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## Rock Glacier Velocity: An Essential Climate Variable Quantity for Permafrost

Yan Hu, Lukas Arenson, Chloé Barboux, Xavier Bodin, Alessandro Cicoira, Reynald Delaloye, Isabelle Gärtner-Roer, Andreas Kääb, Andreas Kellerer-Pirklbauer, Christophe Lambiel, et al.

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# Reviews of Geophysics®



## REVIEW ARTICLE

10.1029/2024RG000847

## Rock Glacier Velocity: An Essential Climate Variable Quantity for Permafrost

### Key Points:

- Regional interannual synchronicity in relative velocity change provides observational basis for using Rock Glacier Velocity as an Essential Climate Variable Quantity
- Seasonal variations and surface heterogeneities have to be considered for the generation of a Rock Glacier Velocity product
- Air temperature, snow cover, and ground water conditions collectively influence rock glacier kinematics over timescales

### Supporting Information:

Supporting Information may be found in the online version of this article.

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**Abstract** Rock glaciers are distinctive debris landforms found worldwide in cold mountainous regions. They express the long-term movement of perennially frozen ground. Rock Glacier Velocity (RGV), defined as the time series of the annualized surface velocity of a rock glacier unit or a part of it, has been accepted as an Essential Climate Variable Permafrost Quantity in 2022. This review aims to highlight the relationship between rock glacier velocity and climatic factors, emphasizing the scientific relevance of interannual rock glacier velocity in generating RGV products within the context of observed rock glacier kinematics. Under global warming, rock glacier velocity exhibits widespread (multi-)decennial acceleration. This acceleration varies regionally in onset timing (from the 1950s to the 2010s) and magnitude (up to a factor of 10), and has been observed in regions such as the European Alps, High Mountain Asia, and the Andes. Despite different local conditions, a synchronous interannual velocity pattern prevails in the European Alps since the 2000s, highlighting the primary influence of climate. A common pattern is the seasonal velocity rhythm, which peaks in late summer to autumn and declines in spring. RGV assesses permafrost evolution via (multi-)decennial and interannual changes in rock glacier velocity, influenced by air temperature shifts with varying time lags and snow cover effects. Although not integrated into the RGV products, seasonal variations should be examined. This rhythmic behavior is attributed to alterations in pore water pressure influenced by air temperature, snow cover, and ground water conditions.

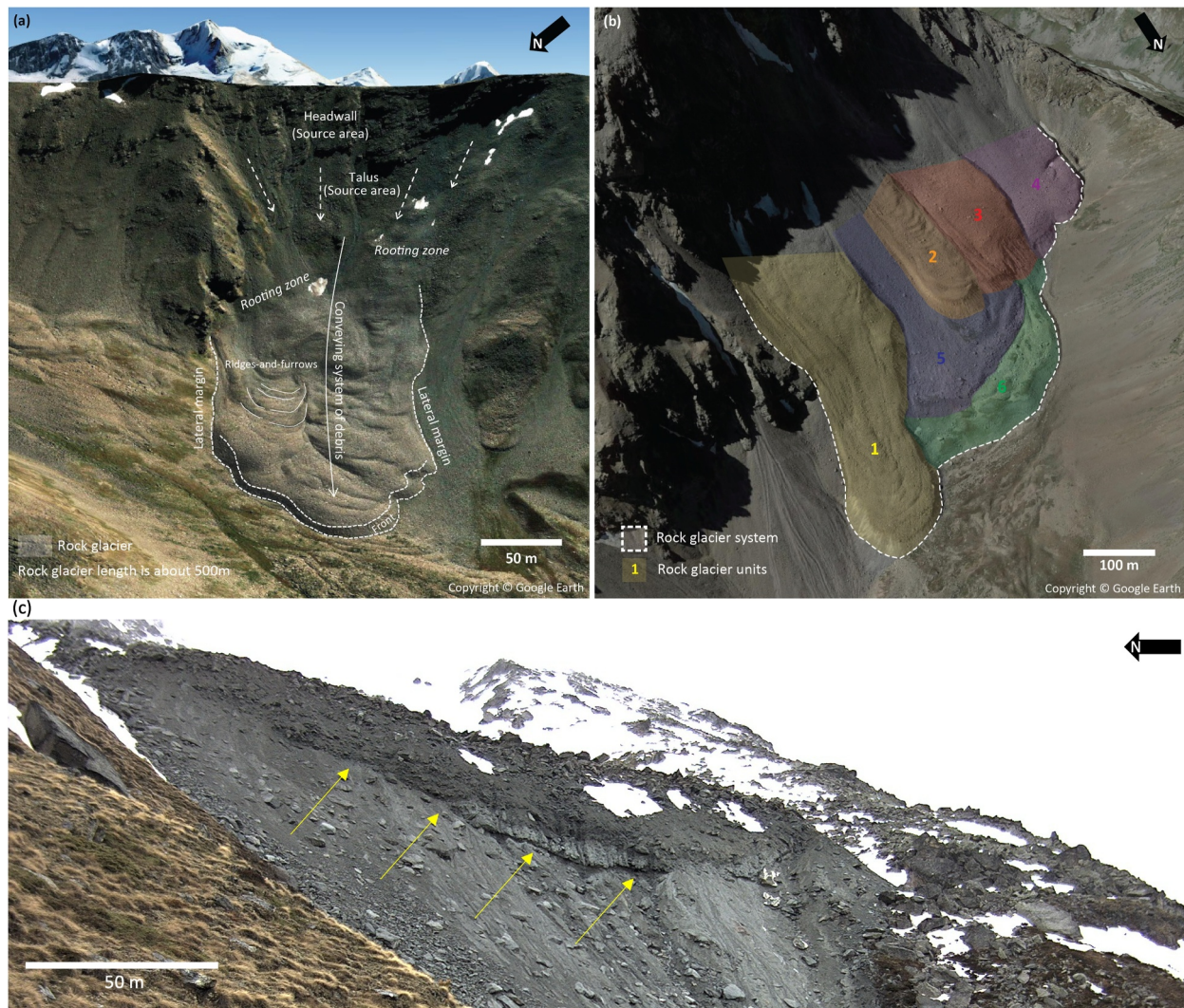
**Plain Language Summary** Rock glaciers are unique debris landforms found in cold mountainous regions around the world that represent the slow movement of permanently frozen ground over long periods of time. Rock Glacier Velocity (RGV) measures how fast these landforms move each year and has become a parameter of the essential climate variable permafrost. With ongoing climate change, rock glaciers are accelerating over decades, but the timing and intensity of this acceleration vary by region. Despite local variations, there is a consistent annual pattern in the European Alps that shows the strong influence of climate. Rock glaciers typically move faster in late summer to autumn and slower in spring. RGV helps us track changes in permafrost by looking at these speed changes over time, which are influenced by factors such as air temperature, snow cover, and precipitation. Standardizing RGV data production and increasing the number of observations will help us better understand how mountain permafrost is changing due to climate change.

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## 1. Introduction

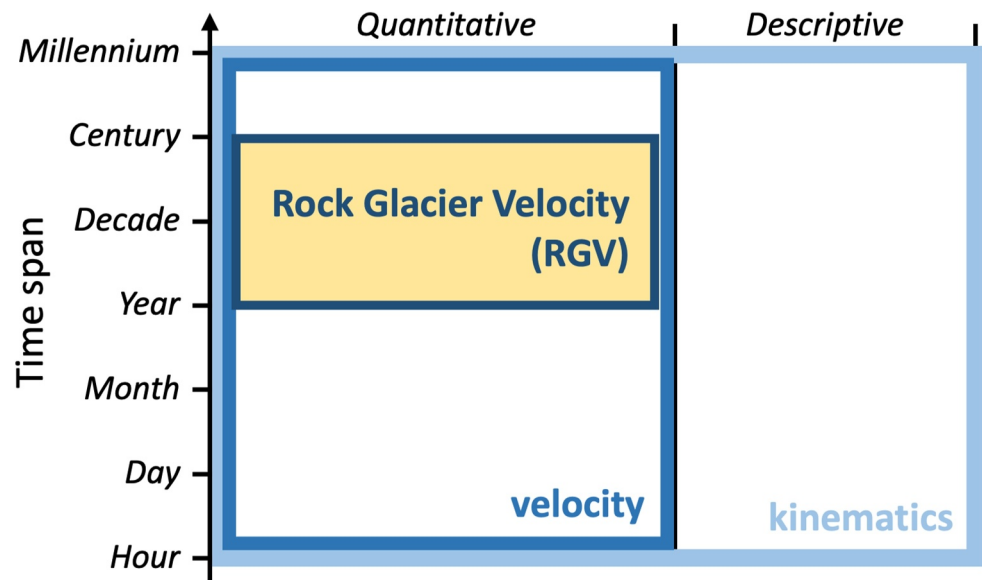
Rock glaciers are debris landforms that constitute an integral part of the mid- and high-latitude mountain permafrost landscape across all continents, making them a valuable indicator of the condition of mountain permafrost globally (Ballantyne, 2018; Barsch, 1996; Berthling, 2011; Clark et al., 1998; Jones et al., 2018).



**Figure 1.** Remote sensing and field photos of rock glaciers. (a) A simple rock glacier unit located in Vallone di Sort, Italy ( $45^{\circ}33'37''\text{N}$ ,  $7^{\circ}9'11''\text{E}$ , 2500–2800 m a.s.l.). (b) Laurichard rock glacier system in France ( $45^{\circ}1'5''\text{N}$ ,  $6^{\circ}23'59''\text{E}$ , 2400–2800 m a.s.l.). It consists of six units marked by color shades. (c) Field photo of Tsarmin rock glacier in Switzerland ( $46^{\circ}2'46''\text{N}$ ,  $7^{\circ}30'25''\text{E}$ , 2460–2700 m a.s.l.) taken on 11 May 2020 by a webcam of the Alpine Geomorphology Research Group, University of Fribourg. The yellow arrows show the location of the shear horizon.

Formed by the gravity-driven creep of ice-rich frozen debris, they develop movement-indicative morphologies such as distinct frontal and lateral margins and often have a surface characterized by ridge-and-furrow topography (Barsch, 1996; Haeberli et al., 2006; RGIK, 2023a). Depending on its geomorphologic complexity, the landform can either consist of a single *rock glacier unit*, or build up a *rock glacier system* composed of spatially connected units (RGIK, 2023a) (Figures 1a and 1b).

The downslope movement that shapes rock glaciers generally originated centuries to millennia ago and in many instances continues today (Amschwand et al., 2021; Haeberli et al., 1999; Konrad et al., 1999; Munroe et al., 2024). Rock glaciers that are currently deforming are referred to as *active* or *transitional* rock glaciers, depending on their kinematic characteristics (RGIK, 2023a). They have drawn particular research interest since the terminology *rock glacier* was coined by Capps (1910) to depict the unique landforms in Alaska. Capps (1910) deduced solely from geomorphologic evidence that “... the forward movement has been continuous and uniform” and “... in somewhat the manner of a glacier.” This observation “... led to the suspicion that ice was in some way responsible for their movement.” This hypothesis concerning *surface movement* was later confirmed by an 8-year monitoring program of geodetic surveys focusing on the kinematics of rock glaciers in the Alaska Range (Wahrhaftig & Cox, 1959). Moreover, based on geomorphologic evidence, Wahrhaftig and Cox (1959) suggested



**Figure 2.** An illustration showing the relationship of the main terminology used in this paper, namely rock glacier kinematics, rock glacier velocity, and Rock Glacier Velocity (RGV) as an associated product to the ECV Permafrost. RGV has an annual temporal resolution, and the monitoring time period is expected to range from multi-year to centennial. Beyond the centennial timescale, debris supply and the consequent changes in morphology become important contributors to the velocity variations of rock glaciers.

the presence of *internal deformation* and that “... most or all of the thickness of each rock glacier is involved in the motion, not merely a thin layer on the surface.” Despite the lack of comprehensive evidences during that time, these pioneering studies reveal the dynamic nature of rock glaciers and distinguish them from glacial or other periglacial landforms (Harris et al., 1998; White, 1976).

