About the relationship between rock glacier velocity and climate parameters in central Austria

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Abstract

Active rock glaciers are permafrost landforms in high relief terrain moving slowly downward. Despite the fact that the movement of a rock glacier is influenced by site specific factors (e.g. slope, bedrock topography), climate and thereby mainly temperature are of main importance for surface flow velocity and its changes over time. However, establishing statistical significant correlations between climatic parameters and interannual variations in velocity is difficult and was hardly attempted because physical processes linking climate to rock glacier dynamics are complex and act at various spatial and temporal scale. In this study we compared rock glacier velocity data with different climatic parameters at three rock glaciers in the Hohe Tauern Range, Central Austria. Our study is based on annual geodetic field campaigns (maximum time span 1995-2011) with complementary data from aerial photogrammetric measurements covering up to 57 years totally. The three time series are some of the longest for the European Alps, therefore provide valuable insight into rock glacier velocity changes. Furthermore, continuous ground surface (maximum 10 years of data) and near ground-surface temperature (maximum 5 years) from the three rock glaciers, air temperature data from two meteorological stations, and complementary climate data from an official meteorological observatory were used. Results show that rock glacier velocities between the mid-1950s and mid-1990s were lower compared to the period afterwards. Either the time spans 2003-2004 or 2010-2011 was the fastest period with velocities about 1.5 to 3.2 times faster compared to the minimums in the last 57 years. Intercomparison of the three velocity time series showed strong correlations also revealing six different main phases: low velocities in the mid-1990s, faster velocities at the end of the 1990s, low velocities in 1999-2000, steady increase in velocity peaking in 2003-2004, steady deceleration in velocities until 2007-2008, and steady but rather fast increase until 2011. Comparison with air temperature data revealed a time lag of one to more years for acceleration caused by warm air temperatures. In contrast, strong cooling causes a slightly faster deceleration possibly related to the availability of liquid water within the rock glacier. Correlation analysis of rock glacier velocity with 13 different climatic parameters revealed that the interrelationships are complex. Only 13 out of 270 pairs of variables correlated statistically significant. Results showed for instance that a four-times milder winter measured at the ground surface causes an increase in velocity by 1.5 times. In contrast, an only two-times milder winter measured at one meter depth causes also an acceleration of 1.5 times indicating different influences of the temperature at the surface or at one meter depth to velocities. Furthermore, a warming of the mean annual ground temperature at one meter depth by only 1°C from -2°C to -1°C increases velocity by 1.5 times. All three studied rock glacier fronts are close to the local lower limits of permafrost. Therefore, the inversion from velocity increase due to warming of permafrost to decrease due to substantial thawing of permafrost will possibly occur in this century, a plausible hypothesis for many other rock glaciers in Austria.

Über den Zusammenhang zwischen Blockgletscherbewegung und Klimaparametern in Zentralösterreich. Aktive Blockgletscher sind gefrorene Schutt- und Eismassen, welche sich langsam talwärts bewegen. Sie können als Leitform des alpinen Permafrosts angesehen werden. Trotz der Tatsache, dass die Bewegung von Blockgletschern von lokalen Faktoren (wie innerer Aufbau, Hydrogeologie, Neigung, etc.) stark beeinflusst wird, sind es vor allem die klimatischen Bedingungen, welche die Geschwindigkeit und deren Veränderung über die Zeit bestimmen. Statistische Korrelationsanalysen zwischen klimatischen Parametern und Blockgletschergeschwindigkeit wurde bisher kaum versucht, da die physikalischen Prozesse, welche das Klima mit der Blockgletscherdynamik verbindet, komplex wirken und in verschiedenen zeitlichen und räumlichen Skalen wirksam sind. In dieser Studie vergleichen wir Bewegungsdaten von drei verschiedenen Blockgletschern in den Hohen Tauern, Zentralösterreich, sowohl untereinander als auch mit verschiedenen Klimaparametern. Grundlage hierfür sind jährliche geodätische Messungen (maximale Zeitspanne 1995-2011) sowie er-gänzende luftgestützte photogrammetrische Messungen, wodurch insgesamt 57 Jahre berücksichtigt werden konnten. Die hier verwendeten Zeitreihen sind eine der längsten im gesamten Alpenbogen. Des Weiteren wurden Bodenoberflächentemperaturdaten (maximal 10 Jahre Datenreihe) und Bodentemperaturdaten aus einem Meter Tiefe (maximal 5 Jahre) von den Blockgletschern, Lufttemperaturdaten von zwei Klimastationen in den Untersuchungsgebieten sowie Klimadaten von einem offiziellen meteorologischen Observatorium verwendet. Die Bewegungsraten der Blockgletscher waren zwischen Mitte der 1950er Jahre bis Mitte der 1990er Jahre geringer als in den Jahren danach. In den beiden Messjahren 2003-2004 oder 2010-2011 wurden die höchsten Bewegungsbeträge im Zeitraum 1954-2011 gemessen, wobei die Geschwindigkeiten 1,5 bis 3,2 mal höher lagen als in den Jahren mit den geringsten Bewegungsbeträgen. Die Bewegungszeitreihen der drei Blockgletscher korrelieren signifikant positiv und können in die folgenden sechs Bewegungsphasen gegliedert werden: geringe Geschwindigkeiten Mitte der 1990er Jahre, Beschleunigung gegen Ende der 1990er Jahre, geringere Beträge in 1999-2000, stetige Zunahme der Bewegung bis 2003-2004, anschließende stetige Abnahme bis 2007-2008 und letzten Endes stetige, relativ schnelle Bewegungszunahme bis 2011. Der Vergleich mit den Lufttemperaturen zeigt eine zeitliche Reaktionsverzögerung von einem oder mehreren Jahren durch Erwärmung bei der Bewegungszunahme, wohingegen die Blockgletscher bei einer Abkühlungsphase zeitlich etwas schneller reagieren was möglicher Weise mit der Verfügbarkeit von flüssigem Wasser im Blockgletscherkörper zusammenhängt. Die Korrelationsanalysen zwischen der Blockgletscherbewegung und den 13 verschiedenen Klimaparametern zeigen komplexe Zusammenhänge auf und nur in wenigen Fällen (13 von 270) konnten statistisch signifikante Korrelationen errechnet werden. Zeitliche Verzögerungen der Blockgletscherbewegung auf klimatische Veränderungen bedingt durch die thermale Diffusion durch den Blockgletscherkörper wurden dabei berücksichtigt. Die Ergebnisse zeigen beispielsweise, dass ein vierfach milderer Winter gemessen an der Blockgletscheroberfläche eine 1,5 fache Geschwindigkeitszunahme bewirkt. Eine gleiche Geschwindigkeitszunahme bewirkt ein nur zweifach milderer Winter jedoch auf Basis von gemessenen Temperaturdaten in einem Meter Tiefe. Dies weist auch auf die wesentlichen Bodentemperaturunterschiede gemessen an der Oberfläche oder in einem Meter Tiefe hin. Die Stirne aller drei untersuchten Blockgletscher befinden sich nahe der Untergrenze des diskontinuierlichen Gebirgspermafrosts. Aus diesem Grund ist anzunehmen, dass möglicher Weise noch in diesem Jahrhundert ein Wendepunkt in der allgemeinen Geschwindigkeitszunahme (bedingt durch die Erwärmung des Permafrosts) zu einer Geschwindigkeitsabnahme (bedingt durch Permafrostdegradation und folgender Zunahme der inneren Reibung) erreicht wird. Diese Hypothese ist auch für viele andere aktive Blockgletscher in Österreich plausibel.

