Multi-decadal (1953 – 2017) rock glacier ~~morphodynamics~~kinematics analysed by high-resolution topographic data in the Upper Kauner Valley, Austria

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Abstract. Permafrost is being degraded worldwide due to the ~~change~~shift in external forcing caused by climate change. This has also been shown to affect the morphodynamics of active rock glaciers. We studied these changes, depending on the analysis, on nine or eight active rock glaciers with different characteristics in multiple epochs between 1953 and 2017 in Kauner Valley, Austria. A combination of historical aerial photographs and airborne laser scanning data and their derivatives ~~are~~were used to analyse surface movement and ~~3D displacements.~~surface elevation change. In general, the studied landforms ~~show~~showed a significant acceleration of varying magnitude in the epoch 1997–2006 and a volume loss to varying degrees throughout the investigation period. ~~Besides, we detect rock glaciers that show indication of inactivation.~~With glacier forefield-connected rock glaciers showing significantly higher rates of subsidence than talus-connected ones. Besides, we detected two rock glaciers with deviating behaviour and one that showed an inactivation of its terminal part. By analysing meteorological data (temperature, precipitation and snow cover onset and duration), we ~~are~~were able to identify possible links to these external forcing parameters. ~~The combined investigation of horizontal and vertical 3D displacements shows that these are temporally decoupled on some rock glaciers.~~ The catchment-wide survey further ~~reveals~~revealed that, despite the general trend, timing, magnitude and temporal peaks of morphodynamic changes indicate a slightly different sensitivity, response or response time of individual rock glaciers to fluctuations and changes in external forcing parameters.

1 Introduction

Rock glaciers are a downslope creep phenomenon of mountain permafrost and responsible for extensive mass transport in alpine environments (Barsch, 1996). Active rock glaciers consist of a coarse debris layer (active layer), covering ice supersaturated debris or pure ice and form lobate or tongue shaped land forms (Haeberli et al., 2006). They can be found in most cold mountain regions of the earth (Jones et al., 2019). It has long been debated whether rock glaciers are of glacial (e.g. Whalley, 1974; Humlum, 1982) or periglacial (e.g. Barsch, 1977; Haeberli, 1985) origin. A review of this topic is presented in Berthling (2011). In his definition, permafrost is the primary condition for rock glaciers to form, but the deforming ice and debris may be of both glacial and periglacial origin, stressing the equifinality of these landforms. Besides, the incorporated ice might, in part, also develop from freezing liquid precipitation or melt water (Humlum, 1998). Borehole cores and inclinometer measurements from different rock glaciers reveal the internal structure and deformation of these landforms (Arenson et al., 2002; Krainer et al., 2015; Buchli et al., 2018). They suggest common layers, although structure, composition and thickness of these layers differ to a certain extent also within individual rock glaciers. The few meters thick topmost active layer consists of unconsolidated boulders and isolates the underlying ice-rich frozen body. Because pores in the active layer are mostly air filled, the thermal regime is governed by freeze-thaw cycles and air convection. These are in turn controlled by ground permeability and the thermal gradient and have an influence on the ground thermal regime of the underlying permafrost (Wicky and Hauck, 2020). The ice-rich permafrost body constitutes the main body of the rock glacier. The volumetric ice content varies between 40% - 90% (Arenson et al., 2002; Haeberli et al., 2006; Hausmann et al., 2012) and the debris size is smaller than in the active layer, which is explained by fall sorting, washing away and kinetic sieving (Haeberli et al., 2006). The thermal regime of the permafrost layer is mainly controlled by heat conduction, therefore temperature signal from the surface is linearly delayed and its amplitude exponentially decreases with depth (Haeberli et al., 2006). This leads to the conclusion that seasonal temperature signals can just penetrate to the permafrost body to the depth of zero amplitude. Changes below this depth require long term changes of the thermal forcing. In the permafrost layer, internal plastic deformation is the main component of deformation, which is governed by temperature and the structure of the debris-ice mixture. A large part of the horizontal deformation (50% - 97 %) takes place in one or more shear zones at the base of the ice-rich permafrost body, which are a few meters thick (Arenson et al., 2002). These shear zones can be active at the same time (Krainer et al., 2015) or if inactive give information on past creep behaviour and failure mechanisms (Buchli et al., 2018). The dynamics of rock glaciers vary at different temporal scales: decadal, inter-annual and intra-annual (Delaloye et al., 2008; Delaloye et al., 2010; Wirz et al., 2016b; Kenner et al., 2017). Studies investigating the decadal-scale variability of rock glacier morphodynamics reveal a significant increase in flow velocities starting in the 1990s, while some studies also report phases of stable flow velocities and velocity decrease since then (Roer, 2005; Kellerer-Pirklbauer and Kaufmann, 2012; Scapozza et al., 2014; Hartl et al., 2016; Kellerer-Pirklbauer and Kaufmann, 2018; Kenner et al., 2020). The increase in flow velocities has been explained by rising mean annual air and ground temperatures and mechanisms of heat conduction and melt water advection (Roer, 2005; Kääb et al., 2007; Ikeda et al., 2008; Delaloye et al., 2010). Kääb et al. (2007) show that in general rock glaciers with ground

temperatures close to 0 °C move faster and are more sensitive to thermal forcing than colder ones. More recent studies highlighted the role of liquid water, especially in the shear horizon, and attribute little or no significance to the change in permafrost temperature to explain the deformation variations on a multi-annual, inter-annual, seasonal and shot-term scale. (Wirz et al., 2016a; Kenner et al., 2017; Buchli et al., 2018; Cicoira et al., 2019a). Kenner et al. (2020) synthesise these findings by showing that water availability in the rock glacier is governed by ground temperature which is a function of mean annual air temperature and onset as well as duration of snow cover and thus correlate with rock glacier deformation as well. Although rock glaciers normally move at rates ranging from a few cm/yr to a few m/yr, some studies show destabilization of rock glaciers leading to rates of movement of several tens of meters per year (Roer et al., 2008; Scotti et al., 2017). Besides, rock glacier dynamics can also be influenced by other factors like topography, temporal and vertical variations in ice content, rheology of the ice-debris mixture, thickness, and input of ice and debris to the system.

The present and former response of rock glacier morphodynamics to atmospheric warming and climate change observed in many high mountain regions (Hock et al., 2019) is of large scientific interest for climate change projections and landscape evolution models. But an understanding of these landforms has also implications for natural hazard protection (Schoeneich et al., 2015) or future water availability (Jones et al., 2019). Although there are several studies investigating rock glacier morphodynamics on different time scales, the number of studies is low compared to ice glaciers. Groh and Blöthe (2019) investigated the recent flow velocities of Kauner Valley rock glaciers and ascertained slightly lower flow velocities between 2001/2003-2009 than between 2010-2015. They also noted that the velocity of rock glaciers in the study area mainly depends on parameters describing the general inclination and that their activity status is controlled by their size and the topoclimate.

Apart from Roer et al. (2005), who investigated multi-decadal catchment wide rock glacier morphodynamics in Turtman Valley, Swiss Alps, most studies investigating rock glacier morphodynamics on a decadal time scale investigate just one or two large and prominent rock glaciers (Scapozza et al., 2014; Scotti et al., 2017; Kellerer-Pirklbauer et al., 2018; Kellerer-Pirklbauer and Kaufmann, 2018; Kaufmann et al., 2019; Kenner et al., 2020).

In this studyRock glaciers are a downslope creep phenomenon of mountain permafrost and are responsible for extensive mass transport in alpine environments (Barsch, 1996). As it has been shown that rock glacier kinematics are affected by changing external forcing factors, the aim of this study was to investigate how rock glaciers of the same catchment area react to these changes on a multi-decadal time scale. Active rock glaciers consist of a generally coarse debris layer (active layer), covering ice supersaturated debris and form lobate or tongue shaped landforms (Haeberli et al., 2006). They can be found in most cold mountain regions of the earth (Jones et al., 2019). Although permafrost is the primary condition for rock glaciers to form, the deforming ice and debris may be of both glacial and periglacial origin (Berthling, 2011). Borehole cores and inclinometer measurements from different rock glaciers reveal the internal structure and deformation of these landforms (Arenson et al., 2002; Krainer et al., 2015; Buchli et al., 2018). They suggest common layers, although structure, composition and thickness of these layers differ to a certain extent also within individual rock glaciers. The few meters thick topmost active layer consists of unconsolidated debris and isolates the underlying ice-rich frozen body. The ice-rich permafrost body constitutes the main layer of the rock glacier, with a smaller proportion of coarser debris per volume than the active layer and volumetric ice

100 contents between 40% - 90% (Arenson et al., 2002; Haeberli et al., 2006; Hausmann et al., 2012). The thermal regime of the permafrost layer is mainly controlled by heat conduction, therefore temperature signal from the surface is linearly delayed and its amplitude exponentially decreases with depth (Haeberli et al., 2006). As a result, changes in temperature of the permafrost body below the depth of zero amplitude require long-term changes of the thermal forcing. In the permafrost layer, internal plastic deformation is the main component of deformation, which is governed by temperature and the structure of the debris-

105 ice mixture. A large part of the horizontal deformation (50% -97 %) takes place in one or more shear zones at the base of the ice-rich permafrost body, which are maximally a few meters thick (Arenson et al., 2002). The dynamics of rock glaciers vary at different temporal scales: decadal, inter-annual and intra-annual (Delaloye et al., 2008; Delaloye et al., 2010; Wirz et al., 2016; Kenner et al., 2017). Studies investigating the decadal-scale variability of rock glacier morphodynamics in the European Alps reveal a significant increase in flow velocities starting in the 1990s, while some studies also report phases of stable flow

110 velocities and velocity decrease since then (Roer, 2005; Kellerer-Pirklbauer and Kaufmann, 2012; Scapozza et al., 2014; Hartl et al., 2016; Kellerer-Pirklbauer and Kaufmann, 2018; Kenner et al., 2020; Marcer et al., 2021). The increase in flow velocities has been explained by rising mean annual air and ground temperatures and mechanisms of heat conduction and melt water advection (Roer, 2005; Kääb et al., 2007; Ikeda et al., 2008; Delaloye et al., 2010). More recent studies highlighted the role of liquid water, especially in the shear horizon, and attribute little or no significance to the change in permafrost temperature to

115 explain the deformation variations on a multi-annual, inter-annual, seasonal and shot-term scale (Wirz et al., 2016; Kenner et al., 2017; Buchli et al., 2018; Cicoira et al., 2019). Kenner et al. (2020) synthesise these findings by showing that water availability in the rock glacier is governed by ground temperature which is a function of mean annual air temperature and onset as well as duration of snow cover and thus correlate with rock glacier deformation as well. Besides, rock glacier dynamics can also be influenced by other factors like topography, temporal and vertical variations in ice content, rheology of the ice-debris

120 mixture, thickness, and input of ice and debris to the system. Although rock glaciers normally move at rates ranging from a few centimetres per year to a few meters per year, some studies show a destabilization of rock glaciers, resulting in a landslide like movement and leading to displacement rates of up to several tens of meters per year (Roer et al., 2008; Scotti et al., 2017; Vivero and Lambiel, 2019; Marcer et al., 2021).

The present and former response of rock glacier morphodynamics to atmospheric warming and climate change observed in
125 many high mountain regions (Hock et al., 2019) is of large scientific interest for climate change projections and landscape evolution models. But an understanding of these landforms has also implications for natural hazard protection (Schoeneich et al., 2015), future water availability (Jones et al., 2019) or sediment connectivity (Kummert and Delaloye, 2018). Although there are several studies investigating rock glacier kinematics on different time scales, the number of studies is low compared to ice glaciers. Apart from Roer et al. (2005), who investigated multi-decadal catchment wide rock glacier kinematics in

130 Turtman Valley, Swiss Alps, most studies investigating rock glacier kinematics on a decadal time scale investigate just one or two large and prominent rock glaciers (e.g. Scapozza et al., 2014; Scotti et al., 2017; Kellerer-Pirklbauer et al., 2018; Kellerer-Pirklbauer and Kaufmann, 2018; Kaufmann et al., 2019; Kenner et al., 2020).

Therefore, we focus on the long-term (1953-2017) ~~morphodynamic~~kinematic investigations of rock glaciers, located in the Upper Kauner Valley, Ötztal Alps, Austria, displaying different characteristics ~~in order~~. By doing so we want to understand

135 their reaction to climate change under similar climatic forcing. We do this by analysing surface movement (flow velocity) of eight rock glaciers by means of image-correlation techniques on the base of orthophotos and hillshades. In addition, multitemporal ~~3D displacements~~ surface elevation changes are derived for one additional rock glacier (nine ~~rock glaciers~~) by a ~~3D distance~~DEM of Difference (DoD) analysis using photogrammetric as well as Airborne Laser Sanning (ALS) ~~point clouds~~data. The identified changes in rock glacier ~~morphodynamics~~kinematics will be discussed with regard to rock glacier

140 characteristics~~, elevation classes~~ and changes in the meteorological forcing, by investigating different climate parameters (temperature, precipitation and snow cover) recorded directly in the catchment and nearby meteorological stations.

2 Study Area ~~and investigated rock glaciers~~

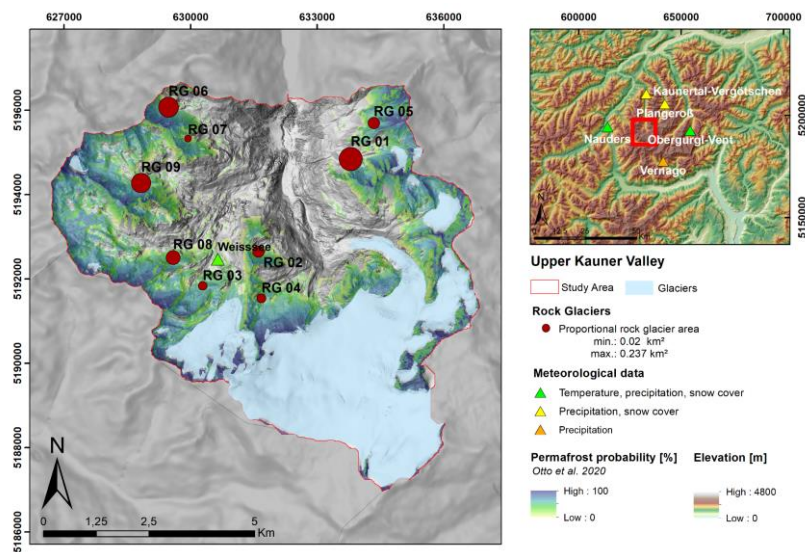



Figure 1. Location and relative size of the investigated rock glaciers in the study area and location of the analysed meteorological stations. The stations Obergurgl and Obergurgl-Vent are marked as one station due to their proximity of 230 m. The permafrost probability (Otto et al., 2020) and glacier extents of 2015 (Buckel and Otto, 2018) are shown. The overview map and the background of the main map were produced using Copernicus data and information funded by the European Union - EU-DEM layers.

The investigated rock glaciers are located in the catchment area of the Upper Kauner Valley within the Ötztal Alps, Austria
145   (Fig. 1). The study area is more precisely defined as the hydrological contributing area at the inlet of the Fagge river into the Gepatsch reservoir. It has an area of ~62 km² and a relief of 1773 m ranging from 1810 m at the inlet to 3583 m at the summit of Hochvernagtspitze. Geologically, the study area belongs to the Eastern Alps crystalline zone and the polymetamorphic Stubai complex. Paragneiss and Orthogneiss are dominant, but Amphibolit and Mica-schist occur subordinately (Hoinkes and Thöni, 1993). The study area is climatically characterized by the central alpine dry region (Fliri, 1975). At Weißsee
150   meteorological station (2470 m), a mean annual air temperature (MAAT) of −0.11 °C (2007-2019) and annual precipitation ranging from 731 mm to 1118 mm are recorded (data source: Tiroler Wasserkraft AG (TIWAG)). Detailed analysis of climate parameters of the study area is provided in Sect. 4.2 of this paper. According to a permafrost pseudo-probability map (Otto et al., 2020), 38% of the study area could be underlain by permafrost and 30% was covered by glaciers in 2015 (Buckel and Otto, 2018). The most prominent, Gepatschferner and Weißseeferner are located in the southern part of the catchment. Due to the
155   glacier road, which makes the valley accessible by car, many studies of various disciplines of geo- and bioscience have been

carried out in this area (Dusik et al., 2015; Groh and Blöthe, 2019; Altmann et al., 2020). But the road and the associated ski area also cause anthropogenic influences on natural systems, which have to be considered.

A rock glacier inventory was compiled for the study area (c.f. Sect.3.1). Within the catchment, 54 rock glaciers can be found, which were classified as active (20), inactive (16) and fossil (19). Due to poor image quality or snow cover (in one or more epochs of the historic data) and the activity status, the vast majority of these rock glaciers had to be excluded from the following analyses. However, eight active rock glaciers representing different characteristics and conditions were investigated in detail regarding flow velocities and nine rock glaciers regarding 3D displacements (Figure 1). Detailed characteristics of these rock glaciers can be found in Table A1. The most prominent of those is the well-studied and largest (0.237 km²) rock glacier Innere Ölgrube (RG 01) (Figure 2).

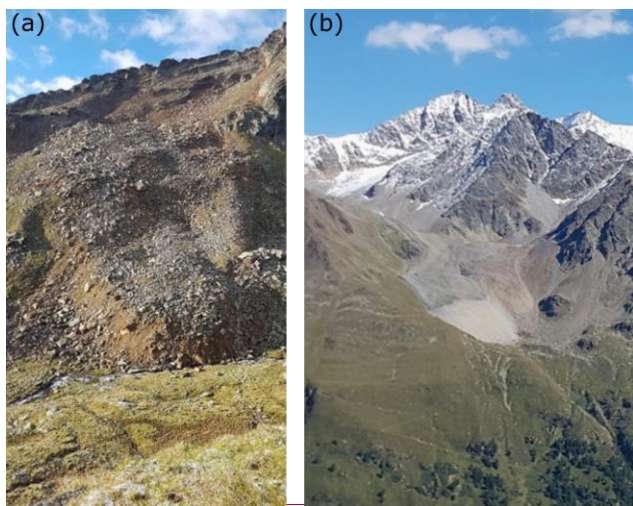



Figure 2. Images of two of the studied rock glaciers. (a) the north-exposed rock glacier RG 08, located at the entrance to the Krummgampen Valley and covering an area of 0.088 km². (b) the well-studied, west-exposed Ölgruben rock glacier RG 01 covering an area of 0.237 km².

On the Ölgrube, the first velocity studies were already carried out by Finsterwalder (1928) and Pillewizer (1957) and more recent studies continue their research and contribute additional information about its hydrology, internal and external structure and morphodynamics (Berger et al., 2004; Krainer and Mostler, 2006; Hausmann et al., 2012; Groh and Blöthe, 2019). The area of the investigated rock glaciers ranges from 0.02 km² (RG 07) to 0.237 km² (RG 01). They show expositions of N, NE, E and W, with minimum elevation ranging from 2446 m to 2727 m. The elongated rock glacier RG 06 spans heights from 2702 m to 3093 m and thus reaches the highest elevation. Without geophysical, geochemical or petrographic information, interpretations about the genesis and internal structure are difficult (Berthling, 2011; Clark et al., 1998). In the case of the rock

glaciers RG 03, RG 04 and RG 09 a complete or partial covering of the rock glaciers by the LIA glacial extent (Fischer et al., 2015) suggests a glacial genesis after 1850 or at least a glacial influence during and after this time as described by Dusik et al.
175 (2015) for RG 09. Some detailed studies about Innere Ölgrube (RG 01) exist, revealing information on internal structure (Hausmann et al., 2012) and genesis (Berger et al., 2004). Berger et al. (2004) show that both lobes of the rock glacier developed from debris covered glaciers after the peak of the Little Ice Age (LIA) (~1850). The rock glacier is composed of a 4 m to 6 m active layer, a 20 m to 30 m thick ice rich permafrost body and a underlying 10 m to 15 m ice free sediment layer and has an ice content of 40% to 60% (Hausmann et al., 2012).

180 **3 Materials and Methods**

3.1 Rock glacier inventory

Although manual mapping of rock glacier landforms is shown to be highly subjective (Brardinoni et al., 2019), we tried to minimize the heterogeneity in the inventory by incorporating the guide lines for inventorying rock glaciers (IPA Action Group Rock glacier inventories and kinematics 2020) and only mandate one operator to compile the inventory on the basis of Krainer
185 & Ribis (2012). Rock glacier outlines were corrected and additional landforms were mapped on the basis of the most recent hillshade derived from the 2017 ALS campaign of the DFG founded project PROSA and an orthoimage of 2015 (data source: Land Tirol - data.tirol.gv.at). Activity status was assigned according to morphological characteristics in combination with a DEM of difference (DoD) of the 2012 and 2017 ALS campaigns and image correlation analysis on the derived hillshades without local alignment of the data. In the case of active rock glacier complexes, which are overflowing fossil ones, they were
190 considered as two separate units.

3.2 Meteorological data

For the analysis of rock glacier morphodynamics over a decadal time period, a reference to climatic conditions that influence such systems in various ways is indispensable. However, long time series data in the high alpine areas are only very sporadically available, as early climate monitoring stations tended to be located in population centres. This also applies to our
195 catchment area, where the meteorological station Weißsee (2540 m) (data source: TIWAG) is recording data since 2006. For this reason, we use additional data from nearby meteorological stations, which have longer time series available, to provide information on the approximate climatic development in the catchment area. The locations of these stations are shown in Figure 1, while an overview of the stations and the used data is given in Table 1.
In earlier studies, it is shown that changes in rock glacier morphodynamics can be related to the warming of permafrost through
200 heat conduction caused by an increase in air temperature (Roer, 2005; Kääb et al., 2007; Delaloye et al., 2010; Kellerer-Pirklbauer and Kaufmann, 2012; Kellerer-Pirklbauer et al., 2018; Cicoira et al., 2019b). But especially on a shorter timescale, it is very likely that rock glacier morphodynamics are also controlled by liquid water availability and snow cover parameters (Ikeda et al., 2008; Wirz et al., 2016a; Kenner et al., 2017; Buchli et al., 2018; Cicoira et al., 2019a; Kenner et al., 2020). We

205 Table 1. Overview of the meteorological stations used. Distance gives the distance to the center of the study area. T – Temperature; Pr - Precipitation, SC - Snow cover. The data were provided by the "Federal Ministry of Agriculture, Regions and Tourism" (BMLRT), the "Central Institute for Meteorology and Geodynamics" (ZAMG), "Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region" (HISTALP), "Autonomous Province of Bozen/Bolzano " (Province BZ) and TIWAG

Station Name	Recording started	Distance [km]	Temporal resolution	Elevation [m]	Parameters analysed	Provider
Kaunertal-Vergötschen	1895	18.1	monthly, daily	1269	Pr, SC	BMLRT
Nauders	1895	19	daily	1330	T, Pr, SC	ZAMG
Obergurgl	1953	21	daily	1942	T, Pr, SC	ZAMG
Obergurgl-Vent	1851	21.4	monthly	1938	T	HISTALP
Plangeroß	1895	16	daily	1605	Pr, SC	BMLRT
Vernago	1953	17	daily	1700	Pr	Province BZ
Weißsee	2006	2.4	15 min	2540	T, Pr, SC	TIWAG

210 therefore analyse changes, anomalies and trends in air temperature, precipitation and snow cover for the whole period of investigation and between the individual epochs. In addition, we analyse temperature and precipitation on a seasonal basis. Snow cover onset and duration were determined according to Peng et al. (2013).

