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Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide

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Supplementary material

Supplementary material A: Description of study areas

A1 Western Swiss Alps, Switzerland

The Western Swiss Alps are located at approximately 46°N 7.5°E and cover around 3,000 km^2 of typical high-mountain terrain with a predominantly continental climate. They consist of nine south-north catchments located on the orographic left side of the Rhône River with altitudes ranging between 500 m (Rhône Valley) and 4,634 m a.s.l. (Dufourspitze). Along the suspended valleys, the vertical slope extent typically ranges between 1,250 m and more than 3,000 m a.s.l.. The periglacial belt – defined as the sparsely-vegetated portion of the mountain slope in between the tree line up to the bottom of the glaciated area – ranges from approximately from 2,300 m to 3,000 m a.s.l. and is characterized by many different Alpine geomorphological processes (Barboux et al., 2015). Moving zones related to the creep of frozen debris (e.g., rock glaciers, push-moraines) and shallow to deep-seated landslides affecting frozen as well as unfrozen debris or rocks are widespread.

In the Western Swiss Alps, the lower limit of discontinuous permafrost is estimated to be at an altitude of about 2,400 m a.s.l. for north-facing slopes and 2,700 m a.s.l. for southern exposures (Lambiel and Reynard, 2003). The area encompasses about 800 active rock glaciers with typical velocities on the order of 0.1 to 2 m/yr. Among them, at least eleven rock glaciers have experienced changes in their kinematics, geometry and topography over recent decades (Delaloye et al., 2010). These features, displaying exceptionally high velocities up to 10 m/yr and often showing distinct cracks as well as significant changes at their fronts, have been identified as destabilized (Delaloye et al., 2010). When located on steep slopes, they may be the source for other mass movement such as rock falls or debris flows (Delaloye et al., 2010).

The additional data used on this region consists of: © Swissimages orthoimages at 0.25 m spatial resolution; © SwissAlti3D high resolution DTM at 2 m spatial resolution (https://www.swisstopo.admin.ch; last access: 2 October 2021).

A2 Southern Venosta, Italy

The study area occupies the north-eastern portion of Ortles-Cevedale massif in South Tyrol, Central- Eastern Italian Alps (46.5°N, 10.9°E). It extends over about 970 km^2 and includes the southern side of the lower Venosta valley, as well as five tributary valleys: Ultental (Val d'Ultimo), Martelltal (Val Martello), Laasertal (Val di Lasa), and Suldental (Val di Solda). Elevation ranges from 3,905 m a.s.l. on Mount Ortles, down to about 500 m at Southern Venosta outlet. Bedrock geology is dominated by metamorphic lithologies (chiefly paragneiss, micaschists, and orthogneiss), with granite outcropping locally in lower Martelltal, and limestones and dolostones in upper Suldental. Climate is dry, with mean annual precipitation ranging from less than 600 mm in Venosta valley floor (Schlanders station) to more than 1,200 mm in upland cirque valleys (Weissbrunn station). According to Permanet modelling (www.permanet.eu; last access: 20 June 2021) and field-based evidence, discontinuous mountain permafrost occurs above threshold elevations varying between 2,300 and 2,700 m a.s.l., depending on topographic (e.g., aspect) and microclimatic (site-specific) conditions (Boeckli et al., 2012). In this context, rock glaciers are dominant geomorphic features above the present treeline. According to an unpublished regional inventory completed in September 2019, the study area hosts 781 rock glaciers, including geomorphological outlines and activity degree based of geomorphological evidence.

The additional data used on this region consists of: several web map service available from GeoCatalogo of Autonomous Province of Bolzano (https://geoportale.retecivica.bz.it/geodati.asp; laste access: 2 November 2021), including orthoimages at 2 – 0.5 m spatial resolution; LiDAR-derived DTM at 2.5 m spatial resolution (taken in 2005) free download available from GeoCatalogo of Autonomous Province of Bolzano.

A3 Vanoise Massif, France

The Vanoise massif is a mountain chain located 45.4° N and 7°E in the French Alps, covering approximately 2,000 km², and reaching 3,855 m a.s.l. at its highest point (la Grande Casse). Though it has no strictly defined boundaries, the massif is often combined with the ‘Parc National de la Vanoise’ area, and it mostly includes the highest parts of the Arc and Isère watersheds. The mean elevation of the massif is 2,325 m a.s.l., about 60 % of the terrain is above 2,500 m a.s.l., and about 4 % is covered by glaciers.

Permafrost is largely present in the region because of its topographical and climatic settings (Marcer et al., 2017), as evident by abundant rock glaciers (n = 518, 38 km²). These landforms are mostly located in valleys above 2,400 m a.s.l., and more than half of them (n = 357) most probably contain ice (Marcer et al., 2017). Among the actively-creeping rock glaciers of the Vanoise massif, 24 landforms presently show evidence of destabilization, such as extensional cracks, crevasses, and scarps (Marcer et al., 2019).

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

The additional data used on this region consists of: multi-temporal high-resolution aerial imagery for the French Alps (IGN France; https://www.ign.fr/; last access: 2 November 2021); DTM at a 10 m spatial resolution (TanDEM-X); BD-Alti at a 25 m spatial resolution (IGN France); MNT RGE at a 5 m spatial resolution (IGN France).

A4 Troms County and Finnmark County, Northern Norway

Troms County covers Kåfjord, Lyngen and Storfjord municipalities and the south-eastern part of Tromsø municipality and corresponds to approximately 4,400 km^2 (69°N 20°E). Finnmark County covers parts of Gamvik, Berlevåg and Tana municipalities and corresponds to approximately 2,600 km^2 (71°N 28°E).

In Northern Norway, rock glacier inventories exist (Lilleøren and Etzelmüller, 2011) and ground temperature are measured at several locations (Blikra and Christiansen, 2014). High resolution SAR data from TerraSAR-X and Radarsat-2 are acquired since 2009. Previous studies applied InSAR for measuring ground displacements (Eckerstorfer et al., 2018; Eriksen et al., 2018) and Sentinel-1 InSAR is now publicly available through the InSAR Norway mapping service (https://insar.ngu.no/; last access: 2 November 2021). A recent study of the Ádjet rock glacier in Troms county demonstrates acceleration in a context of climate change (Eriksen et al., 2018).