1. Introduction

Active rock glaciers are creep phenomena of continuous and discontinuous permafrost in high-relief environments moving slowly downvalley or downslope (Barsch, 1996; Haeberli et al., 2006; Berthling, 2011). Rock glaciers are often characterised by distinct flow structures with ridges and furrows at the surface with some similarity to the surface of pahoehoe lava flows. At steeper parts or at the front of a rock glacier, the rock glacier body might start to disintegrate (e.g. Avian et al., 2009) or even completely tear-apart and collapse (Krysiecki et al., 2008). A typical rock glacier climate is dry to moderately humid with cool summers (Humlum, 1999).

The temporal change of the surface flow velocity of rock glaciers is primarily related to climate. Correlation between air temperature and rock glacier movement variations suggest that the temporal change of the surface flow velocity is primarily related to climatic conditions (e.g. Delaloye et al., 2008; Kääb et al., 2007). Considering this, temperature and its change over time might be regarded as a good proxy for rock glacier velocity changes. However, air temperature and other climate elements such as snow cover influence ground temperatures in a complex way. An increase in ground temperature of an active rock glacier leads to the warming and partial thawing of the permafrost body. Warming permafrost temperatures slightly below 0°C change the rheological properties of the warming rock glacier ice causing higher internal deformation (Roer et al., 2008). Accordingly for cohesive rock masses, laboratoryexperiments showed that frozen rock joints reach minimal stability only little below 0°C (Davies et al., 2001). Furthermore, increasing availability of liquid water due to thawing in the rock glacier might increase rock glacier movement rates (Ikeda et al., 2008). Kääb et al. (2007) conclude that increasing rock glacier temperatures may lead to a marked but both spatially and temporally highly variable speed-up.

In some cases also basal sliding could take place along a water-saturated, fine-grained till layer below the rock glacier body (Hausmann et al., 2007). However, further permafrost thawing approaching complete melting of the internal ice would cause an increase in internal friction due to an increasing degree of clast contacts. This would lead to a decrease in movement rates and final rock glacier stabilisation. In that sense, an active rock glacier (permafrost, movement) turns first to climatic inactive (still widespread permafrost but no movement), second to pseudo-relict (isolated patches of permafrost, no

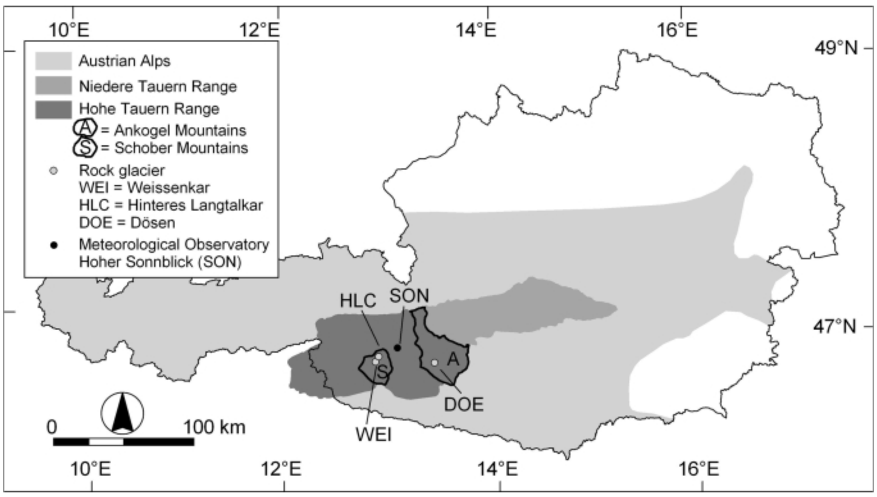


Figure 1: Location of the three rock glaciers Weissenkar (WEI), Hinteres Langtalkar (HLC) and Dösen (DOE) in the Hohe Tauern Range, central Austria. WEI and HLC are located in the sub-unit Schober Mountains, DOE in the Ankogel Mountains. Location of the Meteorological Observatory Hoher Sonnblick (SON) is indicated.

movement), and finally to relict (no permafrost, no movement) (Barsch, 1996; Kellerer-Pirklbauer, 2008a).

Besides climatic conditions, movement rates depend on other factors related to the topographical setting of the rock glacier as well as to its near surrounding. These factors are for instance slope and topography of the rock glacier bed, marginal friction, nourishment of the rock glacier by debris and ice input, and water content, thickness, ice/debris proportion, and inner structure of the rock glacier body.

In this study we focus on long-term observation on the movement of three active rock glaciers located in the Hohe Tauern Range, central Austria, and present results on the combination of movement data with ground temperature and climatic data from the rock glacier sites itself as well as complementary climate data from a nearby high-mountain climate station. The three rock glaciers have been photogrammetrically and geodetically monitored since 1954 (Dösen Rock Glacier/DOE), 1974 (Weissenkar Rock Glacier/WEI), and 1969 (Hinteres Langtalkar Rock Glacier/HLC). Data series on continuous ground temperature monitoring with hourly resolution started in 1997 at WEI (although with data gaps) and in 2006 at DOE and HLC (no data gaps), respectively. This data series provide a relatively good basis for analysing the relationship between rock glacier movement and climate induced ground temperature conditions in the Eastern European Alps during the period 1995-2011. This paper uses these data to address the following three main questions: How were the changes in surface velocity of the three rock glaciers during the last decades at different time scales? What are differences and similarities of the movement behaviours of the three studied rock glaciers? What are the relationships between rock glacier velocity as well as velocity changes and air temperature, snow, ground surface and subsurface temperatures during the last about 1.5 decades? Therefore, this paper aims to increase the general understanding of the relationship between rock glacier kinematics and climate.

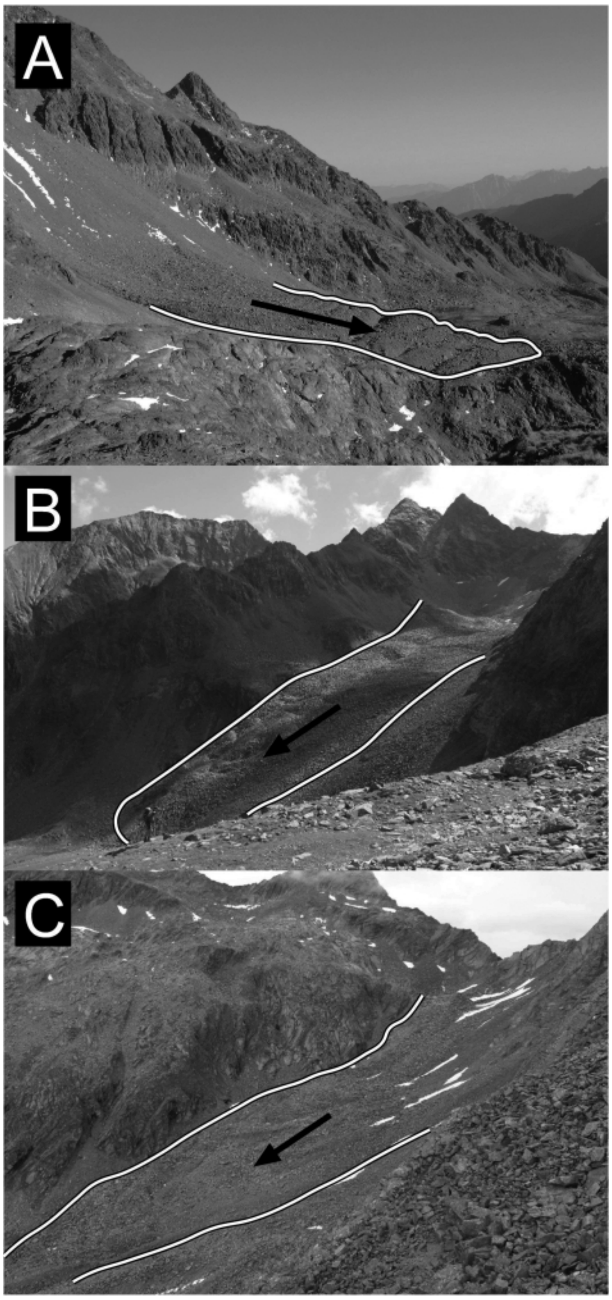


Figure 2: Terrestrial photographs of the three active rock glaciers WEI (A), HLC (B) and DOE (C). Black arrows indicate flowing direction and black-and-white lines the margin of the rock glaciers in the central and lower parts. Note the typical flow structure for rock glaciers. Photographs by A. Kellerer-Pirklbauer.