3.3 Airborne Laser Scanning (ALS) data

To analyse rock glacier flow velocities on hillshades (see Sect. 3.50) and 3D displacements in point clouds (see Sect. 3.6) in
215 the two most recent epochs 2006-2012 and 2012-2017, we used data from different ALS campaigns (see Table 2). The most recent one was acquired on the 5th of June 2017 by a helicopter and a mounted mobile laser scanning system VuxSys-LR from Riegl (www.riegl.com). This ALS flight mission was carried out by the Chair of Physical Geography at the Catholic University of Eichstätt-Ingolstadt during the DFG-funded project (PROSA), achieving a mean point density of 20.0 pts/m² on the studied rock glaciers. Due to weather conditions and organizational problems on the part of the contracted company, which made an
220 area-wide data acquisition on one day impossible, the 2012 ALS data were recorded (also during the PROSA project) on the 4th and 18th of July. An LMS Q680i-S laser scanner from Riegl mounted on a helicopter was used for data recording. Depending on the date of recording, the average point density ranges between 12.3 pts/m² and 12.7 pts/m². Furthermore, an additional ALS data set from the 5th of September 2006 with an average point density of 5.0 pts/m² was provided by the

TIWAG. The investigated rock glaciers are located in the catchment area of the Upper Kauner Valley within the Ötztal Alps,

225 Austria (Fig. 1). The study area is more precisely defined as the hydrological contributing area at the inlet of the Fagge river into the Gepatsch reservoir. It has an area of ~62 km² and a relief of 1773 m ranging from 1810 m at the inlet to 3583 m at the summit of Hochvernagtspitze.

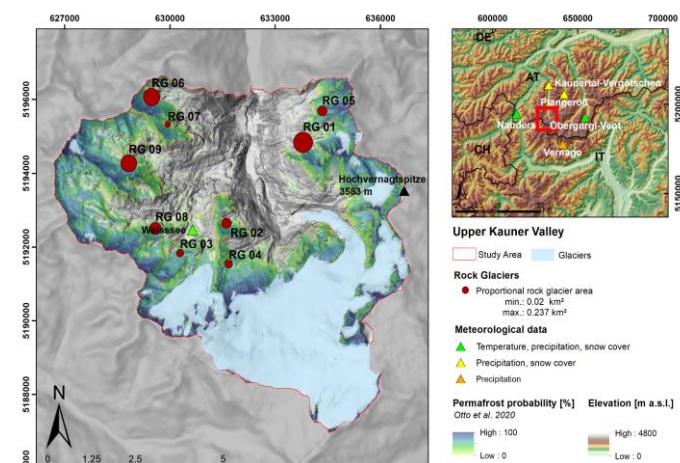



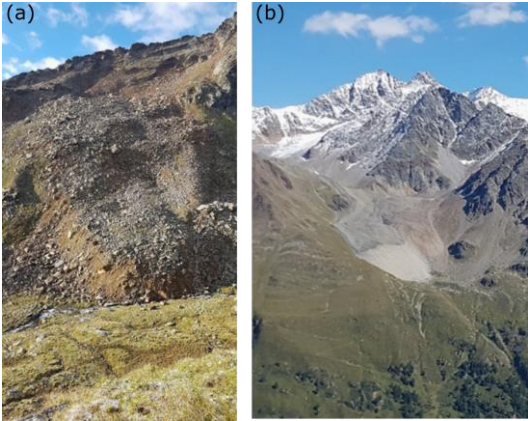
Figure 1. Location and relative size of the investigated rock glaciers and location of the analysed meteorological stations. The stations
Obergurgl and Obergurgl-Vent are marked as one station. The coordinate system used is ETRS89 / UTM zone 32N EPSG:25832
230 **with the unit meter. Background was created using Copernicus data and information funded by the European Union - EU-DEM**
layers.

Geologically, the study area belongs to the Eastern Alps crystalline zone and the polymetamorphic Stubai complex. Paragneiss and Orthogneiss are dominant, but Amphibolit and Mica-schist occur subordinately (Hoinkes and Thöni, 1993). The study area is climatically characterized by the central-alpine dry region (Fliri, 1975). At Weißsee meteorological station (2470 m), a

235 mean annual air temperature (MAAT) of −0.11 °C (2007-2019) and annual precipitation ranging from 731 mm to 1118 mm were recorded (data source: Tiroler Wasserkraft AG (TIWAG)). Detailed analysis of climate parameters of the study area is provided in Sect. 5.3 of this paper. According to a permafrost probability map (Otto et al., 2020), 38% of the study area could be underlain by permafrost and 30% was covered by glaciers in 2015 (Buckel and Otto, 2018). The most prominent, Gepatschferner and Weißseeferner are located in the southern part of the catchment. Due to the glacier road, which makes the

240 valley accessible by car, many studies by geo- and bioscience have been carried out in this area (Dusik et al., 2015; Groh and Blöthe, 2019; Altmann et al., 2020). But the road, which intersects RG03 and the associated ski area also cause anthropogenic influences on natural systems, which have to be considered.

The study of rock glaciers has a long tradition in the Kauner Valley, especially at the rock glacier Innere Ölgrube, wich is named RG01 in this study (Fig.2). The first velocity studies were already carried out by Finsterwalder (1928) and Pillewizer

245 (1957) and more recent studies continue their research and contribute additional information about the hydrology, internal and external structure and morphodynamics of this rock glacier (Berger et al., 2004; Krainer and Mostler, 2006; Hausmann et al., 2012; Groh and Blöthe, 2019). Groh and Blöthe (2019), who investigated the recent development of flow velocity of rock glaciers in Kauner Valley, ascertained a slightly increase and noted that the velocity of rock glaciers in the study area mainly depends on parameters describing the general inclination and that their activity status is controlled by their size and the
250 topoclimate.

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255 We investigated eight active rock glaciers representing different characteristics and conditions in detail regarding flow velocities and one more rock glacier regarding the surface elevation change analysis (Fig. 1). These are described in more detail in Sect. 5.1.

3 MaterialsAll datasets were georeferenced with parameters optimised by an automatic strip adjustment (Glira et al., 2015). To account for possible variable errors throughout the catchment, we locally fine registered the 2006 and 2012 point clouds to
260 the 2017 data set for every single rock glacier by using an iterative closest point algorithm (ICP) (Besl and McKay, 1992) on mapped stable areas around each rock glacier.

Table 2. Overview of ALS data used to derive DEMs and hillshades. These data were used for the 3D displacement analysis as well

3.1 Aerial photographs

~~Flight date~~	~~Scanner model~~	~~Wave length [nm]~~	~~Average point density* [pts/m²]~~	~~Operator~~
~~Sep. 5th 2006~~	~~unknown~~	~~999~~	~~4.95~~	~~TIWAG~~
~~Jul. 4th 2012~~	~~Riegl LMS Q680i S~~	~~1064~~	~~12.65~~	~~Milan Geoservice GmbH (commissioned)~~
~~Jul. 18th 2012~~	~~Riegl LMS Q680i S~~	~~1064~~	~~12.34~~	~~Milan Geoservice GmbH (commissioned)~~
~~Jun. 5th 2017~~	~~Riegl VuxSys LR~~	~~1550~~	~~19.97~~	~~Chair of Physical Geography University of Eichstätt-Ingolstadt~~

~~* Mean point density on studied rock glaciers with snow patches excluded~~

~~3.4 Generation of point clouds and orthoimages from historical aerial images~~

In order to ~~extend the time series of ALS data (2006-2017) and to~~ quantify the morphodynamics of the rock glaciers that occurred in the previous century, we used historical aerial photos ~~acquired at irregular intervals over the entire Austrian territory.~~

~~The useable~~to derive orthophotos and point clouds. ~~aerial photos for the Kauner Valley catchment were collected at six separate epochs between 1953 and 1997. The epochs were chosen based on data availability, similarity in acquisition date (i.e. late summer), image quality, and sufficient image overlap. Note that the photos of 1953 were collected in three different flights on different days. However, considering these three datasets separately was not possible for the 3D reconstruction due to lacking image overlap. Therefore, all the images were processed together to generate one 1953 DEM.~~

The historical aerial photos used in this study were scanned and provided in tiff-format by "Office of the Tyrolean Government-Department of Geoinformation" (https://www.tirol.gv.at/en/) and "Austrian Federal Office of Surveying and Metrology" (BEV) (https: //www.bev.gv.at) along with the camera calibration protocols if available (Table 1). The aerial photos for the Kauner Valley catchment were collected at six separate epochs between 1953 and 1997. The epochs were chosen based on data availability, similarity in acquisition date (i.e. late summer), image quality, and sufficient image overlap.~~(Table 3).~~

~~Using advances in digital photogrammetry, particularly Structure from Motion (SfM) with Multi-View Stereo (MVS), the reconstruction of 3D information in form of point cloud from scanned historical photos does not require specialized knowledge (Bakker and Lane, 2017; Fawcett et al., 2019). The aerial images were processed in Agisoft Methashape (v.1.6.1) using the film camera tool, which estimates the camera calibration parameters based on the fiducial marks. The software automatically derived the locations of the fiducial mark in the images. Their distance in mm and the focal length were available from the calibration protocol. Having defined the camera interior orientation, the camera exterior orientation, the 3D point cloud~~

reconstruction and the orthophoto generation follow the standard SfM-MVS workflow. This includes ground control points (GCPs) measurement for georeferencing and dense image matching. The 3D coordinates of the GCPs were chosen from the ALS 2017 point cloud on stable terrain and were evenly distributed throughout the catchment. The resulting average point density on the studied rock glaciers varies from 1.2 pts/m² to 11.9 pts/m². The ground resolution of the orthoimages varies between 0.2 m and 0.5 m.

The photogrammetric point clouds were co-registered with the reference 2017 ALS data in order to minimize inherent systematic errors (Bakker and Lane, 2017) and by using again an iterative closest point (ICP) algorithm (Besl and McKay, 1992) on mapped stable areas around the rock glaciers. Fine registration was performed for all individual rock glaciers and epochs separately to account for any variable errors throughout the catchment.

Table 1. Overview of the acquired historical aerial image flights used to generate point clouds and orthophotos in Agisoft MethashapeMetashape Professional (v.1.6.1)).

Flight date	Number of images*	Purpose	Source	Camera	Focal length [mm]	Scanning resolution [μm]	Flight altitude [m asl]	Resolution orthophoto [m]	Point density*** [pts/m²]
Jun. 5th Aug. 31st Sep. 8th 1953**	124	Forest condition estimation; Flight C	BEV	unknown	210.11	15	4700 - 8300	0.225	6.6
Sep. 1st 1954	36	Forest condition estimation; Flight D	BEV	unknown	210.11	15	10130	0.225	7.0
Sep. 29th 1970	32	Tyrolean state surveying flight	Land Tirol	Wild RC5/RC8	210.43	12	8665	0.2	10.1
Aug. 18th 1971	91	Tyrolean state surveying flight	Land Tirol	Wild RC5/RC8	209.48	12	5025	0.2	12.0
Sep. 13th 1982	34	Tyrolean state high altitude surveying flight	BEV	Wild RC10	152.58	15	N/A	0.5	1.2

| Sep. 11th 1997 | 25 | KF 173 | BEV | Wild RC10 | 152.70 | 15 | N/A | 0.5 | 1.2 |

* Number of images used to reconstruct the whole catchment
** Three Dates were processed as one dataset
*** Mean point density on studied rock glaciers with snow patches excluded

3.2 Airborne Laser Scanning (ALS) data

To analyse rock glacier flow velocities on hillshades (see Sect 4.3) and surface elevation change using DoDs (see Sect. 4.4) in the two most recent epochs 2006-2012 and 2012-2017, we used data from different ALS campaigns (Table 2). The most recent one was acquired on the 5th of June 2017 by a helicopter and a mounted mobile laser scanning system VuxSys-LR from Riegl (www.riegl.com). This ALS flight mission was carried out by the Chair of Physical Geography at the Catholic University of Eichstätt-Ingolstadt during the DFG-funded project (PROSA), achieving a mean point density of 20.0 pts/m² on the studied rock glaciers. Due to weather conditions and time constrains of the contracted company, which made an area-wide data acquisition on one day impossible, the 2012 ALS data were recorded (also during the PROSA project) on the 4th and 18th of July.

Table 2. Overview of ALS data used for flow velocity analysis and surface elevation change analysis. Average point density is given for the areas of the investigatedrock glaciers without snow patches.

Flight date	Scanner model	Wave length [nm]	Average point density* [pts/m²]	Operator
Sep. 5th 2006	unknown	999	5.00	TIWAG
Jul. 4th 2012	Riegl LMS Q680i-S	1064	12.7	Milan Geoservice GmbH (commissioned)
Jul. 18th 2012	Riegl LMS Q680i-S	1064	12.3	Milan Geoservice GmbH (commissioned)
Jun. 5th 2017	Riegl VuxSys-LR	1550	20.0	Chair of Physical Geography University of Eichstätt-Ingolstadt

Due to weather conditions and time constrains of the contracted

company, which made an area-wide data acquisition on one day impossible, the 2012 ALS data were recorded (also during the PROSA project) on the 4th and 18th of July. An LMS Q680i-S laser scanner from Riegl mounted on a helicopter was used for data recording. Depending on the date of recording, the average point density ranges between 12.3 pts/m² and 12.7 pts/m². Furthermore, an additional ALS data set from the 5th of September 2006 with an average point density of 5.0 pts/m² was provided by the TIWAG. All datasets were georeferenced with parameters optimised by an automatic strip adjustment (Glira et al., 2015).

3.3 Meteorological data

For the analysis of rock glacier morphodynamics over a decadal time period, a reference to climatic conditions that influence such systems in various ways is indispensable. However, long time series data in the high alpine areas are only very sporadically available, as early climate monitoring stations tended to be located in population centres. This also applies to our catchment area, where the meteorological station Weißsee (2540 m) (data source: TIWAG) is recording data since 2006. For this reason, we used additional data from nearby meteorological stations, which have longer time series available, to provide information on the approximate climatic development in the catchment area. The locations of these stations are shown in Fig. 1, while an overview of the stations and the used data is given in Table 3.

Table 3. Overview of the meteorological stations used. Distance gives the distance to the center of the study area. T - Temperature; Pr - Precipitation, SC - Snow cover. The data were provided by the "Federal Ministry of Agriculture, Regions and Tourism" (BMLRT), the "Central Institute for Meteorology and Geodynamics" (ZAMG), "Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region" (HISTALP), "Autonomous Province of Bozen/Bolzano " (Province BZ) and TIWAG.

Station Name	Recording started	Distance [km]	Temporal resolution	Elevation [m]	Parameters analysed	Provider
Kaunertal-Vergötschen	1895	18.1	monthly, daily	1269	Pr, SC	BMLRT
Nauders	1895	19	daily	1330	T, Pr, SC	ZAMG
Obergurgl	1953	21	daily	1942	T, Pr, SC	ZAMG
Obergurgl-Vent	1851	21.4	monthly	1938	T	HISTALP
Plangeroß	1895	16	daily	1605	Pr, SC	BMLRT
Vernago	1953	17	daily	1700	Pr	Province BZ
Weißsee	2006	2.4	15-min	2540	T, Pr, SC	TIWAG

4. Methods

4.1 Rock glacier inventory

Although manual mapping of rock glacier landforms is shown to be highly subjective (Brardinoni et al., 2019), we tried to minimize the heterogeneity in the inventory by incorporating the guide lines for inventorying rock glaciers (IPA Action Group Rock glacier inventories and kinematics 2020) and only mandate one operator to compile the inventory on the basis of the

inventory by Krainer & Ribis (2012). Rock glacier outlines were corrected and additional landforms were mapped on the basis of the most recent hillshade derived from the 2017 ALS campaign of the DFG founded project PROSA and an orthoimage of 2015 (data source: Land Tirol - data.tirol.gv.at). Activity status was assigned according to morphological characteristics in combination with a DoD of the 2012 and 2017 ALS campaigns to detect surface elevation change and therefore ice melting.

360 Image correlation analysis on the derived hillshades was used to derive information on flow velocity. For the inventory of the entire study area, both analyses were carried out without local alignment of the data. The classification is based on the common division into active - contains ice and is in motion, inactive – (almost) no motion but still contains ice, and fossil - contains (almost) no more ice and is not in motion (e.g. Krainer and Ribis, 2012). We then derived rock glacier characteristics such as aspect, slope, and elevation from the elevation model of the 2017 ALS campagne and classified them accoring to their spatial

365 connection to the upslope unit. We further determined whether the area of the investigated rock glaciers were covered by a glacier during the Little Ice Age (LIA) with the help of a glacier inventory (Fischer et al., 2015).

4.2 Processing of aerial images

To derive point clouds and orthofotos of the aerial images, these were processed using advances in digital photogrammetry, particularly Structure from Motion (SfM) with Multi-View Stereo (MVS). The reconstruction of 3D information in form of

370 point cloud from scanned historical photos does not require specialized knowledge when important basic principles are followed (Bakker and Lane, 2017; Fawcett et al., 2019). The aerial images were processed in Agisoft Metashape (v.1.6.1) using the film camera tool, which estimates the camera calibration parameters based on the fiducial marks. The software automatically derived the locations of the fiducial mark in the images. Their distance in mm and the focal length were available from the calibration protocols. Having defined the camera interior orientation, the camera exterior orientation, the 3D point

375 cloud reconstruction and the orthophoto generation followed the standard SfM-MVS workflow. This includes ground control points (GCPs) measurement for georeferencing and dense image matching.

To account for possible shifts in the orthoimages, we resampled them at a resolution of 0.5 m and we locally co-registered all individual rock glaciers for each epoch to the 1953/54 orthoimage. We used 9 to 29 co-registration points equally distributed around the rock glaciers. We obtained co-registration root mean squared errors (RSMEs) between 0.225 m and 0.549 m with

380 an average of 0.316 m.

3.5The 3D coordinates of 101 GCPs were chosen from the ALS 2017 point cloud on stable terrain and were evenly distributed throughout the catchment. In the case of the 1953 data set, three different aerial image flights from this year had to be processed together, as there was insufficient image overlap in the individual flights.

The resulting average point density on the studied rock glaciers varied from 1.2 pts/m² to 11.9 pts/m² (Table 1). Therefore,

385 only the point clouds of the years 1953/54 and 1970/71 with a point density between 6.6 pt/m² and 12 pt/m² were used in the DoD analysis. The ground resolution of the orthoimages varied between 0.2 m and 0.5 m.

