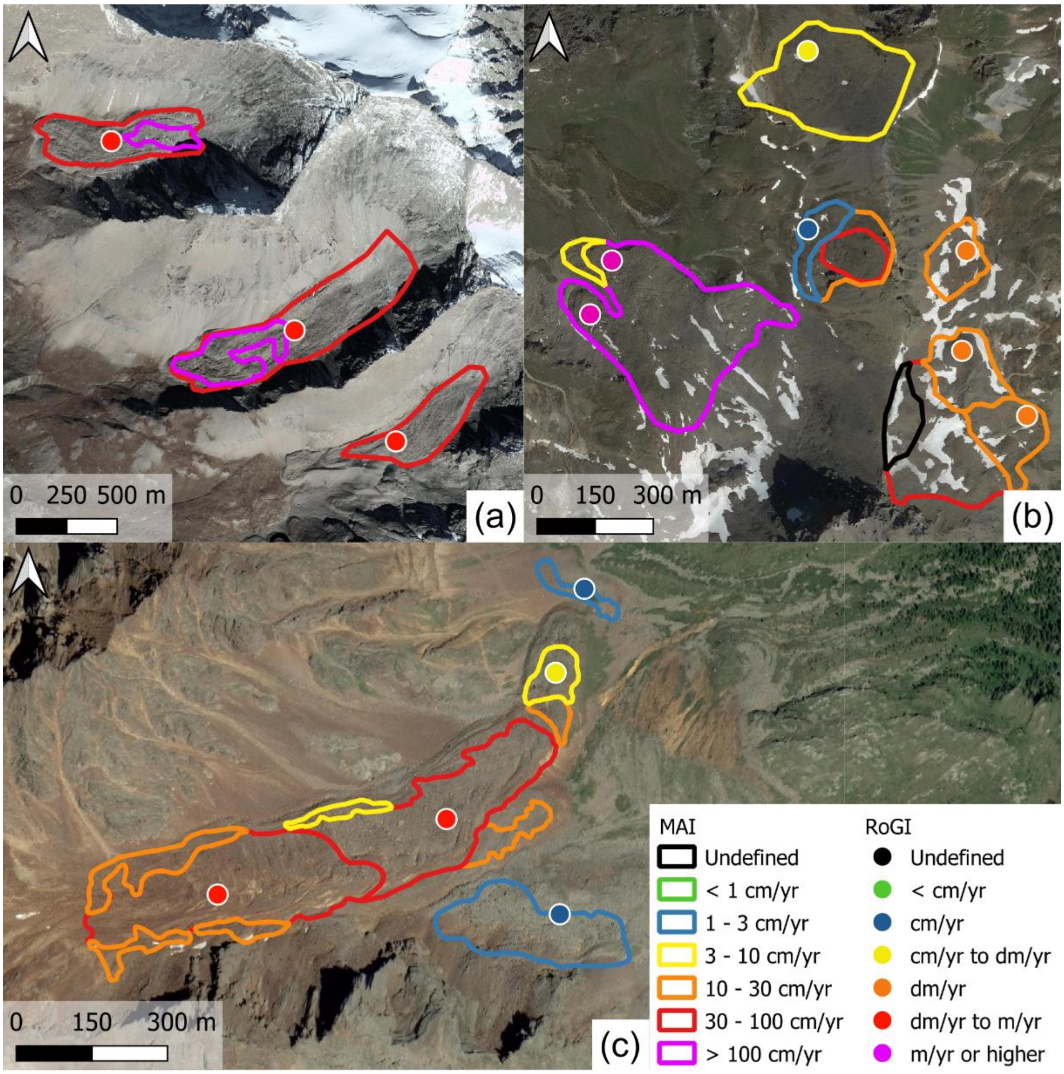
detectable movement over most of its surface. This purely kinematic classification does not consider the permafrost content, which is instead considered by other classifications proposed in the literature (e.g., Barsch, 1996). Information of the moving area(s) used to assign kinematic attributes is also documented, such as the time characteristics (e.g., observation time window and temporal frame) and the spatial representativeness, i.e., the qualitative estimation of the percentage of moving area(s) surface inside the rock glacier unit compared to the total area of the rock glacier (e.g., < 50 %, 50-75 %, > 75 %).

Table 2. Description of the kinematic attribute categorization from the moving areas and the associated velocity classes, according to the IPA Action Group (IPA Action Group - baseline concepts, 2020).

Observation time window	Associated velocity class from MA(s)	Order of magnitude of RG velocity	RG kinematic attribute	Activity degree
≥ 1 year(s)	Undefined	-	Undefined	Undefined
≥ 1 year(s)	< 1 cm/yr	No/little movement	< cm/yr	Relict
< 1 year	1-3 cm/yr	≈ 0.01 m/yr	cm/yr	Transitional
< 1 year	3-10 cm/yr	≈ 0.05 m/yr	cm/yr to dm/yr	Transitional
< 1 year	10-30 cm/yr	≈ 0.1 m/yr	dm/yr	Active
< 1 year	30-100 cm/yr	≈ 0.5 m/yr	dm/yr to m/yr	Active
< 1 year	> 100 cm/yr	≈ 1 m/yr or more	m/yr or higher	Active
	-	Potential velocity	Other	-

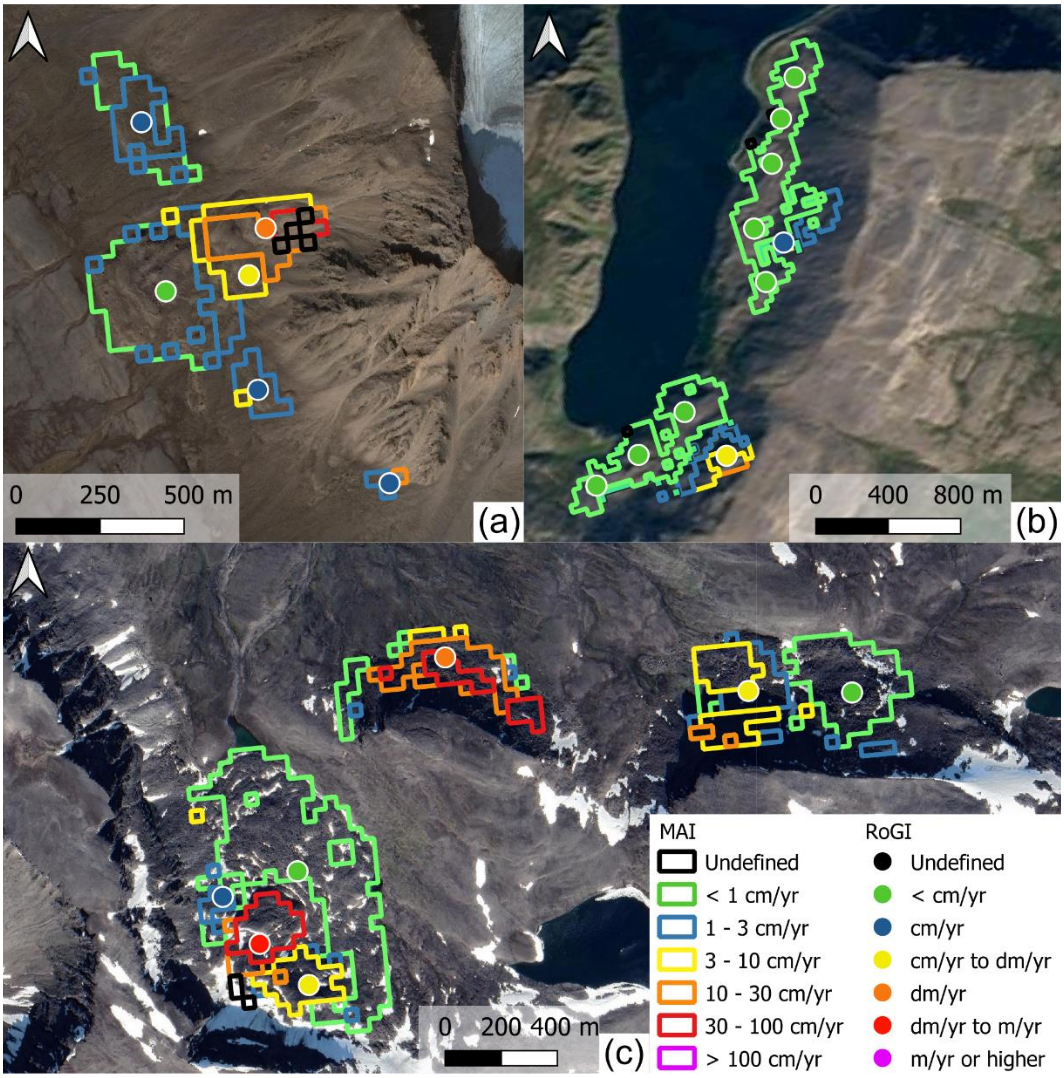
4 Results

The moving areas and kinematic attributes compiled in the eleven investigated regions are shown in Fig. 4-6. A total of 5,077 moving areas covering about 5,140 km^2 are inventoried over 31,500 km^2 of investigated areas. The two different approaches used to map and classify the moving areas (i.e., manual and semi-automated) show some differences. In Troms, Finnmark and Nordenskiöld Land regions we observe a greater number of small, highly fragmented moving area outlines that fit InSAR pixel boundaries without any smoothing (semi-automated approach, Fig. 5). In the other regions investigated with a manual approach, outlines fit the detected slope movements with smooth outlines, and small moving areas (with slow velocities) are frequently not mapped (Fig. 4 and 6).