More recent studies have extensively investigated *rock glacier kinematics* in terms of both *surface movement and internal deformation* (Arenson et al., 2016). Most studies document the *surface movement* using the various available observational tools such as photogrammetry (Janke, 2005a; Kääh & Vollmer, 2000; Kääh et al., 1997; Roer & Nyenhuis, 2007; Vivero & Lambiel, 2019), Global Navigation Satellite Systems (GNSS) (Berthling et al., 1998; Kellerer-Pirklbauer et al., 2024; Krainer & Mostler, 2006; Lambiel & Delaloye, 2004), Synthetic Aperture Radar Interferometry (InSAR) (Barboux et al., 2014; Bertone et al., 2022; Necsoiu et al., 2016; Rott & Siegel, 1999), and laser scanning (Avian et al., 2009; Bauer et al., 2003; Bollmann et al., 2015; Brencher et al., 2021; Kenner et al., 2014). On the other hand, studies of *internal deformation* are limited in number because of the often challenging and costly borehole-based monitoring methods (Arenson et al., 2016), yet they have consistently demonstrated that the observed surface displacements are principally related to the permafrost creep concentrated within a *shear horizon* at depth (Arenson et al., 2002; Buchli et al., 2018; Cicoira et al., 2021; Haerberli et al., 1998; Hoelzle et al., 1998; Ikeda et al., 2008; Wagner, 1992) (Figure 1c).

Traditionally, the term “rock glacier creep” is used generically to refer to the combined deformation in both the shear horizon and the overlying permafrost (RGIK, 2023a). The shear horizon is a layer of frozen material with banded ice and pressurized water, and it generally has a lower ice content compared to the overlying ground (Cicoira et al., 2021; Haerberli et al., 1998). It is important to note that the shear horizon in rock glaciers differs from the base of temperate glaciers, where basal sliding occurs (Cuffey & Paterson, 2010), or from the shear surface that separates the stable lower ground from the upper mobile layer (Ballantyne, 2018).

Here we clarify the relevant terminology used in literature (Figure 2): (a) *Kinematics* describes the general mechanical behavior/process of rock glaciers in the form of surface movement and/or internal deformation. It mostly represents the surface movement due to the limited availability of observations at depth; (b) *Velocity* refers to the quantifiable variable representing the displacement rate measured by specific techniques; (c) *Rock Glacier Velocity (RGV)* refers to the time series of annualized surface velocity of single or a part of rock glacier unit reflecting the movement related to permafrost creep (GCOS, 2022b; RGIK, 2023c). *RGV* products are generated

from systematic measurements of the rock glacier *velocity* with the objective of providing interannual time series to be used as climate change indicators. Unless explicitly stated, the *kinematics* and *velocity* discussed in this review correspond to the *surface lateral (horizontal or downslope) movement* of rock glaciers, primarily driven by shear and creep processes within the landform (Cicoira et al., 2021). These processes are commonly used for generating RGV (e.g., Kellerer-Pirklbauer et al., 2024). In contrast, *vertical thinning or thickening* is beyond the focus of this review, despite its relation to climate change (Bolch et al., 2019; Ulrich et al., 2021). This is because *vertical thinning or thickening* is influenced by multiple factors, such as the ice melt or aggradation process that cannot be unambiguously separated from the permafrost deformation processes—forming the basis for using RGV as an indicator of the state of permafrost (Arenson et al., 2002; Lambiel & Delaloye, 2004).

There are diverse research motivations for monitoring rock glacier velocity such as geohazard management (Avian et al., 2009; Bodin et al., 2018; Dini et al., 2019), sediment transfer assessment (Cusicanqui et al., 2021; Gärtner-Roer, 2012; Kofler et al., 2022; Kummert & Delaloye, 2018; Munroe et al., 2024) and ice storage estimation (Hu, Harrison, et al., 2023). We focus here on its role as an indicator of climate change on mountain permafrost undergoing warming and degradation (Biskaborn et al., 2019; Smith et al., 2022).

Rock glacier kinematics depends on the thermo-mechanical properties of permafrost such as the ice content, the subsurface structure, the ground temperature, and the hydrogeological conditions (Arenson et al., 2002; Cicoira et al., 2021; Haeberli et al., 2006; Käab & Reichmuth, 2005). Multiple geophysical methods have been employed to assess the internal composition and ice content (e.g., Buchli et al., 2018; Hauck, 2013; Mollaret et al., 2020). Increasing evidence of a close relationship between meteorological factors (e.g., air temperature and snow cover regime) and rock glacier velocity provides the basis for using rock glacier velocity as a proxy for assessing the evolution of mountain permafrost under climate change (Delaloye et al., 2010; Käab et al., 2007; Kellerer-Pirklbauer & Kaufmann, 2012).

An Essential Climate Variable (ECV) is defined as “a physical, chemical, or biological variable (or group of linked variables) that is critical for characterizing the Earth’s climate.” An ECV product, now called quantity, refers to a measurable parameter necessary for the characterization of an ECV (GCOS, 2022a). ECV products/quantities are instrumental in assessing climate change across both regional and global scales. In 2022, *Rock Glacier Velocity* (RGV) was accepted by the Global Climate Observing System (GCOS), Global Terrestrial Observation Panel (GTOS) and the Global Terrestrial Network on Permafrost (GTN-P) as a new product of the ECV Permafrost, in addition to the Permafrost Temperature (PT) and the Active Layer Thickness (ALT) (GCOS, 2022b; Pellet et al., 2024; Streletskiy et al., 2021).

In this review, we synthesize knowledge on rock glacier kinematics at different timescales in order to understand the scientific relevance of the interannual observations used to generate RGV products. Specifically, this review addresses two key scientific questions in the main sections (Sections 3 & 4): (a) What are the global and regional patterns of the rock glacier velocity across temporal scales as revealed by observations? (b) How are the observed patterns linked with the long-term climatic and short-term meteorological conditions?

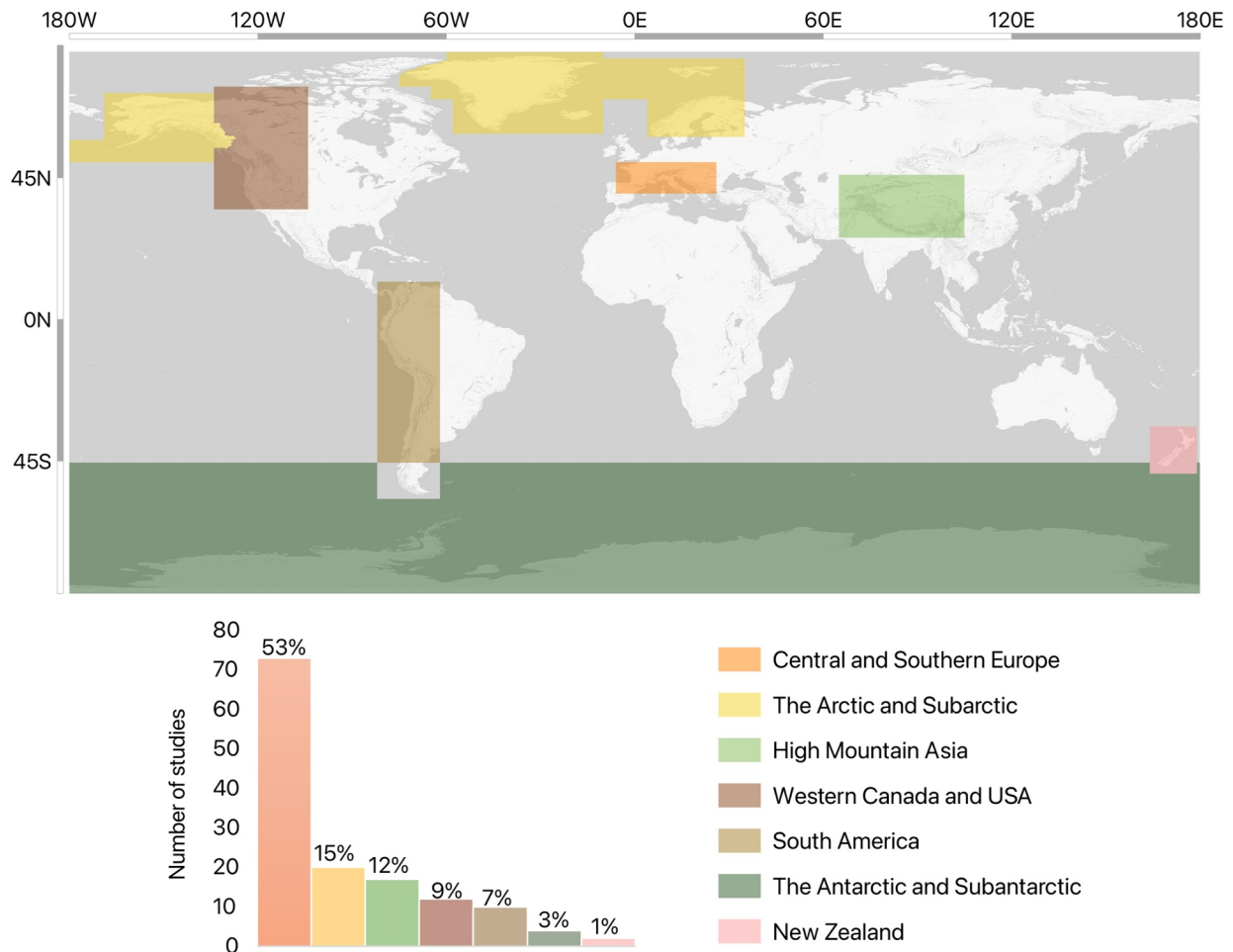
## 2. Materials and Methods

We employed the review methodology with reference to the PRISMA 2020 Statement, aiming to report the literature reviewed in this article transparently and to facilitate consistent updates in the future (Page et al., 2021). This section reports the literature search strategy, the selection process, and a meta-analysis of the publications synthesized in this work.

We conducted the literature search on 22 September 2022 from two scholarly databases—Scopus and Web of Science. We designed the search keywords by combining the variants and synonyms of “rock glacier” (e.g., rockglacier), “kinematics” and “velocity” (e.g., displacement, deformation, movement, motion, creep, dynamics) with logical operators. We applied the same suite of keywords to search within Abstract from the two databases:

(“rock glacier\*” OR “rockglacier\*”) AND (kinematic\* OR velocity\* OR displacement\* OR deform\* OR move\* OR creep\* OR motion OR dynamic\*)

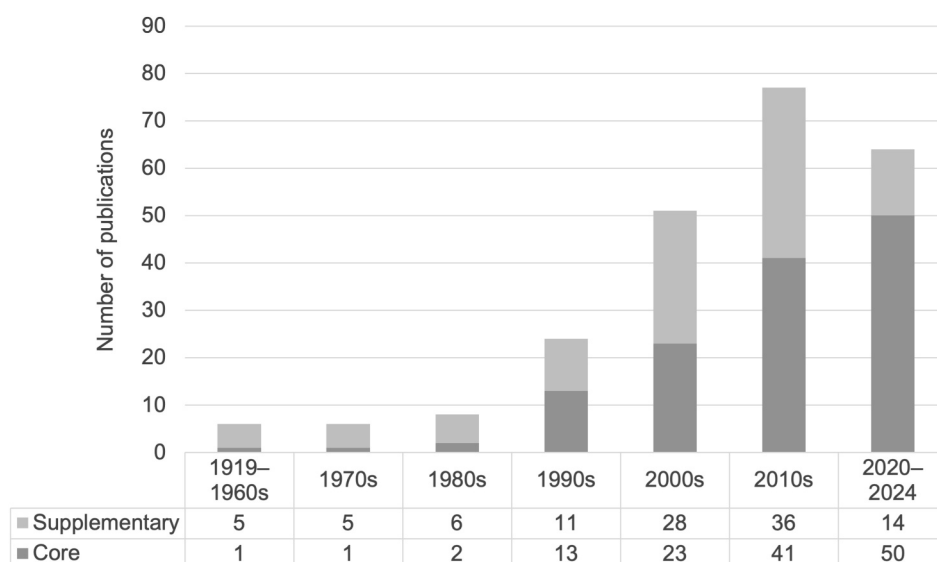
In total, 564 publications were found on Scopus and 423 articles on Web of Science. First, a total of 401 repeated items and 391 studies irrelevant to rock glacier kinematics were removed. Next, we complemented the records by reference harvesting and included 41 studies that could not be collected by the literature search for two reasons:



**Figure 3.** Geographic distribution of the study areas of the 132 publications in the core bibliography. The boundaries of the regions are adapted after the Glacier Regions that are standardized by the Global Terrestrial Network for Glaciers (GTN-G, 2023). Our divisions consider the geographical locations and rock glacier research traditions. The bar chart shows the percentages of publications in different geographic regions.

they were published after the search date (22 September 2022) or they were not indexed in the two databases. Then we identified the core publications that particularly conform to the review objective (detailed in Section 1) after reading the full-text articles. By doing so, we obtained the core and Supporting Information S1 bibliographies consisting of 132 and 104 studies, respectively (Tables S1 and S2 in Supporting Information S1). Publications in the Supporting Information S1 bibliography include papers that report only descriptive results, research on rock glacier behavior on centennial/millennial timescales, studies that focus on the dynamic mechanisms of rock glaciers, and early publications in languages other than English. We systematically reviewed the publications in the core bibliography. In addition, several studies in Supporting Information S1 collection, previous reviews, and monographs are referenced in the main sections (Sections 3 and 4) to facilitate our discussion. Despite having applied a systematic procedure aiming to reduce the subjectivity of the study, we acknowledge that the analyzed collection may remain non-exhaustive.