2. Study area

2.1 Hohe Tauern Range

The Tauern Range is an extensive mountain range in the central part of the Eastern Alps covering 9500 km^2 in Austria (Federal Provinces of Salzburg, Tyrol, Carinthia and Styria) and – to a substantially minor extent – in Italy (Autonomous Province of South Tyrol/Alto Adige). The Tauern Range is commonly separated into the Hohe Tauern Range and the smaller Niedere Tauern Range. The former covers c.6000 km^2 and reaches with Mt. Großglockner 3798 m a.s.l., the highest summit of Austria. This study focuses on three different rock glaciers in the Hohe Tauern Range, two of them are located in the sub-unit Schober Mountains and one in the sub-unit Ankogel Mountains (Fig. 1).

2.2 Weissenkar Rock Glacier (WEI)

WEI is located in the Schober Mountains at N46°57´ and E12°45´ between 2615 and 2790 m a.s.l. in the Federal Province of Tyrol (county of Lienz/Eastern Tyrol). The Schober Mountains are characterized by crystalline rocks and a continental climate (1500 mm at 2000 m a.s.l., 0°C mean annual air temperature at 2300 m a.s.l.) causing minor glaciation and large areas affected by permafrost. The permafrost favourable conditions are indicated by the high number of rock glaciers (n=126), underlining the fact that the Schober Mountains provide suitable topoclimatic and geological conditions for rock glacier formation (Lieb, 1996; Kellerer-Pirklbauer et al., 2012).

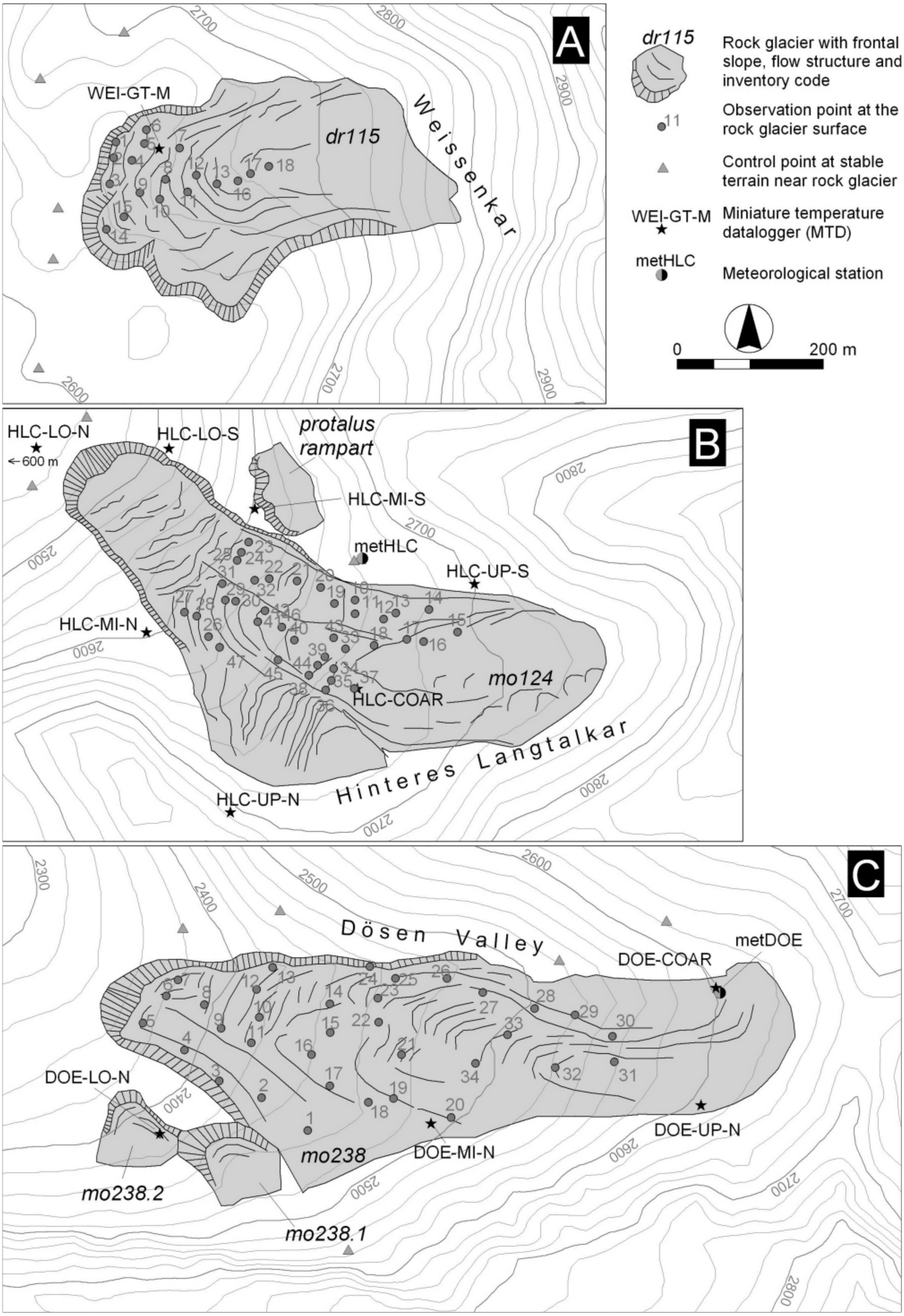
WEI is a west-facing, slowly moving tongue-shaped rock glacier consisting of an active upper lobe presumably overriding an inactive lower lobe (Figs 2A, 3A), hence a polymorphic rock glacier (*sensu* Frauenfelder and Kääb, 2000). The landform is characterized by well developed furrows and ridges at its lower half and fed by active scree slopes. WEI has a length of 500 m, a maximum width of 300 m, and a surface area of 0.11 km². Different types of mica schist form the lithological component of the rock glacier. Present mean surface velocities are below 10 cm a-1, thus this rock glacier is the slowest of the three studied rock glaciers. This rock glacier is labelled as dr115 in the recently elaborated rock glacier inventory for Central and Eastern Austria (Lieb et al., 2010; Kellerer-Pirklbauer et al., 2012). Research at WEI is carried out since the early 1990s (for overview see Table 1).