315 **Figure 4. Examples of moving areas and rock glacier kinematic attributes produced for Vanoise (a, location: 45°16'10"N 7°03'00"E, 2900 m), Western Swiss Alps (b, location: 46°10'25"N 7°30'45"E, 2700 m), and Southern Venosta (c, location: 46°28'20"N 10°48'00"E, 2500 m). Orthoimages from © Google Earth 2019.**

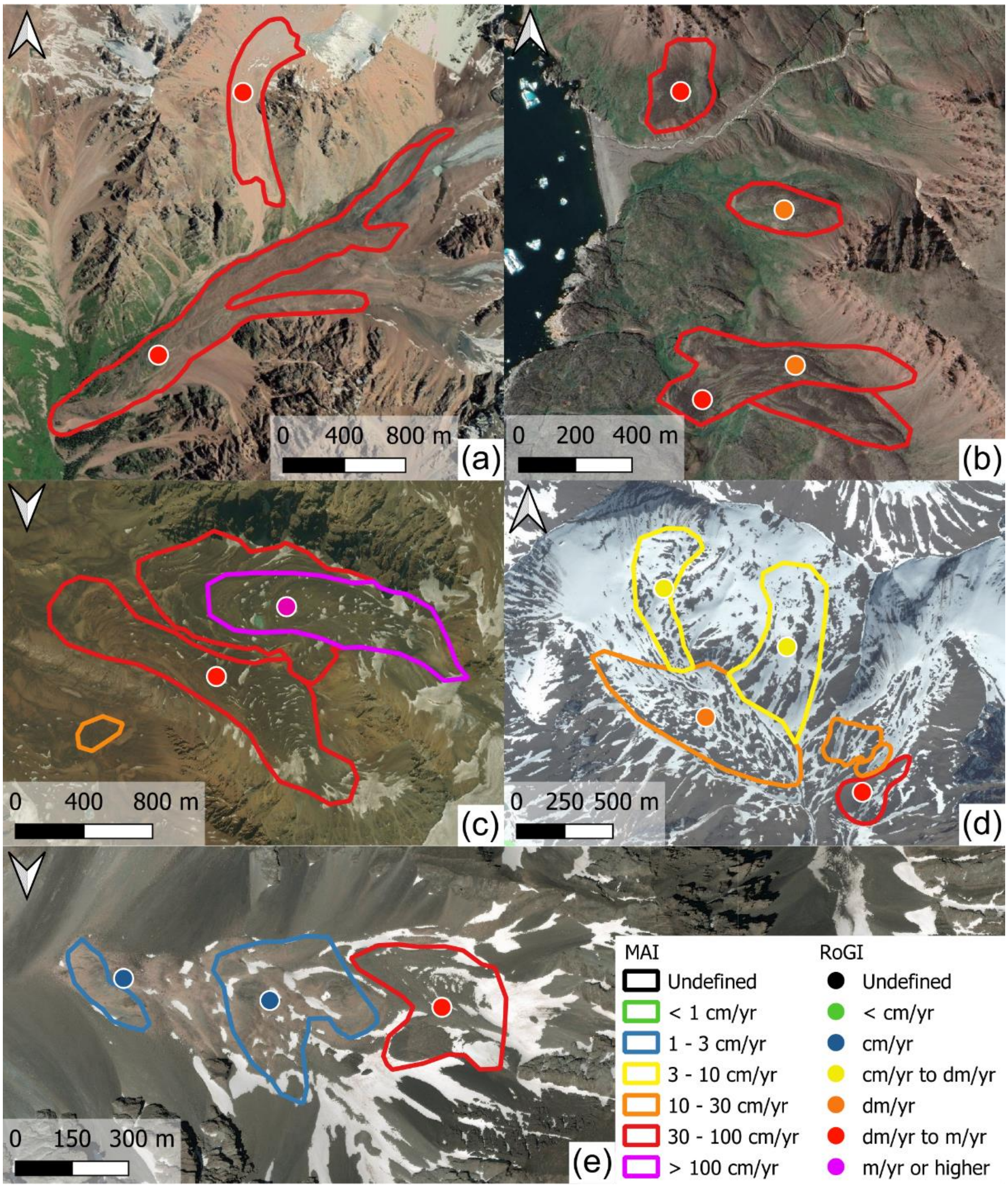
https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022



320 **Figure 5. Examples of moving areas and rock glacier kinematic attributes produced for Nordenskiöld Land (a, location: 77°53'25"N 13°55'35"E, 300 m), Finnmark (b, location: 70°44'50"N 28°01'50"E, 100 m), and Troms (c, location: 69°26'45"N 20°42'40"E, 920 m) based on a semi-automated multiple temporal baseline InSAR stacking procedure (Rouyet et al., 2021). Orthoimages from © Google Earth 2019.**

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions



325 **Figure 6. Examples of moving areas and rock glacier kinematic attributes produced for Northern Tien Shan (a, location: 43°06'00"N 77°12'20"E, 3400 m), Disko Island (b, location: 69°15'50"N 53°37'20"W, 100 m), Central Andes (c, location: 33°00'10"S 69°35'00"W, 4400 m), Brooks Range (d, location: 68°06'25"N 150°00'18"W, 1700 m) and Central Southern Alps (e, location: 43°35'40"S 170°44'00"E, 2000 m). Orthoimages from © Google Earth 2019.**

The number of mapped moving areas and their extent are quite different between the investigated regions. The number of mapped moving areas range from 71 (Finnmark) to 837 (Central Andes), sometime without a proportional increase in the total extent covered by moving areas (Fig. 7, 8a and Table 3). Central Andes, Disko Island and Brooks Range are the regions

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

with a high number of moving areas and a high total extent covered by moving areas, while Troms, Western Swiss Alps and Southern Venosta have a high number of moving areas and a low total extent covered by moving areas (Fig. 8a). Accordingly, the first three regions have the largest moving areas visible from the boxplots of the area distributions (Fig. 8b), while the last three regions have smaller moving areas.

For Disko Island, Brooks Range, Vanoise, Central Andes, Northern Tien Shan, and the Western Swiss Alps region most of the moving areas are classified with fast velocity classes (i.e., "30–100 cm/yr" and "> 100 cm/yr"; Fig. 9a and Table 3). In these regions, with the exception of Western Swiss Alps, few moving areas (less than 12 %) are classified with slow velocity classes (i.e., "< 1 cm/yr" and/or "1–3 cm/yr"). In the other regions slow moving areas are prevalent, at the expense of faster ones. Therefore, in each region, the faster or slower moving areas seem to prevail over their counterparts.

The number of classified rock glaciers is proportional with the number of detected moving areas, but rock glaciers are less numerous (Fig. 7); therefore, this suggests each rock glacier often contains more than one moving area, as illustrated in Fig. 3. The maximum number of moving areas associated with a rock glacier ranges from a minimum of 2 up to 12 (Table 3). Southern Venosta, Troms, Nordenskiöld Land and Central Andes are the regions with the highest number of moving areas associated with one rock glacier, and also with a large number of moving areas mapped (Fig. 8a and Table 3).

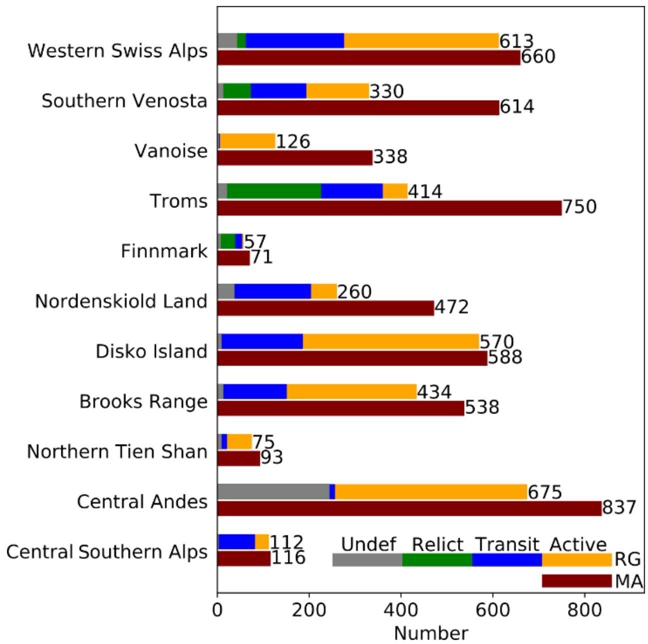


Figure 7. Number of inventoried moving areas (brown bars), and rock glaciers classified as undefined (grey bars), relict (green bars), transitional (blue bars) and active (orange bars) for each investigated region. The size of the horizontal bars is proportional to the number of observations (x axis). The numbers to the right of the bars indicate the total number of moving areas and rock glaciers.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions
Open Access
EGU