To illustrate the research extensiveness in different regions, we categorized papers according to the geographical locations of the study areas. Studies in the core bibliography have a near-global, yet uneven, regional coverage as more than half of the papers (53%) investigated rock glacier kinematics and velocity in Central and Southern Europe (Figure 3). The publication years were analyzed to reveal the research trend during the past decades. With the considerable increase in the number of research during the recent decades, most of the studies (97%) reviewed in the core collection were published since the 1990s (Figure 4).



**Figure 4.** The number of studies published from 1919 to 2024 in the core bibliography (in dark gray) and Supporting Information S1 bibliography (in light gray).

### 3. Kinematic Characteristics of Rock Glaciers

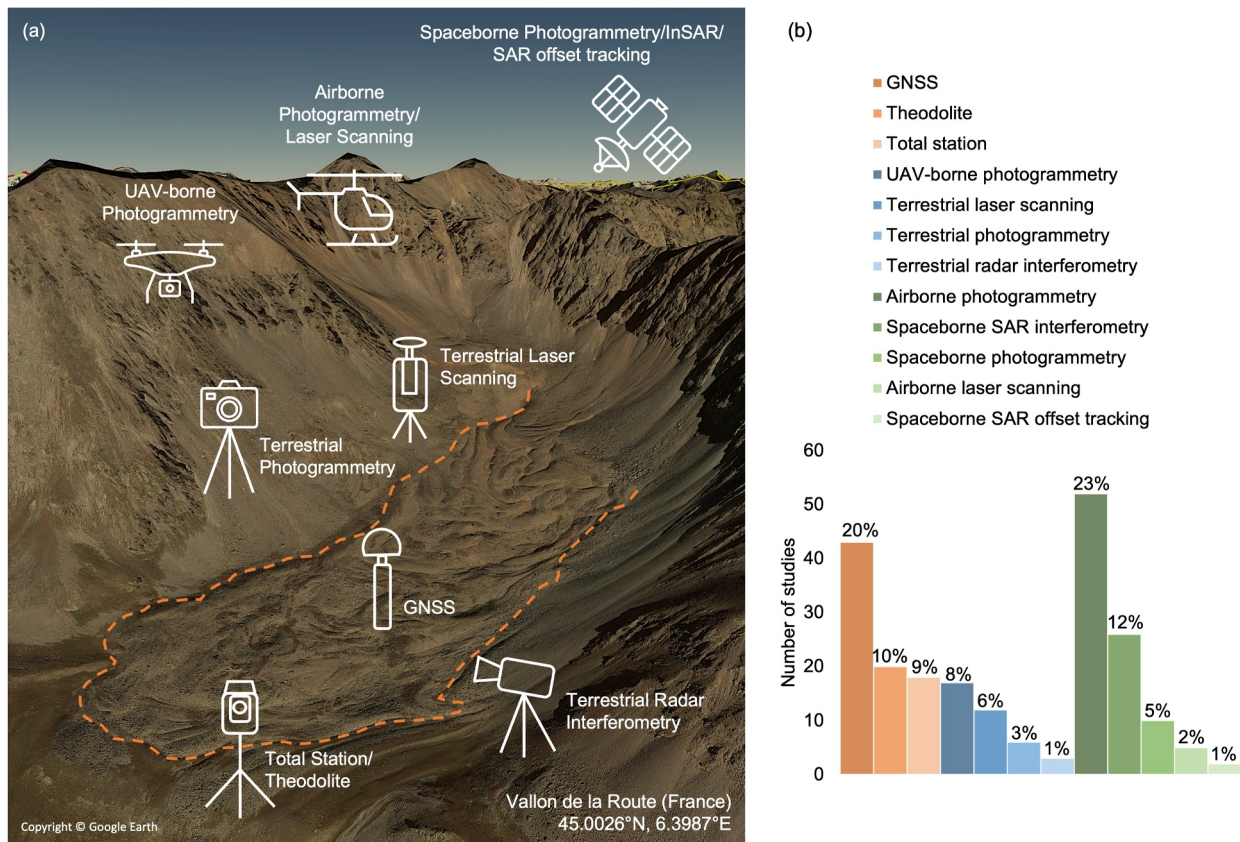
In this section, we summarize the general kinematic characteristics of rock glaciers in terms of their magnitude, direction, and surface spatial distribution (Section 3.1). An assessment of the applied techniques to quantify rock glacier velocity is presented (Figure 5 and Table 1). Then we report the recent findings of regional and global variations of rock glacier velocity across temporal scales (Section 3.2).

#### 3.1. General Kinematic Characteristics: Magnitude, Direction, and Surface Spatial Distribution

Many remote sensing methods, including laser scanning, photogrammetry, InSAR, and Synthetic Aperture Radar (SAR) offset tracking, with spatial resolutions ranging from centimeters to tens of meters, are applicable to quantify the rock glacier surface velocity, in addition to the point-based terrestrial surveys (Table 1). Remote sensing techniques (61%), encompassing both far-range and close-range methods, have become the primary approach for investigating rock glacier velocities (Figure 5).

Rock glacier velocity detected at the surface typically ranges from a few centimeters (Buckel et al., 2022; Kääh et al., 2002; Vespremeanu-Stroe et al., 2012) to decimeters or meters per year (Scapozza et al., 2014; Villarroel et al., 2022), and only occasionally exceeds an annual displacement of three m or more (Blöthe et al., 2021; Bucki & Echelmeyer, 2004; Robson et al., 2022). In recent years, several rock glaciers underwent drastic collapses, accompanied by speed-ups of one or two orders of magnitude (Bearzot, Garzonio, Colombo, et al., 2022; Bodin et al., 2017; Scotti et al., 2017). For instance, an extreme value equivalent to  $>100 \text{ m yr}^{-1}$  was observed on the Grabengufer rock glacier in the Swiss Alps in 2009–2010 (Delaloye et al., 2010), and was reached again in 2023 (unpublished data by R. Delaloye). This abnormal kinematic behavior is referred to as rock glacier destabilization, which is suspected to become more frequent in a warming future but is highly dependent on suitable local conditions (Marcer et al., 2019, 2021). It is important to point out that the term destabilization in the context of rock glacier kinematics is used to describe an extreme acceleration in surface velocity, and is not a reference to a slope instability that may result in a catastrophic slope failure.

In general, the surface movement of rock glaciers occurs in the downslope direction, as a consequence of gravity-driven deformation (Arenson et al., 2002; Cicoira et al., 2021; Haeberli et al., 2006). Many studies using 3D measuring techniques reconstructed the surface velocity fields and demonstrated the overall consistency between the flow direction and the terrain slope (Bucki & Echelmeyer, 2004; Kääh et al., 1997). This kinematic feature supports the simplified derivation of downslope velocities from the reprojection of InSAR line-of-sight and 2D SAR offset tracking measurements (Hu et al., 2021; Rott & Siegel, 1999). However, this reprojection can introduce uncertainties related to the vertical component of deformation, for example, in cases simultaneously



**Figure 5.** (a) An illustration showing different survey methods for quantifying rock glacier velocity. (b) Percentages of the different methods adopted for measuring or computing rock glacier velocity by studies in the core bibliography. The shaded bars in orange (39%), blue (18%), and green (43%) represent in situ, close-range remote sensing, and far-range remote sensing methods, respectively. Note that methods for measuring rock glacier activity at and beyond the centennial timescale, including various geochronological techniques, are not represented in this figure.

impacted by thaw subsidence due to significant ice-core melting. In addition, the movement direction may locally deviate from the downslope direction. For instance, backward creep has been observed in the upper part of a rock glacier in Austria, triggered by thinning of the root zone (Kellerer-Pirklbauer & Kaufmann, 2018).

Transversely across the surface of rock glaciers, the greatest velocities are usually found along the central flow line and decrease toward the lateral margins (Benedict et al., 1986; Berger et al., 2004; Chueca & Julián, 2005; Konrad et al., 1999; Whalley et al., 1995). Longitudinally, the upper and lower parts, which represent extensive and compressive flow, respectively, can exhibit contrasting velocity magnitudes (Berthling et al., 1998; Halla et al., 2021; Serrano et al., 2006; Villarroel et al., 2022) or different velocity variations through time (Bodin et al., 2018; Thibert & Bodin, 2022). Multi-generational rock glacier systems usually exhibit a longitudinal pattern in which the lower and older units often have lower velocities (Amschwand et al., 2021).

Furthermore, an individual rock glacier can develop multiple moving sections, showing more or less uniform kinematic behavior within each extent, but with different magnitudes and directions from other sections (Bearzot, Garzonio, Mauro, et al., 2022; Buchelt et al., 2023). These variations are primarily controlled by the local topography (Buckel et al., 2022), the subsurface structure (Buchli et al., 2018), and the interactions with other periglacial processes such as the debris transport and thermokarst development (Avian et al., 2005; Gärtner-Roer et al., 2022; Kääh et al., 1997). Additionally, within the same moving section, spatial heterogeneity in velocity can exist, sometimes influenced by slope inclination. Where the slope is steeper, the velocity appears to be greater (Blöthe et al., 2021; Bodin et al., 2018), yet this correlation is not always present (Bodin et al., 2018; Bucki & Echelmeyer, 2004). Occasionally, the surface can be affected by discrete dynamic events such as boulder tilting or sliding in the topmost layer, which can be characterized by methods with a high spatial and temporal resolution, such as continuous GNSS stations (Wirz et al., 2015, 2016).