The additional data used on this region consists of: Norgeibilder orthophotos at 0.1 - 1 m spatial resolution (2001-2019) for Troms County and Norgeibilder orthophotos at 0.25 - 0.5 m spatial resolution (2008-2018) for Finnmark County; Norwegian DTM (Norwegian Mapping Agency; https://www.kartverket.no/; last access: 2 November 2021) at 10 m spatial resolution; ArcticDEM at 2 m spatial resolution.

A5 Nordenskiöld Land, Svalbard

The Nordenskiöld Land peninsula is the central land area in Svalbard between Isfjorden and Van Mijenfjorden, and is delimited by the sea to both the west and east. It approximately 4,100 km^2 (77°N 13°E) large. Permafrost is widespread all over the landscape outside the glaciers, as the area is classified as located in the zone of continuous permafrost. In Nordenskiöld Land, the permafrost essential climate variables permafrost temperature and active layer thickness are monitored at several landforms in Nordenskiöld Land (Christiansen et al., 2021). Long data series are available, e.g., in Adventdalen, Longyeardalen, Endalen, and Kapp Linné, and contribute to the study of variable periglacial conditions in the Nordic area (Christiansen et al., 2021) and the impact of meteorological variability on periglacial landforms. Several rock glaciers were studied (Isaksen et al., 2000). High-resolution SAR data from TerraSAR-X and Radarsat-2 are acquired since 2009, and InSAR in relation to permafrost studies was performed around Adventdalen using Sentinel-1 (Rouyet et al., 2019).

The additional data used on this region consists of: TopoSvalbard orthophotos at 0.2 - 0.4 m spatial resolution (2009-2012); Svalbard DTM (Norwegian Polar Institute; https://www.npolar.no/; last access: 2 November 2021) at 20 m spatial resolution.

A6 Disko Island, Greenland

Disko Island is located off the central West Coast of Greenland at approximately 70°N 53°W. It is the largest island in Greenland covering approximately 8,575 km^2, and has a high relief landscape with steep slopes rising up to 900-1,200 m a.s.l. and large glaciers covering up to 20 % of the total land area. The island is located in the zone of continuous permafrost, and rock glaciers are common on the island both inland and especially along its eastern shores, as well as on the mainland shores in Disko Bugt (Disko Bay) (Humlum, 1982). The activity of rock glaciers cannot be determined easily using field observations or photographs only, as rock glaciers may be composed of several superimposed rock glaciers of different generations and activity levels and thus render a complex topography. Remote sensing techniques are thus key to understand rock glacier kinematics and permafrost development better.

Rock glaciers on Disko Island vary considerably in length and thickness. Lobate rock glaciers are typically talus-derived and ice-cemented and are collectively estimated as 30 – 300 m long and 10 – 30 m thick, with a general surface slope of only 5 - 25° while the frontal lobe slope may be inclined up to 35 - 50° (Humlum, 1982). Furrows and ridges may form a relief up to 5 m on large rock glaciers and less than 2 m on smaller ones. According to Humlum (1982), lobate rock glaciers are predominant on north-facing valley wall slopes and are rare on south-facing slopes. Tongue-shaped rock glaciers reach greater lengths of 500 - 6,000 m with a thickness of 20 - 75 m. Frontal slopes are similarly inclined as lobate rock glaciers. A main difference is the presence of glaciers at the upper end of the majority of tongue-shaped rock glaciers, suggesting a glacial origin and an ice-cored interior (Humlum, 1982). These generally form in steeper terrain and below cirque headwalls. Ridge and furrow topography is equally observed, however, and appears to occur mainly towards the downstream end of rock glaciers. Spatulate rock glaciers are less frequent on Disko Island. They are largely tongue-shaped rock glaciers, but with a much broader, spatulate-like front, which forms when the rock glacier flows onto a less constrained so-called ‘trunk’ valley and spreads laterally (Humlum, 1982). This may often result in the formation of two distinct lobes or tongues.

The additional data used on this region consists of: © Google Earth imagery; DTM at a 10 m spatial resolution (TanDEM-X).

A7 Brooks Range, Alaska

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

Rock glaciers in the Brooks Range received little attention, with previous mapping only by a handful of individuals (Calkin, 1987; Ellis and Calkin, 1979). All of the rock glaciers are located between altitudes of 900 and 2,000 m a.s.l.. Ellis and Calkin (1979) determined that the vast majority of the rock glaciers occur north of the Continental Divide. Very few measurements of movement rates have been made on the Brooks Range rock glaciers. Rates measured on the central lobes of two rock glaciers in the early 1980s indicate rates of 0.4 and 0.1 m/yr (Calkin, 1987).

Recent studies were conducted on frozen debris lobes (FDLs) (Darrow et al., 2016). These features consist of soil, rock, organic debris, and areas of infiltration ice, with annual movement rates for eight investigated FDLs ranging from 1.0 to 25.0 m/yr.

The additional data used on this region consists of: © Google Earth imagery; TanDEM-X DTM at 10 m spatial resolution; LiDAR coverage only on specific sites.

A8 Northern Tien Shan, Kazakhstan

The mountain ranges Ile Alatau (former names Zailijskij or Transili Alatau, 43°N 77°E) of the Northern Tien Shan rise to nearly 5,000 m a.s.l. The main ridges mark the border between Kazakhstan and Kyrgyzstan. The predominant rocks are granites of Devonian, Silurian, and Carboniferous age.

The main precipitation is from frontal cyclonic activities occur in early summer in this subregion and intrusions from cold and moist air masses from the north. Therefore, the northern windward slopes are more humid. At altitudes of about 3,000 m a.s.l., precipitation can exceed 1,000 mm/yr on the northern slopes (mean annual precipitation at the Tuyuksu glacier station (3,434 m a.s.l. is 1390 mm) or be less than 800 mm/yr in leeward valleys south of the main mountain ridges. Precipitation minima occur in all areas in winter. Mean annual air temperature at the Tuyuksu station, located close to the glacier terminus, is -3.7 °C. The study region has a large periglacial zone (Marchenko, 2003). Studies indicate that permafrost is extremely rare below 2,700 m a.s.l., likely above 3,200 m a.s.l. and very likely above 3,500 m a.s.l. (Gorbunov et al., 1998). The thickness of the permafrost varies between 10 and 80 m (Marchenko, 2003).