4.3 Horizontal flow velocities

~~3.5.1 Calculation of horizontal flow velocities~~

Horizontal flow velocities of the rock glaciers were calculated for the six processed time steps between 1953 and 2017. ~~For this purpose, an image correlation approach was chosen, which is a common method to derive glacier and rock glacier velocity from orthoimage, hillshades and satellite images (Scambos et al., 1992; Kääb and Vollmer, 2000; Heid and Kääb, 2012; Monnier and Kinnard, 2017; Kellerer-Pirklbauer and Kaufmann, 2018). In this study, orthoimage and hillshade image pairs were utilized.~~ For this purpose, an image correlation approach was chosen, which is a common method to derive glacier and rock glacier velocity from orthoimage, hillshades and satellite images (Scambos et al., 1992; Kääb and Vollmer, 2000; Heid and Kääb, 2012; Monnier and Kinnard, 2017; Kellerer-Pirklbauer and Kaufmann, 2018). In this study, orthoimage and hillshade image pairs were utilized. In order to ensure their comparability and to account for possible shifts in the orthoimages, we resampled them at a resolution of 0.5 m and locally co-registered all individual rock glaciers for each epoch to the 1953/54 orthoimage. We used 9 to 29 co-registration points equally distributed around the rock glaciers, obtaining co-registration root mean squared errors (RSMEs) between 0.23 m and 0.55 m with an average of 0.32 m. ~~For the time step 1997 – 2006, where orthoimage and hillshade were used in combination, illumination was chosen for the 2006 DEM according to the exact position of the sun in the 1997 orthoimage. To calculate flow velocity vectors, the image correlation algorithm IMCORR (Scambos et al., 1992) within SAGA-GIS software was applied. The algorithm attempts to match small sub-scenes from two images by applying a fast Fourier transform-based version of a cross- correlation. It can locally adjust the intensity values between two image pairs and therefore compensate for differences in illumination. Using this algorithm, sub-pixel precision of displacement vectors can be achieved. We used search and reference chip size combinations of 64/32, 128/64 and 256/128 with a fixed spacing of 5 m. The combinations were calculated for all image pairs and the most reasonable was chosen for further analysis. This was done by visually analysing the resulting displacement vectors in combination with the input data. In general, larger chip sizes were chosen for faster moving rock glaciers and/or long time spans between the image pairs. The resulting raw vector maps can contain erroneous displacement measurements or decorrelation, where no measurement is possible, due to snow, strong shading effects, areas where displacements are dominated by rock fall and large displacements, which cause a change of texture. These vectors were excluded manually for all time steps with the help of the matching orthoimages or hillshades. Subsequently, a mask was created for the areas where measurements were possible in all time steps and just measurements in these areas were used for further analysis to make the individual time steps comparable.~~

For the time step 1997 – 2006, where orthoimage and hillshade were used in combination, illumination was chosen for the 2006 DEM according to the exact position of the sun in the 1997 orthoimage. To calculate flow velocity vectors, the image correlation algorithm IMCORR (Scambos et al., 1992) within SAGA-GIS software was applied. The algorithm attempts to match small sub-scenes from two images by applying a fast Fourier transform-based version of a cross- correlation. It can locally adjust the intensity values between two image pairs and therefore compensate for differences in illumination. Using this algorithm, sub-pixel precision of displacement vectors can be achieved. We used search and reference chip size

420 combinations of 64/32, 128/64 and 256/128 with a fixed spacing of 5 m. The combinations were calculated for all image pairs and the most reasonable was chosen for further analysis. This was done by visually analysing the resulting displacement vectors in combination with the input data. In general, larger chip sizes were chosen for faster moving rock glaciers and/or long time spans between the image pairs. The resulting raw vector maps can contain erroneous displacement measurements or decorrelation, where no measurement is possible, due to snow, strong shading effects, areas where displacements are

425 dominated by rock fall and large displacements, which cause a change of texture. These vectors were excluded manually for all time steps with the help of the matching orthoimages or hillshades. Subsequently, a mask was created for the areas where measurements were possible in all time steps and just measurements in these areas were used for further analysis to make the individual time steps comparable. ~~The combination of orthoimages and hillshades has to be chosen because low point densities in some of the aerial images derived point clouds resulted in low details in the resulting DEMs. Tests regarding image~~

430 ~~correlation on these DEMs showed very poor results. We are aware that the low point densities also affect the accuracy of the resulting orthoimages and outline the variable errors in Sect. 4.1. On the other hand, we decided not to use orthoimages for the more recent epochs from 2006 to 2017, available from "Office of the Tyrolean Government Department of Geoinformation" (https://www.tirol.gv.at/en/) for the reason that they are orthorectified utilizing the most up to date DEM with a resolution of 5 m, which could result in erroneous displacement measurements. If a non-matching DEM is used, it would lead to~~

435 ~~orthorectification errors particularly on moving landforms, like rock glaciers (Kaufmann and Kellerer-Pirklbauer, 2015). The measurement of horizontal flow velocities of rock glaciers on remote sensing data, especially when using historical aerial images and their derivatives, is prone to errors. As described by Kääb et al. (2020), the error budget is composed of the following components: 1) overall shifts between the orthorectified data 2) lateral shifts in the orthoimages due to errors in the DEM used for orthorectification 3) distortions in the aerial images or in the sensor model that propagate into the orthoimages~~

440 ~~4) image matching uncertainties and errors. We minimized the shifts between the orthoimages by local co-registration of the orthoimages. By using the matching DEMs of the individual years for orthorectification, we addressed error type 2). However, quality of the DEMs varies locally in a single epoch and more crucially between the epochs and therefore are still a source of error. The DEMs with the lowest quality were the epochs 1982 and 1997. These were also the years with the worst quality of the raw aerial images (error type 3). Another source of error when working with historical aerial images are scratches and~~

445 ~~alterations on the original image film caused by storage and age. These can lead to problems in the processing and thus were masked out before processing. Errors of type 4) contain errors caused by the image correlation method itself. The measurement errors as consequence of image correlation vary with the image quality like resolution, shadow, contrast and noise of the image pairs (Kääb et al., 2020). We removed both directional and magnitudinal gross outliers manually by counterchecking the resulting displacement vectors with the corresponding orthoimage and hillshade pairs.~~

450 **~~3.5.2 Error assessment for horizontal flow velocities~~**

418

The combination of orthoimages and hillshades had to be chosen because low point densities in some of the aerial images derived point clouds resulted in low details in the resulting DEMs. Tests regarding image correlation on these DEMs showed very poor results. We are aware that the low point densities also affected the accuracy of the resulting orthoimages and outline the variable errors in Sect. 5.2. On the other hand, we decided not to use orthoimages for the more recent epochs from 2006 to 2017, available from "Office of the Tyrolean Government-Department of Geoinformation" (https://www.tirol.gv.at/en/) for the reason that they were orthorectified utilizing the most up to date DEM with a resolution of 5 m, which could result in erroneous displacement measurements. If a non-matching DEM is used, it would lead to orthorectification errors particularly on moving landforms, like rock glaciers (Kaufmann and Kellerer-Pirklbauer, 2015).

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To quantify the overall error budget for horizontal flow velocities, we mapped close stable areas of similar texture/roughness and exposition on the single rock glaciers for all time steps. Due to snow and shading effects, these stable areas had to be adjusted slightly for some ~~time steps~~epochs. Subsequently, displacement vectors in these areas were analysed for all individual epochs and rock glaciers. As no gross outliers were found in these areas, we used the mean value ($disp\overline{x}$) added by two times the standard deviation ($disp\sigma$) as measure for error budget ($error_{disp}$) of flow velocity measurements.

$$error_{disp} = disp\overline{x}_{\Delta epoch1-epoch2} + 2disp\sigma_{\Delta epoch1-epoch2} \qquad (18)$$

This measure was also applied by Fey and Krainer (2020) to determine a level of detection (LoD) for rock glacier flow velocity and mean and standard deviation in stable areas are recommended as a statistical measure of flow velocity error by Paul et al. (2017).

4.4 Surface elevation and volume change

For the analysis of surface elevation and volume change on the rock glaciers we used both photogrammetric and ALS point clouds in a DoD analysis. All processing steps were performed in SAGA LIS (Laser Information System; Laserdata.at). The epochs for this analysis differ slightly from the datasets used for the flow velocity analysis as the processing of the aerial images did not lead to sufficient point cloud resolutions for the datasets 1982 and 1997. Therefore, four epochs between 1953 - 2017 were analysed. All point clouds (photogrammetrically derived and ALS) were thinned (0.5 m) to produce homogeneous point densities for all epochs and outliers were removed. In order to minimize inherent systematic errors (Bakker and Lane, 2017) all point clouds were co-registered with the reference 2017 ALS data by using an iterative closest point (ICP) algorithm (Besl and McKay, 1992) on mapped stable areas around the rock glaciers. Fine registration was performed for all individual rock glaciers and epochs separately to account for any variable errors throughout the catchment. This measure was also applied by Fey and Krainer (2020) to determine a level of detection (LoD) for rock glacier flow velocity and recommended as a statistical measure of flow velocity error by Paul et al. (2017). We have decided not to use a LoD for calculating rock glacier flow velocity statistics for the fact that even in areas below the LoD there might be actual displacement (Anderson, 2019). We therefore rather illustrate the errors as red bars in Figure to give an assessment of the uncertainties and data quality of the individual time steps and discuss possible implications in Sect. 4.1.

3.6 3D displacements on rock glaciers

For the documentation of 3D displacements on the rock glaciers we used both photogrammetric and ALS point clouds. The datasets for the 3D reconstruction differ slightly from the datasets used for the velocity analysis on the rock glaciers as the processing of the aerial photographs did not lead to sufficient point cloud resolutions for all of them. Thus the 1982 and 1997 epochs had to be excluded and the analysis could only be performed for the 1953-1970/71, 1970/71-2006, 2006-2012, and 2012-2017 epochs, where the 2006, 2012 and 2017 datasets represent ALS data. In 1970 and 1971, only a portion of the valley was covered in each case, so this epoch had to be composed of two partial data sets.
As already described, the point clouds were locally fine-registered (c.f. Sect. 3.4) and then thinned (0.5 m) during the import process into LIS SAGA in order to produce homogeneous point densities for all epochs. To account for the sometimes very long time intervals between individual data sets and the expected high 3D displacements, we used the 3D distance between points approach by Fey & Wichmann (2017), which is based on Lague et al. (2013) and is recommended as a robust distance measurement for geomorphological change detection in a complex terrain. For each point, the normal vector for a best fitting plane (including the point neighborhood) with a radius of 5 m around the point was calculated in a first step (module "point cloud features" in LIS SAGA). Using this normal information of individual points, the approach (implemented in LIS SAGA) determines corresponding points in two point clouds of different epochs along the normal or flipped normal vector and derives the 3D distance (perpendicular distance) and thus the 3D displacement between these corresponding point pairs by using a distance threshold (10 m) and a threshold for the maximum normal difference (15°). The relatively high threshold for the

radius was chosen to account for the expected high 3D displacements over the long investigation periods. In addition, we decided to use the same limit for all data sets to ensure comparability of the data. A detailed description of the workflow can be found in Fey & Wichmann (2017). Analogous to the rock glaciers, the calculations were also performed on the stable areas around the single rock glaciers for all epochs in order to calculate the measurement error. At the end of this workflow, the 3D displacements for the rock glacier areas as well as for the stable areas were assigned as an attribute to the respective point clouds and were used for the following analyses. As for the flow velocities, we have omitted an LoD and have included the error values as additional information in the corresponding figures. The volume claculations were also performed based on the point cloud information. For this purpose, raster data sets (1m) were aggregated form the mean annual 3D displacement point cloud attribute and the volume was claculated form this raster dataset.

4 The point clouds were then converted into a DEM with a cell size of 1 m. The elevation change for each epoch and rock glacier was derived by subtracting the earlier DEM from the newer DEM (DoD). These values were summed and multiplied by the squared cell size to obtain the volume change. In order to be able to compare epochs, annual values were calculated. To avoid surface elevation changes and volume changes being influenced by snow, snow masks were created and these areas were excluded from the analysis.

For the uncertainty analysis we strictly followed the approach proposed by Anderson (2019), who presented an error propagation methods to derive uncorrelated, correlated and systematic errors and combine them to a total uncertainty without applying a minimum LoD. We carried out this procedure on stable areas that we mapped in proximity to the rock glaciers. For visualisation, however, we applied a LoD of 1.96 times the standard deviation in stable areas.

4.5 Meteorological data

In order to identify possible links between rock glacier kinematics and external frocing factors, we analysed the changes in temperature, precipitation and snow cover during the study period from 1953 to 2017. In addition to a trend analysis of the data, we also calculated the annual anomalies based on the reference period 1961 to 1990 and the 5-year running mean to smooth out short-term fluctuations. In addition, we disaggregated these analyses by season, here, spring was defined as March – May, summer as Juli – August, autumn as September – November and winter as December – February. The variables snow cover onset and duration were determined according to Peng et al. (2013) From the depth of snow data of the individual station we also calculated the dates when a significant snow cover (> 50 cm) is established, allowing for ground isolation. Besides this we derived the date of complete snow melt in spring.

5 Results ~~and Discussion~~

5.1 Rock glacier inventory and investigated rock glaciers

A rock glacier inventory was compiled for the Upper Kauner Valley. Within the catchment, 40 rock glaciers were found, which were classified as active (15), inactive (11) and fossil (14) (Fig. 3). Due to poor image quality or snow cover and the activity status, the vast majority of these rock glaciers had to be excluded from the following analyses.

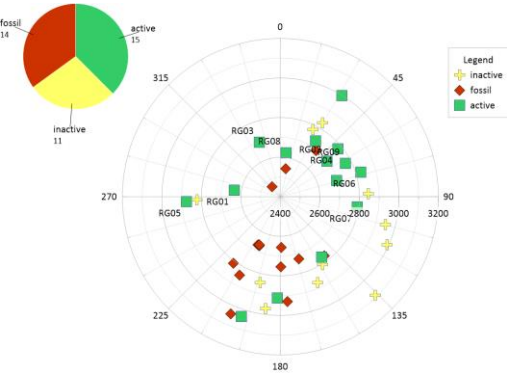



Figure 3. Roseplot of the rock glacier inventory of the Upper Kauner Valley. The radial axis gived the mean elevation of the rock glaciers [m], the agular axis gives the exposition of the rock glaciers [°]

Nevertheless, eight active rock glaciers representing different characteristics and conditions were investigated in detail regarding flow velocities and one more regarding surface elevation change. The most prominent of those is the well-studied and largest (0.237 km²) rock glacier Innere Ölgrube (RG01) (Fig. 2). The area of these rock glaciers ranges from 0.02 km² (RG07) to 0.237 km² (RG01). They show expositions of N, NE, E and W, with minimum elevation ranging from 2446 m to 2727 m. Without geophysical, geochemical or petrographic information, interpretations about the genesis and internal structure are difficult (Berthling, 2011; Clark et al., 1998). In the case of the rock glaciers RG03, RG04 and RG09 a complete or partial covering of the rock glaciers by the LIA glacial extent (Fischer et al., 2015) suggested a glacial genesis after 1850 or at least a glacial influence during and after this time as described by Dusik et al. (2015) for RG09. In the case of RG06, a thermokarst lake suggested a glacier coverage of the root zone during LIA and the presence of massive sedimentary ice.

Table 4. Characteristics of the rock glaciers studied. Permafrost occurrence gives the pseudo-probability of permafrost (Otto et al. 2020). Area covered by 1850 glacier extent is ascertained according to LIA glacier extends (Fischer et al. 2015) if not specified otherwise.

Rock glacier	RG 01	RG 02	RG 03	RG 04	RG 05	RG 06	RG 07	RG 08	RG 09
Exposition	W	NE	N	NE	W	E	E	N	NE
Area [km²]	0.237	0.058	0.036	0.036	0.059	0.182	0.02	0.088	0.171

Slope [°]	25	26	26	20	31	24	30	30	22
4.1									
Elevation [m]									
min	2446	2 615	2596	2 727	2702	2 695	2709	2 510	2627
max	2780	2 755	2787	2 812	3093	2 948	2861	2 761	2925
Permafrost occurrence [%]									
min	0	0	16.97	0	0	0	0	0	0
max	65.41	57.95	45.68	70.53	76.04	81.42	50.52	60.52	78.57
mean	14.49	33.22	48.99	47.08	48.24	44.04	20.54	38.33	37.57
Connection to the upslope unit	GFC; TC	TC	GFC	GFC	TC	TC	TC	TC	GFC; TC
Area covered by 1850 glacier extent	Yes*	No	Yes	Yes	No	No***	No	No	Yes**

565 *As described in (Berger et al. 2004);
** As described in (Dusik et al. 2015);
 *** A thermokarst lake suggests massive ice and a covering of the root zone by LIA glacier.

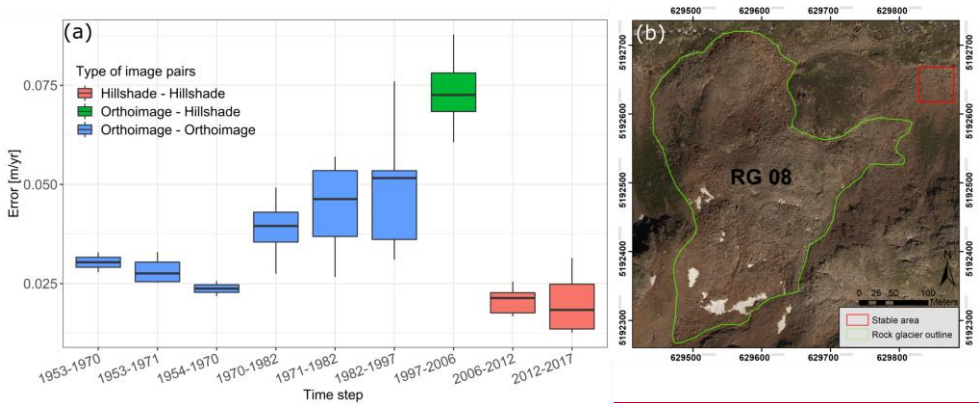
Concerning the connetion to the upslope unit both glacier forefield connected (GFC) and talus connected (TC) rock glaciers were included in the further analysis. Detailed characteristics of the studied rock glaciers can be found in Table 4 and a KMZ-
570 file containing the locations of the investigated rock glaciers is included in the supporting materials.

5.2 Errors and uncertainties

~~Despite efforts to~~ Although the workflow was chosen to minimise errors, ~~in particular by image co-registration in the case of flow velocities and ICP in the case of 3D displacements~~ during data processing, they are still present to some extent in the
575 data. ~~The errors are~~ Wherever necessary and possible, we indicated the uncertainties of the values in the ~~corresponding Fig. 6, 7, 8~~ text and ~~9.~~ in the figures.

For flow velocity measurements, error values ~~range~~ ranged between 0.~~013~~01 m/yr and 0.~~088~~09 m/yr. ~~For the 3D displacements, the values range on all stable areas for all epochs from -1.38 m to 1.4 m with a mean value of -0.0007 m, a σ of 0.014 and the 95% quantile of 0.02. The~~ The distribution of ~~error~~ these values from individual rock glaciers per image pair combination are
580 displayed in Fig. 4. In general, best results were obtained for epochs where hillshade image pairs were utilized. ~~3. In general, best results were obtained for epochs where hillshade image pairs were utilized.~~ The largest errors on average were determined for the epoch 1997-2006, in which a combination of orthoimages and hillshade was used. We ~~attribute~~ attribut this to the poor image quality of the 1997 dataset and the use of orthoimages in combination with hillshades. Although the illumination of the hillshades was adapted to the orthoimages, only contrasts and patterns, which are caused by the illumination, can be used to
585 determine the flow velocity by image correlation. On the contrary, contrasts and patterns that are caused by different colours

in the orthoimage are not taken into account or can even lead to incorrect measurements. In other cases, the variability of the errors may be related to the accuracy of the co-registration, but also to differences in the quality of the image in terms of contrast, illumination, and resolution.

590 ~~To assert the validity of our results we performed a qualitive comparison with dGPS measurements, which were taken by Krainer and Mostler (2006) between 2002 and 2004 for Ölgruben rock glacier (RG 01), confirm the magnitude, flow direction and pattern that were determined by our method. In addition, a comparison of flow velocities derived by Groh and Blöthe (2019) by feature tracking for Kauner Valley rock glaciers between 2001 and 2015, showed good agreement. Although other time-steps were used, span, mean and median values show similar and plausible results when comparing them to the two most recent time steps of our study.~~

595

To assert the validity of our results we performed a qualitive comparison with dGPS measurements, which were taken by Krainer and Mostler (2006) between 2002 and 2004 for Ölgruben rock glacier (RG01). This confirmed the magnitude, flow direction and pattern that were determined by our method. In addition, a comparison of flow velocities derived by Groh and Blöthe (2019) by feature tracking for Kauner Valley rock glaciers between 2001 and 2015, showed good agreement. Although

600 other time-steps were used, span, mean and median values showed similar and plausible results when compared to the values of the two most recent time steps of our study.

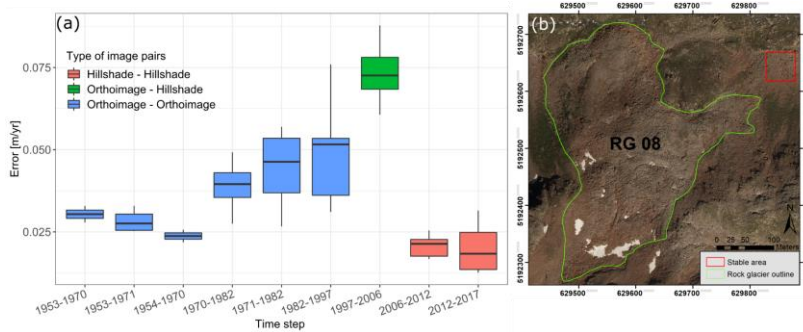



Figure 4. (a) errors derived from stable areas in proximity to the individual rock glaciers for all image pair combinations. (b) example of a stable area displaying similar exposition, texture/roughness used to analyse error for ~~RG 08.~~ RG08

605 ~~Due to~~For the ~~generation~~surface elevation change and volume change analysis, the uncertainties were largely determined by the magnitude of ~~masks~~ the systematic error of the DoD. The analysis of the errors revealed that a systematic error mostly occured if one or both DEMs used to calculate the DoD were photogrammetrically created from historical imagery. This is reasoned by the fact that, due to the quality of the data, these point clouds could not be matched to the reference dataset by the ICP algorithm with the ~~aim of~~same accuracy as, for example, high-resolution and high-precision modern ALS datasets. Since

610 the data quality of the point clouds generated from historical images varies spatially, a systematic error did not occur to the same severity in all investigated rock glaciers of an epoch. The spatially correlated random error, on the other hand, always occured in DoDs with at least one DEM generated from historical images, whereas it was not present in DoDs created from ALS data. However, similar to the uncorrelated random error, this contributed only ~~taking into account~~little to the total uncertainty in case a systematic error was present.

615 Since areas of snow cover, strong shadows or decorrelation in the image correlation would bias the results, masks were created comprising areas in which ~~measurements were~~ an unbiased analysis was possible in all epochs in order to ensure ~~better~~ comparability~~, some areas of the rock glaciers had to be excluded (Table 4). In the case~~. Therefore, the analysis of the flow velocity ~~analysis, between~~could be conducted on 27.39% ~~and~~to 80.00% of the rock glacier area ~~could be taken into account.~~ ~~In~~, while, regarding the ~~ease of the 3D distance~~surface elevation change analysis, ~~it was~~ a coverage of 50.50% to 95.67~~%.~~%

620 could be achieved (Table 5).

Table 5. Percentage of the rock glacier area in which measurements were possible in all time steps and which were therefore considered for the analysis of ~~the~~ flow velocity and ~~3D displacement.~~surface elevation change. Reasons for exclusion were snow cover, shading effects or decorrelation in the image correlation.