2.3 Hinteres Langtalkar Rock Glacier (HLC)

HLC is located in the Schober Mountains at N46°59´ and E12°47´ between 2455 and 2720 m a.s.l. some 3.8 km to the northeast of WEI. HLC is a very active, monomorphic (*sensu* Frauenfelder and Kääb, 2000), tongue-shaped rock glacier with two rooting zones facing towards generally northwest (Figs 2B, 3B). The rock glacier is 900 m long, up to 300 m wide, covers an area of 0.17 km², consists of mica-schist and amphibolites, and has the inventory code mo124 (Lieb et al., 2010). Distinct changes of the rock glacier surface were detected on aerial photographs from 1997 on with formation of cracks and destabilisation of the frontal part. The frontal part or rock glacier tongue is heavily influenced by disintegration through active sliding processes since about 1994 (e.g. Avian

Site	Method	Initiated/carried out	Publications
WEI	Geodetic surveys	1997 -	Buchenauer, 1990; Buck and Kaufmann 2008; Delaloye et al., 2008; Kaufmann et al., 2006; Kellerer-Pirklbauer, 2008b; Kienast and Kaufmann, 2004; Krobath, 1999; Lieb, 1987; 1991; 1996
	Aerial photogrammetry	1974 -	
	Airborne laser scanning	2008	
	Geomorphological mapping	1997 -	
	Ground surface temperature	1997 -	
	Near ground surface temperature	1999 -	
	Relative dating of rock glacier	2007	
HLC	Geodetic surveys	1999 -	Avian et al., 2005; 2008; 2009; Bauer et al., 2003; Buchenauer, 1990; Buck and Kaufmann, 2008; Delaloye et al., 2008; Kaufmann and Ladstädter 2002; 2003; 2004; 2010; Kellerer-Pirklbauer 2008c; Kellerer-Pirklbauer and Kaufmann, 2007; Kellerer-Pirklbauer et al., 2008; 2010; Kienast and Kaufmann, 2004; Krainer and Mostler, 2001; 2002; Krainer et al., 2000; Krobath, 1999; Lieb, 1987; 1991; 1996
	Aerial photogrammetry	1954 -	
	Terrestrial laser scanning	2000 -	
	Airborne laser scanning	2008	
	Geomorphological mapping	1999 -	
	Meteorological monitoring	2006 -	
	Monitoring of snow cover by automatic digital cameras	2006 -	
	Ground surface temperature	2006 -	
	Near ground surface temperature	2006	
	Hydrology	late 1990s	
DOE	Geodetic surveys	1995	Buck and Kaufmann, 2008; Delaloye et al., 2008; Kaufmann and Ladstädter, 2007; Kaufmann et al., 2007; Kellerer-Pirklbauer, 2008b; Kenyi and Kaufmann, 2003; Kienast and Kaufmann, 2004; Lieb, 1991; 1996; 1998; Lieb et al., 2012; Schmöller and Fruhwirth, 1996
	Aerial photogrammetry	1954	
	Geophysics (seismics, geomagnetics and georadar)	1994	
	Geomorphological mapping	1994	
	Meteorological monitoring	2006	
	Monitoring of snow cover by automatic digital cameras	2006	
	Ground surface temperature	1998	
	Near ground surface temperature	2006	
	Relative dating of rock glacier	2007	

Table 1: Research carried out previously at the three rock glaciers WEI, HLC and DOE.


A
dr115
Weissenkar
WEI-GT-M
2600
2700
2800
2900
dr115
Rock glacier with frontal slope, flow structure and inventory code
11
Observation point at the rock glacier surface
Control point at stable terrain near rock glacier
WEI-GT-M
Miniature temperature datalogger (MTD)
metHLC
Meteorological station
0
200 m
B
HLC-LO-N
←600 m
HLC-LO-S
protalus rampart
HLC-MI-S
metHLC
HLC-UP-S
HLC-MI-N
HLC-COAR
mo124
Hinteres Langtalkar
HLC-UP-N
2500
2600
2700
2800
C
Dösen Valley
metDOE
DOE-COAR
DOE-LO-N
DOE-MI-N
DOE-UP-N
mo238
mo238.1
mo238.2
2300
2400
2500
2600
2700
2800

Site	Geodetic measurements	Number of observation points on rock glacier used for the mean value	Photogrammetric measurements	Relevant sites for ground temperature measurement; elevation (m a.s.l.) and sensor depths (cm) are indicated in brackets	Ground temperature data series (month/year)
WEI	annually since 1997 (in 2002 no measurements)	18 (16 for 1997/98)	1974, 1998, 2002	WEI-GT-M (2655; 0 and 100)	09/97-08/01 and 09/04-08/11; for 100cm: 09/07-08/11
HLC	annually since 1999	9 (for upper/ slower part = HLC-U) 6 (for lower/ faster part = HLC-L)	1954, 1969, 1974, 1981, 1991, 1997, 1998, 1999, 2002, 2006	HLC-LO-S (2489; 0) HLC-MI-S (2581; 0) HLC-UP-S (2696; 0) HLC-LO-N (2485; 0) HLC-MI-N (2601; 0) HLC-UP-N (2693; 0) HLC-COAR (2672; 100)	all 09/06-08/11
DOE	annually since 1995 (in 2003 no measurements)	11	1954, 1969, 1975, 1983, 1993, 1997, 1998	DOE-LO-N (2407; 0) DOE-MI-N (2501; 0) DOE-UP-N (2616; 0) DOE-COAR (2603; 100)	all 09/06-08/11

Table 2: Geodetic, photogrammetric and ground temperature data used in the present study. Abbreviations: HLC-U and HLC-L=upper (slow) and lower (fast) parts of the rock glacier HLC. Number of observation points at the rock glacier surface used for computing the mean values used are indicated. For location of these points as well as the relevant sites for ground temperature measurements see Fig. 3. For references see Table 1.

et al., 2005, 2008; Roer et al., 2008). This partial break is caused by enhanced strain due to movement of HLC over a terrain ridge into steeper terrain. The increasing strain caused morphological changes similar to landslides with indications for potential shear zones causing the process of sliding (Avian et al., 2009). The current movement pattern of the rock glacier area above the disintegrating frontal zone allows the differentiation of an fast moving lower part (HLC-L) – with maximum horizontal displacement rates up to almost 3 m a^{-1} – and a substantially slower upper part (HLC-U). Therefore one might distinguish three subunits at HLC – front (strongly influenced by gravitation), lower part (HLC-L) and upper part (HLC-U). With these high velocities, HLC is one of the currently fastest moving rock glaciers at least in the European Alps (see Delaloye et al., 2008 for comparison). At this rock glacier, a comprehensive set of methods is applied since the late 1990s (Table 1).

2.4 Dösener Rock Glacier (DOE)

DOE is located at the inner part of the glacially shaped, W-E trending Dösen Valley in the Ankogel Mountains, at N46°59´ and E13°17´ between 2355 and 2650 m a.s.l. (Figs 2C, 3C). This part of the valley is characterised by four north-to-west facing rock glaciers, a cirque floor with a tarn lake and distinct terminal moraines of Younger Dryas age. The four rock glaciers consist primarily of granitic gneiss. The largest of the four rock glacier is DOE, an active monomorphic tongue-shaped rock glacier with the inventory code mo238 (Lieb et al., 2010), a length of 950 m, a width of maximum 300 m and a surface area of 0.19 km^2. Mean surface velocities during the last decades were below 40 cm a^{-1}. Therefore, the velocities here are in between the rates of HLC and WEI. At DOE, a comprehensive set of methods comparable to HLC is applied in particular since 2006 (Table 1).

Figure 3: The three rock glaciers WEI (A), HLC (B) and DOE (C) with locations of relevant miniature temperature datalogger/MTD (for details see Table 5), meteorological stations (metDOE, metHLC), the individual observation points at the rock glacier surface and the stable control points in close vicinity (not all control points are shown in the map due to map extent restrictions) used for the geodetic measurements. Rock glacier codes according to the inventory by Lieb et al. (2010).