Gorbunov et al. (1998) found based on aerial photography and field investigations many rock glaciers in Ile Alatau which cover a total area of 90.3 km^2. Most rock glaciers occur between 3,000 to 3,800 m a.s.l. (mean elevation 3,400 m a.s.l.) and are, hence, located at elevation where permafrost is likely (Gorbunov and Titkov, 1989; Bolch and Gorbunov, 2014). One front of an active rock glacier is located at about 2,500 m a.s.l. which is even below the treeline. Quite a few rock glaciers are larger than 1 km^2 with the largest covering more than 2 km^2 (Gorbunov and Titkov, 1989). Investigations of displacement rates characteristic boulders on rock glacier surfaces indicate displacement rates from less than 1 m to about 11 m (Gorbunov and Titkov, 1989).

The additional data used on this region consists of: orthorectified Landsat ETM+ data (1999 - 2002); ASTER scenes (2000 - 2019); Sentinel-2 images; © Google Earth imagery; GeoEye and Pleiades satellite images, aerial photographs, Corona KH-4 optical satellite data at 2 m spatial resolution from the 1960s; SRTM DTM at 30 m spatial resolution; TanDEM-X DTM at 10 m spatial resolution.

A9 Central Andes, Argentina

The selected area is situated in the Central Andes of Mendoza, Argentina (33°S 69°W). The region corresponds to the most southern part of the Dry Andes, where extensive areas have permafrost conditions. Most of the selected area is represented by the Cordón del Plata mountain range, Cordillera Frontal, where the maximum height surpasses 6,000 m a.s.l., and the minimum altitude is approximately 2,000 m a.s.l.. Furthermore, it is possible to find permafrost occurrence from 3,600 m on upwards (Ruiz and Trombotto Liaudat, 2012).

The total area selected (2,900 km^2) is one of the regions of the Central Andes where more rock glaciers and debris-covered/rock glacier composites or transitional landforms are located. Almost 25 % of the debris-covered and rock glaciers identified in the National Glacier Inventory of Argentina (IANIGLA; https://www.mendoza.conicet.gov.ar/; last access: 2

November 2021) are located inside the selected area and due to the topography of Cordon the Plata, glaciers, rock-glaciers, and transitional landforms area oriented to the east or west.

Cordón del Plata has the most extensive active layer monitoring record in the area (continuously since 1999). One of the most-studied rock glaciers of the Southern Andes, Morenas Coloradas rock glacier, is located there and some unique surface velocity measurements have been performed. Inside the study area, there is a real-time automatic weather station of the IANIGLA Network (http://estaciones.ianigla.mendoza-conicet.gob.ar/; last access: 2 November 2021). Weather data indicate that, in this region, the mean annual air temperature at 2,500 m a.s.l. is around 6 - 7°C stations and total annual precipitation is around 400 - 500 mm.

The additional data used on this region consists of: © Google Eart imagery; National orthoimages; DTM at 30 m spatial resolution (combining SRTM and ALOS DTM).

A10 Central part of the Southern Alps, New Zealand

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

The study area is situated in the central part of the Southern Alps, between roughly 42.9°S, 171.9° E and 44.3°S, 169.22°E. This area contains the highest elevations of the Southern Alps, and most of the rock glaciers mapped within an existing inventory (Sattler et al., 2016). The rock glaciers are mainly concentrated on the east side of the Main Divide, from south-west to north-east, in the Barrier Range, the Ben Ohau Range, the Liebig Range, the Two Thumb Range, as well as in the Lake Heron and Arthur’s Pass regions. Sattler et al. (2016) identified 383 rock glaciers based on aerial photograph analyzes. From this inventory, the authors assessed the permafrost lower limit at around 1,850 m a.s.l. on south-exposed slopes. Little attention has been paid to the dynamics and evolution of rock glaciers in the Southern Alps (Sattler et al., 2016). Therefore, their rate of activity remains largely unknown.

The additional data used on this region consists of: New Zealand aerial images (LINZ data service; https://data.linz.govt.nz/; last access: 2 November 2021); DTM at 8 m spatial resolution (originally created from January 2012 LINZ Topo50 20 m contours).

Supplementary material B: Description of conducted validation

B1 Validation in Western Swiss Alps

Within the Western Swiss Alps region, DGNSS campaigns are systematically-repeated twice per year, at the beginning and at the end of the summer season, for about fifteen active rock glaciers (Delaloye and Staub, 2016; Delavoye and Lambiel, 2017; PERMOS, 2019). In addition, permanent Global Navigation Satellite System (GNSS) stations, allowing for the continuous measurement (hourly, daily, etc.) of the movement of a single point, are operated (Delaloye and Staub, 2016; Wirz et al., 2016; PERMOS, 2019). On 7 rock glaciers, GNSS data acquired in summers 2018 and 2019 are therefore available. These rock glaciers are described below, and the velocities detected by InSAR in summers 2018 and 2019 are compared with the 3D GNSS measurements during the same time frame.

The Petit Vélan rock glacier may be considered as partially destabilized since around 1995. Following the opening of a transversal crevasse about 200 m above the front, the terminal tongue was gradually separating itself from the main rock glacier body and started to move at several meters per year before to dramatically decelerate since 2015. Annual velocity measurements of the rock glacier have been carried out by GNSS since 2005. During the summers (from July to October) 2018 and 2019, GNSS measured 3D velocities around 0.69 - 1.43 m/yr (summer 2018) and 0.73 - 2.02 m/yr (summer 2019) in the intact part (upper part), and 1.02 - 2.22 m/yr (summer 2018) and 0.67 - 1.69 m/yr (summer 2019) in the destabilized part (lower part). Furthermore, few points in the central axis of the moving part are still moving significantly fast, else is much less (5-10 cm/yr). With InSAR data two moving areas were mapped, with velocity classes of 30-100 cm/yr (in the lower part) and >100 cm/yr (in the upper part). The rock glacier was classified by distinguishing three units, whose kinematics were defined respectively as "dm/yr to m/yr" for one unit and "m/yr or higher" for two uppermost units.

On the Mille rock glacier, GNSS measurements indicate that it is still moving at a few centimetres per year in spite of its inactive appearance. During the 2018 - 2019 period, GNSS measured velocities around 2.5 – 3.5 cm/yr. With InSAR data a moving area was mapped, with velocity class of 1 - 3 cm/yr. The rock glacier was classified as “cm/yr”.

The small active rock glacier Lapires moves at a speed of 50 cm to more than one meter per year, but the summer velocity (from July to October) is about 60 - 80 % faster than the annual velocity. During the 2018 - 2019 period, GNSS measured annual velocities around 0.75 – 0.8 m/yr, but summer velocities as high as 1.5 m/yr in 2018 (not measured in 2019). With InSAR data a moving area was mapped, with a velocity class of >100 cm/yr. The rock glacier was classified as “m/yr or higher”.