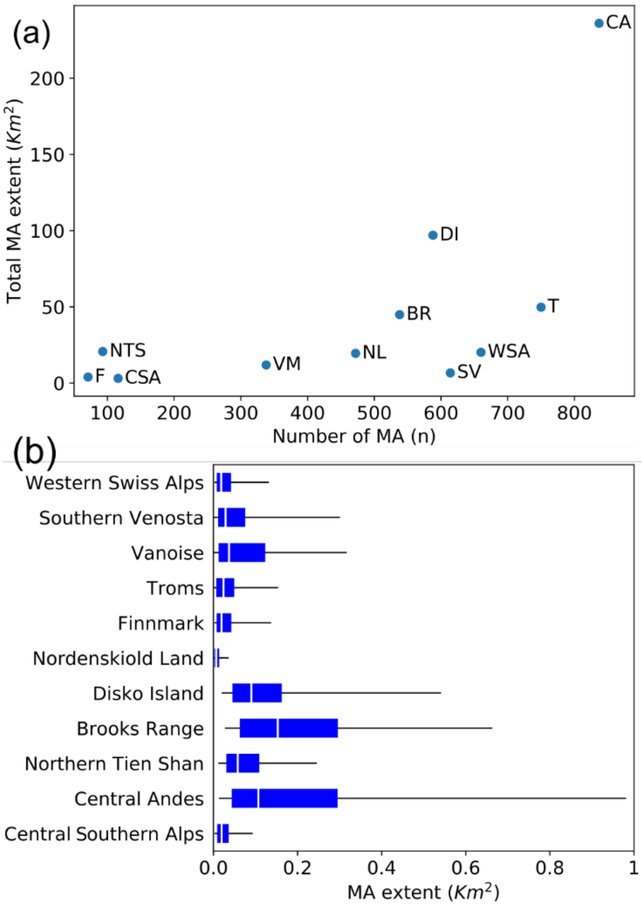
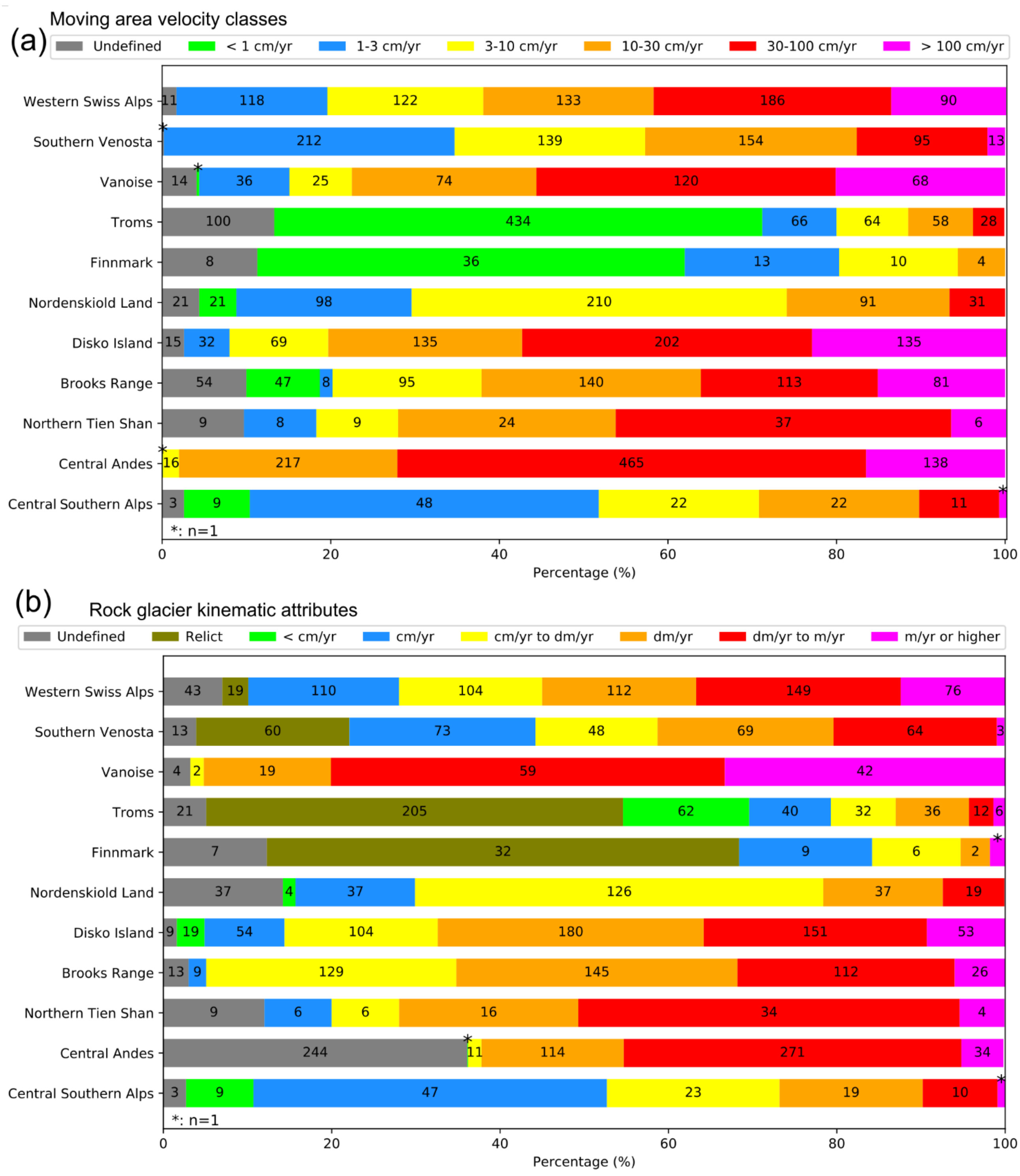


Figure 8. (a) Scatterplot between the number of mapped moving areas (x axis) and the total area covered by the moving areas (y axis) for Nordenskiöld Land (NL), Disko Island (DI), Brooks Range (BR), Northern Tien Shan (NTS), Central Andes (CA), Central Southern Alps (CSA), Western Swiss Alps (WSA), Southern Venosta (SV), Vanoise Massif (VM), Troms (T) and Finnmark (F). (b) Boxplots show the area distribution of the moving areas; bars enclose interquartile ranges, whiskers show 5 and 95 percentile.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022



355 **Figure 9. Assigned moving area velocity classes (a) and rock glacier kinematic attributes (b) for each investigated region. The size of the horizontal bars is proportional to the percentage (x axis), the values inside the bars are the numbers for each category.**

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

Table 3. Number of moving area velocity classes (percentage in brackets) and extent for each region.

Region	Undefined (%)	< 1 cm/yr (%)	1-3 cm/yr (%)	3-10 cm/yr (%)	10-30 cm/yr (%)	30-100 cm/yr (%)	>100 cm/yr (%)	Total number MA	Total extension MA [km^2]	Total region extension [km^2]	Maximum number of MAs associated with one RG
Western Swiss Alps	11 (2)	0	118 (18)	122 (18)	133 (20)	186 (28)	90 (14)	660 (100)	20.2	1100	6
Southern Venosta	1 (1)	0	212 (34)	139 (23)	154 (25)	95 (15)	13 (2)	614 (100)	6.7	970	9
Vanoise	14 (4)	1 (1)	36 (11)	25 (7)	74 (22)	120 (35)	68 (20)	338 (100)	11.9	2000	2
Troms	100 (13)	434 (57)	66 (9)	64 (9)	58 (8)	28 (4)	0	750 (100)	49.8	4400	12
Finnmark	8 (11)	36 (51)	13 (18)	10 (14)	4 (6)	0	0	71 (100)	4	2600	6
Nordenskiöld Land	21 (4)	21 (4)	98 (21)	210 (45)	91 (19)	31 (7)	0	472 (100)	19.5	4100	8
Disko Island	15 (3)	0	32 (5)	69 (12)	135 (23)	202 (34)	135 (23)	588 (100)	97	7200	2
Brooks Range	54 (10)	47 (9)	8 (1)	95 (18)	140 (26)	113 (21)	81 (15)	538 (100)	44.9	1250	2
Northern Tien Shan	9 (10)	0	8 (9)	9 (10)	24 (26)	37 (39)	6 (6)	93 (100)	20.7	250	3
Central Andes	0	1 (1)	0	16 (2)	217 (26)	465 (55)	138 (16)	837 (100)	236	2900	8
Central Southern Alps	3 (3)	9 (8)	48 (41)	22 (19)	22 (19)	11 (9)	1 (1)	116 (100)	3.1	4800	2

Kinematic attributes are assigned at 3,666 rock glaciers investigated into the study regions. The number of classified rock glaciers range between a maximum of 675 in Central Andes and a minimum of 57 in Finnmark (Fig. 7, Table 4); rock glaciers with an "undefined" kinematic attribute are less than 15%, with the exception of Central Andes (36 %). Most of the rock glaciers are classified as active and transitional in all the regions investigated, with the exception of Troms (46 %) and Finnmark (32 %). Relict rock glaciers (i.e., without detected movements) are classified only in Troms (205; 49 %), Southern Venosta (60; 18 %), Finnmark (32; 56 %), and Western Swiss Alps (19; 3 %), while are not mapped in the other regions for specific motivations (Fig. 7, Table 4). In the Western Swiss Alps region, the initial rock glacier inventory used to identify rock glaciers has been compiled following a "kinematic approach" (IPA Action Group - baseline concepts, 2020), i.e., identifying and inventorying only rock glaciers with a detectable signal of movement, thus excluding relict forms (Barboux et al., 2015). Consequently, when compiling the kinematic attributes in this region, a limited number of rock glaciers without detectable movements are classified. In the Nordenskiöld Land region, relict rock glaciers are not classified because the completely new inventory is also compiled with a “kinematic approach”. However, in the other regions, the initial inventories used to identify rock glaciers have been compiled with geomorphological approaches (IPA Action Group - baseline concepts, 2020), i.e., recognizing and inventorying rock glaciers by a systematic visual inspection of geomorphological evidence on imaged landscape, DTM-derived products, as well as local field visits, thus including relict landforms (Ellis and Calkin, 1979; Gorbunov, 1983; Humlum, 1982; Lilleøren and Etzelmüller, 2011; Mair et al., 2008; Marcer et al., 2017; Sattler et al., 2016; Zalazar et al., 2020). In the Vanoise, Brooks Range, Disko Island, Northern Tien Shan and Central Andes regions, kinematic analyzes are conducted only on landforms identified by a clear InSAR signal of movement, thus without carrying out a thorough and comprehensive kinematic investigation of rock glaciers and excluding relict forms. Also for this reason, slow-moving rock glaciers (i.e., “< cm/yr” and/or “cm/yr”) are not mapped in Vanoise, and few slow-moving landforms are classified in the Brooks Range and Central Andes regions (Fig. 9b and Table 4). In Brooks Range and Disko Island regions, analyzes on rock glaciers without a clear signal of movement are also not conducted due to the lack of high-resolution optical imagery. In Central Southern Alps, a comprehensive kinematic investigation is conducted, but only rock glaciers with detectable movements are included in the inventory here presented.

Looking in detail at the classifications, the kinematic attributes of rock glaciers reflect the velocity classes of moving areas, with most of rock glaciers in Disko Island, Brooks Range, Vanoise, Central Andes, Northern Tien Shan, and Western Swiss Alps regions classified with fast kinematic attributes (i.e., “dm/yr to m/yr” and “m/yr or higher”), and a consistent portion of slow-moving rock glaciers (i.e., “< cm/yr” and/or “cm/yr”) in the other regions (Fig. 9b and Table 4). In Southern Venosta, Troms and Finnmark a large number of slow moving areas (i.e., “< 1 cm/yr” and/or “1-3 cm/yr”) are associated to slow-moving rock glaciers.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions

Table 4. Number of activity degrees and kinematic attributes assigned to rock glaciers (percentage in brackets) for each region.