**Table 1**  
*Characteristics of the Available Survey Methods for Quantifying Rock Glacier Velocity (Adapted After RGIK, 2023c)*

	In situ		Close-range remote sensing			
	Total station	GNSS	Terrestrial laser scanning	Terrestrial photogrammetry	Terrestrial radar interferometry	UAV-borne photogrammetry
Measurement resolution	Single point(s) based measurement	Single point(s) based measurement	Area based measurement, cm resolution	Area based measurement, cm resolution	Area based measurement, m–1 km resolution	Area based measurement, cm resolution
Measurement constraints (non-exhaustive)	Clear line of sight, field access	Satellite shadowing, field access	Surface shadowing, field access, weather-dependant	Surface shadowing, field access, light/weather-dependant	Surface shadowing, field access	Surface shadowing, light/weather-dependant
Measurement value and dimension	3D point coordinates of a single point	3D point coordinates of a single point	3D coordinates of surface point clouds	Indirect 3D coordinates of surface point clouds	1D distance in the line of sight	3D coordinates of surface point clouds
Accuracy (between 2 measurements)	mm-cm	cm	cm	cm	mm	cm–dm
	Far-range remote sensing					
	Airborne laser scanning	Airborne photogrammetry	Spaceborne photogrammetry	Spaceborne SAR interferometry	Spaceborne SAR offset tracking	
Measurement resolution	Area based, dm	Area based, cm–m	Area based, cm–m	Area based, m	Area based, m	
Measurement constraints (non-exhaustive)	Shadowing in steep terrain, weather-dependant	Shadowing in steep terrain, light/weather dependant	Shadowing in steep terrain, light/weather dependant	Layover and shadowing in steep terrain	Layover and shadowing in steep terrain	
Measurement value and dimension	3D coordinates of surface point clouds	3D coordinates of surface point clouds	3D coordinates of surface point clouds	1D change of distance in the line of sight	2D coordinates of surface point clouds	
Accuracy (between 2 measurements)	dm	cm–m	dm–m	mm–cm	dm–m	

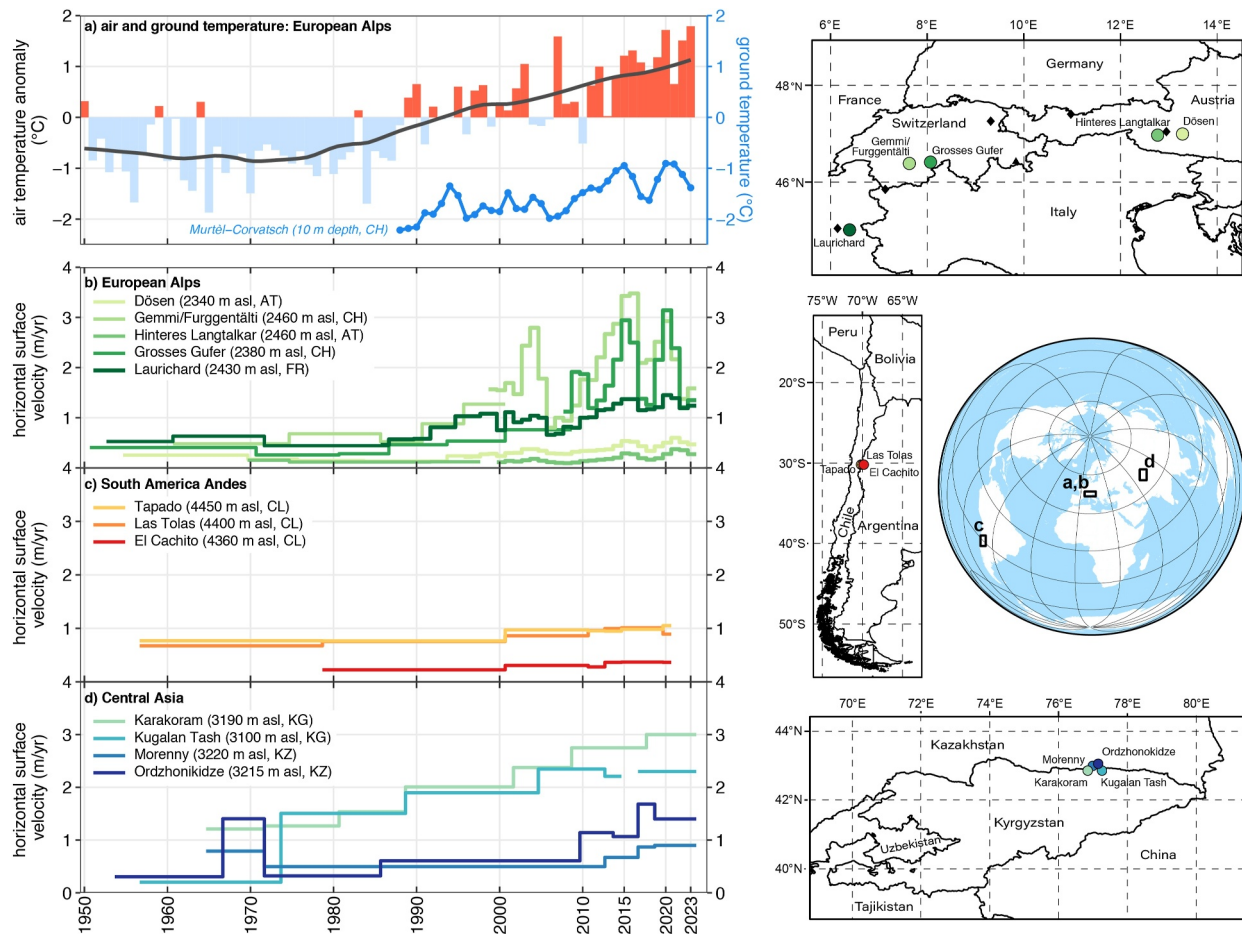
### 3.2. Temporal Kinematic Patterns Around the Globe

In situ and remote sensing observations have revealed that many rock glaciers exhibit typical kinematic patterns across temporal scales: from the seasonal rhythm to the multi-decennial trends documented globally with regional variabilities. Recently, a significant effort has been placed on collecting systematic measurements and comparing rock glacier velocities in various mountain ranges worldwide (Figure 6). In this section, we present the characteristic patterns in different regions around the globe. It is important to note that rock glaciers are also present in regions not covered in this section (e.g., Northern Asia and Caucasus), as there is currently no information available on their kinematics.

#### 3.2.1. Central and Southern Europe

Rock glacier velocity in Central Europe has been quantified by in situ geodetic survey and photogrammetry since the 1910s (Chaix, 1919; Pillewizer, 1938), which allows reconstructing velocity time series of up to a century (Scapozza et al., 2014). Beyond this time frame, kinematic status is interpreted based on geochronological information derived from cosmogenic nuclide exposure dating (Amschwand et al., 2021; Charton et al., 2021; Lehmann et al., 2022), Schmidt-hammer exposure-age dating (Böhlert et al., 2011; Rode & Kellerer-Pirklbauer, 2012; Scapozza et al., 2014), weathering rind thickness measurements (Böhlert et al., 2011; Laustela et al., 2003), pollen analysis and radiocarbon dating (Haeberli et al., 1999; Krainer et al., 2015).

Rock glacier formation, often referred to as centennial to millennial rock glacier activity, occurred during or shortly after the Quaternary climate shifting periods, such as the Gschnitz stadial (~16 ka) (Steinemann et al., 2020), the Younger Dryas (~12.9–11.6 ka) (Amschwand et al., 2021; Böhlert et al., 2011; Charton



**Figure 6.** Rock glacier velocities based on in situ geodetic surveys or photogrammetry in the context of long-term air and ground temperature observations. (a) In situ hydrological mean annual permafrost temperature measured at 10 m depth (blue line) at Murtèl Corvatsch (black triangle on Europe map) and air temperature: composite anomaly to the 1981–2010 norm (bars) and composite 20-year running mean (solid line) at Besse (FR), Grand Saint-Bernard (CH), Saentis (CH), Sonnblick (AT) and Zugspitze (black diamonds on Europe map). Note that the temperature data are only from European observations. (b) Rock glacier velocities at selected sites in the European Alps. (c) Velocities of three rock glaciers in the South America Andes (adapted from Vivero et al., 2021). (d) Velocities of four rock glaciers in Central Asia (adapted from Käab et al., 2021) (Updated after Pellet et al., 2024).

et al., 2021; Lehmann et al., 2022; Steinemann et al., 2020), the Holocene Climatic Optimum (~9–5 ka) (Amschwand et al., 2021; Scapozza et al., 2014), the end of Subboreal Period (~2.5 ka) in Late Holocene (Amschwand et al., 2021; Cossart et al., 2010), and the Little Ice Age (1303–1850 CE) (Berger et al., 2004). In addition to the responsive formation phases, possible accelerations occurred during the Medieval Warm Period (950–1250 CE), according to a case study in the Swiss Alps (Scapozza et al., 2014).

In the European Alps, an active phase occurred in the 1950s–1960s at a few sites, followed by a low-velocity period until the 1980s or early 1990s (Kaufmann et al., 2021; Kellerer-Pirklbauer & Kaufmann, 2012; Kummert et al., 2021; Lugon & Stoffel, 2010), yet in some cases, a consistent acceleration trend dated back to the 1960s (Micheletti et al., 2015). Prevalent rock glacier accelerations started in the 1980s–1990s (Avian et al., 2005; Bodin et al., 2009; Delaloye et al., 2010; Fleischer et al., 2021; Haberkorn et al., 2021; Hausmann et al., 2007; Kellerer-Pirklbauer et al., 2018; Kellerer-Pirklbauer & Kaufmann, 2012; Kenner et al., 2020; Marcer et al., 2021; Roer et al., 2005; Scapozza et al., 2014), and have been strengthened since the 2010s (Hartl et al., 2016; Kaufmann, 2016; Kaufmann et al., 2019, 2021; Kellerer-Pirklbauer et al., 2018; PERMOS, 2024; Thibert & Bodin, 2022; Vivero et al., 2022) (Figure 6b). Occasionally, individual sites could remain at a nearly constant velocity for decades (Gärtner-Roer et al., 2022; Käab et al., 1997), and destabilized rock glaciers may have had earlier speed-up phases (Roer et al., 2008) or have recently experienced a decadal slowdown (Kummert et al., 2021). Four rock glaciers (Tantermozza, Valletta, Val Sassa, and Val da l’Acqua) under influence of nearby

glaciers in the eastern Swiss Alps have exhibited an overall decelerating trend since the first half of the 20th century (Manchado et al., 2024). In the mountain ranges other than the Alps, multi-decadal studies are scarce: Necsoiu et al. (2016) reported a slight acceleration of a rock glacier in the Southern Carpathians, which had been moving at a slow rate ( $<1 \text{ cm yr}^{-1}$ ) since 1968, to an annual displacement of a few centimeters since 2007.

Interannual fluctuations of rock glacier velocity are superimposed on the decadal trend and display a regional synchronous pattern since the 2000s when continuous monitoring was initiated at many sites over the Alps (Delaloye, Perruchoud, et al., 2008; Delaloye, Strozzi, et al., 2008, 2010; Kellerer-Pirklbauer et al., 2024) (Figure 6b). The decennial acceleration since the 1980s–1990s led to a velocity peak in 2003/04 (Avian et al., 2005; Bodin et al., 2009; Krainer & Mostler, 2006), followed by a short-lived deceleration until 2007/08 (Ikeda et al., 2008; Kellerer-Pirklbauer et al., 2017; Kellerer-Pirklbauer & Kaufmann, 2012). The multi-year acceleration then led to a velocity maximum in 2015/16 and after a temporary decrease in velocity in 2016/17 (Bodin et al., 2018; Fey & Krainer, 2020; Groh & Blöthe, 2019; Haberkorn et al., 2021; Kenner et al., 2020), the acceleration continued until 2020/21 (Bearzot, Garzonio, Mauro, et al., 2022; Buchli et al., 2018; Kellerer-Pirklbauer et al., 2018; Thibert & Bodin, 2022). Since then, a general decrease in velocity has been observed until 2023 (PERMOS, 2024). Note that individual rock glaciers, such as the Ritigraben, Gruben, and the terminal part of Dirru in the Swiss Alps, can exhibit interannual variations deviating from the regional pattern (Gärtner-Roer et al., 2022; Kenner et al., 2017; Kummert et al., 2021). In the Pyrenees, the velocity of the Argulus rock glacier started to increase in the 1990s (Serrano et al., 2006), and a general decreasing trend occurred on the Posets rock glacier in the 2000s with a velocity peak in 2006/07 (Serrano et al., 2010). In Sierra Nevada of Spain, one of the southernmost active rock glaciers in Europe reached a velocity maximum in 2004/05, while it has been dominated by degradation processes and advancing at low rates since 2001 (Blasco et al., 2022).