The rock glacier located at the eastern slopes of Mont de l’Etoile moved at several meters per year around 1995. GNSS measurements, which have been performed between 2013 and 2018, have indicated velocities of 5-7 m/yr, decreasing over time. During the last investigated period (2017 - 2018), GNSS measured velocities of 1.3 m/yr in the upper part, and 1.9 m/yr in the lower part. With InSAR data two moving areas were mapped, with velocity classes of 30-100 cm/yr (in the lower part) and >100 cm/yr (in the upper part). The rock glacier was classified by distinguishing two units, whose kinematics were defined respectively as “dm/yr to m/yr” and “m/yr or higher”.

On the Tsarmine rock glacier the displacement measurements started in 2004 and show velocities of several meters per year. During the 2018 - 2019 period, GNSS measured annual velocities between 2.5 and 11 m/yr, with summer velocities being close to the annual mean. With InSAR data a moving area with velocity class of >100 cm/yr was mapped. The rock glacier was classified as "m/yr or higher".

The displacement of Tsavolire (La Tsevalire) rock glacier has been monitored from 2013 onwards with a permanent GNSS station. During the 2018-2019 period, GNSS measured 3D summer velocities around 1.0 (+/-0.1) m/yr. With InSAR data a moving area was mapped, with velocity class of >100 cm/yr. The rock glacier was classified as "m/yr or higher".

The last site is the Becs-de-Bosson rock glacier. The deformation field of the rock glacier is of a complex nature. Maximum speeds locally exceeded two meters per year for instance between 2013 and 2017 while the main front moved only a few centimetres. During the 2018 - 2019 period, GNSS permanent stations in the faster area measured summer velocities by 2.0 (+/- 0.8) m/yr, whereas a GNSS survey revealed 4-12 cm/yr of displacement in the terminal section. With InSAR data two moving areas were mapped, the largest one located in the main body of the rock glacier with a velocity class of >100 cm/yr, and the smaller one located in the frontal part with a velocity class of 3-10 cm/yr. The rock glacier was classified by distinguishing two units, whose kinematics were defined as "m/yr or higher" for both.

B2 Validation in Vanoise Massif (France)

On the complex of active rock glaciers Lou, repeated GNSS annual survey of blocks during the 2018 - 2019 period yields surface velocities ranging from several meters per year on the fastest Western lobe to 50 - 100 cm per year on the eastern lobe. Taking into account that the movement of the rock glacier complex is mostly south-north, two moving areas were mapped, one over most of the landform with a velocity class of 10-30 cm/yr, and a smaller one on the Western lobe with a > 100 cm/yr class. The rock glacier complex was classified as "m/yr or higher".

B3 Validation in Troms (Norway)

Feature tracking on repeat optical airphotos for two rock glaciers in Signaldalen and one at Skaiddevarri has been performed to derive 2011-2016 average velocities. In the period 2015 - 2016, the velocities range between 1 - 2 m/yr for rock glacier in Skaiddevarri and 0.5 - 1 m/yr for rock glaciers in Signaldalen. The results are in agreement with the order of magnitude documented by the InSAR-based rock glacier kinematic attributes ("m/yr or higher" for rock glacier in Skaiddevarri; dm/yr to m/yr for rock glaciers in Signaldalen) and moving area velocity classes (> 100 cm/yr for rock glacier in Skaiddevarri; 30-100 cm/yr for rock glaciers in Signaldalen).

B4 Validation in Nordenskiöld Land (Svalbard)

In Nordenskiöld Land, the 'Huset' rock glacier in Longyearbyen is monitored by annual GNSS and inclinometer measurements (collaboration between the University of Tsukuba and UNIS). Creep rates (documented since 2009) are between 2.4 and 5 cm/yr (Matsuoka et al., 2019). The InSAR moving areas highlight similar velocities (1–3 and 3–10 cm/yr). The rock glacier kinematic attribute based on InSAR has been set to “cm/yr to dm/yr”. For a large rock glacier complex at Nordenskiöldkysten the InSAR-derived kinematic class indicates < cm/yr. This is consistent with aerophotogrammetric measurements over 1970 - 1990 that did not find any significant movement, e.g., movement <= 1 cm/yr (Kääb, 2002). The latter study also found movement of several cm/yr in a small section of the upper talus, also in agreement with the InSAR results used for kinematic classification (i.e., velocity classes of < cm/yr and 1 – 3 cm/yr, kinematic attribute < cm/yr).

B5 Validation in Brooks Range (Alaska)

Since 2012, independent measurements of surface movement of eight frozen debris lobes are conducted in the Alaskan Brooks Range. Measurements are made using GNSS surveys. Four of these frozen debris lobes are included in the current rock glacier study area, and show average rate of 13, 2.1, 5.7 and 0.9 m/yr in the period 2015-2019. The assigned InSAR-based rock glacier kinematic attributes are “m/yr or higher” for all the investigated rock glacier; the assigned moving area velocity classes are > 100 cm/yr

B6 Validation in Northern Tien Shan (Kazakhstan)

For five rock glaciers in Northern Tien Shan, velocities are available from offset tracking based on repeat high-resolution optical satellite data (GeoEye and Pleiades 0.5 m) acquired between 2015 and 2019 (Kääb et al., 2021). For all five rock glaciers the velocity class was correctly determined. Velocity rates of 1 – 4 m/yr and 2.3 – 2.8 m/yr are observed within two rock glaciers classified as “m/yr or higher” and contain moving areas classified as > 100 cm/yr. Within three rock glaciers velocity rates of 0.5 – 1 m/yr, 0.4 – 1 m/yr and 0.1 – 1.2 m/yr are observed; these landforms are classified as “dm/yr to m/yr” and contain moving areas classified as 30 – 100 cm/yr. The photogrammetric velocity fields enable also a more detailed comparison of the delineations of moving areas. Overall, the InSAR outlines fit very well to the photogrammetric velocity fields.