3. Material and Methods

In order to assess the relationship between rock glacier movement and climate change in central Austria, we used data based on (a) geodetic field campaigns with complementary data from photogrammetric velocity analysis, (b) continuous ground surface and near ground-surface temperature data based on automatic miniature temperature datalogger (MTD) at the three rock glacier sites, (c) air temperature data from meteorological stations at the two sites HLC and DOE, and (d) complementary climate data from the nearby Meteorological Observatory Hoher Sonnblick (SON).

3.1 Rock glacier velocity

At WEI a geodetic monitoring program was initiated in 1997 and was carried out annually – except in 2002 – since then. The surveys were always accomplished in August (mostly mid-August). The annual vertical and horizontal displacement rates of 15 (1997-1998) to 18 (1998-2007) marked observation points (nr. 1-18, see Fig. 3A, Table 2) were recorded by a total station. The observation points are stabilized using fixed brass bolts on large boulders of the rock glacier surface. For reference and accuracy calculations, six control points on stable terrain around the rock glacier are used (five are shown in Fig. 3A) yielding general horizontal movement accuracies of ±1 cm a^{-1}.

At HLC a geodetic monitoring program was initiated in 1999 on an annual basis. At this rock glacier 38 marked observation points (nr. 10-47) are measured once per year in August (Fig. 3B, Table 2). For reference, eight control points (partly depicted in Fig. 3B) are used in the vicinity of the rock glacier. Due to the fact that the lower part is substantially faster moving compared to the upper part, two different mean values are calculated for this rock glacier. The one of the upper part is based on the mean of nine observation points (nr. 10-17 and 37), the one of the lower part of six (nr. 23-25, 27, 28 and 31). Finally, at DOE a geodetic monitoring program with 34 marked observation points (nr. 1-34) and five control points on stable terrain around was initiated in 1995 (Fig. 3C). The annual measurements were carried out at DOE again each August apart from 2003 due to lack of funding. At DOE the mean velocity value is based on eleven selected observation points (nr. 10-17 and 21-23). Representative velocity data for each rock glacier was retrieved from selected observation points only in order to support a sound correlation analysis. These points are supposed to belong to areas of similar surficial movement pattern. In the case of WEI we took all observation points into account; it was a compromise to a certain extent due to the general low velocity values.

Additionally, photogrammetric velocity analysis at the three rock glaciers cover periods of four to almost six decades (Table 2) and therefore belong to the longest rock glacier velocity records in the European Alps (cf. Schneider & Schneider, 2001). The horizontal movement accuracies for the photogrammetric velocity data are generally lower compared to the geodetic ones and are in the order of ±1 to 5 cm a^{-1} primarily depending on the respective time span for scaling measured displacements to annual values, i.e. velocities. A direct comparison of photogrammetric and geodetic measurements is not possible since the observation periods generally do not coincide. One exception is WEI and the period 1998-2002, where the geodetically horizontal creep velocities at the 18 object points produced a value of 5.5 cm a^{-1} which is in very good agreement with the photogrammetrically derived value of 5.3 cm a^{-1}. (Kaufmann et al., 2006). This result gives confidence in the comparability of the two applied methods. For completeness, satellite based radar interferometry was also applied for DOE (Kenyi and Kaufmann, 2003).

The mean value in rock glacier velocity (based on six to 18 individual points as described above and with horizontal movement accuracies of ±1 cm a^{-1}) was used in the subsequent comparison with the ground temperature data. With this approach, it was aimed to balance the spatial variation in surface velocity as well as in ground temperature. In contrast, Kääb et al. (2007) proposed to use the maximum surface velocity value instead of the mean value in order to get the “optimal” speed factor. However, correlation analyses of the mean versus the maximum surface velocity of the three rock glaciers showed strong correlations with r=0.99 at HLC-L and DOE, r=0.94 at HLC-U, and still r=0.67 at WEI (all p<0.01). The low r for WEI is related to low absolute movement values where “outlier” and surface deformation have a larger effect. Therefore, it was decided only for WEI to analyse mean and maximum surface velocities separately (Table 3).

3.2 Ground temperature

At WEI automatic and continuous (most time of the year; 1 hour record interval) measurements of ground surface tempe-

Movement parameter	Climatic parameter (data availability given in month/year)
Rock glacier velocity •Mean values for WEI (1997-2011), HLC-U, HLC-L (1999-2011) and DOE (1995-2011) •Maximum values for WEI (1997-2011)	Air temperature •MAAT for HLC and DOE (09/93-08/11); MAAT values for the period 09/93 -08/06 were calculated for both sites based on correlation analysis with SON •FDDair for HLC, DOE (09/06-08/11) and SON (09/93-08/11) •FDDair for HLC, DOE (09/06-08/11) and SON (09/93-08/11)
	Snow depth •SNOWmean for SON (09/93-08/11) •SNOWsum for SON (09/93-08/11) •SNOWdec for SON (12/95-12/11) •SNOWapma for SON (04/96-05/11)
	Ground surface temperature •MAGST for WEI (09/97-08/01 and 09/04-08/11), HLC and DOE (09/06-08/11) •FDDsurf for WEI (09/97-08/01 and 09/04-08/11), HLC and DOE (09/06-08/11) •TDDsurf for WEI (09/97-08/01 and 09/04-08/11), HLC and DOE (09/06-08/11)
	Ground temperature at 1 m depth •MAGT for WEI, HLC (09/07-08/11) and DOE (09/06-08/11) •FDDdepth for WEI, HLC (09/07-08/11) and DOE (09/06-08/11) •TDDdepth for WEI, HLC (09/07-08/11) and DOE (09/06-08/11)

Table 3: List of movement and climatic parameters used in the correlation analysis. MAAT=mean annual air temperature, FDDair/surf/depth=freezing degree days based on air, ground surface or 1 m depth temperature, TDDair/surf/depth=thawing degree days based on air, ground surface or 1 m depth temperature, SNOWmean=mean annual snow depth based on mean monthly snow depth values, SNOWsum=annual snow sum based on mean monthly snow depth values, SNOWdec=mean monthly snow depth in December, SNOWapma=mean monthly snow depth of April and May, MAGST=mean annual ground surface temperature, MAGT=mean annual ground temperature at 1 m depth.

rature were started in autumn 1997 using UTL-1 miniature temperature dataloggers/MTDs focussing on the central part of the rock glacier tongue at about 2660 m a.s.l. (Fig. 3A, site WEI-GT-M). According to the producer, UTL-1 logger have an accuracy of +/-0.1°C, data resolution of 0.27°C, and a temperature range of -29°C to +39°C. During each year for the period 1997-2007, one (1997-1999: only surface at 0 cm) to three (1999-2007: 0, 30 cm and 100 cm depth) UTL-1 loggers were installed during the autumn months and were recollected in the subsequent early to late summer. Thereby, ground temperatures were measured between 231 to 331 days by the MTD. Data gaps during the snow free periods in between were filled up by correlation analysis with neighbouring air temperature data. Technical problems caused a continuous data gap in the period 2001-2004.

In September 2007 the UTL-1 logger at site WEI-GT-M was replaced by a 3-channel GeoPrecision datalogger (Model M-Log6) with three PT1000 temperature sensors at 0, 30 cm and 100 cm depths. Furthermore, the site WEI-GT-M was slightly shifted by about 3 m to a coarse-grained blocky site at the rock glacier surface. This allowed the monitoring of subsurface temperatures in the blocky surface layer of the rock glacier. According to the producer, the PT1000 temperature sensors of the GeoPrecision logger have an accuracy of +/-0.05°C, a range -40 to +100°C and a calibration drift <0.01°C yr^{-1}. In our analysis, ground temperature data from 0 and 100 cm depths at site WEI-GT-M were used. Mean annual ground surface temperature (MAGST), mean annual ground temperature at 1 m depth (MAGT), thawing degree days (TDD), and freezing-degree days (FDD) were calculated based on daily data (Table 3). TDD is the cumulative value of positive daily mean ground temperature, whereas FDD is the sum of negative daily mean ground temperature for one year. A winter snow cover influences the values of TDD and FDD. Therefore, by using the two parameters TDD and FDD, the effect of the winter snow cover on the ground temperature is to some extent indirectly considered.