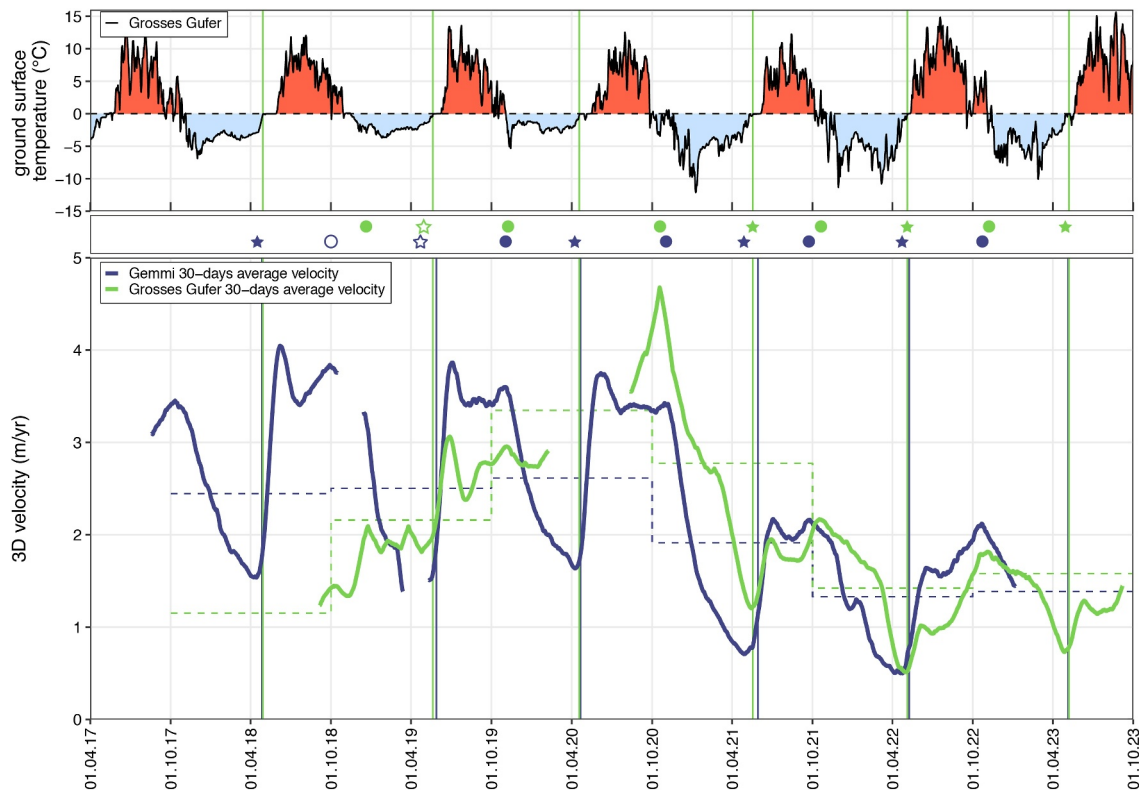
In the Alps, many rock glaciers display a pronounced seasonal rhythm: they accelerate abruptly and reach an initial velocity peak during the snowmelt period, followed by a slowdown in early summer, then accelerate again, reaching their maxima in late summer/early autumn, then gradually decelerate during the freezing season and reaching their velocity minima in late winter/early spring (Figure 7); the magnitude of seasonal maxima can be up to 10 times the minimum velocity (Arenson et al., 2002; Cicoira, Beutel, Faillettaz, Gärtner-Roer, & Vieli, 2019; Cicoira, Beutel, Faillettaz, Gärtner-Roer, & Vieli, 2019; Delaloye & Staub, 2016; Delaloye et al., 2010; Kenner et al., 2017, 2020; Papke et al., 2012; Perruchoud & Delaloye, 2007; Staub et al., 2016; Strozzi et al., 2020; Wirz et al., 2015, 2016). In addition, a case study in the Carpathian Mountains showed a similar seasonal rhythm to the pattern occurring in the Alps (Necsoiu et al., 2016). There are exceptions: Krainer and Mostler (2006) reported that the fast-moving Reichenkar rock glacier moved at an almost constant rate ( $>1 \text{ m yr}^{-1}$ ) throughout the year. For rock glaciers with complex internal structures, the seasonal variations may only develop on part of the landform (Buchli et al., 2018). It can be challenging to depict the seasonal changes in the velocity of slow-moving rock glaciers, such as the Murtèl Corvatsch rock glacier ( $\sim 1 \text{ dm yr}^{-1}$ ) (Haerberli et al., 1998).

Velocity variations at shorter timescales spanning from hours to weeks tend to be linked with the deformation of the active layer, such as boulder sliding and tilting (Cicoira et al., 2021; Kummert et al., 2018; Wirz et al., 2015, 2016). At the hourly timescale, ground-based SAR observations during September–October 2018 revealed a “step-like” pattern on Lazaun rock glacier in the Italian Alps: the rock glacier appeared to experience alternated active and stagnant phases for several hours (Bertone et al., 2023).

### 3.2.2. High Mountain Asia

Across the large cold region of High Mountain Asia, systematic quantification of rock glacier velocity is limited in number and mostly focused on the Tien Shan region, where the longest monitoring history dated back to the 1920s, employing dendro-geomorphology and photogrammetry (Bolch & Marchenko, 2006; Gorbunov et al., 1992; Palgov, 1948; Sorg et al., 2015). Additionally, a few non-continuous measurements were conducted using traditional survey or InSAR in the 1980s and 2000s (Wang et al., 2017; Zhu, 1996; Zhu et al., 1996). Several rock glaciers have been revisited throughout history through photogrammetry and InSAR, yet it poses challenges to reconstruct a consistent kinematic pattern from the landforms due to the complex periglacial processes they undergo and the variability in resolution and precision of the measurements (Kääb et al., 2021).

At a decennial timescale, despite the local variabilities among rock glaciers and sometimes within the extent of one landform, characteristic patterns in surface velocities have been found through photogrammetry and InSAR



**Figure 7.** Evolution of the seasonal 3D surface velocity at the Gemmi (blue) and Grosses Gufer (green) rock glaciers in the Swiss Alps. The velocities are computed over 30-day periods. The horizontal dotted lines represent the annual surface velocity measured by terrestrial geodetic surveys at the nearest boulder. The blue and green vertical lines represent the respective start of the zero-curtain period (when ground temperature remain at 0°C due to the release of latent heat during the phase transition of water), as determined for each site using nearby ground surface temperature (GST) loggers. The sub-panel at the top shows the daily ground surface temperatures measured at Grosses Gufer. The sub-panel in the middle indicates the winter minimum (star) and end of summer (dot) rock glacier velocity. Empty symbols represent inferred timing due to missing and/or uncertain velocity data (adapted from PERMOS, 2024).

(Figure 6d). Similar acceleration trends since the 2000s/2010s occurred on all six rock glaciers investigated recently, among which, two landforms (Karakoram and Kugalan Tash) have been accelerating steadily since the 1950s (Kääb et al., 2021), and two others (Archaly and Morenny) have undergone velocity increases since the 1980s (Bolch & Marchenko, 2006; Gorbunov et al., 1992). Furthermore, high velocities during the second half of the 1960s were detected on four rock glaciers (Gorodetsky, Ordzhonikidze, Morenny, and Archaly), one of which (Gorodetsky) experienced even higher velocities in the 1950s (Kääb et al., 2021). In addition, previous dendrogeomorphological measurements revealed an early active phase of four rock glaciers in the 1940s (Sorg et al., 2015).

The seasonal rhythm often typical for rock glacier movement was observed by InSAR at one site in the East Kunlun Mountains, where surface velocities reached the maxima in late summer and reduced to close to zero during winter to early spring (Hu et al., 2021). In the Nyainqêntanglha Range, however, no significant seasonal pattern was detected by InSAR in two basins (Buckel et al., 2021, 2022; Reinosch et al., 2020; Zhang et al., 2023), which is probably due to their transitional kinematic status ( $<1 \text{ dm yr}^{-1}$ ).

In other mountain ranges, such as the Hengduan (Cai et al., 2021), Western Karakoram (Hassan et al., 2021), Western Kunlun (Hu, Liu, et al., 2023), and Himalayan Mountains (Dini et al., 2019; Zhang et al., 2021), the surface velocities of rock glaciers averaged over a period of days to years have been measured by InSAR, ranging from millimeters to more than a meter per year.

The kinematics of rock glaciers in the extensive High Mountain Asia region have not been systematically surveyed. In particular, there is a complete lack of research focused on interannual timescales.

### 3.2.3. Western Canada and USA

In the Rocky Mountains and the contiguous western USA, centennial-scale studies through dendrogeomorphology revealed slow advancing movements at similar rates ( $<2 \text{ cm yr}^{-1}$ ) during 1576–1999 (Bachrach et al., 2004; Carter et al., 1999; Shroder-Jr, 1978; Shroder-Jr & Giardino, 1987). Cosmogenic surface-exposure dating reported that a rock glacier in the Unita Mountains of Utah formed at the start of the Holocene, with current velocity at around  $10 \text{ cm yr}^{-1}$  (Munroe et al., 2024). Decennial-scale in situ investigations and photogrammetric measurements showed stable velocity since the 1960s/70s until the beginning of the 2000s (Janke, 2005a, 2005b; Potter-Jr. et al., 1998). In the past two decades, using GNSS and photogrammetry methods, Janke and Bellisario (2010) reported a slight acceleration at the California rock glacier during 2003–2008. Kääh and Røste (2024) reconstructed the velocity history of 16 rock glaciers by aerial photogrammetry and found overall accelerations since 1940s/1950s until around 2020. At a seasonal scale, rock glaciers situated in the Uinta Mountains exhibited strong velocity variations, with late summer peaks five times faster than velocities of the rest of the year during 2016–2019 revealed by InSAR (Brencher et al., 2021).

Similar kinematic patterns are observed on rock glaciers in other mountain ranges of North America. Stable movement rates over millennial and decadal scales (1983–1995) were observed in the Selwyn Mountains using lichenometry and traditional survey (Sloan & Dyke, 1998). Seasonal rhythm with autumn velocity maxima twice the spring minimum during 2007–2008 was detected by InSAR on a rock glacier in the Sierra Nevada of California (Liu et al., 2013).

Overall, research on rock glacier kinematics in Western Canada and the USA is limited in both spatial coverage and temporal resolution. Specifically, kinematics at the interannual timescale, which are closely associated with rock glacier velocity (RGV), have not been systematically surveyed.

### 3.2.4. South America

The Andes host a number of active rock glaciers that are connected to upslope glacier systems, that is, glacier-connected rock glaciers according to RGIK (2023a), and that move downslope at relatively fast velocities ( $>1 \text{ m yr}^{-1}$ ) (Blöthe et al., 2021; Villarroel et al., 2022). For instance, the terminus of one rock glacier system reached velocities exceeding  $4 \text{ m yr}^{-1}$  during 2012–2020 (Robson et al., 2022), and underwent acceleration or even destabilization between 2000 and 2012 (Monnier & Kinnard, 2017). The velocity increase since the 2000s occurred on three other rock glaciers in the same area (Vivero et al., 2021) (Figure 6c). These multi-annual resolution velocities were measured by photogrammetry.

In contrast, three glacier-connected rock glaciers displayed an overall deceleration trend from 1955 to 2014 as measured by photogrammetry (Monnier & Kinnard, 2017). A four-year GNSS measuring campaign (2012–2016) focusing on a talus-derived rock glacier implied an ongoing deceleration process leading to a potential halt (Martini et al., 2017).

Using photogrammetry, Blöthe et al. (2024) analyzed the decadal kinematics (1968–2023) of 21 rock glaciers in northwestern Argentina, all of which are either talus-connected or debris-mantled slope-connected. Their findings revealed that the velocity of most rock glaciers remained stable throughout the study period, ranging from  $0.28$  to  $0.70 \text{ m yr}^{-1}$ .

A distinct seasonal cycle was detected by InSAR on the Dos Lenguas rock glacier in the Argentinian Andes, with high velocities at the end of summer (Strozzi et al., 2020), yet seasonal variations measured by InSAR were minimal for the El Gigante rock glacier located in another region during a drought period (2014–2017) (Villarroel et al., 2022).

Considering that the South America Andes hosts thousands of rock glaciers of various morphological histories and ages and that the climate gradient is large here, relatively few studies have been published in this region compared to other mountain ranges. There is a huge potential to increase our knowledge of rock glacier kinematics in the Andes.

### 3.2.5. The Arctic and Subarctic

In Scandinavia, several rock glaciers located in Norway, including active and relict ones, have been investigated by Schmidt-hammer exposure-age and radiocarbon dating to determine their formation periods which roughly

corresponded to the Lateglacial Interstadial (~14.8 ka) or the regional retreat of the Scandinavian Ice Sheet (~10 ka) (Nesje et al., 2021; Paasche et al., 2007). At decennial timescale, a destabilized rock glacier system in Northern Norway has experienced acceleration detected by airborne photogrammetry and SAR offset tracking from 0.5 m yr<sup>-1</sup> during 1954–1977 to 3.6 m yr<sup>-1</sup> during 2006–2014, and the movement rate has further increased from 4.9 to 9.8 m yr<sup>-1</sup> during 2009–2016 (Eriksen et al., 2018). InSAR-based measurements at the regional scale conducted across the surrounding area reported annual displacements of rock glaciers ranging from millimeters to meters during 2015–2019 (Lilleøren et al., 2022; Rouyet et al., 2021). Over the same period, a few rock glaciers in Southern Norway underwent movements at rates of millimeters to centimeters per year, as measured by InSAR (Nesje et al., 2021).