B7 Validation in Central Andes (Argentina)

Independent measurements of the surface displacement of Morenas Coloradas and Stepanek rock glaciers for the austral summers of 2017, 2018, and 2019 are collected (Blöthe et al., 2021). Using repeated GNSS measurement of ground control points located on individual boulders in the rock glaciers' lower reach, horizontal displacements of >3.0 m/yr (range of 0.5 to 3.5 m/yr) and >1.5 m/yr are measured, for Morenas Coloradas and Stepanek, respectively. Morenas Coloradas moving areas were mapped with InSAR data with a velocity class of >100 cm/yr. Meanwhile, Stepanek's moving area was mapped with velocity class 30-100 cm/yr. For Morenas Coloradas rock glacier, the spatial pattern of surface displacement interpreted from the Sentinel-1 interferograms agrees with the spatial pattern observed in the GNSS measurements.

B8 Validation in Central Southern Alps (New Zealand)

The kinematics of two rock glaciers located in the Irishman stream, Ben Ohau range, was investigated through two GNSS measurements campaigns in January 2016 and February 2017. The first rock glacier has horizontal surface velocities lower than 3 cm/yr. With InSAR data a moving area with velocities lower than 1 cm/yr was detected. Velocities measured on the second rock glacier are comprised between 2 - 5 cm/yr in the lower part and up to 14 cm near the roots. An InSAR-detected moving area of 3-10 cm/ry was mapped for this rock glacier. For the first rock glacier the InSAR velocity is therefore slight underestimated, while for the second rock glacier the spatial pattern of surface displacement interpreted from InSAR agrees with the spatial pattern observed in the GNSS measurements.

Table S1. List of attributes assigned during the compilation of the moving area inventories, according to the version 3.0.2 (June 2020) of RGIK - kinematic approach (2020).

Name	**Definition**	**Values**
ID	A unique alpha-numerical identifier of the moving area	*CodeRG_N* *CodeRG*: ID of the related rock glacier unit *N*: numerical code allowing the differentiation of each moving area related to a single rock glacier unit (defined by the user)
Vel_class	Velocity class: variable characterizing the surface displacement rate observed in the LOS during the specified observation time window	1. Undefined 2. < 1 cm/yr (no movement up to some mm/yr) 3. 1-3 cm/yr (some cm/yr) 4. 3-10 cm/yr 5. 10-30 cm/yr (some dm/yr) 6. 30-100 cm/yr 7. > 100 cm/yr (m/yr and higher) 8. Other (velocity can be then expressed in a field "Remarks") *Note:* - *when it is possible to distinguish in between the additional velocity classes 100-300 cm/yr and > 300 cm/yr, class 6 is chosen and the specific class can be indicated in the field "Remark".* - *When the reliability of the detected moving area is low due to specific technical limitation, the moving area has to be outlined and the velocity class has to be set as "undefined".*
Time	*Observation time window* (period during which the detection and characterization is computed/measured), and *temporal frame* (duration during which the periodic	Text containing: SENSOR(s)_ OBSERVATION-TIME-WINDOW_TEMPORAL-FRAME e.g.: S1 Summer Y1-Y2 (velocity observed from Sentinel-1 with a summer length observation time

	measurements/computations are repeated and aggregated for defining the moving area, i.e. during which year(s)). Sensor type used to perform the characterization is included here	window each year in between year Y1 to year Y2) ALOS 08-10 Y1-Y2 (velocity observed from ALOS with an observation time window centered in between August and October each year in between year Y1 and year Y2) Note: "Summer" length must be described into the metadata, and it should be at least 2-3 months
Reliability	Reliability of the detected moving areas	1. Low: signal interpretation (velocity estimation) and outline are uncertain but there is something to consider. 2. Medium: signal interpretation (velocity estimation) or outline is uncertain 3. High: obvious signal, best appropriate configuration (back-facing slope) Notes: When looking N-S facing slope or the number of InSAR data allowing detection is low, the reliability of the detection decreases.
Remarks	Notes related to the detection and characterization (if needed)	Text (e.g.: N-S facing slopes, few data, noisy signal, faster velocity in the rooting zone, etc.)

Table S2. List of attributes assigned during the compilation of the rock glacier inventories, according to the version 3.0.2 (June 2020) of RGIK - kinematic approach (2020), and to the version 4.1 (May 2020) of RGIK - baseline concepts (2022).

Name	***Definition***	***Values***
ID*	A unique alpha-numerical identifier of the rock glacier unit	*ZZ-XXXX-UU* ZZ: Area number: 06: Switzerland, Western Swiss Alps 07: Norway, Troms 08: Norway, Finnmark 09: Svalbard, Nordenskiöld 10: France, Vanoise 11: Italy, Southern Venosta 12: Greenland, Disko Island 13: Northern Tien Shan 14: Alaska, Brookes Range 15: Argentina, Central Andes 16: New Zealand, Central Southern Alps *XXXX:* numerical code of the rock glacier (defined by the user) *UU*: numerical code of the rock glacier unit (defined by the user)
Coord_X*	X coordinate of the point	WGS 84 coordinate system
Coord_Y*	Y coordinate of the point	WGS 84 coordinate system
Morph_Type**	Unit morphology	1. Undefined 2. Simple 3. Complex
Spatia_Con**	Spatial connection to the upslope unit	1. Undefined 1. Talus

		2. Debris mantle 3. Landslide 4. Glacier 5. Glacier forefield 6. Poly
Activity**	Efficiency of the sediment conveying (expressed by the surface movement) at the time of observation	1. Undefined 2. Active 3. Transitional 4. Relict
Destabiliz (optional)**	Signals of abnormally fast behavior, which can be expressed geomorphologically by the opening of large cracks and/or scarps	1. Undefined 2. Yes 3. No
Kin_attrib*	Kinematic attribute assigned to a rock glacier unit, based on the previously delineated moving areas. It indicates the overall multi-annual downslope movement rate of an inventoried rock glacier unit	1. Undefined 2. < cm/yr 3. cm/yr* 4. cm/yr to dm/yr 5. dm/yr* 6. dm/yr to m/yr 7. m/yr* 8. > m/yr 9. Other (velocity can be then expressed in a field “Remarks”)
Val_time_frame*	Multi-year *validity time frame* of the assigned Kin_attrib	Ya-Yb: between year Ya to year Yb (snapshot)
Data_used*	Data type, observation time window, temporal frame and dimensionality of the data used (e.g. related to the moving area) to assign the Kin_attrib	Text containing: DIMENSIONALITY-DATA-TYPE_ TIME-OBSERVATION-WINDOW_TEMPORAL-FRAME e.g: 1D InSAR S1 Summer Y1-Y2 (velocity observed with Sentinel1 InSAR in the LOS using a summer length observation time window each year in between year Y1 to year Y2) 1D InSAR S1 Summer Y1, Y2, … (velocity observed with Sentinel-1 InSAR in the LOS using a summer length observation time window at year Y1, year Y2, etc.) Note: “Summer” length must be described into the metadata, and it should be at least 2-3 months
Spatial_rep*	Spatial representativeness: percentage of surface that is documented by supporting kinematic data	1. Undefined 2. < 50% 3. 50-75% 4. > 75%
Reliab*	Reliability of the kinematic attribute	1. Undefined 2. Low 3. Medium 4. High
Remarks*	If needed	Text
* according to the version 3.0.2 (June 2020) of RGIK - kinematic approach (2020) ** according to the version 4.2.2 (March 2022) of RGIK - baseline concepts (2022).		