At HLC a comprehensive network for ground surface and near-surface temperature monitoring was initiated in summer 2006 comprising 18 MTD sites. At these sites 1-channel (Model M-Log1) and 3-channel (Model M-Log6) dataloggers produced by GeoPrecision were installed. For this study, ground surface data from six sites with 1-channel datalogger located at and around the rock glacier were used; three facing south to southwest and three facing north to northeast (Fig. 3B, Table 2). Four of them are at snowy depressions whereas two are at wind-exposed sites. Furthermore, the six loggers cover an elevation range of between 2485 and 2696 m a.s.l., hence are regarded as representative for the rock glacier HLC. A mean daily ground surface temperature value for the rock glacier was calculated based on the six MTD sites. Furthermore, data from a seventh MTD (Model M-Log6) site located at 2672 m a.s.l. (HLC-COAR) were additionally used (Fig. 3B). At this site, ground temperature at 0, 30 and 100 cm depths were monitored in coarse-grained material of HLC. In the analysis MAGST, MAGT, TDD and FDD were calculated as described above for the rock glacier surface and for 1 m depth.

Similar to HLC, a comprehensive network for ground surface and near-surface temperature monitoring was initiated at DOE in summer 2006 comprising 13 MTD sites using GeoPrecision dataloggers Models M-Log1 and M-Log6 as described above. Similar to HLC, a calculated mean ground surface temperature value taken from three different MTD sites was used in the subsequent correlation analyses. The three MTD sites are equipped with 1-channel dataloggers and are located at or very near to the rock glacier. All three are on generally north to northwest facing slopes covering an elevation range of 2407 to 2616 m a.s.l. (Fig. 3C, Table 2). As at the other two rock glacier sites, ground temperature data from 1 m depth measured in coarse-blocky material at the rock glacier surface (site DOE-COAR in Fig. 3C) were used additionally in the analysis. The same ground climatic parameters as described above were calculated.

3.3 Climatic data

Two meteorological stations have been installed in 2006 at the two sites HLC (metHLC,) and DOE (metDOE). Station metHLC is located at 2655 m a.s.l. in close vicinity to the rock glacier. metDOE is located on a large boulder at the surface of the rock glacier at 2603 m a.s.l. (Fig. 3). At both stations air temperature, air humidity, wind speed, wind direction and global radiation are continuously logged on an hourly interval. No meteorological station exists at site WEI. However, due to its close distance to HLC (less than 4 km) and the same elevation, the temperature data collected at HLC might be also regarded as valid for WEI. For the present study, air temperature data were used for the period 09/06 to 05/11 at site metDOE, and 09/06 to 08/11 at site metHLC. Data gaps were closed by using correlation analysis and temperature data from the Meteorological Observatory Hoher Sonnblick (SON) as described in the next paragraph.

Air temperature and snow depth data from the alpine meteorological Observatory Hoher Sonnblick (3106 m a.s.l.) were additionally used. This observatory is the highest permanently staffed meteorological observatory in the Alps providing a record of climate data since 1886. It is located 15 km northeast of HLC, 19 km northeast of WEI and 26 km northwest of DOE (Fig. 1). In order to compare the rock glacier velocity changes with the temperature evolution, it was necessary to fill data gaps and extend the time series of the temperature data from metHLC and metDOE to a longer period. This was accomplished by correlation analysis with temperature data from Sonnblick. The correlation of mean monthly temperatures between Hoher Sonnblick and metDOE as well as Hoher Sonnblick and metHLC is strong and statistically significant (for metDOE: $r=0.998$, $p<0.01$; for metHLC: $r=0.997$, $p<0.01$). As a result, vertical lapse rates of 0.54°C/100 m for metDOE and 0.70°C/100 m for metHLC were derived and used for filling gaps and extending the time series back to 1993. Results showed that despite the fact that metHLC is located 52 m higher in elevation compared to metDOE, the mean air temperature is 0.45K warmer. In the subsequent data analysis, mean annual air temperature (MAAT), TDD and FDD were calculated for metDOE and metHLC for the period September 2006 to August 2011 and for SON for September 1993 to August 2011. Mean monthly snow depth values from SON were used for calculating the mean annual snow depth (SNOWmean) and the annual snow sum based on mean monthly snow depth values (SNOWsum). Finally, mean snow depth in December (SNOWdec) and mean snow depth of the two months April and May (SNOWapma) were used in the analysis. As shown by Bodin et al. (2009) at the Laurichard rock glacier, the snow cover in early winter has a strong influence on rock glacier velocity. Furthermore, Ikeda et al. (2008) point out that rock glaciers accelerate during snowmelt period related to water availability during snow melt. SNOWapma was used as a proxy for snow availability during the spring melting period.

Table 3 summarises all different movement and climatic parameters used in the correlation analysis. In the analysis, annual data sets were compared in four different ways: (A) annual movement data (mid August through mid August of the subsequent year) versus annual climatic data (1st September to 30th August of the subsequent year) from almost identical one-year periods, (B) annual movement data versus annual climatic data where the beginning of the climatic data period was shifted to six months earlier (1st March to 28/29th February of the subsequent year), (C) twelve months earlier or, respectively, (D) 24 months earlier. This was done in order to consider and test the importance of the time lag caused in particular by thermal diffusion through the permafrost body in the response of the rock glaciers to climate/weather changes. For the two parameters SNOWdec and SNOWapma solely the movement data from the same year were used. Data of the different movement and climatic parameters were tested regarding normality (Shapiro-Wilk test) and excluded if appropriate.

4. Results

4.1 Velocity variations 1954-2011

The mean horizontal surface velocity and its change over time for all three rock glaciers of interest during similar periods are depicted in Fig. 4. For HLC, the slower upper part (U) was separated from the substantially faster lower (L) part. The graphs show that it is not possible to recognize a homogeneous and/or synchronous behaviour of the three rock glaciers during the period where only photogrammetric data is available (1954/1974 to mid 1990s). The main drawback in this analysis is the limited availability of aerial photographs in high quality for this period. However, the mean values for this "photogrammetric period" at all three rock glaciers were sub-