In Svalbard, early photogrammetric studies documented slow velocities ( $\leq$  cm yr<sup>-1</sup>) with negligible changes between the 1960s/70s and 1990s (Kääb et al., 2002). Similar characteristics in terms of velocity range and temporal variation were found by in situ and photogrammetry measurements at the interannual scale during the late 1980s and early 2000s (Isaksen et al., 2000; Sollid & Sørbel, 1992; Ødegård et al., 2003). A more recent InSAR-based inventory at the regional scale documented a larger range of velocities up to m yr<sup>-1</sup>. The variability appears to be related to the geomorphological characteristics of the upslope, with talus-connected rock glaciers typically creeping slower than glacier-connected ones (Bertone et al., 2022).

In Iceland, rock glaciers have undergone a complex formation history, as revealed by Schmidt-hammer dating (Kellerer-Pirklbauer et al., 2008; Wangensteen et al., 2006). At both decennial and interannual scales before 2000, photogrammetry and in situ measurements showed that rock glaciers in Iceland shared a similar kinematic behavior as talus-connected rock glaciers in Svalbard: annual velocities were generally at magnitudes of centimeters per year or less and few temporal changes were detected (Campos et al., 2019; Tanarro et al., 2019; Wangensteen et al., 2006; Whalley et al., 1995). In the northern Iceland, some active rock glaciers moved at 0.2–0.5 m yr<sup>-1</sup>, with a maximum over 3 m yr<sup>-1</sup> in the autumn of 2007 as revealed by InSAR (Lilleøren et al., 2013).

In Greenland, InSAR investigations detected fast movements ( $>2$  m yr<sup>-1</sup>) with seasonal variations of the Manissuarsuk rock glacier in Qeqertarsuaq during 2015–2019: the seasonal velocity maximum is up to twofold of the minimum (Strozzi et al., 2020). Recent studies using GNSS and photogrammetry measured slow movements (a few cm yr<sup>-1</sup>) of the Bjørneø rock glacier in the southern region during 2016–2021 (Abermann & Langley, 2022; Kellerer-Pirklbauer et al., 2022).

In Alaska, in situ investigations of rock glacier kinematics date back to the 1940s/50s. Wahrhaftig and Cox (1959) reported velocities of the Clear Creek rock glacier in the range of a few decimeters per year from 1949 to 1957. However, recent studies are generally lacking. Bucki and Echelmeyer (2004) reconstructed a unique motion pattern of the Fireweed rock glacier which moved at high rates ( $>3.5$  m yr<sup>-1</sup>) for decades (1950s–1970s–1990s) and experienced velocity minimum in the summer of 1999.

In summary, research on the kinematics of rock glaciers in many regions of the Arctic and Subarctic has been scarce across various timescales since the 2000s. Moreover, those rock glaciers with recent data are limited in both number and monitoring duration.

### 3.2.6. The Antarctic and Subantarctic

A small number of studies presented multi-annual mean velocities of several rock glaciers in eastern Antarctica during the 1970s (Hassinger & Mayewski, 1983) and the early 2000s (Fukui et al., 2008). Velocities derived from in situ surveys and InSAR generally ranged from a few centimeters to one or two decimeters per year. In addition, the annual velocities of several rock glaciers in western Antarctica were estimated from the debris volume and transport rate, ranging from a few centimeters to nearly one m each year since the formation of these landforms (Serrano & López-Martínez, 2000). At a decadal timescale, Prates and Vieira (2023) used photogrammetry to measure the velocity of the Hurd rock glacier from 1956 to 2019. They found that the velocity remained largely stable, ranging from 12 to 36 cm yr<sup>-1</sup>.

Overall, rock glacier kinematics in the Antarctic and Subantarctic remain largely uninvestigated.

### 3.2.7. New Zealand

A very limited number of studies on rock glaciers have been carried out in New Zealand, and only two of them provide data on kinematics. Winkler and Lambiel (2018) have shown that two rock glaciers of the Ben Ohau Range have developed during the entire Holocene, with average velocities of  $\sim 3 \text{ cm yr}^{-1}$ . Lambiel et al. (2023) presented the kinematic data of 123 rock glaciers inventoried in the Central Southern Alps of New Zealand based on Sentinel-1 InSAR data from 2015 to 2019. Their findings revealed that the velocities vary from less than a centimeter per year to over a meter per year. Notably, 67% of the rock glaciers fall into the transitional category, with velocities less than a decimeter per year.

## 4. Responses of Rock Glacier Kinematics to Climatic Forcing

### 4.1. Responsive Kinematic Behaviors Across Timescales

The observed rock glacier velocity is mainly the consequence of permafrost creep controlled by the topography, the material constituents, and the environmental factors including the ground temperature and the amount of unfrozen water in the pore spaces (Arenson & Springman, 2005; Cicoira et al., 2021; Haeblerli et al., 2006; Moore, 2014). Therefore, climatic conditions, such as air temperature and snow cover regime, contribute to shaping the kinematic characteristics of rock glaciers by influencing the environmental factors listed above. Current knowledge of rock glacier kinematic responses to climatic factors at a range of temporal scales is reviewed in this section.

#### 4.1.1. Decadal Timescale

The overall accelerating trend of rock glaciers in the Central Alps has coincided with the general increase in mean annual air temperature (MAAT) since the 1990s (Hartl et al., 2016; Käab et al., 2007; Roer et al., 2005; Scapozza et al., 2014) (Figures 6a and 6b). The observed speed-up of rock glaciers during the 1950s and 1960s followed by a deceleration in the 1970s is also in concert with changes in air temperatures in the European Alps (Kellerer-Pirklbauer & Kaufmann, 2012; Lugon & Stoffel, 2010). The slight acceleration of rock glaciers in the Southern Carpathian Mountains appeared to be synchronous with the warming of air temperature in recent decades (Necsoiu et al., 2016).

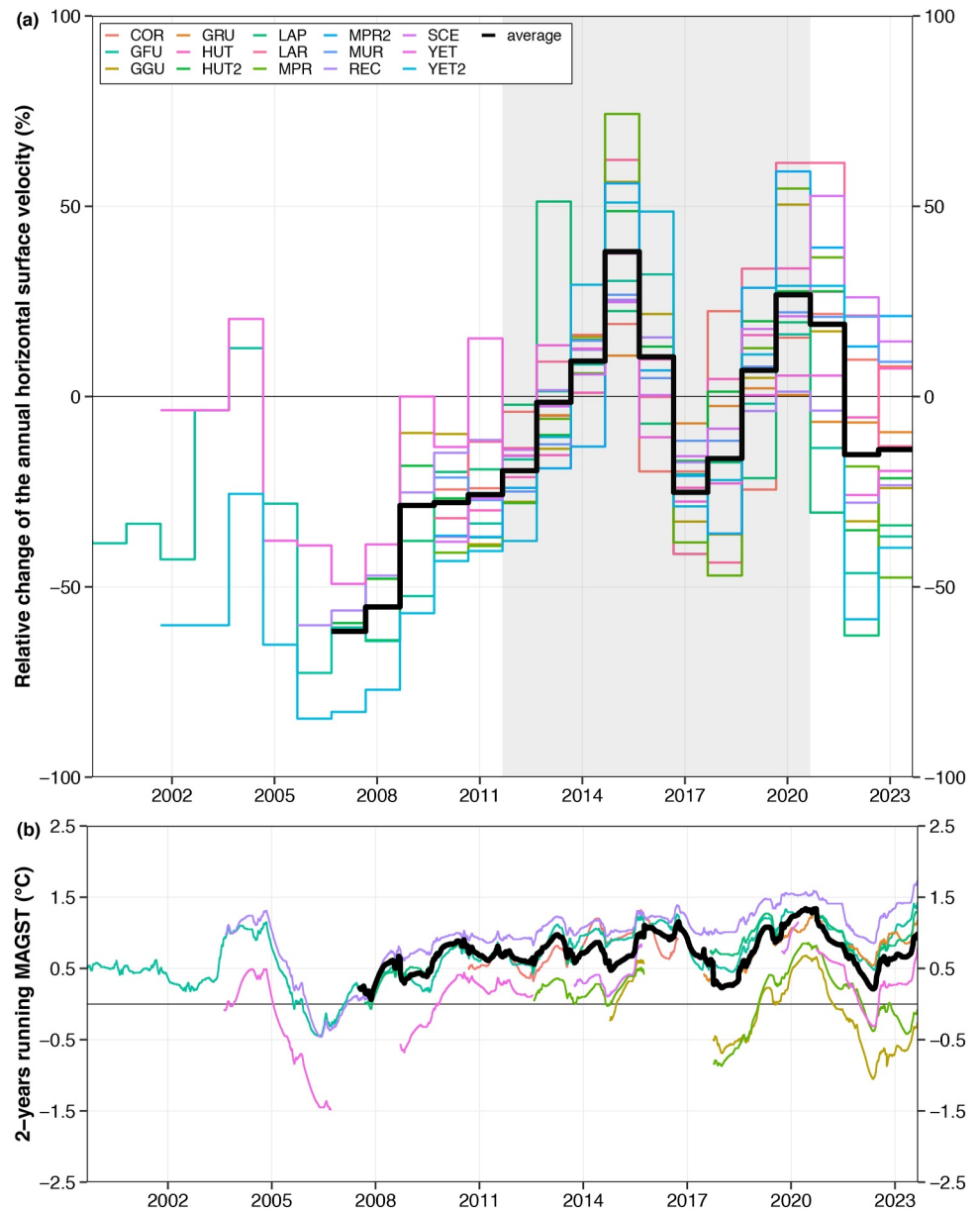
The steady accelerations of rock glaciers in the Northern Tien Shan since the 1950s, with enhanced speed-ups over the last decades, are consistent with the kinematic response of rock glaciers to atmospheric warming in the European Alps (Käab et al., 2021; Sorg et al., 2015) (Figure 6d). However, local variability has been identified in the Northern Tien Shan: three rock glaciers showed high movement rates during 1966–1971 when the air temperatures were cold (Käab et al., 2021). High rock glacier velocity during these cold years is probably attributed to the early onset of snow cover of above-average depths, as recorded by nearby meteorological stations (Bolch & Marchenko, 2006), which may have increased ground temperatures and thus rock glacier velocity (Käab et al., 2021).

In the Rocky Mountains, early studies showed the small variations in rock glacier velocity during 1961–2002, associating with the cooling trend observed at above-timberline meteorological sites across the mountain range (Janke, 2005b; Pepin, 2000). Käab and Røste (2024) extended the study period and reported significant accelerations (by a factor of 2–3) in 16 rock glaciers from the 1940s/1950s to around 2020. These accelerations coincide with the rising air temperatures observed over recent decades.

In the Chilean Andes, multi-decadal decelerations (1955–2014) have been observed on three glacier-connected rock glaciers, suggesting an ongoing stabilization process (Monnier & Kinnard, 2017). The Las Tetas rock glacier has been accelerating during 2000–2012 at the terminus part where the periglacial processes dominate (Monnier & Kinnard, 2017), which is related to the lasting atmospheric warming trend of  $0.19^\circ\text{C decade}^{-1}$  during 1958–2007 in the nearby area (Rabatel et al., 2011). In the Argentinian Andes, several talus-connected or debris-mantled slope-connected rock glaciers exhibited a stable velocity pattern during the past decades (1968–2023) in this cold and (semi-)arid region (Blöthe et al., 2024).

#### 4.1.2. Interannual Timescale

Hoelzle et al. (1998) were the first to hypothesize a relationship between interannual velocity variations and ground temperatures, suggesting thermal control on rock glacier velocities at the interannual timescale. Frauenfelder



**Figure 8.** Comparison between the relative annual horizontal surface velocity of rock glaciers in the Swiss Alps and the 2-year running mean ground surface temperature (GST) during 2000–2023. Data source: Swiss Permafrost Monitoring Network (PERMOS). The reference period of (a) is 2011–2020 (marked by the gray shade) (Updated after PERMOS, 2024).

et al. (2003) revealed an insignificant correlation between the annual mean velocity and the MAAT. Comparisons between rock glacier velocity and air temperature revealed a delayed pattern: accelerations tended to occur one or a few years later than the warm air temperature (Kellerer-Pirklbauer & Kaufmann, 2012); in contrast, the time lag between decelerations and cold air temperatures was relatively insignificant (Kellerer-Pirklbauer & Kaufmann, 2012).