Region	Undefined (%)	Relict (%)	Transitional			Active			Total number RG (%)	Total region Extension [Km^2]
			< cm/yr (%)	cm/yr (%)	cm/yr to dm/yr (%)	dm/yr (%)	dm/yr to m/yr (%)	m/yr or higher (%)		
Western Swiss Alps	43 (7)	19 (3)	0	110 (18)	104 (17)	112 (18)	149 (24)	76 (13)	613 (100)	1100
Southern Venosta	13 (4)	60 (18)	0	73 (22)	48 (15)	69 (21)	64 (19)	3 (1)	330 (100)	970
Vanoise	4 (3)	0	0	0	2 (2)	19 (15)	59 (47)	42 (33)	126 (100)	2000
Troms	21 (5)	205 (49)	62 (15)	40 (10)	32 (8)	36 (9)	12 (3)	6 (1)	414 (100)	4400
Finnmark	7 (12)	32 (56)	0	9 (16)	6 (11)	2 (3)	0	1 (2)	57 (100)	2600
Nordenskiöld Land	37 (14)	0	4 (2)	37 (14)	126 (49)	37 (14)	19 (7)	0	260 (100)	4100
Disko Island	9 (2)	0	19 (3)	54 (9)	104 (18)	180 (32)	151 (27)	53 (9)	570 (100)	7200
Brooks Range	13 (3)	0	0	9 (2)	129 (30)	145 (33)	112 (26)	26 (6)	434 (100)	1250
Northern Tien Shan	9 (12)	0	0	6 (8)	6 (8)	16 (21)	34 (46)	4 (5)	75 (100)	250
Central Andes	244 (36)	0	1 (1)	0	11 (2)	114 (16)	271 (40)	34 (5)	675 (100)	2900
Central Southern Alps	3 (3)	0	9 (8)	47 (42)	23 (20)	19 (17)	10 (9)	1 (1)	112 (100)	4800

Morphological characteristics of rock glaciers such as the upslope connections are examined and six main classes of upslope connection are assigned (Fig. 10) according to the IPA baseline concepts: talus, debris mantle, landslide, glacier, glacier forefield and poly connected (i.e., multiple connections) (IPA Action Group - baseline concepts, 2020); unclear upslope connection are classified as "Undefined." This classification is not performed in Disko Island and Brooks Range, because the available optical data have too low resolution to document this attribute. In the Central Andes region, the classification is not provided because of many cases with unclear upslope connection; only glacier upslope connection and non-glacier upslope connection are separated. For the Western Swiss Alps, Southern Venosta, Vanoise, Troms, Finnmark, Nordenskiöld Land, and Central Southern Alps regions, the highest number of rock glaciers is classified with an upslope connection of talus type (at least 67 %). Only for the Tien Shan region is the glacier upslope connection type identified as the main class (43 %).

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

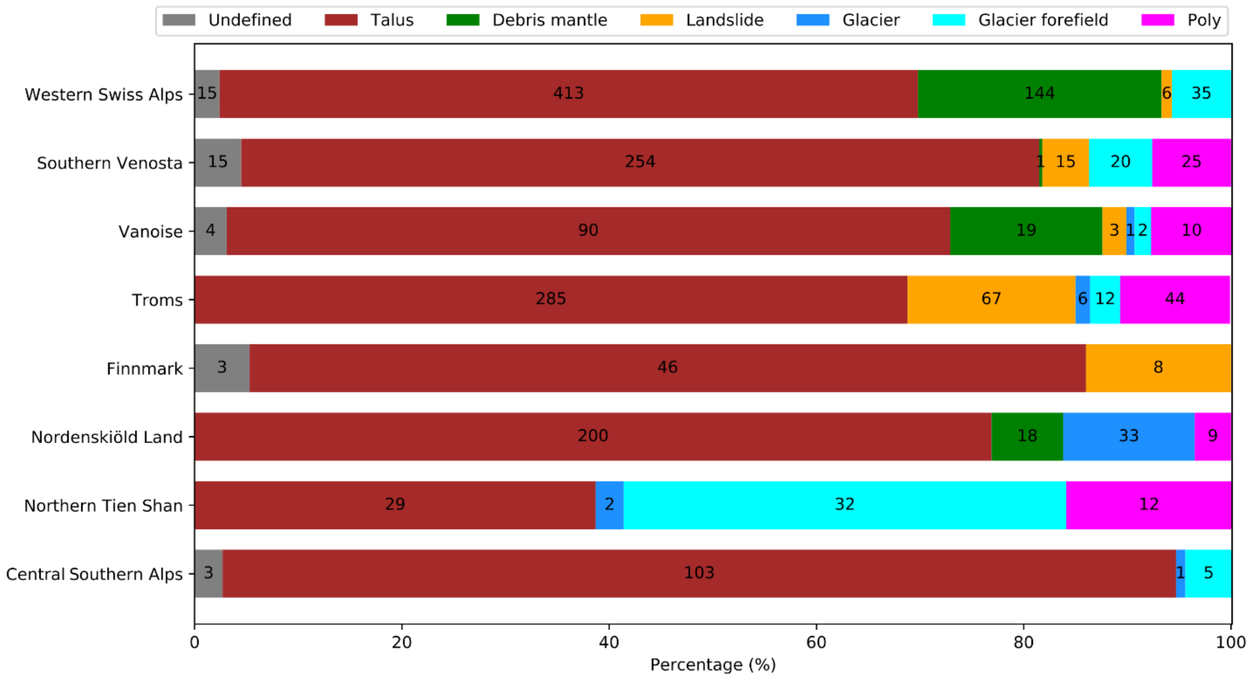


Figure 10. Upslope connection classes for most of the investigated regions. The size of the horizontal bars is proportional to the percentage (x axis), the values inside the bars are the numbers for each upslope connection class. Disko Island and Brooks Range regions are not shown because of lack of high-resolution optical data needed to document this attribute. The Central Andes region is not shown because of many cases with undefined upslope connection.

The validation of the assigned kinematic information is conducted on 30 rock glaciers with available DGNSS and feature tracking measurements acquired during the same time frame of InSAR measurements. For 24 rock glaciers, the assigned moving area velocity classes and rock glacier kinematic attributes are in agreement with the available kinematic measurements. For four rock glaciers the assigned kinematic is slightly underestimated with InSAR, and for two rock glaciers the kinematic is slightly overestimated (Table 5). Detailed results obtained from the validation are included in Supplementary material C “Description of conducted validation”.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

The Cryosphere Discussions Open Access EGU

Table 5: Validation conducted between the detected kinematic information (i.e., MA velocity classes and RG kinematic attributes) and the independent dataset available for some regions.

Region	Associated MA velocity classes [cm/yr]	RG kinematic attribute	Validation dataset	Velocity recorded [m/yr]	Disagreement
Western Swiss Alps	> 100	m/yr or higher	DGNSS	0.7 – 2	
	> 100	m/yr or higher	DGNSS	0.7 – 2	
	30 – 100	dm/yr to m/yr	DGNSS	0.1 – 2.2	Underestimation
	1 – 3	cm/yr	DGNSS	0.025 – 0.035	
	> 100	m/yr or higher	DGNSS	0.75 – 0.8	Overestimation
	> 100	m/yr or higher	DGNSS	1.3	
	30 – 100	dm/yr to m/yr	DGNSS	1.9	Underestimation
	> 100	m/yr or higher	DGNSS	2.5 – 11	
	> 100	m/yr or higher	DGNSS	0.9 – 1.1	
	> 100	m/yr or higher	DGNSS	1.2 – 2.8	
	3 – 10 and > 100	m/yr or higher	DGNSS	0.012 – 2.8	
Vanoise	10 – 30 and > 100	m/yr or higher	DGNSS	0.5 – 2	
Troms	> 100	m/yr or higher	Feature tracking	1 – 2	
	30 – 100	dm/yr to m/yr	Feature tracking	0.5 – 1	
	30 – 100	dm/yr to m/yr	Feature tracking	0.5 – 1	
Nordenskiöld Land	1 – 3 and 3 – 10	cm/yr to dm/yr	DGNSS	0.024 – 0.05	
	< 1 and 1 – 3	< cm/yr	Feature tracking	0 – 0.02	
Brooks Range	> 100	m/yr or higher	DGNSS	13	
	> 100	m/yr or higher	DGNSS	2.1	
	> 100	m/yr or higher	DGNSS	5.7	
	> 100	m/yr or higher	DGNSS	0.9	Overestimation
Northern Tien Shan	> 100	m/yr or higher	Feature tracking	1 – 4	
	30 – 100	dm/yr to m/yr	Feature tracking	0.5 – 1	
	30 – 100	dm/yr to m/yr	Feature tracking	0.4 – 1	
	30 – 100	dm/yr to m/yr	Feature tracking	0.1 – 1.2	
	> 100	m/yr or higher	Feature tracking	2.3 – 2.8	
Central Andes	> 100	m/yr or higher	DGNSS	0.5 – 3.5	
	30 – 100	dm/yr to m/yr	DGNSS	> 1.5	Underestimation
Central Southern Alps	< 1	< cm/yr	DGNSS	0 – 0.03	Underestimation
	3 – 10	cm/yr to dm/yr	DGNSS	0.02 – 0.14	

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

5 Discussion

5.1 Subjectivity of the method

The main problem for integrating standardized kinematic information within inventories compiled from different operators is the subjectivity of the operator himself in carrying out the work. The inherent degree of subjectivity is a typical source of uncertainty and variability within inventories compiled from remotely sensed imagery (Brardinoni et al., 2019; Jones et al., 2018a). The proposed guidelines contain specific rules to guide the operator and reduce the operator's freedom to make specific choices, thus reducing and limiting the subjectivity. Unlike other techniques, the InSAR signal provides an accurate measurement of movement, but the interpretation of the signal can still be affected by some degree of variability; therefore, the multiple phases of correction and adjustment conducted by a second operator were applied to further reduce the subjectivity and increase the overall reliability of the results. In addition, since the assigned moving area velocity classes and rock glacier kinematic attributes refer to a range and not a precise value, this contributes to further reduce the degree of subjectivity.