	~~Measurement area [%]~~								
Rock glacier	RG01~~Flow velocity~~	~~3D distances~~RG02	RG03	RG04	RG05	RG06	RG07	RG08	RG09

Eingefügte Zellen
Eingefügte Zellen
Eingefügte Zellen
Eingefügte Zellen
Eingefügte Zellen
Eingefügte Zellen
Eingefügte Zellen
Eingefügte Zellen

~~RG 01~~			~~41.97~~				~~92.09~~			
~~RG 02~~ ~~Area~~	Flow velocity	41.97	75.94	45.42	~~87~~65.72	27.39	39.12	70.62	80	~~-~~
~~RG 03~~			~~45.42~~				~~70.93~~			
~~RG 04~~			~~65.72~~				~~90.71~~			
~~RG 05~~			~~27.39~~				~~81.10~~			
~~RG 06~~			~~39.12~~				~~64.40~~			
~~RG 07~~	Surface elevation change	92.09	87.72	70.6~~2~~93	90.71	81.1	64.4	92.~~9~~09	95.67	50.5
~~RG 08~~			~~80.00~~				~~95.67~~			
~~RG 09~~			~~-~~				~~50.50~~			

Eingefügte Zellen (×16)

~~4.2~~5.3 Changes in meteorological forcing

~~As it is known from many studies that the changes in the external (meteorological) forcing (temperature, precipitation, snow cover) play an important role for changes in the periglacial system and thus rock glaciers, we analysed climate data from weather stations within and close to our catchments, which was challenging due to the large temporal scale (1953-2017).~~ All stations ~~show~~showed similar patterns of change, even if the manifestation of the anomalies ~~are~~was slightly different in some cases. We note that the positive trend of temperature increase ~~is~~was slightly higher for stations of higher elevation in the study period. In the case of temperature and snow cover, we mainly present data from the stations Obergurgl-Vent (1938 m a.s.l.) and Obergurgl (1942 m a.s.l.), as these are located at the highest elevation and only about 21 km away from the centre of our study area. In the case of precipitation, we mainly present data from the Plangeroß station (1605 m a.s.l.), because although it is located at a significantly lower elevation than the Weißsee station (2540 m a.s.l.) and the studied rock glaciers, it ~~offers~~offered the best agreement with the Weißsee station data in terms of monthly precipitation (r= 0.892, p<0.001). ~~Wherever~~

possible, we try to confirm the observations with the limited time series (2007-2017) of the Weißsee station. In the following sections, we describe the general trend of meteorological forcing which is further discussed with regard to changes in flow velocity in Sect. 4.4.

4.2.1 Temperature

During the period of investigation (1953-2017), the temperature trend shows an increase of 1.92 °C in 65 years at the Obergurgl-Vent (1938 m a.s.l.) station (Fig. A1). This is a stronger increase than at the lower elevated station Nauders (1330 m a.s.l.), where the increase is 1.29 °C. If only the last two epochs, 2006-2012 and 2012-2017, are taken into account, it becomes apparent that the station Weißsee (2540 m a.s.l.) shows the greatest increase in the mean temperature values of these time periods of 0.57 °C. Possible reasons and explanations for the elvation-dependend warming are given in Rangwalla and Miller (2012). In general, the temperature increase goes well in line with the alpine-wide temperature increase, which has a significantly higher amplitude than the global average (Beniston, 2006). The seasonal development of the temperature trends shows a stronger increase in temperatures in spring and summer of 2.73 °C and 2.64 °C, respectively, in 65 years compared to the winter and autumn temperatures. For these, the positive trend is clearly weakened and amounts to only 1.6 °C for winter and 0.69 °C for autumn. If one compares the seasonal temperatures with the reference period 1961 - 1990, it is noticeable that in the case of summer and spring temperatures, only positive anomalies occur from the beginning of the 1990s onwards (Fig. 6). The summers of 2015, 2017 and in particular the summer of 2003 are conspicuous for their high temperatures and are known to have brought profound change to permafrost-affected systems (Ravanel et al., 2017). In the case of spring temperatures, the spring of 2007 stands out in particular, and to a lesser extent 2011 and 2017. Conditions causing these heat waves are expected to increase throughout the 21st century (Gobiet et al., 2014). Although positive anomalies also accumulate from this period onwards in the case of autumn and winter temperatures, there are also periods or years showing comparatively cold temperatures. Particularly warm winters were recorded in 1988, 1989, 2006 and 2015, with mean temperatures more than 3 °C higher than the long-term average. In the case of autumn temperatures, the warm autumn of 2006 stands out in particular. For the period before the beginning of the 1990s, periods/years with positive and negative anomalies are visible, whereby the strong anomalies are mostly in the negative range. The summer temperature anomalies show the lowest variance. Particularly striking is the period between 1970-1982 with its continuously comparatively low summer and autumn temperatures and a period of relatively cold winters from 1962-1970.

4.2.2 Precipitation

All considered meteorological stations, except for the station Nauders (1330 m a.s.l.), recorded a slightly positive trend in terms of precipitation, translating to an increase between 53 mm and 241 mm during the investigation period. The positive trend for the station Plangeroß (1605 m a.s.l.) is expressed in an increase in precipitation of 152 mm per 65 years (Fig. A2). The mean annual precipitation accounts to 931 mm/yr during the period of investigation and to 957 mm/yr at the Weißsee station (2540 m a.s.l.) in the period from 2007 to 2017. The greatest positive trend is recorded in autumn (52 mm per 65 years),

680   the least in winter (18 mm per 65 years). On average, most precipitation falls in the summer months, with an average of 362 mm/yr, and the least in winter, with an average of 171 mm/yr. Throughout the Alps, there is only a very small or no clear trend with regard to the annual precipitation development in the 20ⁿᵈ century (Beniston, 2006). But during the 21ˢᵗ century, a decrease in summer precipitation, an increase in winter precipitation and an increase in the frequency and intensity of extreme precipitation events are predicted for the European Alps (Gobiet et al., 2014).

685   Looking at the precipitation anomalies, there is a clear increase from the mid-1990s for positive summer and autumn precipitation anomalies, which is particularly pronounced in the period 1995-2002. For the 1999-2002 period and the most recent time step from 2013-2017, this can also be seen in the spring precipitation (Fig. 6). Another period with clustered positive precipitation anomalies can be observed in the case of spring and summer precipitation between 1963 and 1967 and for autumn precipitation between 1972 and 1981, with both showing single years with just slightly positive or negative

690 anomalies. Relatively dry summers were recorded from 1954-1984 and 1990-1994, dry autumns from 1984-1991. In the case of winter precipitation, there are some positive and negative anomalies, but these do not occur in clusters. Nevertheless, the winters with high precipitation in 2011 and 2012 should be mentioned here.

4.2.3 Snow cover

The onset and duration of snow cover is described below for the Obergurgl station (1942 m a.s.l.), as this is the closest and

695 highest station with a long data series. As with the other parameters, the values are difficult to transfer to the study area, but can provide an indication of general trends and anomalies in snow cover onset and duration (Fig. A3). Looking at the entire study period from 1953 to 2017, there is a slightly negative trend both for the start of the snow cover and for its duration. This fits in with the results of Olefs et al. (2020) , who found an elevation-dependent reduction in snow depth and duration in Austria between 1961 and 2020, but this only applies to elevations below 2000 m.

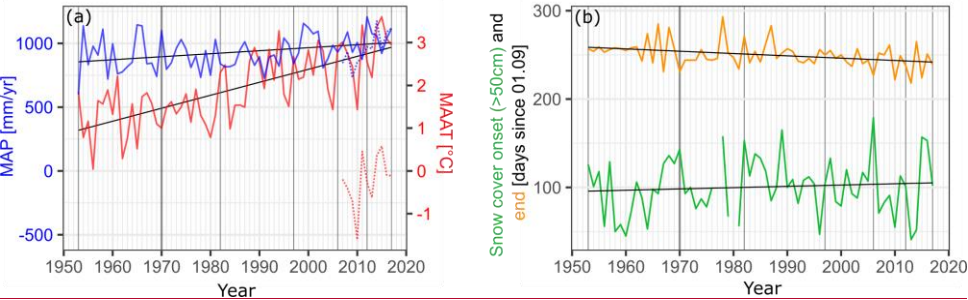
700   Although this is not always the case, in general, the data show that when the onset takes place earlier, the duration of snow cover is longer and vice versa (Fig. 6). Particularly striking is the period from 2007-2016 where snow cover onset anomalies show consistently negative values and are also associated with a long duration of snow cover, particularly between 2007 and 2011. Although no long time series data is available for Weißsee station, the early onset and long duration of the snow cover for this period can also be observed here. This effect is also evident in a period between 1956 and 1962 and in two shorter

705 periods from 1971 to 1974 and 1978 to 1981. The opposite is visible for the epoch 1983-1997, as the snow cover tends to set in late and often melts again more quickly.

4.3During the period of investigation (1953-2017), the temperature trend showed an increase of 1.92 °C in 65 years at the Obergurgl-Vent (1938 m a.s.l.) station (Fig. 5). This was a stronger increase than at the lower elevated station Nauders (1330 m a.s.l.), where the increase was 1.29 °C. Possible reasons and explanations for the elevation-dependend warming are given

710 in Rangwalla and Miller (2012). In general, the temperature increase goes well in line with the alpine wide temperature increase, which has a significantly higher amplitude than the global average (Beniston, 2006). The seasonal development of the temperature trends showed a strong increase in temperatures in spring and summer of 2.73 °C and 2.64 °C, respectively.

This trend was clearly weakened for winter and autumn temperatures and amounted to 1.6 °C for winter and 0.69 °C for autumn. The derived temperature anaomalies showed exclusively positive anomalies from the beginning of the 1990s onwards

715 for spring and summer temperatures (Fig. 12). The summers of 2015, 2017 and in particular the summer of 2003 were conspicuous for their high temperatures and are known to have brought profound change to permafrost-affected systems (Ravanel et al., 2017). For the period before the beginning of the 1990s, periods/years with both positive and negative anomalies occured, whereby the strong anomalies were mostly in the negative range.

720 **Figure 5. Change in meterorological forcing (a) Mean annual precipitation (MAP) for the station Plangeroß (1605 m a.s.l.) and Mean annual air temperatur (MAAT) for the station Obergurgl-Vent (1938 m a.s.l.); the dashed lines indicate the values for the Weißsee station (2540 m a.s.l.). (b) Snow cover onset and end for the station Obergurgl (1942 m a.s.l.). The black lines show the trend of the respective parameters.**

All considered meteorological stations, except for the station Nauders (1330 m a.s.l.), recorded a slightly positive trend in

725 terms of precipitation, translating to an increase between 53 mm and 241 mm during the investigation period. The positive trend for the station Plangeroß (1605 m a.s.l.) was expressed in an increase in precipitation of 152 mm per 65 years (Fig.5). The mean annual precipitation accounted to 931 mm/yr during the period of investigation at the station Pangeroß (1605 m a.s.l.) and to 957 mm/yr at the Weißsee station (2540 m a.s.l.) in the period from 2007 to 2017. The greatest positive trend was recorded in autumn (52 mm per 65 years), the least in winter (18 mm per 65 years). On average, most precipitation fell in the

730 summer months, with an average of 362 mm/yr, and the least in winter, with an average of 171 mm/yr.

Precipitation anomalies showed a clear increase from the mid-1990s for positive summer and autumn anomalies, which is particularly pronounced in the period 1995-2002 (Fig. 12). Throughout the Alps, there is only a very small or no clear trend with regard to the annual precipitation development in the 20st century (Beniston, 2006).

The derived snow cover parameters are difficult to transfer to the study area, as the station Obergurgl (1942 m a.s.l.) is located

735 at a lower elevation than the rock glaciers studied but could provide an indication of general trends and anomalies in snow cover onset and duration (Fig. 5). For the entire study period from 1953 to 2017, no significant trend could be observed for the onset of the snow cover, significant snow cover and snow cover duration. This fits in with the results of Olefs et al. (2020), who found an elevation-dependent reduction in snow depth and duration in Austria between 1961 and 2020, but this only

applies to elevations below 2000 m. However, there were some periods and years showing a particularly early or late onset of snow cover and significant snow cover respectively (Fig. 12). On the other hand, a significant negative trend of -17 days was observed for the end of snow melt over the study period, meaning the snow melt takes place earlier with time (Fig.5). Although this was not always the case, in general, the data showed that when the onset was earlier, the duration of the snow cover was also longer and vise versa.

5.4 Flow velocities

4.3.1 General trends

For the whole period of investigation, we derived maximum flow velocities ranging between 0.089 m/yr and 1.721 m/yr and mean flow velocities ranging between 0.035 m/yr and 0.485 m/yr for the eight individual rock glaciers (Fig. 4). All of the investigated rock glaciers, except for RG 08, which has the highest maximum flow velocities in the epoch 1953 to 1971, show the highest mean and/or maximum values either in the epoch 1997-2006 or 2012-2017. RG 01, RG 02, RG 03, RG 06, RG 07 and RG 08 show a distinct acceleration of flow velocities beginning in the epoch 1997-2006. This fits well with other studies investigating rock glacier morphodynamics in the European Alps over a multi-decade period, all observing a significant acceleration of flow velocity in the early to late 1990s (Roer et al., 2005; Delaloye et al., 2010; Kellerer-Pirklbauer and Kaufmann, 2012; Micheletti et al., 2015; Scapozza et al., 2014; Hartl et al., 2016; Kaufmann et al., 2018; Kellerer-Pirklbauer and Kaufmann, 2018; Kellerer-Pirklbauer et al., 2018; Kenner et al., 2020).

All of the investigated rock glaciers of the Kauner Valley show an increase in flow velocities in the most recent epoch (2012-2017) compared to the previous 2006-2012 epoch. For this period of time, measurements with a higher temporal resolution show an annual increase in flow velocities from 2005 or 2007/08 and a particularly strong increase from 2010 onward with a maximum in 2015 and a slowdown since then (Hartl et al., 2016; Bodin et al., 2018; Kaufmann et al., 2018; Kellerer-Pirklbauer and Kaufmann, 2018; Kenner et al., 2020).

Exceptions to the general trend can particularly be seen in the case of RG 04. This rock glacier is characterised by very low and relatively constant flow velocities, which even decrease slightly in the two periods following 2006. Many studies mentioned periods of slight decrease or constant flow velocities following the strong acceleration in the 1990s (Delaloye et al., 2010; Kellerer-Pirklbauer and Kaufmann, 2012; Hartl et al., 2016). But there is no known example in the literature which shows a decrease in flow velocities over the entire surface area of the rock glacier in recent years, relative to the period at the beginning of the 1950s with no increase in the 1990s.

Although there is a general trend towards higher flow velocities for all rock glaciers, apart from RG 04, regarding flow velocity patterns and trends, there are different characteristics observable on the individual rock glaciers.

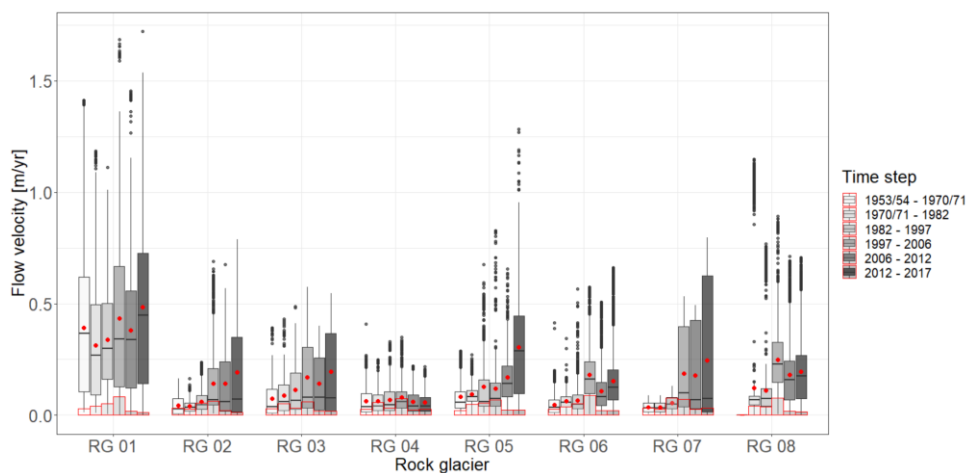



Figure 4. Flow velocities for individual rock glaciers for six distinct epochs from 1953 to 2017. Rock glacier KT 09 was not included in the flow velocity analysis and rock glacier RG 08 had to be excluded from time step 1 due to extensive decorrelations in the frontal part because of large displacements.

4.3.2 Magnitude of change

770 Although some rock glaciers show their minimum mean flow velocity in the epoch 1970/71-1982 and some their maximum in the epoch 1997-2006, in the following chapter we compare the magnitude of the velocity increases between the first and the last epoch.

In the first epoch, all rock glaciers, except for RG 01 (0.393 m/yr) and RG 08 (just manual mapping possible) which show higher values, display similar mean values ranging from 0.035 m/yr to 0.082 m/yr. If the maximum flow velocities are taken

775 into account, this similarity is put into perspective somewhat, as the range here is significantly greater and lies between 0.089 m/yr and 0.409 m/yr. In the epoch 2012-2017, the range of the mean values increases significantly and is now between 0.056 m/yr and 0.305 m/yr and 0.485 m/yr for RG 01. The strongest proportional increase can be seen in rock glaciers RG 07 and RG 02, where mean flow velocities increased by 602.00% and 356.03% and maximum flow velocities increased by 799.10% and 383.20%, respectively. Beside the rock glacier destabilisation that has been observed for some rock glaciers in recent years

780 (Roer et al., 2008; Scotti et al., 2017), these are the highest relative movement changes compared to other studies (c.f.Roer, 2005; Kellerer-Pirklbauer and Kaufmann, 2012, 2018; Kenner et al., 2020). In contrast, in the case of RG 04, the average and maximum flow velocity is reduced by -12.51% and -47.14%, respectively. Since rock glaciers RG 02, RG 07 and RG 04 show

similar exposition, size, and elevation ranges, we assume that the different behaviour is explained by a topographic or structural control rather than different external forcing.

785 The relative changes For the whole period of investigation, we derived maximum flow velocities ranging between 0.09 m/yr ± 0.03 m/yr and 1.72 m/yr ± 0.01 m/yr and mean flow velocities ranging between 0.08 m/yr ± 0.03 m/yr and 0.60 m/yr ± 0.01m/yr for the eight individual rock glaciers (Fig. 6). The mean values were calculated for values above the maximum LoD of the respective rock glacier in order to exclude marginal areas, showing values close to zero, that do not move homogeneously with the rock glacier and to ensure comparability between the epochs. All of the investigated rock glaciers showed the highest

790 mean and/or maximum values either in the epoch 1997-2006 or 2012-2017.

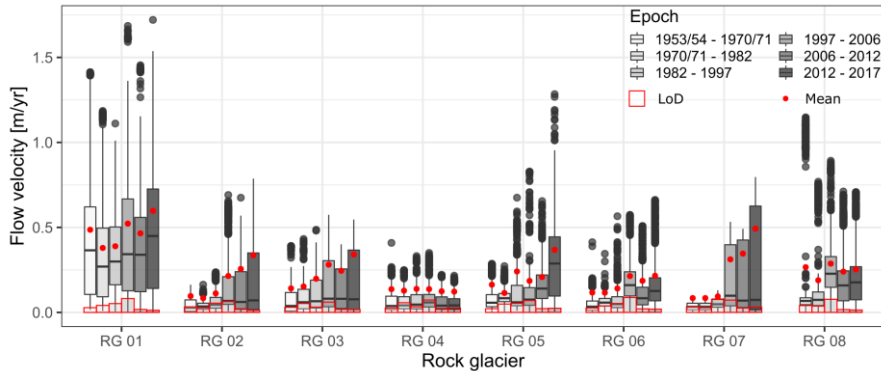
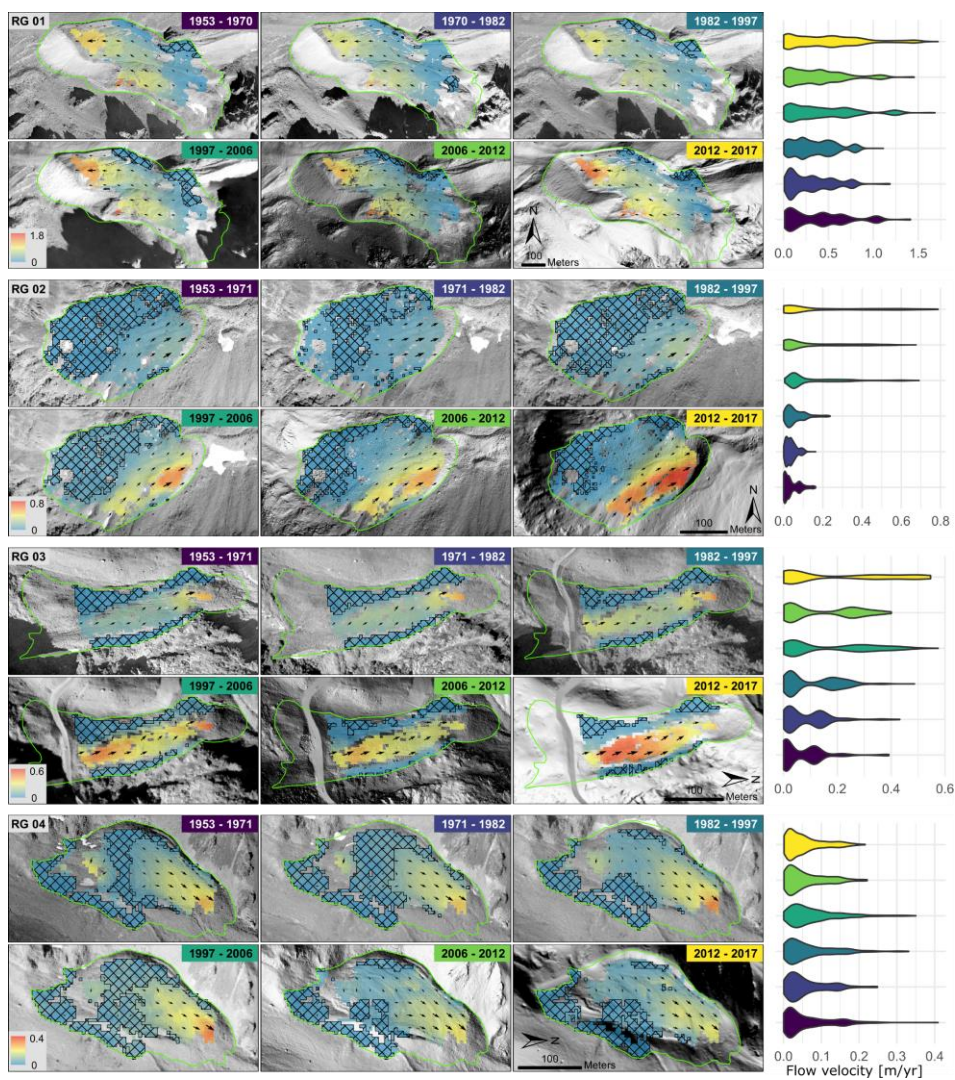
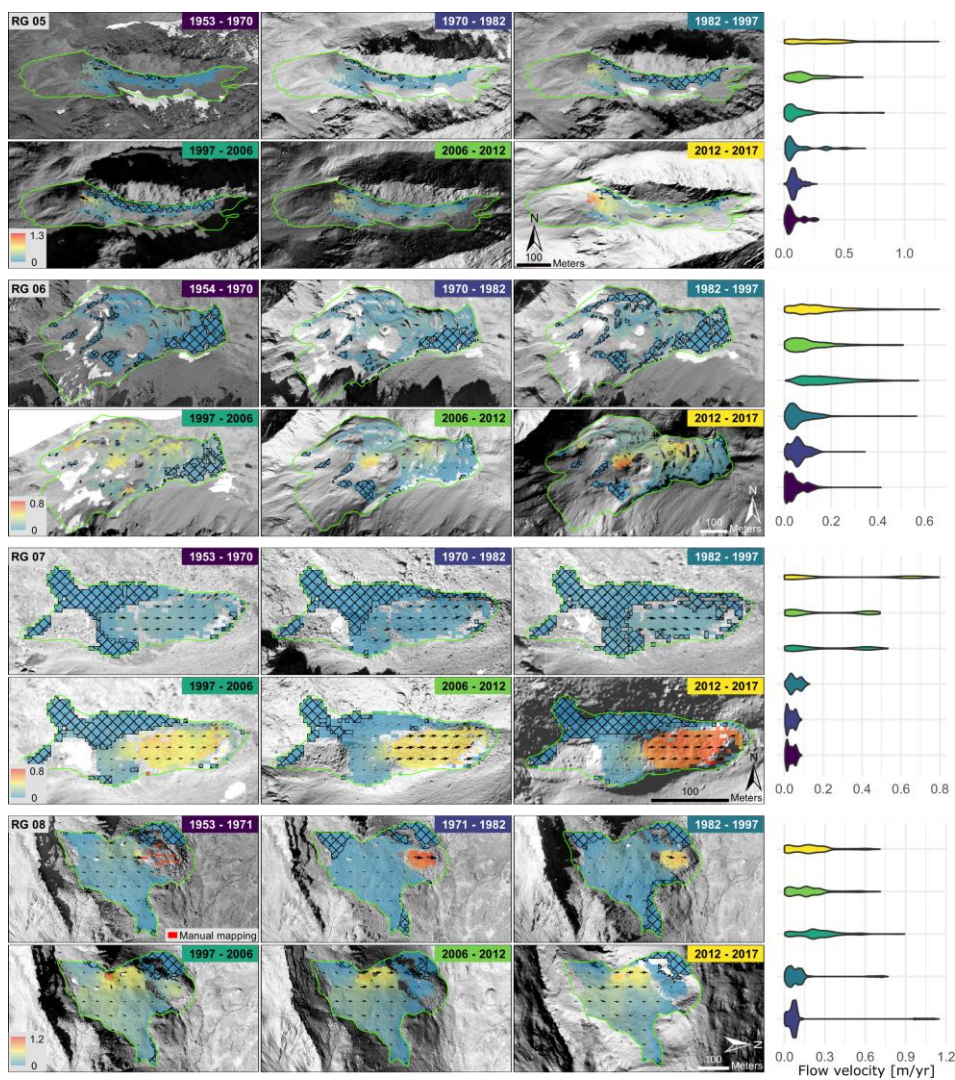