A less asynchronous relationship between interannual velocity variations and mean annual ground surface temperature (MAGST) was found on many sites in the European Alps (Bodin et al., 2009; Delaloye et al., 2010; Ikeda et al., 2008; Wirz et al., 2015). The observed interannual velocity fluctuations were correlated with the shifts of MAGST with a phase lag of a few months up to 1 year (Figure 8). Rock glaciers usually moved at high annual horizontal surface velocities in the years with high MAGST, and vice versa (Delaloye, Perruchoud, et al., 2008; Delaloye, Strozzi, et al., 2008, 2010). In addition, Staub et al. (2016) found that the best correlation



exists between the mean annual horizontal surface velocity and the anomaly of the mean ground surface temperature (GST) over  $\sim 2.5$  years with a delay of 3–6 months, further supporting the driving influence of GST on velocity changes on the interannual timescale.

The MAGST is influenced by both the air temperature, especially summer temperature, and the snow cover conditions (thickness, onset, and duration) because the snow cover acts as an insulating layer and influences the surface albedo, which modulates the thermal state of the ground (Haeberli et al., 2006). By analyzing the time series of Laurichard rock glacier velocity and snow accumulation, Bodin et al. (2009) highlighted the importance of snow cover as a controlling factor: early and thick snow cover insulated the ground from winter cooling and increased the MAGST. A positive correlation between snow cover duration and rock glacier velocity was observed at different sites in the Swiss Alps (Wirz et al., 2015).

Additionally, previous research hypothesized that the melt of accumulated snow provides external water into the frozen body, resulting in summer acceleration and hence a high annual mean velocity (Bodin et al., 2009; Ikeda et al., 2008). By simulating the water infiltration from the upstream catchment, Cicoira, Beutel, Faillettaz, and Vieli (2019) reproduced the interannual (and seasonal) velocity variations of the fast-moving Dirru rock glacier during 2011–2019.

#### 4.1.3. Seasonal and Short-Term Timescales

Seasonal variations of rock glacier velocity were originally compared with the changes in temperature, that is, time series of GST, by which a time lag of a few months between the extreme values of velocity and GST was observed (e.g., Delaloye et al., 2010; Kääh et al., 2007). Such delay was attributed to the time required for the heat to propagate into the landform and adjust the shallow ground temperature (e.g., Haeberli et al., 2006). However, it has been quantitatively demonstrated that the thermal conduction process alone cannot explain the observed kinematic variations in terms of both the amplitude and phase lags (Cicoira, Beutel, Faillettaz, Gärtner-Roer, & Vieli, 2019).

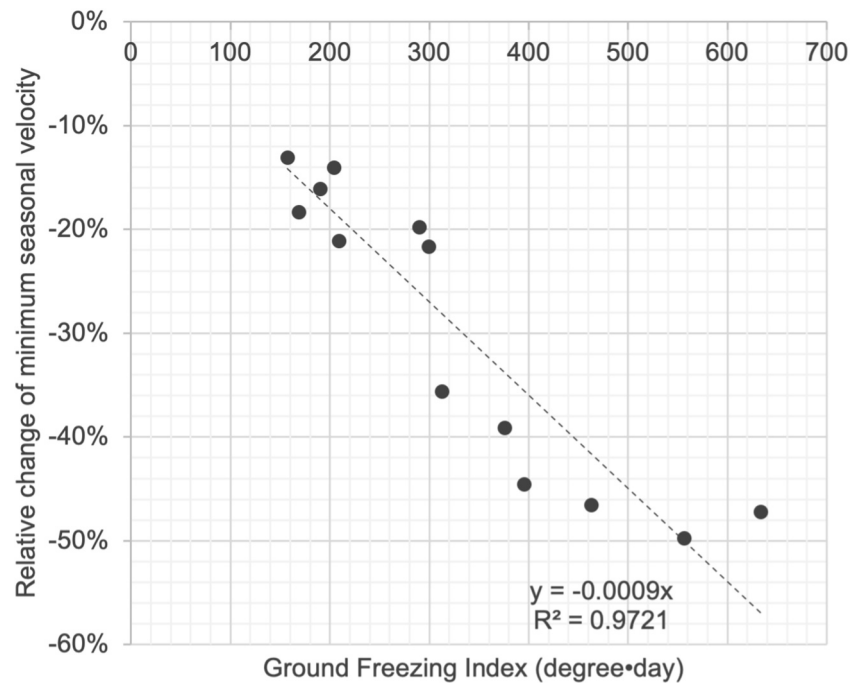
Early observations have revealed a synchronous relationship between the abrupt seasonal acceleration and the onset of snowmelt (Ikeda et al., 2008; Kenner et al., 2017; Perruchoud & Delaloye, 2007). Occasionally the increase of velocity is progressive and delayed by about 2 months compared with the melt of snow, as on the Muragl rock glacier (Kääh et al., 2007). Winter deceleration typically began after the decrease in air temperature and GST with a lag of weeks to months, and the magnitude of the deceleration appeared to be controlled by the coldness of the winter temperature (Ikeda et al., 2008; Wirz et al., 2016; Figure 9).

Researchers have long speculated that water in the frozen body of rock glaciers plays an important role in controlling the seasonal rhythm of velocities (Bast et al., 2024; Buchli et al., 2018; Delaloye et al., 2010; Hartl et al., 2016; Ikeda et al., 2008; Kenner et al., 2017; Krainer & Mostler, 2006; Wirz et al., 2016). This hypothesis was then examined at one site using the numerical modeling approach (Cicoira, Beutel, Faillettaz, & Vieli, 2019). The authors concluded that water from snow melt combined with liquid precipitation is the major factor controlling the seasonal rhythm of rock glacier creep by altering the pore pressure in the debris-rich shear horizon (Cicoira, Beutel, Faillettaz, & Vieli, 2019). In addition, recent observations on rock glaciers in the Rocky Mountains reported a positive correlation between the seasonal acceleration and the snow water equivalent of snowpack accumulated in the previous winter (Brencher et al., 2021).

Finally, at shorter timescales (days to weeks), previous studies reported the synchronous relationship between heavy rainfalls and rock glacier speed-ups (Kenner et al., 2017; Wirz et al., 2016), which tend to be related to movement such as tilting and sliding within the active layer.

#### 4.1.4. Rock Glacier Destabilization

Rock glacier destabilization, not to be confused with slope instabilities in a geotechnical context, refers to the kinematic behavior of a drastic increase in velocity of up to two orders of magnitude relative to the past rate, accompanied by the development of shear and tension cracks. Over the past two decades, destabilized rock glaciers have occurred more frequently (Allstadt et al., 2024; Avian et al., 2005; Bodin et al., 2017; Delaloye et al., 2013; Ghirlanda et al., 2016; Morriss et al., 2023; Roer et al., 2008). Historical imagery revealed cyclic behavior of destabilization on Äußeres Hochebenkar rock glacier in the Austrian Alps: the first cycle occurred from the 1950s to the mid-1970s; and the second cycle initiated around 2017 and lasted until today (Hartl et al., 2023).



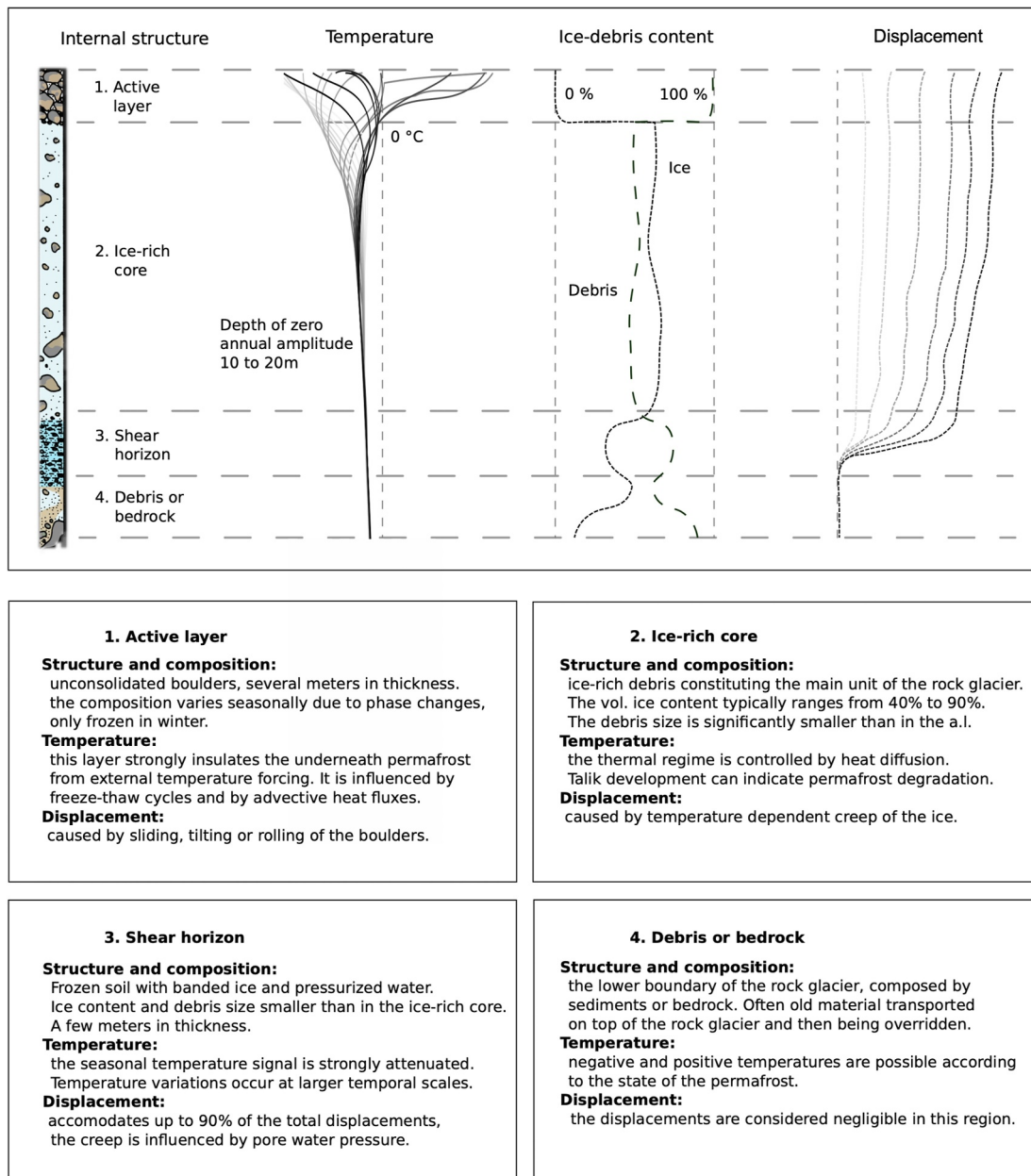
**Figure 9.** The linear relationship between the Ground Freezing Index (GFI) and the relative change of the minimum seasonal velocity (usually reached in April–May) compared to the mean velocity between 2005 and 2017 at Becs-de-Bosson rock glacier in the Swiss Alps (Unpublished data by the Alpine Geomorphology Research Group, University of Fribourg). Velocity data were the average of seven points on the rock glacier through GNSS surveys conducted every 2 months. GFI is the sum of the daily negative GSTs from six locations on the rock glacier during the entire freezing season, indicating the coldness of the winter temperature.

Rock glacier destabilization is triggered by the interaction of combined climatic and geomorphologic factors, including localized debris overload, landform topography, and in particular permafrost warming (Bodin et al., 2017; Delaloye et al., 2013; Ghirlanda et al., 2016; Marcer et al., 2019; Morriss et al., 2023; Roer et al., 2008; Scotti et al., 2017; Vivero et al., 2022). For instance, 5.3% of rock glaciers (18 out of 337) across the French Alps experienced destabilization under regional atmospheric warming since the 1990s (Marcer et al., 2021). The 2015 summer heat wave in Europe warmed the mountain permafrost and may have created favorable conditions for the 2016–2017 destabilization of the La Roussette rock glacier (Vivero & Lambiel, 2019). In addition, a rapid snowmelt event was concurrent with the detected morphologic changes in the summer of 2016 (Vivero & Lambiel, 2019).