Table S3. 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 extent MA [km^2]	Total region extent [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

Table S4. Number of activity degrees and kinematic attributes assigned to rock glaciers (percentage in brackets) for each region.

Region	Undefined (%)	Relict (%)	Transitional			Active			Total number RoG (%)	Total region Extent [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

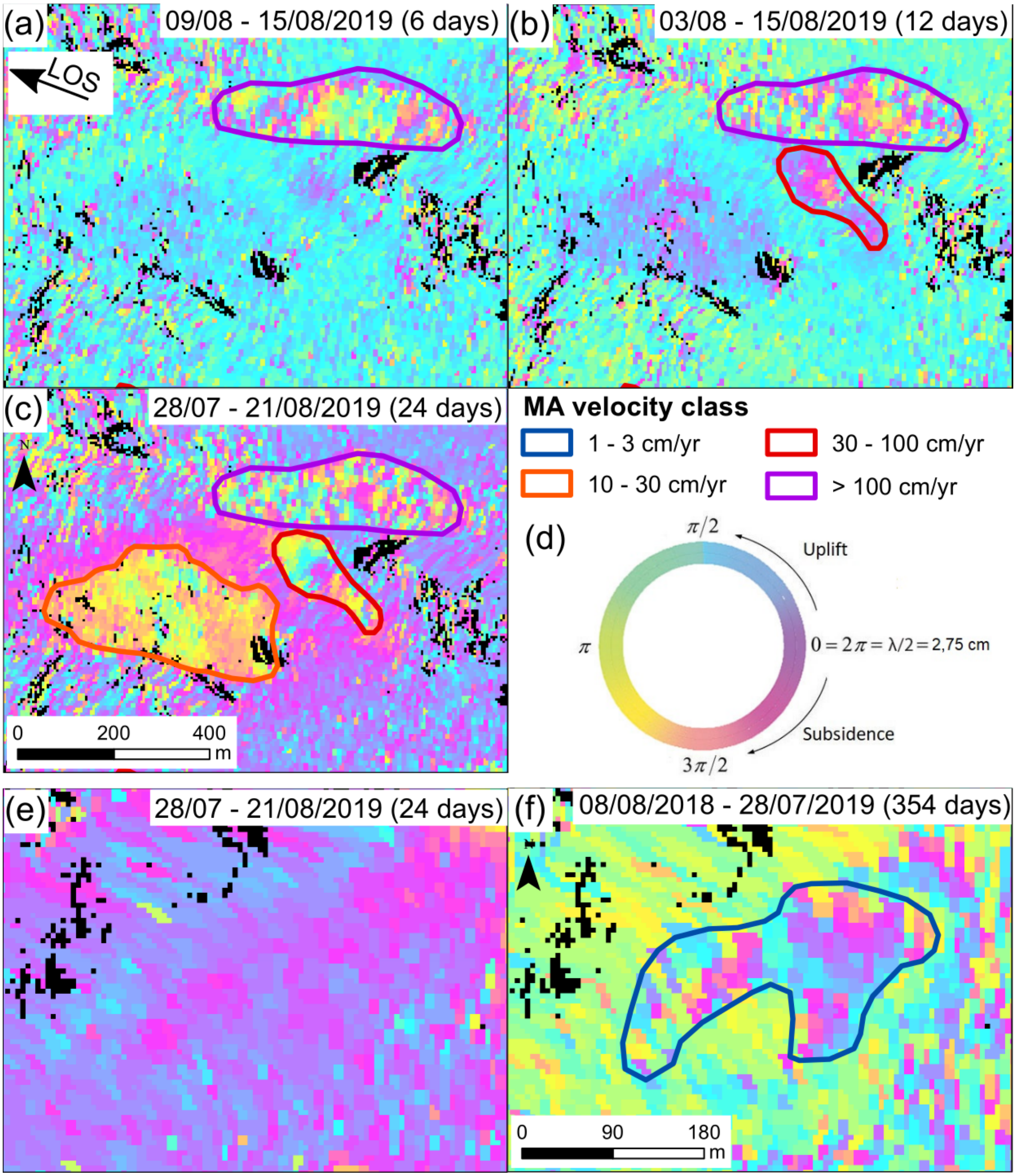

Figure S1. Sentinel-1 interferograms from descending orbit (a, b, c, e and f) and phase cycle (d). In the first example (from a to c) with a 6-day interferogram (a) a fringe pattern with a complete phase cycle (corresponding to 2.75 cm in 6 days, i.e., 167 cm/yr) is outlined and classified as > 100 cm/yr. With a 12-day interferogram (b) the previous fringe pattern become decorrelated, and a new fringe pattern with a half phase cycle (corresponding to 2.75/2 cm in 12 days, i.e., 42 cm/yr) is outlined and classified as 30-100 cm/yr. Observing a 24-day interferogram (c) a complete phase cycle within the previous mapped 30-100 cm/yr moving areas is visible, along with a new fringe pattern with a half phase cycle (corresponding to 2.75/2 cm in 24 days, i.e., 21 cm/yr, 10-30 cm/yr). In the second example (e and f), with a 24-day interferogram (e) a fringe pattern is not detectable, and a half phase cycle becomes visible with a 354-day interferogram (f, corresponding to 2.75/2 cm in 354 days, i.e., 1.5 cm/yr, 1-3 cm/yr).