Despite the guidelines adopted, some degree of subjectivity can still occur. Therefore, before starting this work on the eleven investigated sites, the operators involved in this work independently tested the guidelines on two regions in the Western Swiss Alps. Such an inter-comparison exercise has shown to be a useful approach to evaluate the operator subjectivity (Brardinoni et al., 2019). Results of this inter-comparison exercise are included in a specific document of the ESA Permafrost_CCI project (ESA - PVIR report, 2021). Outcomes show an increase in variability (i) in delineation and velocity classification of moving areas affected by large temporal- and spatial- variations in velocity, and (ii) in the kinematic classification of rock glaciers affected by a greater velocity heterogeneity of the related moving areas; however, often the same landforms have been classified with similar or adjacent classes, especially for fast landforms, because fast-moving classes include wider velocity ranges than slow-moving classes with smaller velocity ranges (ESA - PVIR report, 2021). Results of this inter-comparison exercise were also useful in establishing more strict and clear rules to further reduce the subjectivity, releasing the most refined version of the guidelines presented here. Furthermore, this initial stage conducted on two limited regions improved the knowledge and confidence of the method proposed by researchers.

5.2 Dependencies related to moving area inventories

The guidelines presented here define rules that can be followed using different remote sensing techniques. In this work we used the InSAR technology, and therefore moving area inventories are affected by limitations related to radar interferometry (Barboux et al., 2014; Klees and Massonnet, 1998; Strozzi et al., 2020). The use of the same platforms (i.e., Sentinel-1 and ALOS-2) that share the same technical limits in all the investigated regions, however, simplifies the comparison between the moving area inventories.

The first limit related to InSAR is the general underestimation of displacements measured in the moving areas (Klees and Massonnet, 1998; Massonnet and Souyris, 2008). The downslope direction is generally assumed to represent the real 3D movement of rock glaciers (Barboux et al., 2014), therefore the magnitude of displacement of moving areas on north- and south-facing slopes is more underestimated, even if both ascending and descending geometries are used.

The second limit related to InSAR concerns moving areas with slow movements (i.e., with velocities slower than 3 cm/yr), mainly investigated using annual interferograms with Sentinel-1 and ALOS-2 (Barboux et al., 2014; Yague-Martinez et al., 2016). With long time intervals (i.e., annual), the quality of the interferograms is lower due to loss of phase coherence (Barboux et al., 2014; Bertone et al., 2019; Klees and Massonnet, 1998; Touzi et al., 1999). Slow movements are therefore more complicated to be assessed with enough precision, and the reliability is consequently lower. For this reason, moving areas with velocity class "< 1 cm/yr" are probably not mapped in the Central Andes, Northern Tien Shan, Disko Island, Vanoise, Southern Venosta, and the Swiss Alps regions (Fig. 9a and Table 3), where the focus is set on the more active landforms. In Troms and Finnmark regions, the large number of slow moving areas is related to the semi-automated method, able to better derive slow movements by exploiting a large set of interferograms with long time intervals.

Despite the limitations, InSAR is an appropriate tool for this exercise aimed at compiling kinematic inventories in as many representative periglacial regions worldwide as possible (Yague-Martinez et al., 2016). The InSAR image processing effort has been split across many sites. More advanced interferometric processing strategies such as Persistent Scatterer Interferometry (Crosetto et al., 2016; Ferretti et al., 2001) would allow to derive slow surface motion precisely, but the processing load is much more significant, and special attention has to be paid to the long-lasting snow-cover and the atmospheric stratification at high altitudes (Barboux et al., 2015; Osmanoğlu et al., 2016).

To reduce the intrinsic limitations of InSAR, additional or alternative techniques may be used to support kinematic classification. For example, feature tracking conducted on airborne high resolution optical images represent a potential technique to provide kinematic information on large areas, depending on the availability of optical images (Kääb et al., 2021; Necsoiu et al., 2016).

5.3 Characteristics related to the kinematic of rock glaciers

The guidelines used for assigning kinematic attributes to rock glaciers aim to be technology independent. However, the inherent dynamic characteristics of the rock glacier can have impacts on the results. The seasonal variability (Berger et al., 2004; Cicoira et al., 2019; Delaloye and Staub, 2016; Kenner et al., 2017; Wirz et al., 2016) is considered when the velocity classes of moving areas assigned during an observation time window of a few months are converted to kinematic attributes of rock glaciers (the latter refer to a multi-annual validity time frame, Table 2); however, the kinematic information might still be overestimated in cases where the rock glacier undergoes a strong seasonal acceleration. Furthermore, during an observation time window of a few months (snow-free periods) local effects such as residual snow can further reduce the amount of available interferometric data. Coherent 6-days winter interferograms with Sentinel-1 could be used in the future to highlight the seasonal fluctuations (Strozzi et al., 2020).

The kinematic attributes assigned in this work provide general information about the kinematic status of rock glaciers only during the periods investigated with InSAR data, and without any monitoring purpose. Monitoring activities on rock glaciers are conducted using specific and more precise techniques (Delaloye et al., 2013; Fey and Krainer, 2020; Kääb et al., 2021; Strozzi et al., 2020), and the approach here described can only support the identification of sites to start monitoring activities. However, kinematic information obtained from this approach can also be used as a support for future work on the calibration of permafrost numerical models (Boeckli et al., 2012; Sattler et al., 2016; Westermann et al., 2017) and artificial intelligence algorithms (Boeckli et al., 2012; Frauenfelder et al., 2008; Kofler et al., 2020; Robson et al., 2020).

In addition to the kinematic information, the high-quality optical data and the investigated connections of rock glaciers with other landforms (Fig. 10) provide useful information (IPA Action Group - baseline concepts, 2020; Kääb et al., 2021; Necsoiu et al., 2016; Seppi et al., 2012); for example, in glacier-connected and glacier-forefield connected landforms the distinction between rock glaciers and debris-covered glaciers is sometimes complicated (Berger et al., 2004; Bolch et al., 2019; Bosson and Lambiel, 2016), and analyzes of high-quality optical data help to discriminate the upper glacial part from the real lower rock glacier part. In the Central Andes region – where the upslope connections are often unclear - the distinctions between rock glaciers and debris-covered glaciers have not always been possible. Furthermore, the identification of glacier-connected and glacier-forefield connected rock glaciers improve the kinematic information, because these forms are frequently characterized by ice melting that induce subsidence in summer time (Delaloye and Staub, 2016). The portion of rock glaciers potentially affected by consistent subsidence (i.e., glacier- and glacier-forefield upslope connected) is lower than 13 % in the investigated regions, except in Northern Tien Shan region where it is around 45 %.

5.4 Kinematic analysis of produced moving areas and rock glaciers

A total of 5,077 moving areas were inventoried in the investigated regions and provide information of slope movements related to rock glaciers. Both manual and semi-automated methods are used in this work, but slight discrepancies are detected between these two approaches, with fragmented outlines that fit the pixel boundaries without any smoothing in Norway and Svalbard regions (Rouyet et al., 2021). Manually drawn moving areas better follow the standards defined in guidelines, smooth outlines fit the detected slope movements, and small moving areas (with slow velocities) are often not mapped. Therefore, the choice between manual and semi-automated methods should be made according to the region extent and the available time, favoring semi-automated methods mainly for very large regions, where manual approaches take too much time.

Despite the slight discrepancies detected in the moving area inventories, the kinematic attributes were successfully assigned to 3,666 rock glaciers. The main irregularities are related to the absence of rock glaciers classified as relict in the Vanoise, Nordenskiöld Land, Disko Island, Brooks Range, Northern Tien Shan, Central Andes, and Central Southern Alps regions (Fig. 7 and Table 4). Only Southern Venosta, Troms and Finnmark regions include a consistent number of rock glaciers without detectable movements. In Nordenskiöld Land and Western Swiss Alps regions, relict rock glaciers were not mapped because the method used to produce the rock glaciers inventories exclude these landforms without movement. Therefore, the completeness of the inventories used to identify rock glaciers is essential to obtain a thorough and comprehensive kinematic investigation. In Vanoise, Disko Island, Brooks Range, Northern Tien Shan, Central Andes, and Central Southern Alps regions relict rock glaciers were not mapped because the classification effort was placed only on faster moving landforms. The choice not to carry out analyzes on rock glaciers without a clear signal of movement in these regions can be related to two reasons. First, the aim of this approach is to implement the kinematic information of rock glaciers affected by movement, without paying too much attention to the slowest landforms. Second, rock glaciers without movements or with slow movements are more difficult to investigate, because the quality of the InSAR signal of yearly interferograms is generally lower, as explained above (Barboux et al., 2014; Bertone et al., 2019; Touzi et al., 1999); consequently, relict and slow-moving rock glaciers are more easily omitted or classified as undefined. For the above reasons, some compiled inventories only provide preliminary results, which still need improvement and investigation. However, the use of InSAR data allowed to update the inventories, leading to a more accurate classification, especially for active and transitional landforms.

In this work we observed a large number of fast-moving rock glaciers (i.e., with kinematic attributes of "dm/yr to m/yr" and "m/yr or higher") in the Vanoise, Central Andes, and Northern Tien Shan regions (Fig. 9b and Table 4). Higher velocity rates of rock glaciers in Northern Tien Shan and Central Andes than in the Alps have already been observed (Kääb et al., 2021; Roer et al., 2005). However, as already documented by other authors (Delaloye et al., 2010, 2013; Delaloye and Staub, 2016; Marcer et al., 2019; Roer et al., 2008; Seppi et al., 2019), there are also fast-moving rock glaciers situated on steep slopes in the Alps. In Troms, Finnmark and Nordenskiöld Land, the high number of slow-moving rock glaciers (i.e., "< cm/yr", "cm/yr" and "cm/yr to dm/yr") has also been observed in other studies (Eriksen et al., 2018; Kääb, 2002; Rouyet et al., 2019). In contrast, little attention had been paid to the dynamics and evolution of rock glaciers in Brooks Range, Disko Island, and Central Southern Alps regions (Calkin, 1987; Sattler et al., 2016); this work therefore presents preliminary results on the kinematics of rock glaciers in these study areas.