Figure 6. Flow velocities for individual rock glaciers for six distinct epochs from 1953 to 2017. Rock glacier KT 09 was not included in the flow velocity analysis and rock glacier RG 08 had to be excluded from epoch 1 due to extensive decorrelations in the frontal part because of large displacements. The mean value was calculated for values above the maximum LoD of the respective rock

795 **glaciers.**

An exeption to this was RG08, which had the highest maximum flow velocity of 1.66 m/yr in the epoch 1953 to 1971. In this epoch, flow velocities for RG08 could only be determined by manual mapping of a few blocks, as image correlation resulted in decorrelation due to excessive changes in surface structure. RG01, RG02, RG03, RG06, RG07 and RG08 showed a distinct acceleration of flow velocities beginning in the epoch 1997-2006. All of the investigated rock glaciers of the Kauner Valley

800 showed an increase in flow velocities in the most recent epoch, 2012-2017 compared to the previous 2006-2012 epoch. Exceptions to the general trend could particularly be seen in the case of RG04, as it was characterised relatively constant mean flow velocities well below 0.15 m/yr during the whole investigation period.

805 **Figure 7. Flow velocity maps and violin plots for the individual rock glaciers for the six epochs between 1953 and 2017. Unit of the colour scale is m/yr. Areas with flow velocities below LoD are marked with a black grid. Background image is always the older date of the epoch.**

In the first epoch, all rock glaciers, except for RG01 (0.49 m/yr ± 0.03 m/yr) and RG08 (max. 1.66 m/yr by manual mapping),

810 displayed similar, low mean values ranging from 0.08 m/yr ± 0.03 m/yr to 0.16 m/yr ± 0.02 m/yr and value ranges (Fig. 6). If the maximum flow velocities are taken into account, this similarity is put into perspective somewhat, as the range here was significantly greater and lies between 0.09 m/yr ± 0.03 m/yr and 0.41 m/yr ± 0.03 m/yr, due to the higher flow rates of RG 03-05 at their terminal part (Fig. 7).

Compared to the first epoch, the range of the mean values increased significantly in the epoch 2012 - 2017 and was now between 0.12 m/yr ± 0.03 m/yr and 0.49 m/yr ± 0.03 m/yr and 0.60 m/yr ± 0.01 m/yr for RG01. The st rongest proportional

815 increase could be seen in rock glaciers RG07 and RG02, where mean flow velocities increased by 485% and 251% and maximum flow velocities increased by 799% and 383%, respectively. In contrast, in the case of RG04, the average and maximum flow velocity was reduced by -11% and -47%, respectively.

The relative changes between the first and the last epoch regarding the remaining rock glaciers ~~ranges~~differed clearly and ranged between 23.~~45~~% and ~~271.87~~141% for mean flow velocity and ~~21.77~~22% and 348.~~20~~% for maximum flow velocity.~~ If~~

820 ~~RG 04, which has a very low slope, is not taken into account, one could say that higher elevated rock glaciers change their~~ ~~relative flow velocity to a greater extent. Apart from this observation, none of the topographic factors could explain the~~ ~~different magnitude of the change.~~ (Fig.6).

~~4.3.3 Local temporal peaks - sensitivity of~~**Some** rock glaciers ~~to external forcing~~

also showed a local temporal peak in one or more epochs, which was characterised by higher flow rates. On rock glaciers ~~RG~~

825 ~~01~~RG01 and ~~RG 08~~RG08, higher mean flow velocities ~~have been~~were measured between 1953/54 and 1970/71 compared to the subsequent ~~periods. Although there are not many studies covering this period, this phenomenon has also been~~ two epochs. Higher mean flow velocities were also observed ~~in case studies~~ on ~~other individual~~ rock glaciers RG01, RG03, RG06 and RG08 in the ~~Austrian (Kellerer Pirklbauer and Kaufmann, 2012; Kellerer Pirklbauer et al., 2018) and Swiss Alps (Kenner et~~ ~~al., 2020) and is explained by decennial variations in mean annual air temperature (Delaloye et al., 2010). In the~~ epoch 1997

830 to 2006, ~~higher flow velocities were measured~~ compared to the epochs before and after.~~ This is especially the case for rock~~ ~~glaciers RG 01, RG 03, RG 06 and RG 08,~~ although caution is required in the interpretation due to the higher error values~~.~~ ~~Those higher velocities might be explained by high flow velocities in the years 2000/1, 2003/4 and 2006/7 reported for many~~ ~~rock glaciers in the Alps, due to high summer temperatures (Delaloye et al., 2010). In addition, Kaufman et al. (2018) also~~ ~~found considerably higher mean flow velocities in the period from 2002-2006 than from 1992-2002 and 2006-2009 for~~

835 ~~Tschadinhorn rock glacier, Hohe Tauern (Austria). These peaks might not be found on the other rock glaciers due to~~ ~~superimposing effects over the long time steps and indicate a slightly different sensitivity, response or response time of~~ ~~individual rock glaciers to intra-annual, inter-annual or multi-annual fluctuations in external forcing parameters. In the case of~~

~~4.3.4 Patterns of flow velocity and elevation dependency~~

~~To better place the general trends in a spatial and temporal context, flow velocities in individual epochs and rock glaciers were analyzed for altitudinal zones of 20 meter along the rock glacier surface. Fig. 8 clearly shows the different size and height coverage of the various rock glaciers.~~ Furthermore, ~~it becomes apparent that many~~ rock glaciers ~~do~~did not move uniformly, but ~~have~~ had zones with higher and lower flow velocities (Fig. 7). The zones ~~with higher and lower flow velocities. The zones~~ of higher flow velocity ~~are~~were usually, but not always, located in the terminal section of the rock glacier ~~front~~. Exceptions ~~to this are~~were mainly ~~RG 03~~RG03, which ~~shows~~showed a gradual change in its flow pattern over time ~~(see Sect. 4.6.1), RG 06~~and RG06 which ~~in particular shows~~showed its maximum flow velocities in an area above a thermokarst depression ~~(see Sect. 4.6.3)~~in particular in the latest epoch ~~and RG 08 where~~. On RG08 maximum flow velocities were measured in the ~~front~~terminal part, which gradually ~~decrease~~decreased and ~~are shifted~~were close to higher elevations (see Sect. 4.6.2).

~~If we look at the percentage increase~~zero in the ~~mean values of the last two epochs, the two lowest elevated rock glaciers, RG 01 and RG 08, show the smallest increases, while the sharpest increase was measured on the highest elevated rock glacier RG 05~~most recent epoch, whereas the ~~remaining rock glaciers showing relatively similar increase rates. This could point to the fact that from 2006 to 2017 higher elevated rock glaciers enter an unstable state as a reaction of changes in the external forcing. Since rock glaciers tend to react with a certain time lag to changes in e.g. temperature, our data cannot be used to make any statements about e.g. temperature limits or similar. As it is very likely that such a time lack differs between single rock glaciers, we cannot find a general elevation dependent temporal change regarding the elevation classes.~~rest of the rock glacier accelerated from the epoch 1997–2006 onwards.

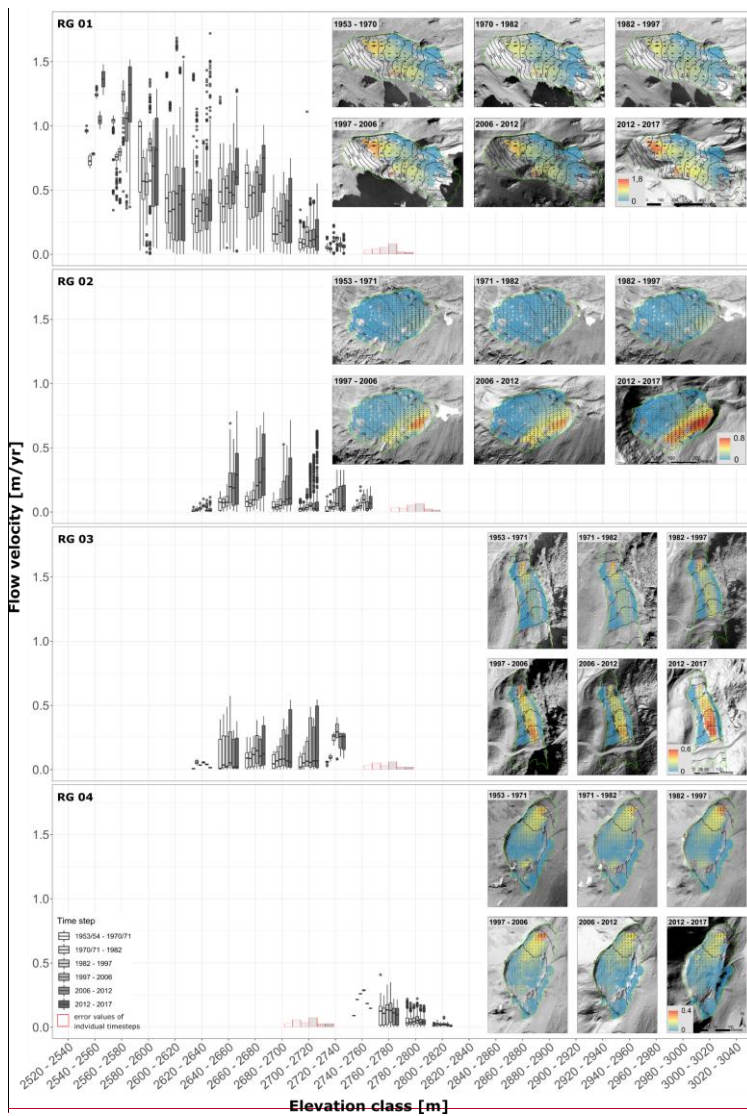
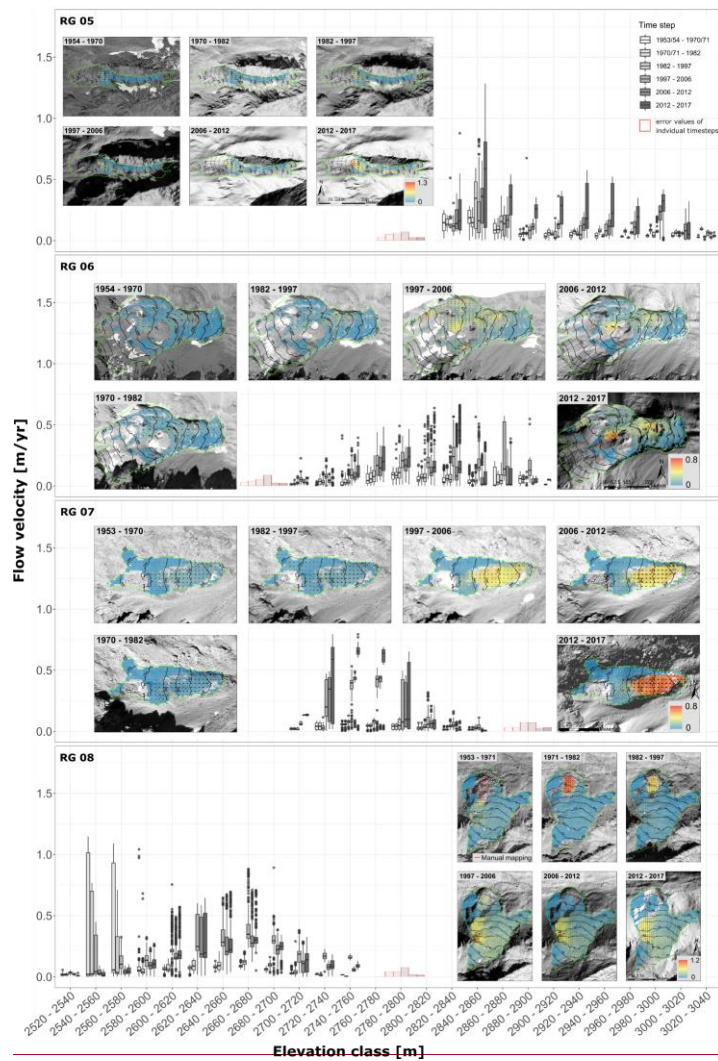



Figure 5. Flow velocities per elevation class for For all landforms, there were areas of varying extent that showed very little to no measurable movement over the entire study period. Apart from these areas, most of the remaining rock glacier areas

865 accelerated especially from the epoch 1997 - 2006, though to varying degrees. The taper (entire area accelerated) and thickening (individual ~~rock glaciers and six epochs between 1953 and 2017. In the~~ areas of different velocities) of the violin plots~~,~~ as well as the observation of the flow velocity maps gives an indication for the acceleration of different zones of the individual rock glaciers studied (Fig. 7).

5.5 Surface elevation and volume changes

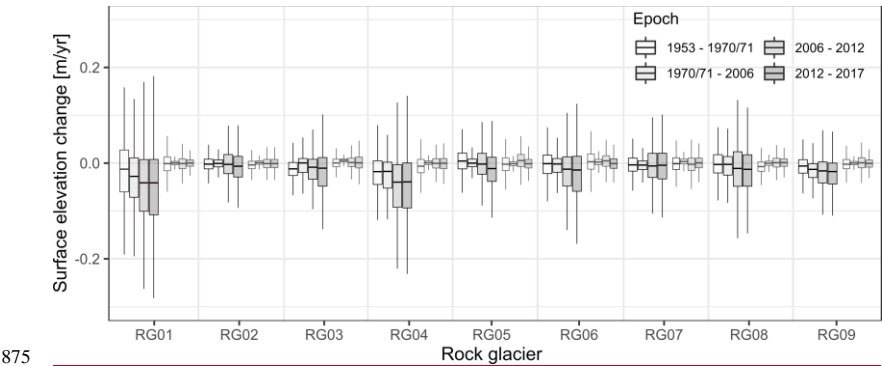
870 The calculation of the surface elevation and volume change could be carried out on a total of nine rock glaciers in four epochs. The volume changes of the investigated rock glaciers ranged from -9931 m³/yr ± 57m³/yr (RG1, epoch 2012 – 2017) to 235 m³/yr ± 121 m³/yr (RG05, epoch 1953 – 1970) (Fig. 9). Since the mean annual surface elevation changes allow for a better comparison of rock glaciers of different sizes, we will describe them in more detail in the text. However, the volumetric changes of the individual rock glaciers are ~~displayed~~shown in Fig. 9.

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Figure 8. Annual surface elevation changes on the single rock glaciers and corresponding stable areas (greyed out) for the four epochs between 1953 and 2017.

The mean values ranged from 0.005 m/yr ± 0.003 m/yr (RG05, epoch 1953 - 1970) to -0.047 m/yr ± 0.001 m/yr (RG04, epoch 2006-2012) (Fig. 9). In the entire study period, the values were predominantly in the negative range, with only 3 measurements

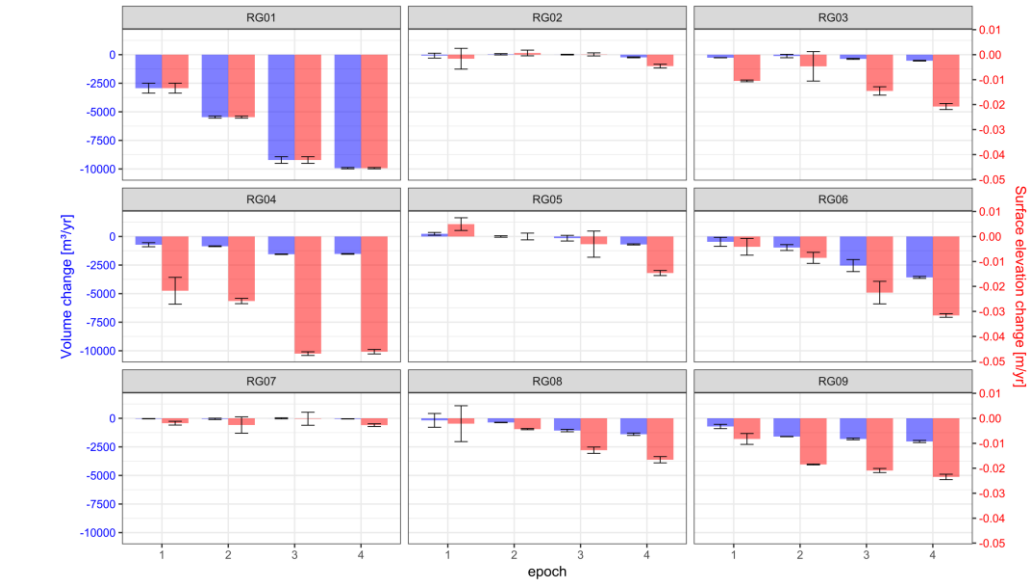
880 showing positive values very close to zero. All rock glaciers showed values of surface elevation change in the negative and the positive range (Fig. 8). A clear difference could be seen in the temporal development of the surface and volume changes of different the rock glaciers. On RG01, RG03, RG04 and RG09, negative values ranging between -0.022 m/yr ± 0.005 m/yr and -0.008 m/yr ± 0.002 m/yr already occoured in the first epoch and became increasingly negative in the following epochs, reaching values ranging between -0.046 m/yr ± 0.001 m/yr (RG04) and -0.021 m/yr ± 0.001 m/yr (RG03) in the last epoch.

885 All of these rock glaciers were classified as GFC and were covered or partially covered by glaciers during the LIA (Table 4). On the other rock glaciers, which are TC, considering the uncertainties, there were no negative mean surface elevation changes or volume changes measurable in the first epoch. For RG02, RG05 and RG07 they only occured in the last epoch between

2012 and 2017 and ranged from -0.015 m/yr ± 0.001 m/yr (RG05) to -0.003 m/yr ± 0.001 m/yr (RG07). Whereas for RG06 and RG08, these already became increasingly negative from the epoch 1970 - 2006 onwards and in the last epoch showed

890   values of -0.032 m/yr ± 0.001 m/yr (RG06) and -0.017 m/yr ± 0.001 m/yr (RG08).

The investigated rock glaciers differed not only in their temporal development but also in the magnitude of the change in surface elevation. RG01 and RG04 showed similar and very high values, and RG06, RG08 and RG 09 were in a similar, middle of the range. RG02, RG05 and RG07 showed values close to zero, with the exception of RG05 which had clearly negative values in the most recent epoch (Fig. 9). Figure 10 shows the spatial patterns of the surface changes of the rock glaciers and

895   their temporal development. It can be seen that for a large part of the rock glaciers the spatial patterns of positive and negative surface change remained relatively consistent and the magnitude, mostly of the negative values, increased as time progresses. Exceptions to this spatial development are RG02, RG05 and RG07, where hardly any significant surface change was measured in the first epoch and therefore a spatial pattern only emerged from 1970/71 onwards.

900   **Figure 9. Mean annual volume change and mean annual surface elevation change of the individual rock glaciers for four epochs between 1953 and 2017. Black error bars give the uncertainty of measurements.**

RG04 only showed negative values of surface elevation change in the upper part in the first epoch, which were measured on the entire rock glacier from the second epoch onwards. Probably the greatest exception in the case of spatial patterns was RG08. After high values of both positive and negative surface elevation change were measured in the terminal area between

905   1953 and 2006, only small negative changes could be observed in this area thereafter. From 1971 onwards, however, the upper part of the rock glacier showed increasingly negative values.