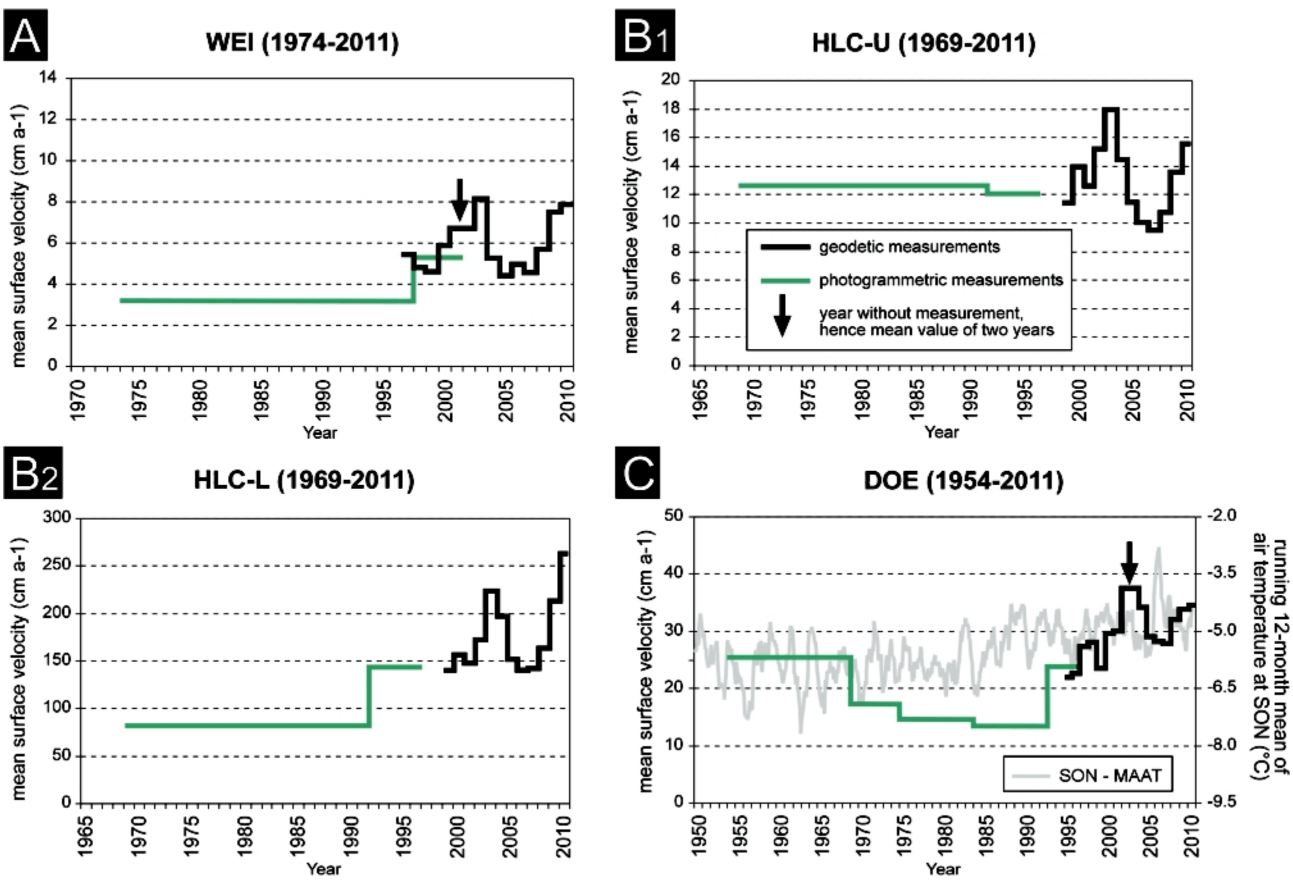


Figure 4: Mean annual horizontal surface velocities of the three rock glaciers WEI (A), HLC (B) and DOE (C). For HLC, the upper and slower moving part (B1) is separately considered from and lower and faster moving part (B2). In (C) the 12-month running mean values of air temperature (MAAT) at SON during the period 1950-2011 are additionally plotted.

stantially lower compared to the highest mean values measured in the later period with geodetic data of annual temporal resolution.

For the "geodetic period" the three rock glaciers show rather synchronous flow behaviour despite different flow complexity, morphology and mean annual surface velocity. Table 4 lists the coefficients of correlation for the geodetic period between the rock glaciers thereby separating for HLC the slower/upper from the faster/lower part. Correlation results indicate strong and highly significant positive correlations between the three rock glaciers with coefficients of 0.71-0.79.

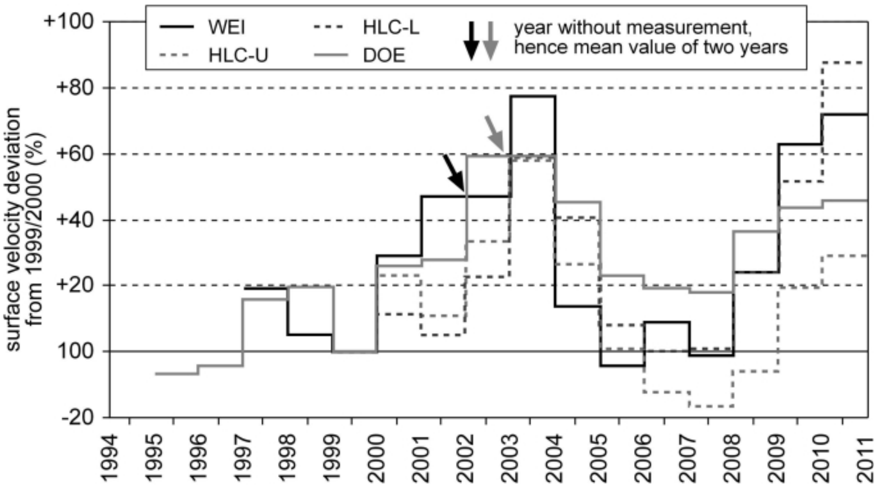


Figure 5: Relative velocity changes to the velocity rates of 1999-2000 at all three rock glaciers. For HLC, the upper and slower moving part (U) is separately considered from and lower and faster moving part (L).

Figure 5 shows the relative flow velocity for all three rock glaciers for the geodetic period 1995-2011. The velocity of the measurement period 1999-2000 was taken in this graph as 100% because 1999 was the first year where geodetic measurements were carried out at all three rock glaciers. The figure clearly depicts that the velocity during 1999-2000 was lower compared to the two years of measurements before and preceded a period of at least five years with partly substantially higher values. 1999-2000 was also the slowest year for DOE in the entire period 1999-2011. A first phase of higher velocity occurred in 2000-2001. After 2002 all rock glaciers accelerated substantially peaking in 2003-2004. In 2003-2004 the velocity was about 1.6 to 1.8 times higher compared to 1999-2000 at all sites. Due to missing measurements in 2003 at DOE, the probable peak at this rock glacier in 2003-2004 was missed.

After the peak in 2003-2004, the velocity dropped – first fast, afterwards more slowly – to a level similar or even lower compared to 1999-2000. At WEI, a further small peak in velocity was observed in 2006-2007. Surface velocities during 2007-2008 were the lowest at all rock glaciers during the period 2004-2011, although similar (WEI, HLC-L), below (HLC-U), or even above (DOE) compared to the values of 1999-2000. After 2006-2007 surface velocities increased continuously again substantially up to values even exceeding (HLC-U) or almost reaching (WEI) the values of 2003-2004. DOE reacted more balanced regarding velocity decrease and increase during the period 2004-2011 compared to the other rock glaciers. Furthermore, the very first year of geodetic measurements at DOE (1995-1996) was also the slowest one over the entire 16 year measurement period.

4.2 Rock glacier velocity and air temperature evolution

The evolution of the 12-month running mean of the annual air temperature during the period 1990-2011 and the mean annual surface velocities since geodetic measurement initiation for each of the three rock glacier are shown in Figure 6. Air temperature of HLC was also taken for WEI due to its close proximity. The effects of the exceptional warm winter 2006-2007 caused even a positive MAAT at site HLC. Furthermore, the heat wave in summer 2003 was not as effective in causing higher MAAT values as in the Western Alps (Delaloye et al., 2008).