Based on observations and empirical modeling, Cicoira et al. (2021) introduced a theoretical variable known as the Bulk Creep Factor (BCF), which is defined as the ratio between the observed creep rate and the modeled theoretical creep rate. This factor serves as a representation of the kinematic behavior of rock glaciers, accounting for material properties such as density, ice content, cohesion, friction angle of the shear horizon material, and the critical shear strain rate. The BCF value provides insight into the extent to which the rock glacier's kinematics deviate from steady-state creep behavior. One application of the BCF is to identify the destabilized rock glacier in a quantitative way: in a destabilizing section, the BCF can abruptly jump to high values close to 20 and show a discontinuous profile in connection to the upslope steady-creep sections where BCF values are usually smaller than 5. The BCF can serve as a reference value for monitoring the potential transition from accelerating to destabilizing responses to climate warming in the long run (Hartl et al., 2023).

#### 4.2. Mechanical Interpretations

The surface velocity of rock glaciers represents the cumulative deformation of the frozen ground material distributed from the shear horizon to the surface (Arenson et al., 2002; Bucki et al., 2004; Cicoira et al., 2021; Haerberli et al., 2006) (Figure 10). A constitutive relationship adapted from Glen's flow law (Glen, 1955), which



**Figure 10.** Graphical illustration and textual description of vertical profiles (conceptualized) of a typical rock glacier. From left to right the internal structure, the ground temperature variations, the material composition and the displacement profiles of a typical rock glacier are shown. The concept is based on the most influential publications on borehole investigations in rock glaciers (e.g., Arenson & Springman, 2005; Arenson et al., 2002; Krainer et al., 2015). The profiles are drawn on the basis of data from the Murtél borehole (adapted after Cicoira et al., 2021).

relates the strain rate ( $\dot{\epsilon}$ ) with effective stress ( $\delta_e$ ), is usually adopted to depict the debris-ice flow (Amschwand et al., 2021; Arenson & Springman, 2005; Monnier & Kinnard, 2016; Müller et al., 2016):

$$\dot{\epsilon} = A(T, \omega_i) \delta_e (\rho, h, \alpha, P_w)^{n(\omega_i)} \quad (1)$$

where  $A$  and  $n$  are the creep parameters influenced by ground temperature ( $T$ ) and volumetric ice content ( $\omega_i$ ); the effective stress ( $\delta_e$ ) is affected by material density ( $\rho$ ), thickness ( $h$ ), slope ( $\alpha$ ), and pore water pressure ( $P_w$ ).

The rheological behavior of the debris-ice mixture is primarily controlled by the debris concentration. Pioneering research on frozen soil mechanics has discovered that pore ice governs the deformation when volumetric debris

content is less than ~42%. As the debris fraction increases (>42%), it causes the strengthening of the mixture by introducing the inter-particle friction that impedes the creep deformation of the ice matrix (Ting et al., 1983).

Meanwhile, contradictory observations have been reported: several studies have found that the addition of debris decreases the shear strength and makes the mixture deform more rapidly than pure ice under similar conditions (Bucki & Echelmeyer, 2004; Ikeda et al., 2008). This phenomenon can partly be attributed to the lubricating and stress-modulating effects exerted by the unfrozen water concentrating at the debris-ice interfaces (Arenson et al., 2007; Cuffey & Paterson, 2010). This pair of competing effects produced by the presence of debris has been reviewed comprehensively by Moore (2014), which highlights other first-order variables governing the debris-ice deformation, such as debris particle size, temperature, salinity, and stress.

#### 4.3. Impacts of Climatic and Meteorological Factors on Rock Glacier Movement

Against the above background (Sections 4.1 and 4.2), both internal (e.g., composition and subsurface structure) and external factors (e.g., ground temperature and pore pressure) control the kinematic behavior of rock glaciers. Climatic and meteorological factors influence rock glacier velocities by altering the external properties. Air temperature affects the ground temperature across all timescales, especially at the interannual and decadal scales. Snow cover regime (onset, thickness, and duration) adjusts the ground temperature and may provide water to change the pore water pressure at seasonal and interannual timescales. Liquid precipitation can induce short-term velocity peaks. For a given rock glacier, warm ground temperature and high pore water pressure favor its movement (Arenson & Springman, 2005; Cicoira et al., 2021).

### 5. Summary and Future Perspectives

In this section, we first recap the key points of this review by addressing the two primary questions raised in the *Introduction*:

Question 1: What are the global and regional patterns of the rock glacier velocity across temporal scales as revealed by observations?

1. On a global scale, rock glacier velocity is primarily characterized by a (multi-)decennial acceleration trend with regional variabilities in terms of onset timing and magnitude. This long-term pattern is found on rock glaciers in different areas, especially since the 2000s, including the European Alps, Scandinavia, High Mountain Asia, the Rocky Mountains, and the Andes.
2. On a regional scale, the interannual variations of rock glacier velocity display a synchronous pattern in many cases of the European Alps, where continuous and Alpine-wide monitoring has been available for more than two decades, despite the differences in local topo-climatic conditions.
3. On a seasonal scale, rock glaciers typically accelerate during the snowmelt season, reaching their maximum in late summer/early autumn and their minimum in late winter/early spring. These variations are present on many active rock glaciers around the globe but can be difficult to detect on slow-moving rock glaciers.

Question 2: How are the observed kinematic patterns linked with climatic and meteorological conditions?

1. Air temperature influences the velocity variations of rock glaciers by changing the ground temperature via heat exchanges across temporal scales. Field data evidence in support of this relationship includes:
  - a) the synchronization between rock glacier active phases and warm periods;
  - b) the positive correlation between MAAT and rock glacier velocity at the (multi-) decadal timescale;
  - c) the delayed correlation (over weeks to months) between MAAT and rock glacier velocity at the interannual timescale;
  - d) the synchronous relationship between mean bi-annual ground surface temperature and rock glacier velocity at the interannual timescale;
  - e) the correlation between the magnitude of seasonal deceleration in winter and the coldness of winter temperature (depending also on snowcover characteristics, see below).
2. Snow cover regime affects the kinematic variations in two ways:
  - a) by adjusting the ground temperature as an insulation layer;
  - b) by providing water input during the melting season to the rock glacier system.

Observations of interannual and seasonal velocity variations are consistent with these mechanisms.

**Table 2**

*A Selection of Research Milestones (Until 2023) in the Studies of Rock Glacier Kinematics*

Year	Research milestone	References
1900	First article on “ <i>a peculiar form of talus</i> ” was published in <i>Science</i> .	Spencer (1900)
1910	The term “rock glacier” was coined with a detailed geomorphic description.	Capps (1910)
1919	Field measurements of rock glacier movement were carried out.	Chaix (1919)
1928	Terrestrial photogrammetry was applied to measure rock glacier kinematics.	Finsterwalder (1928)
1957	Rock glacier movement was described as the creep of frozen soil masses.	Jäckli (1957)
1959	First comprehensive kinematic study on rock glaciers by theodolite/traditional survey.	Wahrhaftig and Cox (1959)
1968	Aerial photogrammetry was used for measuring rock glacier movement.	Messerli and Zurbuchen (1968)
1985	First monograph on rock glaciers was published.	Haerberli (1985)
1987	First borehole was drilled on the Murtèl-Corvatsch rock glacier.	Haerberli et al. (1988)
1996	The role of rock glaciers as indicators of high mountain environments was highlighted in a monograph.	Barsch (1996)
1997	GNSS was used for rock glacier kinematics survey.	Berthling et al. (1998)
1998	“Shear horizon” was observed and coined.	Haerberli et al. (1998)
1999	InSAR was introduced to measure rock glacier movement.	Rott and Siegel (1999)
2000	Laser scanning was adopted in rock glacier kinematics monitoring.	Bauer et al. (2003)
2002	Seasonal rhythm of rock glacier movement was first depicted.	Arenson et al. (2002)
2005	Triaxial tests were conducted on rock glacier borehole samples.	Arenson and Springman (2005)
2007	Influence of temperature forcing on rock glacier dynamics was assessed	Kääb et al. (2007)
2008	Rock glacier destabilization was reported.	Roer et al. (2008)
2008	Regional similarity of interannual variations in rock glacier velocity was reported.	Delaloye, Perruchoud, et al. (2008), Delaloye, Strozzi, et al. (2008)
2016	Detailed characterization of short-term variations in rock glacier velocity	Wirz et al. (2016)
2018	<i>IPA Action Group on Rock Glacier Inventories and Kinematics</i> was established.	Delaloye et al. (2018)
2019	Influence of water forcing on rock glacier dynamics was assessed.	Cicoira, Beutel, Faillettaz, and Vieli (2019)
2021	Conceptual representation of rock glacier destabilization was proposed based on regional observations.	Marcer et al. (2021)
2022	RGV was accepted as a new product of ECV Permafrost.	GCOS (2022b)
2023	The <i>IPA Action Group on Rock Glacier Inventories and Kinematics</i> initiated the transition to the <i>IPA Standing Committee on Rock Glacier Inventories and Kinematics (RGIK)</i> .	RGIK (2023b)

- Liquid precipitation contributes to seasonal acceleration by changing the pore water pressure in the shear horizon and increasing heat extraction at depth through convection, as supported by recent modeling work.
- Rock glacier destabilization is a consequence of multiple factors including long-term warming, excess water, and local topography. The recently proposed BCF can be used for monitoring the possible long-term kinematic evolution from acceleration to destabilization in the current warming climate.

Based on our review, we chronicle some milestones in scientific investigations of rock glacier kinematics for more than one century (Table 2). Finally, we present our perspectives on future research:

- Our review indicates a prevalent correlation between climate change and long-term variations in rock glacier velocity. As continuous monitoring of rock glacier kinematics is lacking in many cold regions around the world, we call for more systematic and consistent velocity measurements that can be used to generate Rock Glacier Velocity (RGV) products. A standardized data set generated according to the GCOS requirements (GCOS, 2022a) and the “*Best practice for monitoring permafrost*” compiled in the “*World Meteorological Organization Guide for Instruments and Methods of Observation (WMO No. -8)*” will serve as a regional reference for evaluating changes in mountain permafrost (<https://community.wmo.int/en/activity-areas/imop/wmo-no.8/wmo-no-8-provisional-2024-edition>).

2. Systematic investigations of rock glacier velocity at fine spatial and temporal resolutions (e.g., seasonal and shorter timescales) and with different methods (e.g., complementary measurement coverage and data dimensions) are encouraged to contribute to the development of RGV monitoring strategy in three ways:
  - a) by identifying and filtering the short-term kinematic variations and refining processing strategies to temporally aggregate observations and provide annualized products;
  - b) by assessing the spatial homogeneity/heterogeneity and distinguishing different moving sections;
  - c) by discerning and excluding the vertical thinning or thickening processes, especially for ice-rich (often glacier-connected) rock glaciers.
3. Several interconnected factors collectively govern the creep of rock glaciers. Mechanisms linking climate/meteorological factors to rock glacier velocity still need to be further explored, such as:
  - a) how water infiltrates—or not—the (partially) frozen body of a rock glacier;
  - b) how cold temperatures influence winter decelerations.
4. Observations combined with laboratory work and numerical modeling, for example, hyper-gravity modeling and material point method, are needed for an in-depth understanding of the relationship between rock glacier kinematics, environmental factors, and permafrost conditions. This is required to incorporate rock glacier processes in land surface models and project future changes in a warming climate.

### Data Availability Statement

Figures 1, 2, and 5 were made with Adobe Illustrator. Figures 6–8 were plotted with Rstudio 2024.09.0 Bulid 375 (RStudio Team, 2024). Figure 9 was plotted with Matplotlib version 3.4.1 (Caswell et al., 2021; Hunter, 2007). Figure 3 was plotted by using QGIS (QGIS Development Team, 2009). Figure 4 was produced by Microsoft Excel (Microsoft Corporation, 2021). Data used for plotting Figure 6 are from PERMOS (PERMOS, 2024), Vivero et al. (2021), and Kääh et al. (2021). Data used for producing Figures 7 and 8 are available at PERMOS (PERMOS, 2024). Data used for creating Figure 9 are available on Zenodo (Delaloye, 2024).

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