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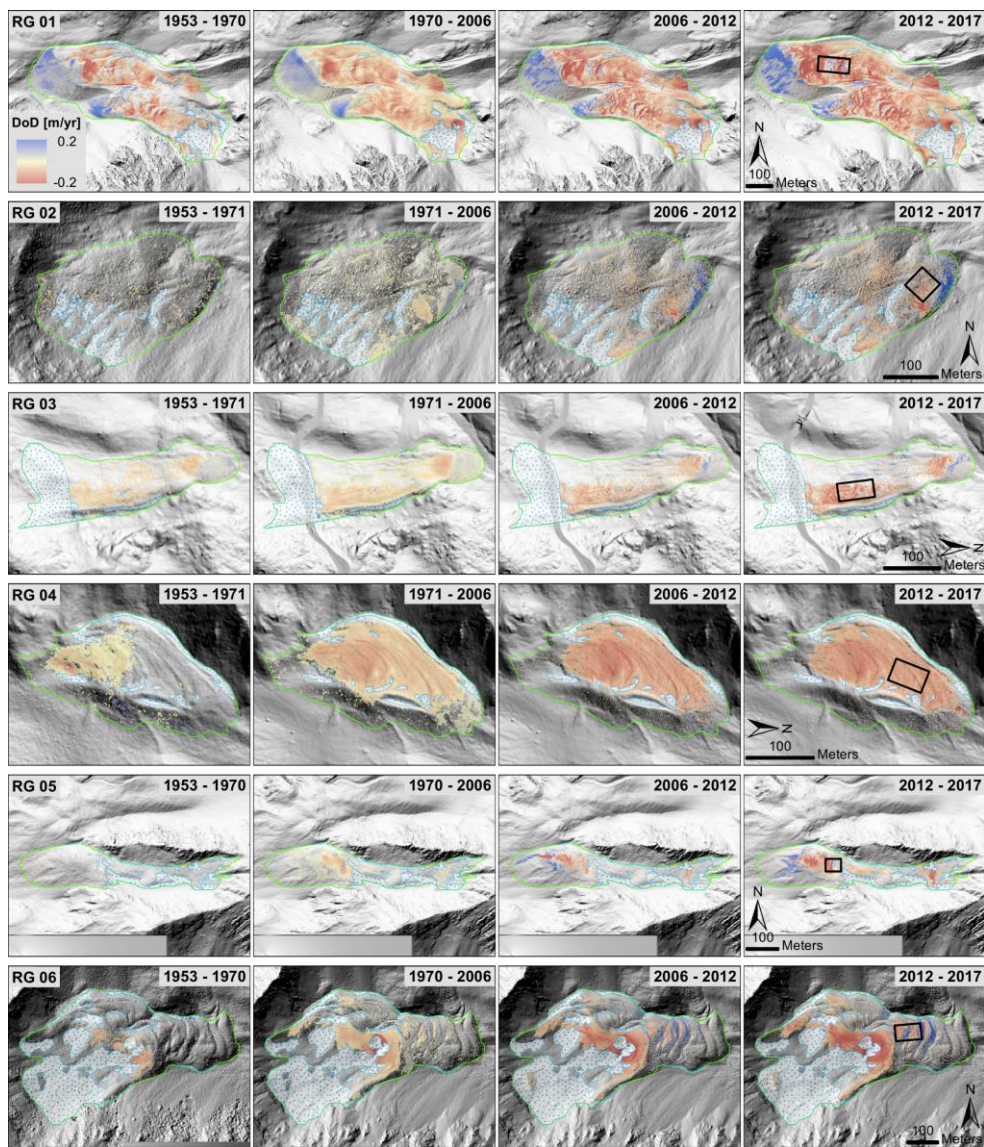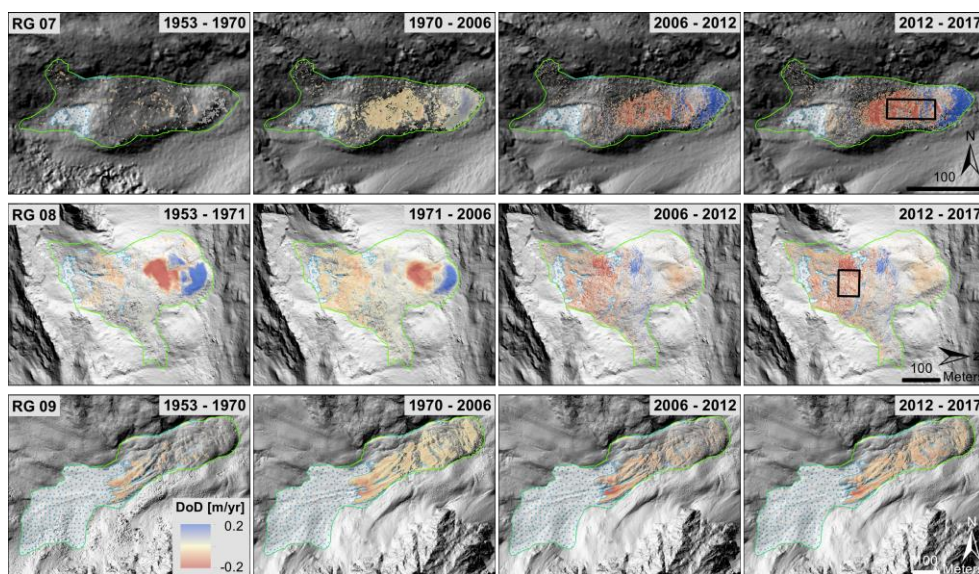
Figure 10. Mean annual surface elevation change maps for all ~~time steps~~ individual rock glaciers and four epochs between 1953 and 2017. A LoD of twice the standard deviation of measurements in stable areas was applied for reasons of visualisation. The background image is a hillshade of the more recent DEM of the epoch. The white area with blue dots represents the snow mask. The black boxes in the maps of epoch 2012 – 2017 represent the respective subareas used for Fig. 11.

4.4~~5.6~~ Interaction of surface elevation change and flow velocity

To be able to relate and compare both the changes in flow velocity and the surface elevation change, we have plotted their mean values for subareas of the individual rock glaciers, which are shown in Fig. 9 (Fig. 10). The subareas were selected according to the following criteria: (1) representative of the rock glacier (2) both surface elevation change and flow velocity measurements available (3) areas above the LoD of flow velocity (4) homogeneous flow velocities (5) no influence of obvious thermokarst deepening. To make the two variables comparable for the entire study period, the epoch division of the surface elevation change analysis, which is not as highly resolved in terms of temporal resolution, was used. Although the general pattern of the previous analysis of the entire rock glaciers of increasing velocities and increasingly negative mean surface elevation change values was confirmed, the subarea analysis showed a slightly different pattern for some rock glaciers in terms of values, magnitude of change and timing of change particularly for the surface elevation changes. This is to be expected due to the spatial heterogeneity and the different temporal development of both the flow velocities and the surface elevation changes on some of the investigated rock glaciers as described in the prvious chapters and illustrated in Fig. 7 and Fig. 10.
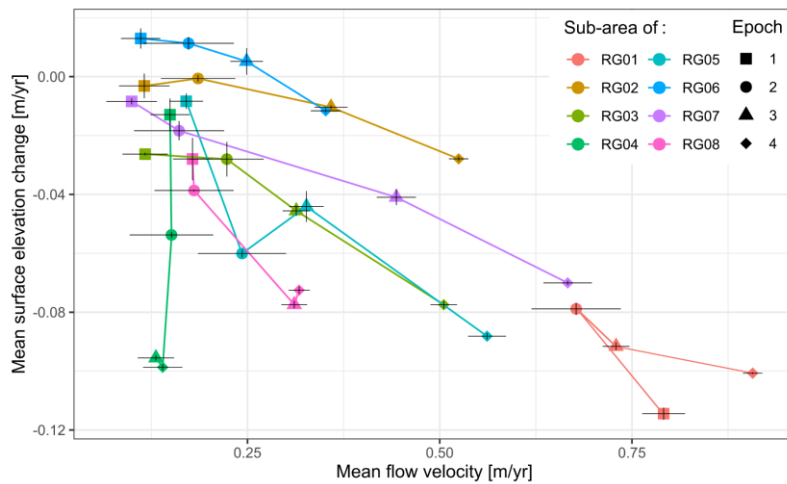
Figure 11. Mean flow velocity plotted against mean surface elevation change for subareas of the investigated rock glaciers and four epochs between 1953 and 2017. The subareas are indicated in Fig. 10.

In the case of the subareas of the rock glaciers RG02, RG03, RG06, RG07 and RG08, the changes tended to be proportional to one another to a certain degree. Although the values of the subareas were obviously different from the mean values of the entire rock glaciers, both showed a similar temporal development. Whereas the values for RG02, RG03, RG06 and RG07 increased significantly in both epochs after 2006, RG08 showed a significant increase in both variables only between the epochs 1970 - 2006 and 2006 - 2012. Rock glaciers RG01, RG04 and RG05 showed a clear deviation from the behaviour described above, since mean surface elevation change and flow velocity did not behave similarly. In addition, the observations in the subareas for RG01 and RG05 also differed from the observations made when considering the entire rock glaciers. RG04 showed no significant change in flow velocity, whereas the surface elevation changes between the 3 epochs between 1953 and 2012 increased significantly. In the case of RG01, the mean surface elevation change showed the most negative value in the epoch 1953 - 1970, to become smaller again after a significant increase between 1970 - 2006. The flow velocity followed this trend, but showed a higher value in the epoch 2012 - 2017 than in the first epoch. RG05, together with RG04, was the only one that showed significantly more negative surface elevation change values from epochs 1 to 2, whereas the flow velocity hardly increased. Between the epochs 2006 - 2012 and 2012 - 2017, the surface elevation changes became significantly more negative and the flow velocity also increased sharply. In summary, in the case of the rock glacier subareas, the change in flow velocity and surface elevation change followed a similar trend. Exceptions to this could be observed in particular on rock glaciers RG04 and RG05.

6. Discussion

6.1 Development of flow velocities in a regional context

The magnitude of the flow velocity of the studied rock glaciers was well within the range of the common movement of a few centimetres per year to a few meters per year over the entire study period (Delaloye et al., 2010). The timing of the acceleration of most rock glaciers in the 1997-2006 epoch also agreed well with other studies that have investigated the kinematics of rock glaciers in the European Alps over a multi-decadal period. All of these studies observed a significant acceleration of flow velocities in the early to late 1990s (Roer et al., 2005; Kellerer-Pirklbauer and Kaufmann, 2012; Micheletti et al., 2015; Scapozza et al., 2014; Hartl et al., 2016; Kaufmann et al., 2018; Kellerer-Pirklbauer and Kaufmann, 2018; Kellerer-Pirklbauer et al., 2018; Kenner et al., 2020). This is not surprising as an almost synchronicity of rock glacier flow velocity on an annual and multi-decadal scale has been ascertained for the European Alps (Delaloye et al., 2008; Delaloye et al., 2010).

Kellerer-Priklbauer and Kaufmann (2012) found values of 150% to 320% for relative changes in mean flow velocities for a similar period of study for three rock glaciers located in the Hohe Tauern Range, Austria. Furthermore, Roer (2005) determined values ranging from 16% to 350% investigating a multitude of rock glaciers located in the Turtmann Valley, Swizerland. Therefore, our value range of 23% to 251%, except for RG04 (-11%) and RG07 (485%), agree well with the previously determined multi-decadal relative velocity increases of rock glaciers. Conversely, rock glacier destabilisation, which is increasingly observed on rock glaciers in recent years (Roer et al., 2008; Scotti et al., 2017; Vivero and Lambiel, 2019; Marcer et al., 2021), could not be identified on any of the studied rock glaciers.

6.2 Atypical development of flow velocities

Although the magnitude of the change spatiotemporally varied both between individual rock glaciers and on different areas of the same rock glacier, the general trends, observed throughout the Alps could be confirmed for most of the studied landforms. On the other hand, a few exhibited special characteristics or an atypical behaviour could be detected. RG 08 is an example of how the lower part of a rock glacier can become inactive. As flow velocities exceeded 1.5 m/yr in 1953-1971 in this area, progressively decreased until 2006 and were close to zero in the two most recent epochs. In the 2006-2017 epoch, a slight subsidence was still visible in this area, with a decreasing trend in the latest epoch. In contrast, as for most of the rock glaciers in our catchment, an acceleration of flow velocities was observed in the upper part of this rock glacier since the epoch 1997-2006. Here, we assume that the topography (terminal part overflowed escarpment and reached low slope valley floor) and altitude of the front of just 2510 m in combination with the separation of the upper part favoured this inactivation.

RG04 showed a clearly atypical temporal course of the flow velocities. These showed low mean values of well below 0.15 m/yr, no acceleration and back creeping-movement in the upper part, which indicates that RG04 is a push-moraine. Constant or even decreasing flow velocities on rock glaciers have also been observed by Roer (2005) on a multidecadal scale. In recent years, for example, the Aget rock glacier, which is also a push-moraine, has followed such a course (PERMOS, 2019). In contrast, RG07 and RG02 showed flow velocities barly above LoD (mean below 0.1 m/yr) in the epochs between 1953 and

445

1997, followed by the strongest proportional acceleration observed in the catchment. Such a behaviour of reactivation has already been described by Michelleti et al. (2015) for a small rock glacier in the Hérens Valley (Switzerland). Beside rock glacier destabilisation, the proportional velocity increase of RG07 of 485% was one of the highest compared to other studies, although its absolute speeds were not particularly high (c.f. Roer, 2005; Kellerer-Pirklbauer and Kaufmann, 2012, 2018; PERMOS, 2019). Since rock glaciers RG 02, RG 07 and RG 04 show similar exposition, size, and elevation ranges, we assume that the different behaviour is explained by a topographic (RG04 has a significantly lower mean slope), structural control (significant volume loss and LIA glacier cover of RG04 indicates high ice content, whereas RG02 and RG07 are TC and with the exception of the most recent epoch, showed no or hardly any volume loss) or change in the mechanisme of flow (creation or reactivation of a sheare zone).

Another atypical development of flow velocities was observed in the case of RG05. Although a slight increase in flow velocity could already be ascertained in the terminal part during the epoch 1997 - 2006, a significant acceleration of whole rock glacier was only observed in the epoch 2012 - 2017. This delayed reaction could be related to the relatively high altitude of the rock glacier (2702 m - 3093 m) in combination with its location between two steep slopes. Although we have no annual data on this, all historical images show avalanche deposition, which have their origin in the steep adjacent slopes, over a large part of the rock glacier area (Fig. 10). This may have prevented effective heat transfer to the permafrost body of the rock glacier during the otherwise snow-free period until the last epoch, and therefore acceleration took place significantly later.

6.3 Possible implications of changes in external forcing for rock glacier flow velocities

Kenner et al. (2017) synthesise findings for external factors controlling rock glacier flow velocity. Accordingly, an increase in the permafrost temperature, which changes the viscosity, hardness, and shear- and crushing strength of the permafrost ice, can thus increase its internal plastic deformation. Another factor would be the increase in water availability and water pressure, which reduces the friction resistance in the shear zone. The former is primarily determined by changes in air temperature leading to changes in ground temperature and the timing and duration of snow cover. The latter can be controlled by precipitation, snowmelt, the formation of new drainage systems and melting permafrost ice. As our analysis covers periods of 5 to 17 years, it is difficult to identify individual meteorological factors that cause changes in rock glacier morphodynamics, as possible influences and reactions superimpose. In addition, in situ measurements of permafrost temperature, water availability and the formation of new drainage systems were not the goal of this study. Nevertheless, the following sections describe possible implications of changes in the meteorological forcing (see Sect. 4.2) based on the development of the flow velocity for the six epochs between 1953 and 2017 (Fig. 6).

4.4Kenner et al. (2017) synthesise findings for external factors controlling rock glacier flow velocity. According to them, an increase in the permafrost temperature, which changes the viscosity, hardness, and shear- and crushing strength of the permafrost ice, can thus increase its internal plastic deformation. Another factor would be the increase in water availability and water pressure, which reduces the friction resistance in the shear zone. The former is primarily determined by changes in air temperature leading to changes in ground temperature and the timing and duration of snow cover. The latter can be

controlled by precipitation, snowmelt, the formation of new drainage systems and melting permafrost ice. The following sections describe possible implications of changes in the meteorological forcing (Sect. 5.3) based on the development of the flow velocity for the six epochs between 1953 and 2017 (Sect. 5.4).

6.3.1 Temperature

As described by numerous studies, the development of temperatures, in particular ground surface temperatures, fits well with the development of flow velocities (e.g. Roer, 2005; Kääb et al., 2007; Delaloye et al., 2010; Scapozza et al., 2014; Hartl et al., 2016; Kenner et al., 2017; Kenner et al., 2020). Even though not covered in Fig. 12, we observed exclusively positive temperature anomalies ranging between 0.5 °C and 1°C between 1946-1951. Relatively warm temperatures were measured throughout the Alps during this period (Beniston, 2006). This could be a possible explanation for the local peak in flow velocities of RG01 and RG08 between 1953 and 1971. This phenomenon has also been observed in the Austrian Alps by Kellerer-Pirklbauer and Kaufmann (2012) and Kellerer-Pirklbauer et al. (2018) and for the Swiss Alps by Kenner et al. (2020) and is explained by decennial variations in mean annual air temperature (Delaloye et al., 2010). Since only the two rock glaciers that are located at the lowest elevation showed this reaction, this might indicate that the remaining rock glaciers have not yet reached a certain system state and have therefore hardly or not at all reacted to the increased temperatures of this period.

Looking at the strong increase in flow velocities from 1997 onwards, it appears that mainly spring and summer temperatures were likely to be responsible for the increase, as the average winter temperature actually decreased and the mean autumn temperature remained constant in the case of the sharp increase in the epoch 1997-2006. This is also supported by the fact that years with exceptional high positive winter anomalies between 1982 and 1997 did not lead to an increase in flow velocities on the studied rock glaciers. As the positive spring and summer anomalies already began in the first half of the epoch 1982-1997, while a sharp increase in flow velocities was only evident from 1997 onwards, it shows that the increase in flow velocity, if simply controlled by temperature, is slightly delayed. This might be due to a delayed warming of the permafrost ice or to the duration of the formation of new drainage systems (Kenner et al., 2017; Kenner et al., 2020), which also might explain the varying magnitude of the increases. The local peak of some rock glaciers between 1997 and 2006 could be explained by the particularly strong increase in spring temperatures or by the heatwave in the summer of 2003, which has also led to flow velocity peaks in annual studies (e.g. Kellerer-Pirklbauer and Kaufmann, 2012, 2018; PERMOS, 2019). The further increase in flow velocities in the epoch 2012-2017 could be due to the fact that, in addition to spring and summer temperatures, winter and autumn temperatures also showed exclusively positive anomalies in this time step. The low, otherwise constant or falling flow velocities in the period 1970/71 to 1982, on the other hand, fit in well with the relatively low summer and autumn temperatures.

As described by numerous studies, this development of temperatures fits well with the development of flow velocities (e.g. Roer, 2005; Kääb et al., 2007; Delaloye et al., 2010; Scapozza et al., 2014; Hartl et al., 2016; Kenner et al., 2017; Kenner et al., 2020). Even though our rock glacier analysis started with the aerial images from 1953, we had a look at temperature data before this date since rock glacier dynamics can have a significant temporal delay. Although not covered in Fig. 4, we observed

447

1050 ~~exclusively positive temperature anomalies ranging between 0.5 °C and 1°C between 1946-1951. Relatively warm temperatures were measured throughout the Alps during this period (Beniston, 2006). This could be a possible explanation for the local peak in flow velocities of RG 01 and RG 08 between 1953 and 1971 and is also suggested as an explanation by Delaloye et al. (2010). However, this would also imply either that these rock glaciers take longer to react to the increase in temperature or that they take longer to slow down after this increase compared to the other rock glaciers studied. It could also~~
1055 ~~indicate that the remaining rock glaciers have not yet reached a certain system state and have therefore hardly or not at all reacted to the increased temperatures of this period.~~

~~When looking at the strong increase in flow velocities from 1997 onwards, it turns out that the spring and autumn temperatures may primarily be responsible for the increase, as the average winter time temperature actually decreases and the autumn mean temperature remains constant in the case of the sharp increase in the epoch 1997-2006. This is also supported by the fact that~~
1060 ~~period of high positive winter anomalies between 1982 and 1997 did not lead to an increase in flow velocities. As the positive spring and summer anomalies already began in the first half of the epoch 1982-1997, while a sharp increase in flow velocities is only evident from 1997 onwards, it shows that the increase in flow velocity, if simply controlled by temperature, is slightly delayed.~~
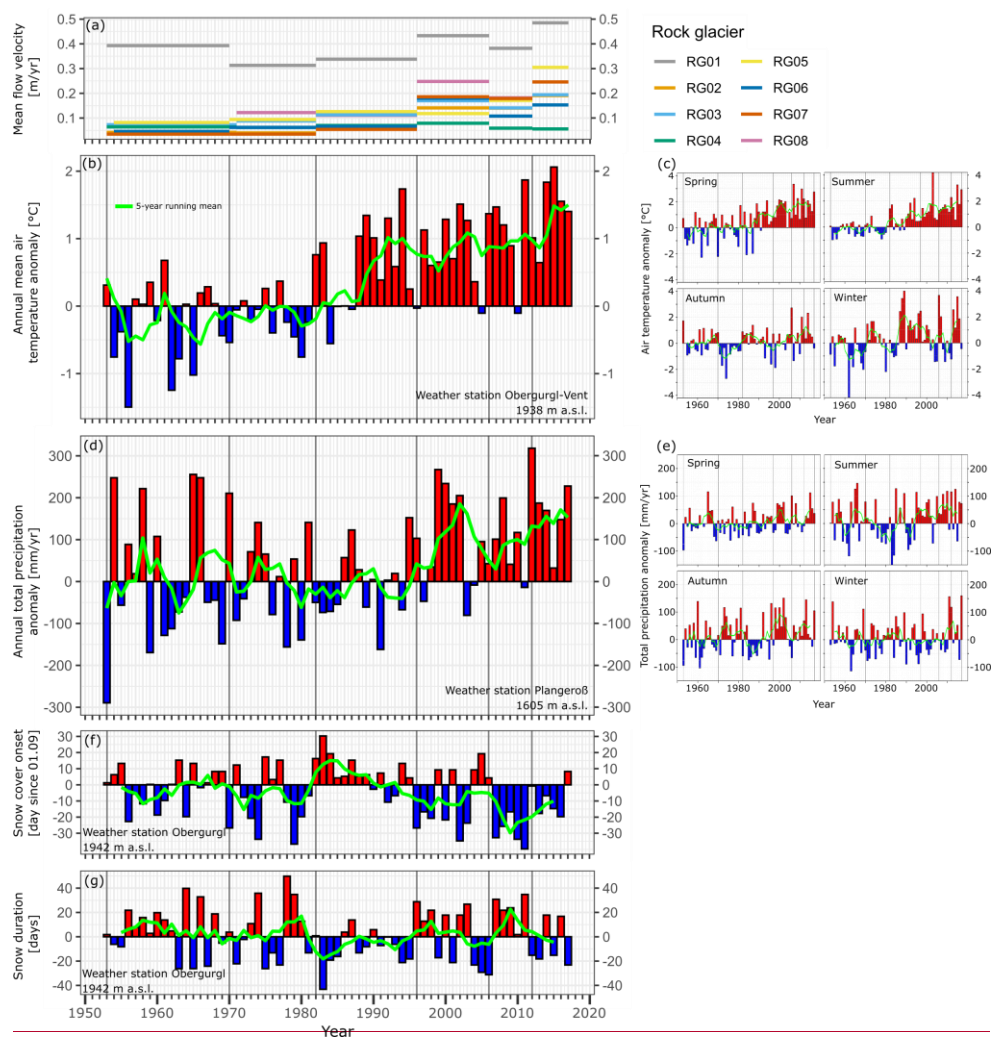
Figure 6.6.3 (a) Mean flow velocities of individual rock glaciers for six epochs between 1953 and 2017. (b) Annual mean air temperature anomalies and (c) seasonal mean air temperatur anomalies at the weather station Obergurgl-Vent (1938 m a.s.l.). (d) Annual total precipitation anomalies and (e) seasonal total precipitation anomalies at the weather station Plangeroß (1605 m a.s.l.).