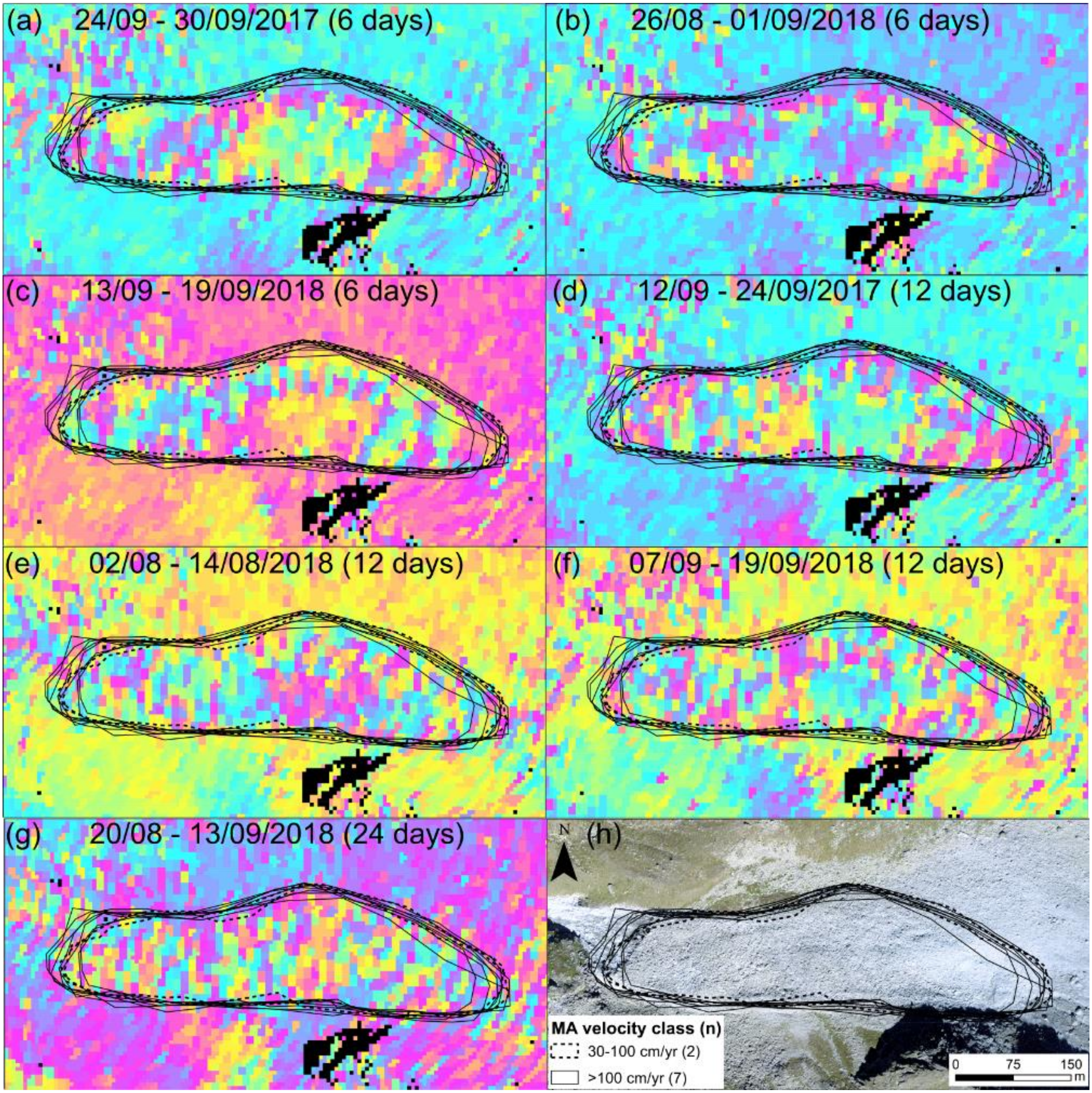

Figure S2. Sentinel-1 interferograms at 6 days (a-c), 12 days (d-f) and 24 days (g) show the temporal variability of the InSAR signals. Orthoimage (h) from © Google Earth 2019. The outlines of moving areas (black polygons) drawn by nine operators on a simple rock glacier case mostly agree with the observed InSAR signal. Large discrepancies between the outlines are not observed, while both velocity classes ">100 cm/yr" and "30-100 cm/yr" are assigned due to temporal variations in interferograms. According to the mapped moving areas, this rock glacier is classified as "m/yr or higher" by seven operators and as "dm/yr to m/yr" by two operators.