The quality of the assigned kinematic information was evaluated according to recent work (Kääb et al., 2021; Strozzi et al., 2020) on thirty landforms in all the investigated regions, except for Southern Venosta, Finnmark and Disko Island (Table 5). The four landforms underestimated may be related to the limits of the InSAR technique, such as the LOS orientation explained above, which generates underestimation especially on north- and south-facing slopes. On the other hand, the two landforms overestimated may be related to the high seasonal variability of rock glaciers and the different observation time windows used to measure the movements between InSAR (i.e., summer for fast moving landforms) and the validation dataset (i.e., annual). As explained above, the seasonal variability is considered when the velocity classes of moving areas are converted to kinematic attributes of rock glaciers; however, if the rock glacier undergoes a strong seasonal acceleration, the assigned kinematic attributes might still be higher than the kinematic information available from the validation dataset.

6 Conclusions

The method and the products presented here are the first results of an internationally coordinated work in which researchers from nine institutes applied common guidelines on numerous regions worldwide, using spaceborne radar interferometry, to systematically integrate kinematic information within rock glacier inventories. Eleven periglacial regions with different environmental parameters on both the Northern and Southern Hemisphere are investigated. Despite the various regions and intensive manual effort, the definition and application of common rules to implement a rock glacier kinematic attribute within inventories have been feasible. It was possible to assign kinematic information to a majority of the investigated rock glacier inventories. However, in some regions, a greater number of landforms need to be validated, and rock glaciers with slow-movements or without movements need to be investigated. The achieved results open up new possibilities for the understanding and numerical modelling of permafrost, mountain landscape dynamics, which until now had to be mainly based on detailed measurements of only a few landforms, if at all. In addition, the compiled inventories, even if still preliminary for some of them, will provide opportune data for training, validation, and testing of artificial intelligence algorithms on rock glaciers using satellite imagery.

Further research – in both remote-sensing and fieldwork-based approaches – is needed to reduce the limitations associated with interferometry. Both the guidelines and the inventories still need improvement, e.g., the application of more advanced InSAR processing strategies such as multi-temporal interferometric approaches, or different remote sensing technologies such as feature tracking on optical airborne images. The lessons learned from the current study are critical in refining the proposed method and applying it widely to more regions.

Supplementary material

The supplementary material includes the description of study areas (A), the tables of the attributes assigned to the moving areas (Table B1) and rock glaciers (Table B2), and the description of the conducted validation (C).

Data Availability

The produced inventories are available at https://www.unifr.ch/geo/geomorphology/en/research/cci-permafrost.html, last access: 12 October 2021.

Author Contributions

CB, RD, LR and TS designed the study and managed the project. AB analysed data and wrote the manuscript. CB, RD, LR and TS contributed to analyse data and wrote the manuscript. AB, CB, XB, TB, FB, RC, HC, MD, RD, BE, OH, CL, KL, GP, LR, LRu produced the inventories. TS and LR produced the interferometric data. All authors contributed to the writing of the final version of the manuscript.

Financial support

This research was funded by the ESA Permafrost_CCI project (grant number 4000123681/18/I-NB).

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. Some authors are members of the editorial board of The Cryosphere. The peer-review process was guided by an independent editor.

Acknowledgments

The SAR data was processed with Gamma software. Moving area inventories and rock glaciers data were produced by the authors involved in this work.

References

Azócar, G. F. and Brenning, A.: Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27–33 S), Permafr. Periglac. Process., 21(1), 42–53, 2010.

Barboux, C., Delaloye, R. and Lambiel, C.: Inventorying slope movements in an Alpine environment using DInSAR, Earth Surf. Process. Landforms, 39(15), 2087–2099, doi:10.1002/esp.3603, 2014.

Barboux, C., Strozzi, T., Delaloye, R., Wegmüller, U. and Collet, C.: Mapping slope movements in Alpine environments using TerraSAR-X interferometric methods, ISPRS J. Photogramm. Remote Sens., 109, 178–192, doi:10.1016/j.isprsjprs.2015.09.010, 2015.

Barcaza, G., Nussbaumer, S. U., Tapia, G., Valdés, J., García, J.-L., Videla, Y., Albornoz, A. and Arias, V.: Glacier inventory and recent glacier variations in the Andes of Chile, South America, Ann. Glaciol., 58(75pt2), 166–180, 2017.

Barsch, D.: Permafrost creep and rockglaciers, Permafr. Periglac. Process., 3(3), 175–188, doi:10.1002/PPP.3430030303, 1992.

Barsch, D.: Rockglaciers: indicators for the Permafrost and Former Geoecology in High Mountain Environment, Springer Sci., Berlin, Heidelberg, Germany, 1996.

Berger, J., Krainer, K. and Mostler, W.: Dynamics of an active rock glacier (Ötztal Alps, Austria), Quat. Res., 62(03), 233–242, doi:10.1016/j.yqres.2004.07.002, 2004.

Berthling, I.: Beyond confusion: Rock glaciers as cryo-conditioned landforms, Geomorphology, 131(3–4), 98–106, doi:10.1016/J.GEOMORPH.2011.05.002, 2011.

Bertone, A., Zucca, F., Marin, C., Notarnicola, C., Cuozzo, G., Krainer, K., Mair, V., Riccardi, P., Callegari, M. and Seppi, R.: An Unsupervised Method to Detect Rock Glacier Activity by Using Sentinel-1 SAR Interferometric Coherence: A Regional-Scale Study in the Eastern European Alps, Remote Sens., 11(14), 1711, doi:10.3390/rs11141711, 2019.

Blöthe, J. H., Rosenwinkel, S., Höser, T. and Korup, O.: Rock-glacier dams in High Asia, Earth Surf. Process. Landforms, 44(3), 808–824, doi:10.1002/esp.4532, 2019.

Blöthe, J. H., Halla, C., Schwalbe, E., Bottegal, E., Trombotto Liaudat, D. and Schrott, L.: Surface velocity fields of active rock glaciers and ice-debris complexes in the Central Andes of Argentina, Earth Surf. Process. Landforms, 46(2), 504–522, 2021.

Boeckli, L., Brenning, A., Gruber, S. and Noetzli, J.: A statistical approach to modelling permafrost distribution in the European Alps or similar mountain ranges, Cryosph., 6, 125–140, doi:10.5194/tc-6-125-2012, 2012.

Bolch, T. and Gorbunov, A. P.: Characteristics and origin of rock glaciers in northern Tien Shan (Kazakhstan/Kyrgyzstan), Permafr. Periglac. Process., 25(4), 320–332, 2014.

Bolch, T. and Strel, A.: Evolution of rock glaciers in northern Tien Shan, Central Asia, 1971 – 2016, in 5th European Conference on Permafrost, Chamonix, France, 23 June - 1 July 2018, pp. 48–49., 2018.

Bolch, T., Marchenko, S., Braun, L. N., Hagg, W., Severskiy, I. V and Young, G.: Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions, IHP/HWRP-Berichte, (8), 132–144, 2009.

Bolch, T., Rohrbach, N., Kutuzov, S., Robson, B. A. and Osmonov, A.: Occurrence, evolution and ice content of ice-debris complexes in the Ak-Shiirak, Central Tien Shan revealed by geophysical and remotely-sensed investigations, Earth Surf. Process. Landforms, 44(1), 129–143, 2019.

Bosson, J.-B. and Lambiel, C.: Internal Structure and Current Evolution of Very Small Debris-Covered Glacier Systems Located in Alpine Permafrost Environments, Front. Earth Sci., 4, 39, doi:10.3389/feart.2016.00039, 2016.

Brardinoni, F., Scotti, R., Sailer, R. and Mair, V.: Evaluating sources of uncertainty and variability in rock glacier inventories, Earth Surf. Process. Landforms, 44(12), 2450–2466, doi:10.1002/esp.4674, 2019.

Brencher, G., Handwerger, A. L. and Munroe, J. S.: InSAR-based characterization of rock glacier movement in the Uinta Mountains, Utah, USA, Cryosph., 15(10), 4823–4844, 2021.

Calkin, P. E.: Rock glaciers of central Brooks Range, Alaska, USA, Rock glaciers, 65–82, 1987.

Charbonneau, A. A. and Smith, D. J.: An inventory of rock glaciers in the central British Columbia Coast Mountains, Canada, from high resolution Google Earth imagery, Arctic, Antarct. Alp. Res., 50(1), 1489026, doi:10.1080/15230430.2018.1489026, 2018.

Cicoira, A., Beutel, J., Faillettaz, J. and Vieli, A.: Water controls the seasonal rhythm of rock glacier flow, Earth Planet. Sci. Lett., 528, 115844, doi:10.1016/J.EPSL.2019.115844, 2019.

Colucci, R. R., Boccali, C., Žebre, M. and Guglielmin, M.: Rock glaciers, protalus ramparts and pronival ramparts in the south-eastern Alps, Geomorphology, 269, 112–121, doi:10.1016/j.geomorph.2016.06.039, 2016.

Cremonese, E., Gruber, S., Phillips, M., Pogliotti, P., Boeckli, L., Noetzli, J., Suter, C., Bodin, X., Crepaz, A., Kellerer-Pirklbauer, A., Lang, K., Letey, S., Mair, V., Morra Di Cella, U., Ravanel, L., Scapozza, C., Seppi, R. and Zischg, A.: Brief communication: "An inventory of permafrost evidence for the European Alps," Cryosphere, 5(3), 651–657, doi:10.5194/tc-5-651-2011, 2011.

Crosetto, M., Monserrat, O., Devanthéry, N., Cuevas-González, M., Barra, A. and Crippa, B.: Persistent scatterer interferometry using Sentinel-1 data, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., 41(B7), 835–839, doi:10.5194/isprsarchives-XLI-B7-835-2016, 2016.