(f) Snow cover onset and (g) duration at the weather station Obergurgl (1942 m a.s.l.). For (c) and (e) spring is defined as March-May, summer as June-August, autumn as September-November and winter as December-Februry.

1070   This could be due to a delayed warming of the permafrost ice or to the duration of the formation of new drainage systems (Kenner et al., 2017; Kenner et al., 2020), which also might explain the varying magnitude of the increases. The local peak of some rock glaciers between 1997 and 2006 could be explained by the particularly strong increase in spring temperatures or by the heatwave in the summer of 2003, which has also led to very high flow velocity rates in annual studies (e.g.Kellerer-Pirklbauer and Kaufmann, 2012, 2018). The further increase in flow velocities in the epoch 2012-2017 could be due to the fact

1075   that, in addition to spring and summer temperatures, winter and autumn temperatures also show exclusively positive anomalies in this time step. The low, otherwise constant or falling flow velocities in the period 1970/71 to 1982, on the other hand, fit in well with the relatively low summer and autumn temperatures.

4.4.2 Precipitation

While many studies, especially recent ones, emphasise the role of liquid water in rock glacier movement (Ikeda et al., 2008),
1080   especially in the shear horizon (Kenner et al., 2017; Cicoira et al., 2019; Kenner et al., 2020), only some show a correlation between precipitation and movement (Micheletti et al., 2015; Hartl et al., 2016; Eriksen et al., 2018), while others find no or only a weak connection (Kenner et al., 2017; Kenner et al., 2020). Kenner et al. (2020) give an increase in runoff efficiency, due to the formation of new drainage pathways in the permafrost body, as a main reason for the observed acceleration.

In our study, the development of flow velocities also corresponded well with the development of precipitation. In the epoch
1085   from 1953 to 1997, no clear accumulation of positive or negative anomalies can be observed in the individual time steps. In case of the epoch 1971 to 1997, the negative summer anomalies were balanced out by positive autumn anomalies and vice versa. In the epoch from 1997 to 2006 and between 2012 and 2017, positive precipitation anomalies occured for spring as well as for summer and autumn. This did not apply to the epoch from 2006 to 2012, where only positive summer anomalies were increasingly observed. As this development fits in well with the determined flow velocities the availability of water by liquid
1090   precipitation might influence acceleration in our catchment, as suggested by Micheletti et al. (2015) for rock glaciers in the Hérens Valley (Switzerland).
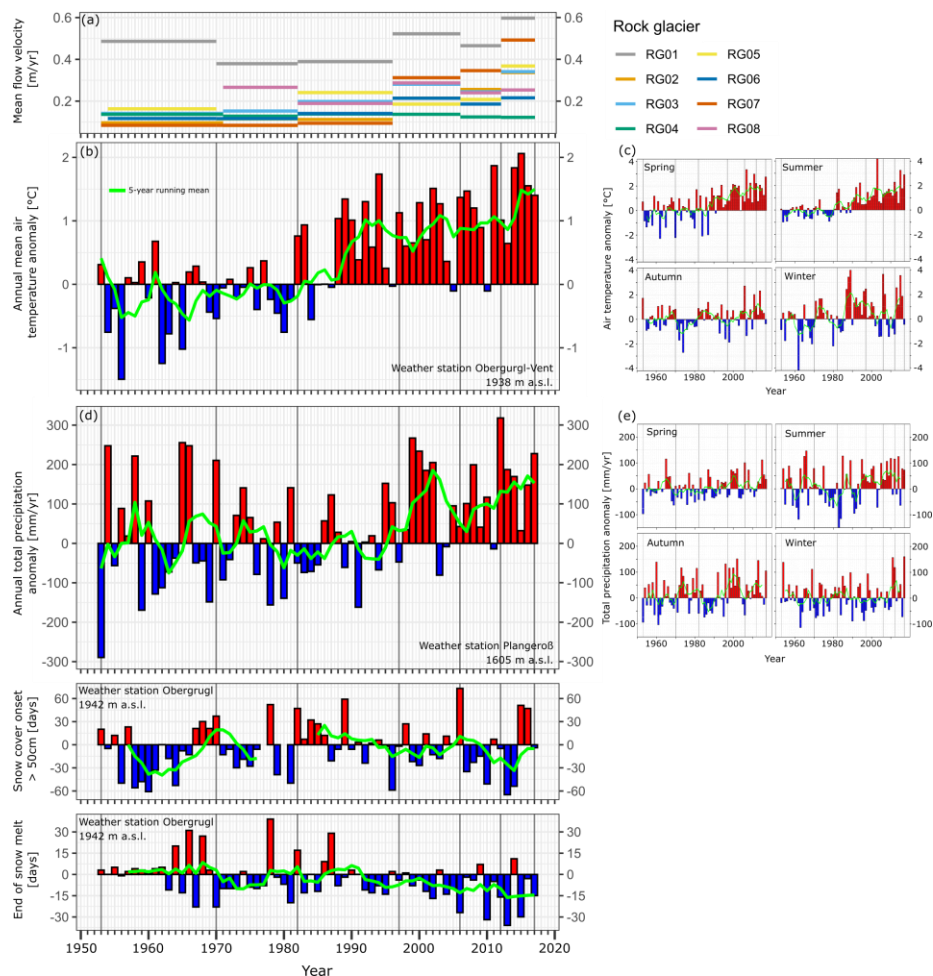
Figure 12. (a) Mean flow velocities of individual rock glaciers for six epochs between 1953 and 2017. (b) Annual mean air temperature anomalies and (c) seasonal mean air temperature anomalies at the weather station Obergurgl-Vent (1938 m a.s.l.). (d) Annual total precipitation anomalies and (e) seasonal total precipitation anomalies at the weather station Plangeroß (1605 m a.s.l.). While many studies, especially recent ones, emphasise the role of liquid water in rock glacier movement (Ikeda et al., 2008), especially in the shear horizon (e.g.Kenner et al., 2017; Cicoira et al., 2019a; Kenner et al., 2020), only some show

451

a correlation between precipitation and movement (Micheletti et al., 2015; Hartl et al., 2016; Eriksen et al., 2018), while others find no or only a weak connection (Kenner et al., 2017; Kenner et al., 2020). In the latter, rock glacier acceleration is explained, among other things, by an increase in runoff efficiency due to the formation of new drainage pathways in the permafrost body. **In our study, the development of flow velocities also corresponds well with the development of precipitation.(f) Onset of a significant snow cover (> 50 cm) (g) end of snow melt at the station Obergurgl (1942 m a.s.l.). For (c) and (e) spring is defined as March-May, summer as June-August, autumn as September-November and winter as December-February. The reference period for the anomaly calculations is 1961 – 1990.**

6 In the epoch from 1953 to 1997, no clear accumulation of positive or negative anomalies can be observed in the individual time steps. In case of the epoch 1971 to 1997, the negative summer anomalies are balanced out by positive autumn anomalies and vice versa. In the epoch from 1997 to 2006 and between 2012 and 2017, positive precipitation anomalies occur for spring as well as for summer and autumn. This does not apply to the epoch from 2006 to 2012, where only positive summer anomalies are increasingly observed. This fits in very well with the determined flow velocities and could be a further explanation for the strong increase from 1997 to 2006, a constant or slight drop between 2006 and 2012 and a renewed increase from 2012 to 2017.

4.4.3.4 Snow Cover

Snow cover onset and duration have been shown to be important factors in the development of rock glacier flow velocities, as it controls the time span of liquid water availability as well as the temperature in the subsurface due to the winter cooling intensity (Kenner et al., 2017; Kenner et al., 2020). As for the other two parameters, temperature and precipitation, links can be found between the temporal development of snow cover onset and duration and the evolution of flow velocities in the rock glaciers studied. In the last three epochs from 1997 to 2017, the snow cover sets in relatively early. In combination with the amount of snow and the temperature, this can decrease the rock glacier deceleration in winter, by isolating the rock glacier from cold winter temperatures, which in turn favours warming in spring and summer. This could have led to an increase in the flow velocity, especially in the most recent time period, since in addition to the early onset of the snow cover, only positive temperature anomalies occur in autumn. The decrease or constant flow rate in the 2006- 2012 epoch could be explained by the relatively long duration of the snow cover, which leads to a shorter availability of liquid water. In the period before 1997, it is more difficult to establish a connection. This may be due to the fact that the time periods are larger and thus positive and negative anomalies balance each other out, but possibly also to the fact that the factor snow cover must always be seen in connection with the temperature, which only changed drastically from the beginning of the 1990s. This possibly has led to the formation of new drainage systems, causing a tipping point of flow velocities to a higher level, which in turn might change the value on the influence of the snow cover and precipitation on the flow velocities.
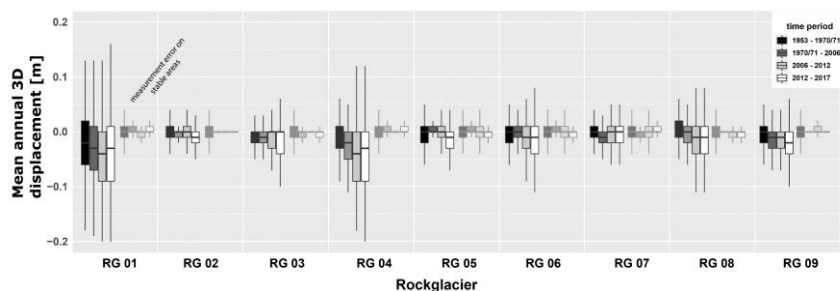
Figure 7. Mean annual 3D displacements on the single rock glaciers and corresponding stable areas for the four epochs.

The calculation of the mean annual 3D displacements could be carried out on a total of 9 rock glaciers in four epochs. Figure 7 shows the values of these 3D displacements on the rock glaciers and additionally the values calculated on stable areas, in 1135 order to give an estimation of the accuracy of the measurements. The mean values range from 0.031 (RG 05, epoch 1970-2006) to -0.047 (RG 04, epoch 2006-2012). In the entire study period, the values are predominantly in the negative range, with only 4 rock glaciers showing positive values very close to zero. These values are in good agreement in terms of their order of magnitude with Kellerer-Pirklbauer & Kaufmann (2018) and Kaufmann et al. (2018), who found values of -0.016 m/yr to -0.058 m/yr and 0.0008 m/yr to 0.013 m/yr for two rock glaciers in the Austrian Alps over a similar study period. For most rock 1140 glaciers, except RG01 and RG 04, the mean values of the 3D displacements in the first epoch are very close to zero and show a sharp shift to the negative in the epoch 1970/71-2006 or 2006-2012. It is clearly visible that almost all rock glaciers show a scattering of the 3D displacements in the negative and the positive range. This scattering can be explained by the flowing movements and the resulting complex topography of migrating ridges and associated depressions on the one hand and the partial "pushing forward" of the entire rock glaciers on the other. Over time, there is a clear tendency towards negative values, 1145 which is also visible in the mass balances of the individual rock glaciers (Fig. 8). Those are decreasing constantly, suggesting a successive subsidence of the landforms. Differences appear in the investigated rock glaciers with respect to the magnitude of the 3D displacements. This is particularly evident in rock glaciers RG 01 and RG 04, where both the mean values and the scatter are significantly more pronounced compared to the others, especially for the epochs since 2006. Both rock glaciers differ with respect to size, slope, spanned altitudinal zones and relief, so that these parameters do not seem to be causal for this 1150 behavior. In contrast, the other rock glaciers show more or less similar scatter and similar magnitudes of 3D displacements. Also with regard to the temporal course, the rock glaciers cannot be divided into different subgroups. Here, one main group exists, consisting of RG 01 and RG 03 to RG 09. Those show a constant increase in the dispersion of 3D displacements with a clearly visible shift of the mean value into the negative range. The values tend to increase from 1953 to 2012 and in the epoch

2012 to 2017 remain roughly at the level of the epoch from 2006 to 2012 or decrease slightly. An exception is RG 02, which shows 3D displacements between 1953 and 2012 that scatter very close around zero with a slightly negative trend in the second epoch between 1970/71 and 2006. Overall, however, the changes are within the range of changes on the associated stable surfaces, so that actual 3D displacements cannot clearly be assumed here. Only for the last epoch of the study period from 2012 to 2017, a clear shift of the 3D displacements into the negative range is visible. Even if these changes are on a low level, it can be assumed that RG 02 changes significantly later in time than the other rock glaciers.
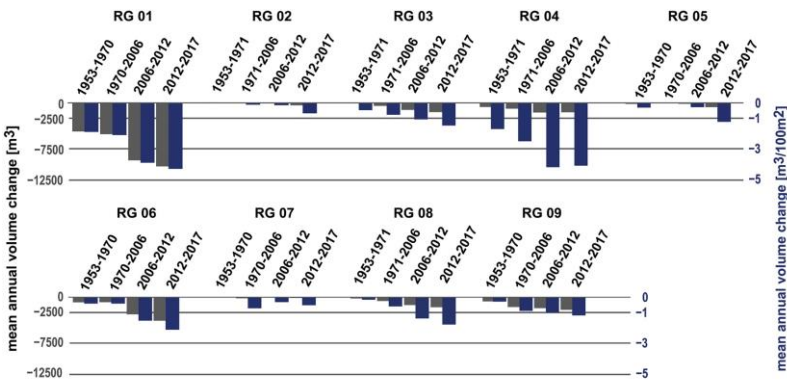
Figure 8: Volume change of the individual rock glaciers for four epochs between 1953 and 2017.

4.5.2 Temporal and spatial trends of the single rock glaciers

To better place the general trends in a spatial and temporal context, 3D displacements in individual epochs were analyzed for individual elevation zones. Figure 9 shows the measured 3D displacements in the individual epochs for 20 m elevation zones along the rock glacier surface and the corresponding maps. In addition, based on the maximum extent of each rock glacier, the volume change within each epoch was calculated. The data show that the individual rock glaciers span different elevation levels and that some of the studied objects have very different sizes. Within each rock glacier, there are zones of positive 3D displacements as well as areas of negative change. These changes are mostly spatially clustered, but in some cases they also show a clear temporal clustering.

Overall, the picture already described for the general trends is confirmed. Thus, all rock glaciers show a very clear dispersion of 3D displacements into the positive and into the negative value range. The fact that this scattering can be explained by the movement of the rock glacier becomes very clear when looking at the spatial patterns on the maps. Thus, areas with negative changes are followed by positive changes downslope. Therefore, the characteristic topography for rock glaciers is formed (Frehner et al., 2015) or the rock glacier advances. Furthermore, Fig. 7 and Fig. 9 show that changes in activity occur between

the individual epochs. These changes in activity correspond to the general trends already described, but are again spatially more finely resolved in Figure 9. This change between epochs is particularly clear in RG 08. Thus, after a high activity phase in the area of the front of the rock glacier in the first two epochs, these zones become almost inactive in the epochs after 2006 (only subsidence are still visible later). On the other hand, RG 02 and RG 07 show hardly any 3D displacements in the epochs before 1970 and 2006, respectively, and show subsidence thereupon (c.f. Sect. 4.6.2).

Nevertheless, the trend towards stronger negative 3D displacements is also confirmed for the other rock glaciers. Here, spatial patterns also exist, suggesting that active and inactive areas are shifting, but a clear elevation dependence is not apparent. The shift in patterns is apparently more due to the dynamics of the individual rock glaciers and less a consequence of elevation. An exception is RG 05, whose rock glacier area extends over a large altitudinal range and whose highest areas are above 3000 m. Here, areas exist that apparently show very clear activity in terms of subsidence only in the last two epochs starting in 2006. This fits well with the statements about flow velocities, but a general altitude-dependent trend in the rock glaciers cannot be derived from the 3D displacement data.

Looking at the absolute volume change in the individual epochs, it becomes clear that all rock glaciers show negative volume balances in almost all epochs. Exceptions here are RG 02 and RG 07, which show almost no volume loss in the first epoch, and RG 05, for which this was the case in the second epoch. Overall, however, the negative volume changes increase very significantly from epoch to epoch. This trend is almost linear for the rock glaciers RG 02, RG 03, RG 06, RG 08, RG 09, but with different characteristics. RG 01 as the largest rock glacier also shows the highest volume changes overall, although a jump in the magnitude of the volume changes can be identified here after the second epoch. RG 04, on the other hand, shows a linear trend from the first to the third epoch, which then reverses from 2012 onwards.

A temporal outlook is not possible since none of the rock glaciers became completely inactive during the observation period and could be used as a reference. Rather, some of the rock glaciers have shown that an inactive phase can be followed by more active phases. An exception may be at RG 04, where a reversal of the trend in volume changes is visible after 2012, which could indicate that here the ice body could thaw in the medium term and thus the rock glacier could become inactive.

A better picture regarding trends would be obtained if the analysis of 3D displacements were combined with the analysis of movement rates. This would allow conclusions to be made as to whether rock glaciers tend to successively sink, followed by a decrease in velocity or whether subsidence is in line with velocities. This synopsis will be done in the following chapter.

456

small rock glacier in the Hérens Valley (Switzerland). In our view, the large changes in the flow velocity of RG 02 and RG 07 can be seen as a reactivation, although flow patterns on the rock glacier surface suggest that flow velocity before 1997 was probably just too small to be detected by our method. The sudden and sharp change might indicate a change in the internal
1240 structure of the rock glacier system and mechanism of flow.

4.6.3 Thermokarst phenomena

Thermokarst is a widespread phenomenon in periglacial landscapes, and such thermokarst depressions can sometimes be filled with water forming lakes (Soare, 2021). This might become a more common feature on rock glaciers due to warming and degradation of permafrost which favours the formation of such depressions also in alpine terrain (Kääb and Haeberli, 2001).
1245 Thermokarst depressions can be observed on RG 04 and particularly on RG 06. Here, in the course of the observation period since 1953, a thermokarst lake developed, which subsequently changed in extent and shape and shifted its location by about 40 m, meaning that this thermokarst depression is part of the moving rock glacier system.
These thermokarst depressions are not only characterised by severe subsidence, but also affect the flow velocity of the surrounding areas when they occur on active rock glaciers. This is evident on RG 06, where high flow velocities were measured
1250 in the area above and below the thermokarst lake during the entire study period and especially from 1997 onwards. This phenomenon can also be observed on RG 04 where a hot spot of higher flow velocities is found around a thermokarst depression, which decrease since 1997. Here, displacements directions are measured contrary to the main flow direction towards the depression, a phenomenon also described in Kellerer-Pirklbauer and Kaufmann (2018).
This indicates that the more efficient heat conduction also in deeper permafrost layers through the depression in combination
1255 with the sinking motion and the liquid water, released by the strong melting of the permafrost leads to an increase in the flow velocities in such areas. In the case of RG 06, the thermal influence of the lake water and the intermittent drainage play surely a role in the development of flow velocities especially in the areas below the lake.

4.7 Analysis of velocity and 3D displacements

On the one hand, the movement of the rock glacier body can result in a change in the complex surface topography, as negative
1260 3D displacements are often linked to positive 3D displacements and characteristic flow lobes are formed and/or the rock glacier advances in the area of the front. In the case of flowing rock glaciers in the area of shear surfaces, despite the movement of parts or the whole rock glacier body, there should be no or only a slight volume changes of the rock glacier. On the other hand, the movement of a rock glacier can also be the consequence of melting of the ice body or the pore ice. If such melting zones are at zones with higher slope inclinations, the rock glacier tends to both move and subside, but with a tendency to a
1265 negative volume balance. If slope inclinations are low, the rock glacier tends to subside with no or only slight movement, which also leads to a negative volume balance. Therefore, it seems reasonable to analyze flow velocities and 3D displacements together, as such an analysis can provide clues to the system state of a rock glacier and regarding a multi-temporal analysis possibly the trends in its behavior.