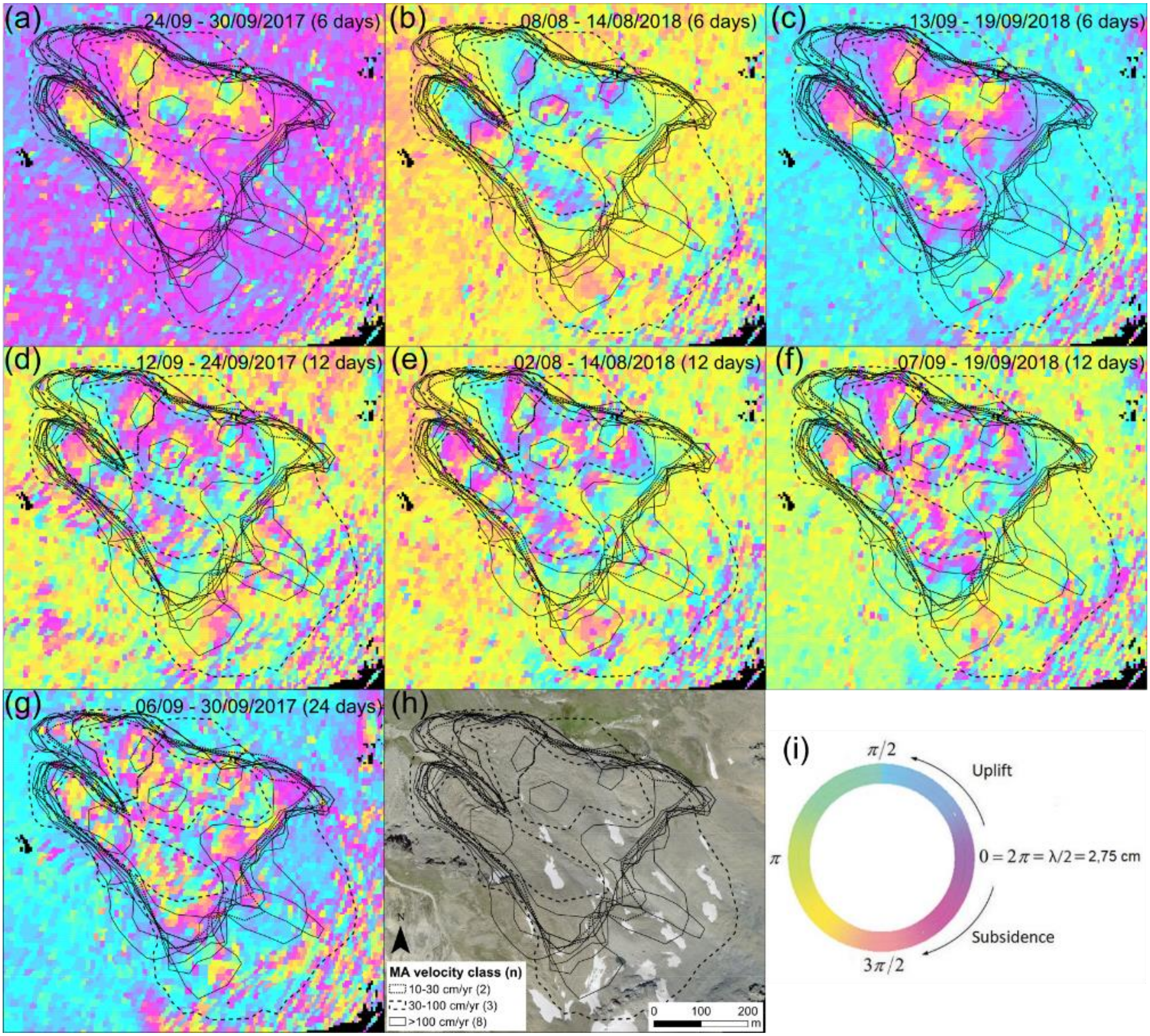

Figure S3. Sentinel-1 interferograms at 6 days (a-c), 12 days (d-f) and 24 days (g) show the temporal and spatial variability of the InSAR signals. Orthoimage (h) from © Google Earth 2019. The outlines of moving areas (black polygons) drawn by nine operators on a complex case of rock glacier show quite large heterogeneities. Several velocity classes (">100 cm/yr", "30-100 cm/yr" and "10-30 cm/yr") are assigned due to large temporal and spatial variations in interferograms. However, this rock glacier is classified as "m/yr or higher" by six operators and as "dm/yr to m/yr" by three operators. Phase cycle for Sentinel-1 in panel i. The single outlines are visible in Figure S4.

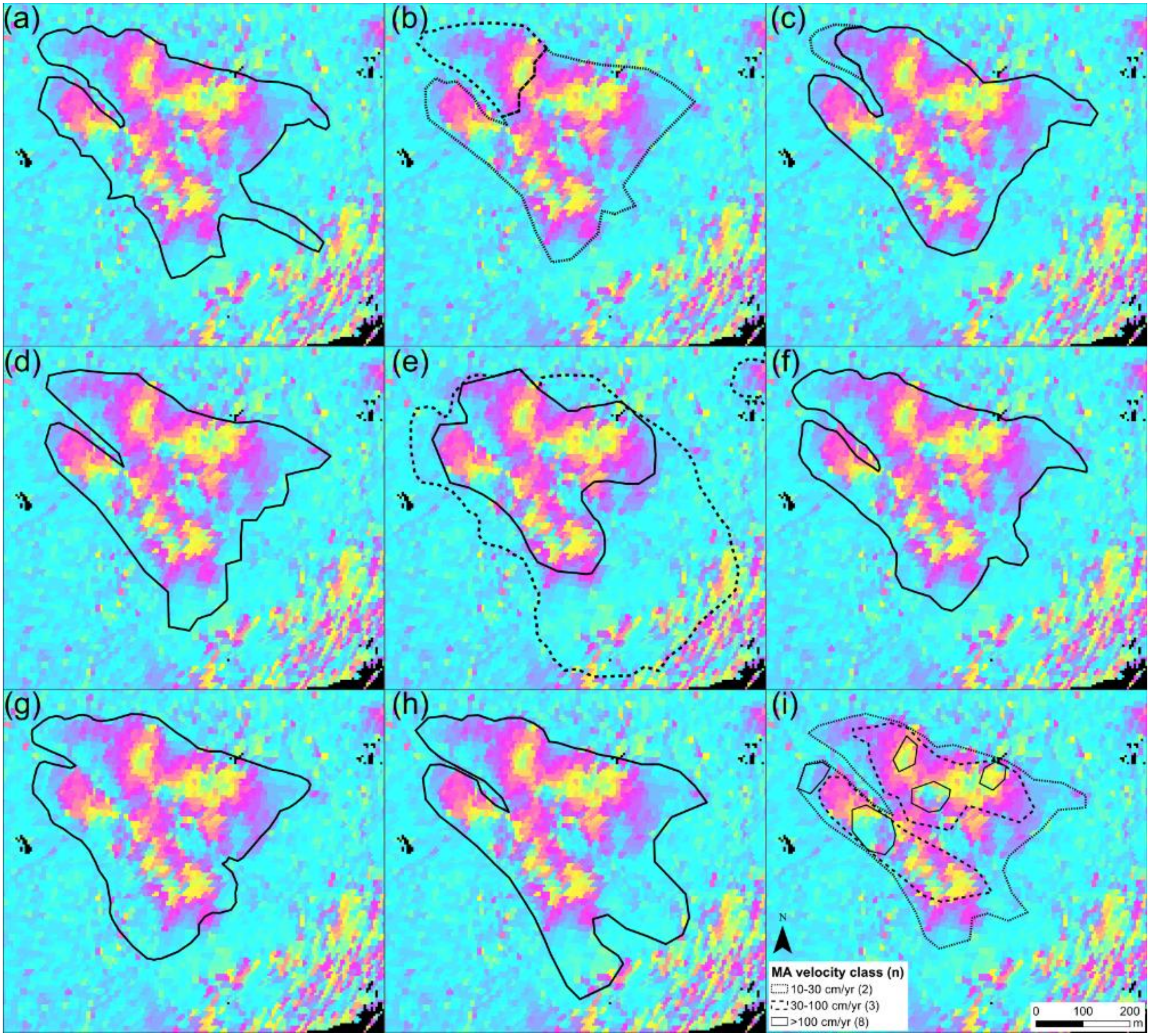

Figure S4. Each panel (a - i) shows the outlines of moving areas (black polygons) drawn by nine operators on a complex case of rock glacier. Sentinel-1 interferogram at 6 days (13/09/2018 – 19/09/2018) as background.

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