Darrow, M. M., Gyswyt, N. L., Simpson, J. M., Daanen, R. P. and Hubbard, T. D.: Frozen debris lobe morphology and movement: an overview of eight dynamic features, southern Brooks Range, Alaska, Cryosph., 10(3), 977–993, 2016.

Delaloye, R. and Staub, B.: Seasonal variations of rock glacier creep: Time series observations from the Western Swiss Alps, in Proceedings of the International Conference on Book of Abstracts, Potsdam, Germany, 20-24 June 2016, pp. 20–24., 2016.

Delaloye, R., Lambiel, C. and Gärtner-Roer, I.: Overview of rock glacier kinematics research in the Swiss Alps, Geogr. Helv., 65(2), 135–145, doi:10.5194/gh-65-135-2010, 2010.

Delaloye, R., Morard, S., Barboux, C., Abbet, D., Gruber, V., Riedo, M. and Gachet, S.: Rapidly moving rock glaciers in Mattertal, Jahrestagung der Schweizerischen Geomorphol. Gesellschaft, 29, 21–31, 2013.

Delaloye, R., Barboux, C., Bodin, X., Brenning, A., Hartl, L., Hu, Y., Ikeda, A., Kaufmann, V., Kellerer-Pirklbauer, A. and Lambiel, C.: Rock glacier inventories and kinematics: A new IPA Action Group, in Eucop5–5th European Conference of Permafrost, Chamonix, France, 23 June - 1 July 2018, vol. 23, pp. 392–393., 2018.

Ellis, J. M. and Calkin, P. E.: Nature and distribution of glaciers, neoglacial moraines, and rock glaciers, east-central Brooks Range, Alaska, Arct. Alp. Res., 11(4), 403–420, 1979.

Eriksen, H. Ø., Rouyet, L., Lauknes, T. R., Berthling, I., Isaksen, K., Hindberg, H., Larsen, Y. and Corner, G. D.: Recent acceleration of a rock glacier complex, Adjet, Norway, documented by 62 years of remote sensing observations, Geophys. Res. Lett., 45(16), 8314–8323, 2018.

ESA - PVIR report: ESA CCI+ Permafrost. CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.1 Product Validation and Intercomparison Report (PVIR)., https://climate.esa.int/media/documents/CCI_PERMA_CCN1_2_D4.1_PVIR_v1.0_20210127.pdf, last access: 12 October 2021.

Falaschi, D., Tadono, T. and Masiokas, M.: Rock glaciers in the patagonian andes: an inventory for the monte san lorenzo (cerro cochrane) massif, 47° s, Geogr. Ann. Ser. A, Phys. Geogr., 97(4), 769–777, doi:10.1111/geoa.12113, 2015.

Ferretti, A., Prati, C. and Rocca, F.: Permanent scatterers in SAR interferometry, IEEE Trans. Geosci. Remote Sens., 39(1), 8–20, doi:10.1109/36.898661, 2001.

Fey, C. and Krainer, K.: Analyses of UAV and GNSS based flow velocity variations of the rock glacier Lazaun (Ötztal Alps, South Tyrol, Italy), Geomorphology, 365, 107261, doi:10.1016/j.geomorph.2020.107261, 2020.

Frauenfelder, R., Schneider, B. and Kääb, A.: Using dynamic modelling to simulate the distribution of rockglaciers, Geomorphology, 93(1–2), 130–143, doi:10.1016/J.GEOMORPH.2006.12.023, 2008.

Gorbunov, A. P., Seversky, E. V, Titkov, S. N., Marchenko, S. S. and Popov, M.: Rock glaciers, Zailiysiky Range, Kungei Ranges, Tienshan, Kazakhstan. National Snow and Ice Data Center/World Data Center for Glaciology, Boulder, CO, Digit. media, 1998.

Guglielmin, M. and Smiraglia, C.: The rock glacier inventory of the Italian Alps, 7th Int. Conf. Permafrost, Yellowknife, Canada. Univ. Laval Press. Nord., (55), 375–382, 1998.

Haeberli, W.: Creep of mountain permafrost: internal structure and flow of alpine rock glaciers, Mitteilungen der Versuchsanstalt fur Wasserbau, Hydrol. und Glaziologie an der ETH Zurich, 77, 1985.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S. and Mühll, D. V.: Permafrost creep and rock glacier dynamics, Permafr. Periglac. Process., 17(3), 189–214, doi:10.1002/ppp.561, 2006.

Humlum, O.: Rock glacier types on Disko, central West Greenland, Geogr. Tidsskr. J. Geogr., 82(1), 59–66, 1982.

IPA Action Group - baseline concepts: Towards standard guidelines for inventorying rock glaciers. Baseline concepts. Version 4.1., https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/IPA/Guidelines/V4/200507_Baseline_Concepts_Inventorying_Rock_Glaciers_V4.1.pdf, last access: 8 October 2021, 2020.

IPA Action Group - kinematic approach: Rock glacier inventory using InSAR (kinematic approach), Practical Guidelines v3.0.2., https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/CCI/Guidelines/RGI_ka_InSAR-based_Guidelines_v.3.0.2.pdf, last access: 8 October 2021, 2020.

Jones, D. B., Harrison, S., Anderson, K. and Betts, R. A.: Mountain rock glaciers contain globally significant water stores, Sci. Rep., 8(1), 2834, doi:10.1038/s41598-018-21244-w, 2018a.

Jones, D. B., Harrison, S., Anderson, K., Selley, H. L., Wood, J. L. and Betts, R. A.: The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya, Glob. Planet. Change, 160(August 2017), 123–142, doi:10.1016/j.gloplacha.2017.11.005, 2018b.

Kääb, A.: Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: Examples using digital aerial imagery and ASTER data, ISPRS J. Photogramm. Remote Sens., 57(1–2), 39–52, doi:10.1016/S0924-2716(02)00114-4, 2002.

Kääb, A., Chiarle, M., Raup, B. and Schneider, C.: Climate change impacts on mountain glaciers and permafrost, Glob. Planet. Change, 56(1–2), vii–ix, doi:10.1016/j.gloplacha.2006.07.008, 2007.

Kääb, A., Strozzi, T., Bolch, T., Caduff, R., Trefall, H., Stoffel, M. and Kokarev, A.: Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s, Cryosph., 15(2), 927–949, 2021.

Kellerer-Pirklbauer, A., Delaloye, R., Lambiel, C., Gärtner-Roer, I., Kaufmann, V., Scapozza, C., Krainer, K., Staub, B., Thibert, E. and Bodin, X.: Interannual variability of rock glacier flow velocities in the European Alps, in 5th European Conference on Permafrost, June 2018, Chamonix, France, 23 June - 1 July 2018, pp. 396–397., 2018.

Kenner, R., Phillips, M., Beutel, J., Hiller, M., Limpach, P., Pointner, E. and Volken, M.: Factors Controlling Velocity Variations at Short-Term, Seasonal and Multiyear Time Scales, Ritigraben Rock Glacier, Western Swiss Alps, Permafr. Periglac. Process., 684(May), 675–684, doi:10.1002/ppp.1953, 2017.

Klees, R. and Massonnet, D.: Deformation measurements using SAR interferometry: potential and limitations, Geol. en Mijnb., 77(2), 161–176, doi:10.1023/A:1003594502801, 1998.

Kofler, C., Steger, S., Mair, V., Zebisch, M., Comiti, F. and Schneiderbauer, S.: An inventory-driven rock glacier status model (intact vs. relict) for South Tyrol, Eastern Italian Alps, Geomorphology, 350, 106887, 2020.

Konrad, S. K., Humphrey, N. F., Steig, E. J., Clark, D. H., Potter Jr, N. and Pfeffer, W. T.: Rock glacier dynamics and paleoclimatic implications, Geology, 27(12), 1131–1134, 1999.

Kummert, M. and Delaloye, R.: Mapping and quantifying sediment transfer between the front of rapidly moving rock glaciers and torrential gullies, Geomorphology, 309, 60–76, 2018.

Kummert, M., Delaloye, R. and Braillard, L.: Erosion and sediment transfer processes at the front of rapidly moving rock glaciers: Systematic observations with automatic cameras in the western Swiss Alps, Permafr. Periglac. Process., 29(1), 21–33, doi:10.1002/ppp.1960, 2018.

Lambiel, C., Strozzi, T., Paillex, N., Vivero, S. and Jones, N.: Mapping rock glaciers in the Southern Alps of New Zealand with Sentinel-1 InSAR, in 1st Southern Hemisphere Conference on Permafrost, Queenstown, New Zealand, 4-14 December 2019., 2019.

Lilleøren, K. S. and Etzelmüller, B.: A regional inventory of rock glaciers and ice-cored moraines in Norway, Geogr. Ann. Ser. A, Phys. Geogr., 93(3), 175–191, 2011.

Lilleøren, K. S., Etzelmüller, B., Gärtner-Roer, I., Kääb, A., Westermann, S. and Guðmundsson, Á.: The distribution, thermal characteristics and dynamics of permafrost in Tröllaskagi, northern Iceland, as inferred from the distribution of rock glaciers and ice-cored moraines, Permafr. Periglac. Process., 24(4), 322–335, 2013.

Liu, L., Millar, C. I., Westfall, R. D. and Zebker, H. A.: Surface motion of active rock glaciers in the Sierra Nevada, California, USA: inventory and a case study using InSAR, Cryosph., 7(4), 1109–1119, doi:10.5194/tc-7-1109-2013, 2013.

Mair, V., Zischg, A., Stötter, J., Krainer, K., Zilger, J., Belitz, K., Schenk, A., Damm, B. and Bucher, K.: PROALP-Mapping and monitoring of permafrost phenomena in the Autonomous Province of Bolzano, Italy, in Geophysical Research Abstracts, p. 10., 2008.

Marcer, M.: Rock glaciers automatic mapping using optical imagery and convolutional neural networks, Permafr. Periglac. Process., 31(4), 561–566, 2020.

Marcer, M., Bodin, X., Brenning, A., Schoeneich, P., Charvet, R. and Gottardi, F.: Permafrost Favorability Index: Spatial Modeling in the French Alps Using a Rock Glacier Inventory, Front. Earth Sci., 5(December), doi:10.3389/feart.2017.00105, 2017.