Thus we plotted the mean values of the 3D displacements against the mean values of the flow velocities, where the scatter of the data is represented by the circles and ellipses (Fig. 10). For this analysis, data from the 1953-1970/71, 1970/71-2006, 2006-2012, and 2012-2017 epochs were used in order to make changes of this interaction over the entire study period visible. From the analyses of flow velocities and 3D displacements in the previous chapters, it was expected that a majority of the rock glaciers would have overall flow velocities and 3D displacements of a similar magnitude. This was also expected for the relationship between flow velocity and 3D displacements. Both are visible in Fig. 10 for RG 02-RG 07. Exceptions are RG 01 and RG 04, which show complete different magnitude as well as a different relationship between velocity and 3D displacements compared to the other rock glaciers.
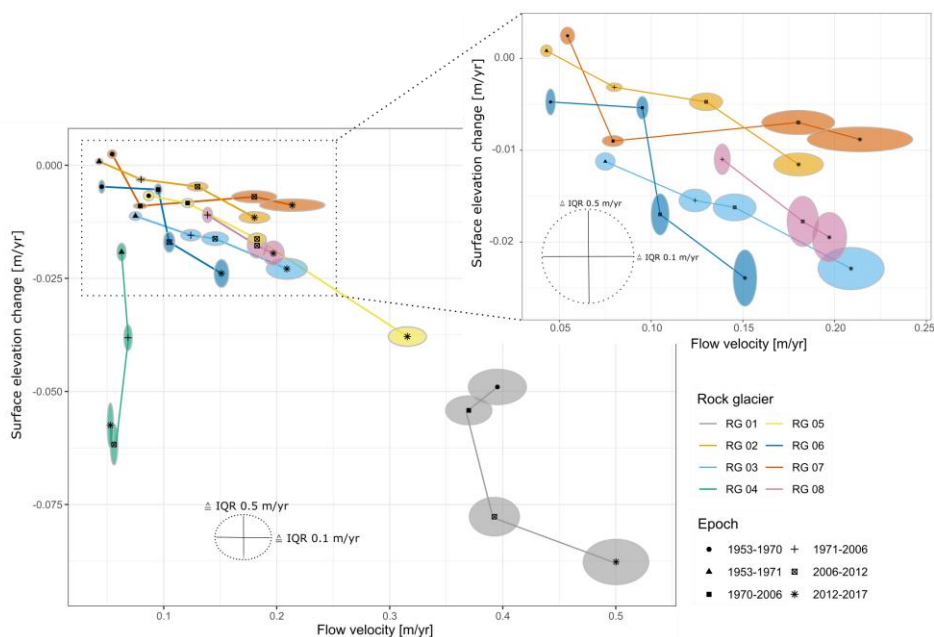
Figure 10: Flow velocity rates plotted against 3D displacement rates. (a) shows all the investigated rock glaciers. (b) shows a subset of rock glaciers displaying a similar value range. The interquantile ranges are shown in scale in the illustrations, which is represented by the dashed ellipses.

While RG 01 as the largest rock glacier of the catchment shows the highest velocities and the highest 3D displacements at all, RG 04 shows no or only a slight velocity, but very high 3D displacements. It is very obvious that in the case of RG 04 thawing permafrost is involved and that this thawing has successively increased from 1953 to 2012. Particularly striking then is the

reversing trend in the epoch 2012 to 2017, where the 3D displacements are lower than in the previous epoch, but are still at a higher level than in the epochs between 1953 and 2012. This fits also well with the volume losses in Fig. 10. The changes in flow velocities, on the other hand, are minimal and move along the zero value with very little scatter, which fits very well with the low slope gradients (20°) in the area of this rock glacier, which probably prevent movement of the rock glacier despite thawing permafrost. Although it remains to be seen whether the emerging trend will continue since 2017, a successive inactivation of this rock glacier seems to be very likely due to the available data and the visible trend.

A different behaviour is visible for RG 01, as this rock glacier shows only slight changes in the flow velocities in the first three epochs (slight decrease between 1970-2006), but a clear increase in negative 3D displacements between 2006 and 2012. This clear increase was already noted in Sect. 4.5.2 as a jump in magnitude after the second epoch, but this jump is not directly linked to a jump in flow velocities. This jump has obviously a delay, as it only becomes visible in the last epoch between 2012 and 2017. Both, the significant jump in magnitude as well as the delay could be the consequence of the changes in the above described external forcing in combination with the known ice body of the rock glacier (Hausmann et al., 2012). It seems that the external forcing leads to a significant melting of the permafrost body, which "stimulates" the rock glaciers to increase the flow velocity. In this context it would be very interesting, if, in which way and in which magnitude the ice body changed since the studies of Hausmann et al. (2012) which did their geophysical field surveys in 2002 and 2007 and thus right before the strong increase in 3D displacements since 2006 and the strong increase in flow velocity since 2012.

Regarding the other rock glaciers, we have included a zoomed section of the diagram for better visibility (Fig. 10b). The graph clearly shows that there are differences between the individual rock glaciers in this area. RG 02, RG 03, RG 05 and RG 08 show a tendency towards increasing flow velocities and increasing negative 3D displacements, which is also reflected in a clearly visible increase in the scattering both in terms of 3D displacements and in terms of flow velocities. Here, neither the mean ratio nor the ratio in the scatter (shape of the circles and ellipses) between flow velocity and 3D displacement seems to change visibly. But there are differences between the rock glaciers in terms of the first epoch as well as in terms of temporal changes. While the trend regarding the relation between 3D displacements and velocity seems to be constant for all three rock glaciers, the temporal course of changes is quite different. While the temporal change for RG 02 and RG 05 is relatively constant and shows only minor activity in the first epoch, RG 05 shows a much greater increase in terms of velocity and 3D displacements compared to the other rock glaciers. Phases with significantly increased activity and phases with only slightly increased activity alternate for RG 03 and RG 08 with an already existing activity in the first epoch of RG 08 and minor activity of RG 03. This alternation, in the case of RG 03, is the consequence of the delayed response to road construction (c.f. Sect. 4.6.1). In the case of RG 08, it is a shifting of activity zones from the area of the tongue to the upper part of the rock glacier, with some time lag between these activity phases, with only a slight increase in 3D displacements and velocity in the third epoch.

RG 06 and RG 07 do not show a stable relationship between 3D displacements and velocity over the study period. RG 07 indicates a clear increase in velocity in the second epoch, which is also accompanied by a negative 3D displacement. After the second epoch, the rock glacier appears to accelerate, but this acceleration is not associated with an increased 3D displacement;

460

rather, they decrease or remain at about the same level. Here, it appears to have been an activation (or reactivation) of the rock glacier in the second epoch, causing the system to move and the rock glacier to advance overall, resulting in an overall decrease in volume loss after a period of higher volume loss in epoch 2. RG 06 shows an increase in velocity in epoch 2, which is not accompanied by higher 3D displacements. In the third epoch, the 3D displacements increased with only a slight increase in velocity. The increase in 3D displacements hold on in the epoch between 2012 and 2017, but is accompanied by an increase in velocity. It is very likely that this temporal behaviour is the consequence of a thermokarst phenomenon including the appearance of a lake (c.f. Sect. 4.6.3). This lake indicates the melting of permafrost in the third epoch and the following activation of this part of the rock glacier regarding flow velocity, probably due to the heat transfer by the water and the building of subsurface flow routes.

In summary, the temporal decoupling of vertical and horizontal movements observed by Ulrich et al. (2021) over a seasonal period can also be observed over a longer period for some rock glaciers. This indicates that both processes have a different sensibility to external forcing parameters, are governed by different external forcing parameters or have a varying time lag.

5The onset and duration of snow cover have been shown to be important factors for the development of rock glacier flow velocities, as they control the time span of liquid water availability as well as the temperature in the subsurface due to the winter cooling intensity (Kenner et al., 2017; Kenner et al., 2020). As for the other two parameters, temperature and precipitation, links could be found between the temporal development of snow cover and the evolution of flow velocities in the rock glaciers studied. In the last three epochs from 1997 to 2017 and in the case of significant snow cover (>50 cm) in the last two epochs between 2006 - 2017, the snow cover set in relatively early. In combination with the amount of snow and the temperature, this could decrease the rock glacier deceleration in winter, by isolating the rock glacier from cold winter temperatures, which in turn favours warming in spring and summer (Wirz et al., 2016). This could have led to an increase in the flow velocity, especially in the most recent time period. This is also suggested as an explanation for the velocity peak in 2015, which was recorded on many rock glaciers in the Alps in annual measurements (PERMOS, 2019). Although we cannot resolve this in terms of temporal resolution, the epoch 2012 - 2017 showed higher values on all rock glaciers than 2006 – 2012 and both winters of 2013/14 and 2014/15 showed a very early development of significant snow cover, although the following winters showed a contrasting development (Fig.12).

Another factor that could be identified from the analysis of snow data is the end of snow melt, which showed a negative trend over the study period and, especially from the beginning of the 1990s, almost exclusively negative anomalies. This is of great importance for the development of the velocity of rock glaciers, as Wirz et al. (2016) show that seasonal rock glacier acceleration coincides with zero curtain during snow melt. Kenner et al. (2020) give the end of active layer freezing and start of snow melt as one of the most important factors controlling rock glacier flow velocities. Therefore, the timing of the end of snow melt in the catchment can be seen as another factor for the acceleration observed.

In the period before 1997, it was more difficult to establish a connection. This may be due to the fact that the time periods were longer and thus positive and negative anomalies balance each other out, but possibly also to the fact that the factor snow cover must always be seen in connection with the temperature, which only changed drastically from the beginning of the

1990s. This possibly led to the formation of new drainage systems, causing a tipping point of flow velocities to a higher level, which in turn might have changed the value on the influence of the snow cover and precipitation on the flow velocities.

6.4 Surface elevation changes in a regional context

The mean surface elevation changes ranged from -0.047 m/yr ± 0.001 m/yr to 0.005 m/yr ± 0.003 m/yr for all rock glaciers during the whole period of investigation. Although, to the best of our knowledge, there are only a few studies that examine surface elevation change and volume change of rock glaciers on a comparable temporal scale, their results are in good agreement with this study in terms of the magnitude of the values. For example, the Hintere Langtalkar rock glacier, located in the Hohe Tauern Range, Austria, which was partially covered by LIA glaciers, showed increasingly negative values between 0.016 m/yr and 0.058 m/yr and a sharp increase in the period 2002 - 2006 (Kellerer-Pirklbauer and Kaufmann, 2018). In terms of temporal development and magnitude, this compares well with RG01 and RG04 of this study.

Kaufmann et al. (2018) derived values of -0.0008 m/yr to -0.013 m/yr for Tschadinhorn rock glacier (Hohe Tauern Range, Austria). Although we found similar values ranges in our study, the temporal development differed, since after an increase in negative values from 1953 - 2009, values very close to zero were recorded in the most recent epoch 2009 - 2015. Whereas for the rock glaciers with comparable value ranges in our study, there was either a steady increase in negative values (RG03, RG06, RG08, RG 09) or values very close to zero followed by a negative surface elevation change in the last epoch between 2012 – 2017 (RG05).

6.5 Interpretation and implications of surface elevation changes

Although an attempt was made to cover the entire area of the rock glaciers by analysing the surface elevation change, snow-covered areas had to be masked out for all epochs in order to increase comparability. Therefore, one cannot speak of a mass balance in the strictest sense, nevertheless, the temporal comparison of the rock glaciers allowed for interpretations to be made. The surface elevation change of rock glaciers reflects the sum of the downslope movement, the strain pattern (compression/extension), compaction, debris input and aggradation/melting of ice. Therefore, surface elevation changes close to zero result either because no significant surface elevation change has occurred (e.g. RG02 1953 - 1971) or because the aforementioned processes that lead to positive and negative changes compensate each other (e.g. RG08 1953 - 1971). The only area of substantial surface elevation gains on most rock glaciers was the front indicating a rock glacier advance or the front of flow bulges, particularly pronounced on RG01 and RG06, which was also largely due to the movement of the rock glacier (Frehner et al., 2015). Major debris mass input onto the rock glacier transport system in the rooting zone of the rock glacier due to larger rockfalls could not be observed. Masking out the patches of snow that often cover the root zones could prevent such detection. These are particularly pronounced on TC rock glaciers RG05, RG06, RG09 and might be an indication of both snow and debris input from avalanches in the rooting zone of these rock glaciers.

Over time, there was a clear tendency towards negative values of varying degrees on the individual rock glaciers, indicating a successive subsidence of the landforms at a rate of only a few cm/yr. Although we could not clearly separate the individual

1385 processes that led to this in this study, we argue that this was mainly due to the melting of ice or loss of pore space/compaction of debris, which clearly outweighed the processes that led to positive changes.

If the negative mean surface elevation changes were mainly due to ice melt, the melt rate increased more and more on a majority of the rock glaciers during the investigated period. It is striking that the TC rock glaciers showed lower melt rates and that the mean surface elevation changes in three cases (RG02, RG05 and RG07) was only significantly negative in the most

1390 recent epoch. In contrast, GFC rock glaciers that were at least partially covered by LIA glaciers showed significantly higher values. As these rock glaciers vary in size, exposure, elevation and slope, we explain this on the one hand by the fact that GFC rock glaciers have no connection with an active feeding mechanism, therefore mass input can just occur by congelation of water. On the other hand, they are characterised by a high ice content and contain large amounts of massive sedimentary ice due to the LIA glacier cover, respectively. This is proven for RG01 (Hausmann et al., 2012) and RG09 (Dusik et al., 2015) by

1395 geophysical investigations and very likely due to the occurrence of thermokarst depressions on RG04 and a thermokarst lake on RG06. On the other hand, the fact that the mean surface elevation change for rock glaciers RG02, RG05 and RG07 was significantly negative only in the last epoch indicated an active feeding mechanism or ice aggregation, a low ice content or efficient isolation of the ice contained. Although the exclusion of the snow-covered areas weakens the validity of the statement to some extent, especially for RG05, RG06 and RG09, many observations indicate that the melt of ice was exceeding the

1400 feeding of the rock glaciers or there is no connection with any active feeding mechanism.

7 Conclusions

~~The aim of this study was to investigate the multi-decadal and catchment wide morphodynamic changes of rock glaciers, based on a spatial analysis and by using high resolution topographic information from aerial images and LiDAR acquisitions. These data were analysed in the context of the climate variability.~~

1405 ~~It could be demonstrated~~We conclude that ~~the approach of~~ the combination of different remote sensing techniques used in this study is well suited for the detection of ~~vertical~~flow velocity and ~~horizontal 3D displacements is well suited to extend the study period~~surface elevation change of rock glaciers back ~~into~~to the mid of the 20th century ~~and thus identify~~. Thus, long-term trends in rock glacier dynamics could be identified and ~~relate them~~linked to climate changes ~~evident~~ over such a long period~~,~~ ~~as the derived changes were above the determined error values.~~ .

1410 As a general result, we were able to demonstrate a significant increase in flow velocities in the epoch 1997 to 2006 and an increase in subsidence to varying degrees over the entire study period. Both observations can be explained by changes in external forcing. The sharp increase especially in spring and summer temperatures since the 1990s ~~leads~~led to a change in the flow properties of the permafrost body due to a warming of the permafrost ice. Although ~~the~~ thawing of the permafrost ice ~~cannot~~could not be distinguished from compaction due to a loss of pore space, trends to negative mass balances suggest a

1415 progressive thaw of the permafrost body throughout the study period~~.~~, which is more pronounced on GFC rock glaciers. Furthermore, the melting of the ice body might create new drainage systems. This results in more water being available to the

system, which is crucial for horizontal movement in shear zones. Flow velocity in this catchment area ~~can~~could also be linked to changes in precipitation pattern, which again governs water availability and the onset and duration of snow cover, which controls the time span of liquid water availability as well as the temperature in the subsurface due to the winter cooling
1420   intensity.

Although we were able to identify a general trend in rock glacier ~~morphodynamics~~kinematics, the catchment wide view also ~~shows~~showed a slightly different response of individual rock glaciers to similar external forcing regarding timing, magnitude and local temporal peaks ~~and the relationship between 3D displacements and flow velocities.~~. No characteristic could be identified that explains the different responses to external forcing over the entire study period. ~~Elevation is suspected to play~~
1425   ~~a role evidenced by some observations, although the investigation of altitudinal zones of the individual rock glaciers did not yield an altitude dependent temporal trend.~~ The different behaviour could be explained by different sensitivity, response or response time of individual rock glaciers to intra-annual, inter-annual or multi-annual fluctuations and changes in external forcing parameters. For some rock glaciers internal structure and topography might explain different reactions, as two rock glaciers of similar size, exposition, elevation and elevation range showed contrasting reactions of ~~inactivation and~~ reactivation
1430   and constant flow velocities.

~~Beside the detection of two rock glaciers showing signs of full or partial inactivation, we were also able to show the influence of thermokarst on rock glaciers. Both phenomena will become more frequent during the 21ˢᵗ century as climate change progresses and permafrost degrades as a result.~~

In addition, we were able to detect a rock glacier which shows an inactivation of its terminal part. By observing the surface
1435   elevation changes of all rock glaciers we conclude that the rates of rock glacier mass transport and volumetric losses of the rock glacier due to ice melt are much higher than debris and ice input, at least in those cases where an almost complete analysis of the entire rock glacier surface was possible. Therefore, the investigated rock glaciers are prone to starvation which will eventually lead to rock glacier inactivation. However, since the current ice content of the rock glaciers is not known and the analysis of future flow rates, melt rates and ice and debris input was not the aim of this study, it is not possible to predict the
1440   timing of this inactivation.

We can also conclude that future ~~investigations~~studies are necessary to better understand the climate forcing on rock glacier morphodynamics. Therefore, the analysis should be transferred to other catchments in order to identify differences and similarities within the Alps. ~~3D displacements~~Surface elevation change and flow velocity analysis should be combined with downscaled reanalysis data to better understand catchment wide differences in external forcing on a longer timescale. If
1445   possible, future studies should combine borehole measurements or geophysical investigation to shed light on the internal structure of rock glaciers and clarify some of the assumptions made in this study and possible explanations of their behavior ~~given in this study~~.

As a ~~last~~final important ~~perspective~~consideration, historical terrestrial images (if available) should be used with monoplotting tools. Mapping on such images would help to shorten the time span of the individual epochs which is crucial to better
1450   differentiate the influence of individual forcing parameters, as it is very likely that there are changes within our analysed

epochs. Beside this, historical terrestrial images would offer the opportunity to expand the analysis back to the 19th century and thus closer to the LIA in order to study an important period in terms of massive system changes in the glacial and periglacial regions of the Alps.

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Appendix

Table A 1: Characteristics of the rock glaciers studied. Permafrost occurrence gives the pseudo-probability of permafrost (Otto et al. 2020). Area covered by 1850 glacier extent is ascertained according to LIA glacier extends (Fischer et al. ,2015) if not specified otherwise.* As described in (Berger et al. 2004); ** as described in (Dusik et al. 2015).

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Rock glacier	RG 01	RG 02	RG 03	RG 04	RG 05	RG 06	RG 07	RG 08	RG 09
Exposition	W	NE	N	NE	W	E	E	N	NE
Area [km²]	0.237	0.058	0.036	0.036	0.059	0.182	0.02	0.088	0.171
Slope [°]	25	26	26	20	31	24	30	30	22

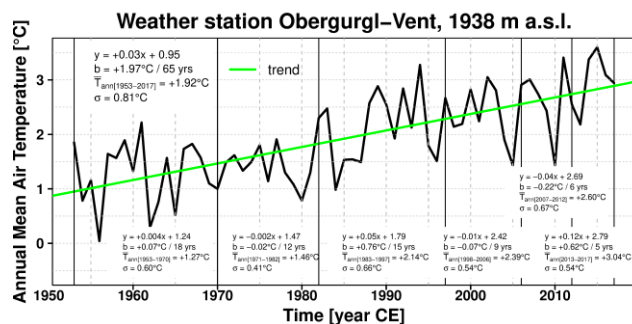
Elevation [m] min	2446	2 615	2596	2 727	2702	2 695	2709	2 510	2627
max	2780	2 755	2787	2 812	3093	2 948	2861	2 761	2925
Permafrost occurrence [%] min	0	0	16.97	0	0	0	0	0	0
max	65.41	57.95	45.68	70.53	76.04	81.42	50.52	60.52	78.57
mean	14.49	33.22	48.99	47.08	48.24	44.04	20.54	38.33	37.57
Connection to the upslope unit	TC; GFC	TC	GC; GFC	GC; GFC	GC; GFC	TC	TC	TC	TC; GFC
Area covered by 1850 glacier extent	Yes*	No	Yes	Yes	No	No	No	No	Yes**

1470

Figure A 3: Snow height, snow cover onset and duration with its trend derived from snow height data of the station Obergurgl (1942 m a.s.l.) for the period 1953 - 2017. Blue lines indicate the epochs of flow velocity measurements

Code ~~availibility~~availability

The image correlation algorithm (IMCORR) is used for the calculation of the rock glacier flow velocities is implemented in the open source geoinformation system SAGA GIS. Furthermore, some modules of the commercial SAGA GIS extension SAGA LIS PRO 3D were used to calculate the ~~3D displacements~~surface elevation change of the rock glaciers. The software which was used to create ~~digiatal~~digital elevation models and orthophotos from historical aerial images was the commercial software Agisoft Metashape.

Data ~~availibility~~availability

The analysed metrological data is ~~availible~~available from the "Federal ~~Misistry~~Ministry of Agriculture, Regions and Tourism" (BMLRT), the "Central Institute for Meteorology and Geodynamics" (ZAMG), the "Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region" (HISTALP), the "Autonomous Province of Bozen/Bolzano" and "Tyrolean Hydropower AG " (TIWAG). The aerial images used to create digital elevation models and ~~orthopotos~~orthophotos are ~~availible~~available from the "Office of the Tyrolean Government-Department of Geoinformation" (https://www.tirol.gv.at/en/) and the "Austrian Federal Office of Surveying and Metrology" (BEV) (https: //www.bev.gv.at). The self-collected ALS data will presumably be made available after completion of the SEHAG ("Sensitivity of High Alpine Geosystems to Climate ~~ChangeSince~~Change Since 1850") research project.

Author Contributions:

Conceptualization, FF, FH and MB; data curation, FF, LP, MA, JR, MP, MS, FH and MW; formal analysis, FF, FH, MP; funding acquisition, MB, FH, TH and NP; investigation, FF, FH; methodology, FF, FH, LP, MP, TH, MA, JR, MS, MW, NP and MB; project administration, MB, FH, TB and NP; supervision, FH, TH and MB; writing—original draft, FF, FH; writing—review and editing, FF, FH, LP, MP, MA, JR, MW, NP. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest:

The authors declare that they have no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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