Marcer, M., Serrano, C., Brenning, A., Bodin, X., Goetz, J. and Schoeneich, P.: Evaluating the destabilization susceptibility of active rock glaciers in the French Alps, Cryosph., 13, 141–155, doi:10.5194/tc-13-141-2019, 2019.

Marcer, M., Ringsø Nielsen, S., Ribeyre, C., Kummert, M., Duvillard, P., Schoeneich, P., Bodin, X. and Genuite, K.: Investigating the slope failures at the Lou rock glacier front, French Alps, Permafr. Periglac. Process., 31(1), 15–30, 2020.

Massonnet, D. and Feigl, K. L.: Radar interferometry and its application to changes in the Earth's surface, Rev. Geophys., 36(4), 441–500, doi:10.1029/97RG03139, 1998.

Massonnet, D. and Souyris, J.-C.: Imaging with Synthetic Aperture Radar, EPFL Press, New York, 2008.

Matsuoka, M., Watanabe, T., Ikea, A., Christiansen, H. H., Humlum, O. and Rouyet, L.: Decadal-scale variability of polar rock glacier dynamics: accelerating due to warming?, in 1st Southern Hemisphere Conference on Permafrost, Queenstown, New Zealand, 4-14 December 2019., 2019.

Munroe, J. S.: Distribution, evidence for internal ice, and possible hydrologic significance of rock glaciers in the Uinta Mountains, Utah, USA, Quat. Res. (United States), 90(1), 50–65, doi:10.1017/qua.2018.24, 2018.

Necsoiu, M., Onaca, A., Wigginton, S. and Urdea, P.: Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery, Remote Sens. Environ., 177, 21–36, doi:10.1016/J.RSE.2016.02.025, 2016.

Noetzli, J., Pellet, C. and Staub, B.: PERMOS reports, Cryospheric Comm. Swiss Acad. Sci., http://www.permos.ch/publications.html, last access: 14 October 2021, 2019.

Osmanoğlu, B., Sunar, F., Wdowinski, S. and Cabral-Cano, E.: Time series analysis of InSAR data: Methods and trends, ISPRS J. Photogramm. Remote Sens., 115, 90–102, doi:10.1016/j.isprsjprs.2015.10.003, 2016.

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P. and Pacheco, P.: A First Rock Glacier Inventory for the Bolivian Andes, Permafr. Periglac. Process., 25(4), 333–343, doi:10.1002/ppp.1816, 2014.

Reinosch, E., Gerke, M., Riedel, B., Schwalb, A., Ye, Q. and Buckel, J.: Rock glacier inventory of the western Nyainqêntanglha Range, Tibetan Plateau, supported by InSAR time series and automated classification, Permafr. Periglac. Process., in press, 2021.

Robson, B. A., Bolch, T., MacDonell, S., Hölbling, D., Rastner, P. and Schaffer, N.: Automated detection of rock glaciers using deep learning and object-based image analysis, Remote Sens. Environ., 250, 112033, doi:10.1016/j.rse.2020.112033, 2020.

Roer, I., Kääb, A. and Dikau, R.: Rockglacier acceleration in the Turtmann valley (Swiss Alps): Probable controls, Nor. Geogr. Tidsskr. - Nor. J. Geogr., 59(2), 157–163, doi:10.1080/00291950510020655, 2005.

Roer, I., Haeberli, W., Avian, M., Kaufmann, V., Delaloye, R., Lambiel, C. and Kääb, A.: Observations and considerations on destabilizing active rock glaciers in the European Alps, Ninth Int. Conf. Permafrost, Univ. Alaska, Fairbanks, Alaska, June 29 - July 3, 2008, (4), 1505–1510, doi:10.5167/uzh-6082, 2008.

Rouyet, L., Lauknes, T. R., Christiansen, H. H., Strand, S. M. and Larsen, Y.: Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR, Remote Sens. Environ., 231, 111236, doi:10.1016/J.RSE.2019.111236, 2019.

Rouyet, L., Lilleøren, K., Böhme, M., Vick, L., Delaloye, R., Etzelmüller, B., Lauknes, T. R., Larsen, Y. and Blikra, L. H.: Regional InSAR inventory of slope movement in Northern Norway, Submitted to Frontiers in Earth Science, 2021.

Sandwell, D. T. and Price, E. J.: Phase gradient approach to stacking interferograms, J. Geophys. Res. Solid Earth, 103(B12), 30183–30204, doi:https://doi.org/10.1029/1998JB900008, 1998.

Sattler, K., Anderson, B., Mackintosh, A., Norton, K. and de Róiste, M.: Estimating Permafrost Distribution in the Maritime Southern Alps, New Zealand, Based on Climatic Conditions at Rock Glacier Sites, Front. Earth Sci., 4, 4, doi:10.3389/feart.2016.00004, 2016.

Schmid, M. O., Baral, P., Gruber, S., Shahi, S., Shrestha, T., Stumm, D. and Wester, P.: Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth, Cryosphere, 9(6), 2089–2099, doi:10.5194/tc-9-2089-2015, 2015.

Scotti, R., Brardinoni, F., Alberti, S., Frattini, P. and Crosta, G. B.: A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps, Geomorphology, 186, 136–149, doi:10.1016/j.geomorph.2012.12.028, 2013.

Scotti, R., Crosta, G. B. and Villa, A.: Destabilisation of Creeping Permafrost: The Plator Rock Glacier Case Study (Central Italian Alps), Permafr. Periglac. Process., 28(1), 224–236, doi:10.1002/ppp.1917, 2017.

Seppi, R., Carton, A., Zumiani, M., Dall'Amico, M., Zampedri, G. and Rigon, R.: Inventory, distribution and topographic features of rock glaciers in the southern region of the Eastern Italian Alps (Trentino), Geogr. Fis. e Din. Quat., 35(2), 185–197, doi:10.4461/GFDQ.2012.35.17, 2012.

Seppi, R., Carturan, L., Carton, A., Zanoner, T., Zumiani, M., Cazorzi, F., Bertone, A., Baroni, C. and Salvatore, M. C.: Decoupled kinematics of two neighbouring permafrost creeping landforms in the Eastern Italian Alps, Earth Surf. Process. Landforms, 44(13), 2703–2719, doi:10.1002/esp.4698, 2019.

Strozzi, T., Caduff, R., Jones, N., Barboux, C., Delaloye, R., Bodin, X., Kääb, A., Mätzler, E. and Schrott, L.: Monitoring rock glacier kinematics with satellite synthetic aperture radar, Remote Sens., 12(3), 559, doi:10.3390/rs12030559, 2020.

Touzi, R., Lopes, A., Bruniquel, J. and Vachon, P. W.: Coherence estimation for SAR imagery, IEEE Trans. Geosci. Remote Sens., 37(1), 135–149, doi:10.1109/36.739146, 1999.

Villarroel, C., Tamburini Beliveau, G., Forte, A., Monserrat, O., Morvillo, M., Villarroel, C. D., Tamburini Beliveau, G., Forte, A. P., Monserrat, O. and Morvillo, M.: DInSAR for a Regional Inventory of Active Rock Glaciers in the Dry Andes Mountains of Argentina and Chile with Sentinel-1 Data, Remote Sens., 10(10), 1588, doi:10.3390/rs10101588, 2018.

https://doi.org/10.5194/tc-2021-342
Preprint. Discussion started: 17 January 2022

Wagner, T., Pleschberger, R., Kainz, S., Ribis, M., Kellerer-Pirklbauer, A., Krainer, K., Philippitsch, R. and Winkler, G.: The first consistent inventory of rock glaciers and their hydrological catchments of the Austrian Alps, Austrian J. Earth Sci., 113(1), 1–23, 2020.

Wang, X., Liu, L., Zhao, L., Wu, T., Li, Z. and Liu, G.: Mapping and inventorying active rock glaciers in the northern Tien Shan of China using satellite SAR interferometry, Cryosphere, 11(2), 997–1014, doi:10.5194/tc-11-997-2017, 2017.

Westermann, S., Peter, M., Langer, M., Schwamborn, G., Schirrmeister, L., Etzelmüller, B. and Boike, J.: Transient modeling of the ground thermal conditions using satellite data in the Lena River delta, Siberia, Cryosph., 11, 1441–1463, doi:10.5194/tc-11-1441-2017, 2017.

Wirz, V., Gruber, S., Purves, R. S., Beutel, J., Gärtner-Roer, I., Gubler, S. and Vieli, A.: Short-term velocity variations at three rock glaciers and their relationship with meteorological conditions, Earth Surf. Dyn., 4(1), 103–123, doi:10.5194/esurf-4-103-2016, 2016.

Yague-Martinez, N., Prats-Iraola, P., Rodriguez Gonzalez, F., Brcic, R., Shau, R., Geudtner, D., Eineder, M. and Bamler, R.: Interferometric Processing of Sentinel-1 TOPS Data, IEEE Trans. Geosci. Remote Sens., 54(4), 2220–2234, doi:10.1109/TGRS.2015.2497902, 2016.

Yu, C., Li, Z. and Penna, N. T.: Interferometric synthetic aperture radar atmospheric correction using a GPS-based iterative tropospheric decomposition model, Remote Sens. Environ., 204, 109–121, doi:10.1016/J.RSE.2017.10.038, 2018.

Zalazar, L., Ferri, L., Castro, M., Gargantini, H., Gimenez, M., Pitte, P., Ruiz, L., Masiokas, M., Costa, G. and Villalba, R.: Spatial distribution and characteristics of Andean ice masses in Argentina: results from the first National Glacier Inventory, J. Glaciol., 66(260), 938–949, 2020.

Zwieback, S., Liu, X., Antonova, S., Heim, B., Bartsch, A., Boike, J. and Hajnsek, I.: A statistical test of phase closure to detect influences on DInSAR deformation estimates besides displacements and decorrelation noise: Two case studies in high-latitude regions, IEEE Trans. Geosci. Remote Sens., 54(9), 5588–5601, 2016.