The evolution of the air temperature indicates cooler conditions in 1995-1997 with low surface velocities at DOE in this first two measurement years. A peak in air temperature in 1998 was accompanied by a first minor peak in faster rock glacier velocity at DOE; to a minor extent at WEI. A lower 12-month running mean MAAT around 1999 was followed by low velocities in 1999-2000. Afterwards, the time period from 2000 to mid 2003 shows relatively constant high MAAT values causing a steady increase in surface velocity at all three sites peaking in 2003-2004. The following period until late 2006 is characterised by more-or-less gradually decreasing 12-month running mean MAAT as well as decreasing velocities. After this, the distinct double peak of MAAT in late 2007 caused by the warm winter 2006-2007 was of special relevance for rock glacier velocities, although the velocities of the two measurement periods 2006-2008 were still influenced by the cooler conditions before.

All three rock glaciers gained substantially in speed after

	HLC-U		HLC-L		DOE	
	r	n	r	n	r	n
WEI	0.78	12	0.78	12	0.76	14
HLC-U	-	-	0.72	12	0.79	12
HLC-L	-	-	-	-	0.71	12

Table 4: Correlation matrix of the mean horizontal surface velocity of the three rock glaciers WEI, HLC (upper/slower and lower/faster parts differentiated) and DOE. All correlations are significant at the 0.01 (**) level. Number of value pairs/common measurement years are indicated.

2008 until 2011. Within only three years, the lower part of HLC almost doubled its surface velocity. For WEI, the increase in surface velocity was still 73% in only three years. The 12-month running mean MAAT decreased substantially until end of 2008 but is still at a relatively high level comparable to the time period from 2000 to mid 2004.

At DOE the temporal resolution of photogrammetrically derived velocity data is the best of all three rock glaciers. Therefore, the MAAT at SON during the period 1950 to 2011 was additionally plotted in Fig. 4C. The MAAT evolution indicates a slight cooling trend until the late 1960s, relatively cool conditions until the mid 1980s, followed by a slight warming trend since then. However, the entire period is characterised by high interannual variations. Correlating the velocity data with MAAT is not feasible with the given temporal resolution of the data. However, Fig. 4C clearly shows the generally cooler temperatures in the pre-geodetic period also caused generally lower rock glacier velocities.

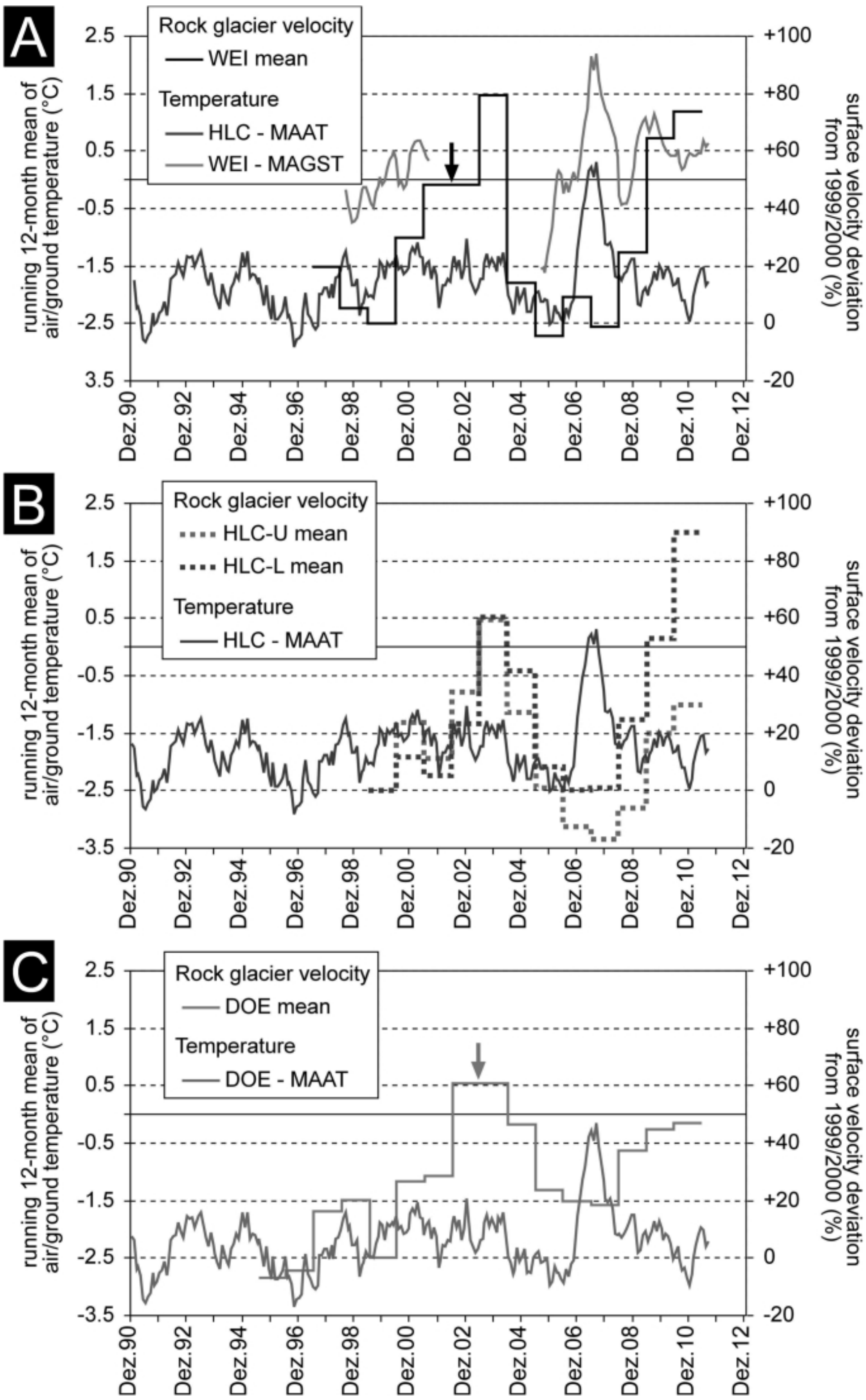


Figure 6: Relationship between 12-month running mean values of air (MAAT) and the mean surface velocity (relative to measurement period 1999-2000) at the three rock glaciers WEI (A), HLC - upper and lower part - (B) and DOE (C) for the period 1990-2011. The MAAT at HLC and DOE was measured directly (autumn 2006 to summer 2011) or calculated (remaining period) based on correlation analysis with data from SON. Only at WEI a longer time series (>5 years) of MAGST data was available and therefore plotted here. Arrows indicate years without geodetic measurements, hence mean velocity values of two years are shown.

4.3 Correlation between movement and climatic parameter

Figure 7 depicts the mean monthly temperatures during the period 1997-2011 at the ground surface at WEI as well as at the ground surface and at 1 m depth at all three rock glaciers WEI, HLC and DOE covering the period 2006-2011. As it is shown by this graph (and also Figure 6A), air temperature generally differs from ground surface and ground temperature. The difference between mean monthly values in ground and air temperatures is substantially larger in winter compared to summer. As shown in the graph, temperatures at the surface at each of the three rock glaciers are warmer during summer (mainly July or August; up to 7°C difference) and colder during winter (October until April; up to 4°C difference) compared to the temperatures at 1 m depth. Hence at already a depth of only one meter, the temperature signal at the ground surface is more balanced and very different from the one measured at one meter depth in coarse-grained blocky material.

Results on the correlation analysis between the movement parameter and the different climatic parameters (see Table 3) revealed that only 13 out of 270 (5%) pairs of variables show statistical significant correlations at the 0.05 level, none at the

0.01 level. To some extent this circumstance is simply related to the limited extent of data series particularly regarding ground temperatures.

Out of the 13 significantly correlating pairs of variables, ten are positive/direct and three are negative/inverse. Regarding different rock glaciers and movement parameters, five correlating pairs of variables were calculated for WEI-mean, three for WEI-max, none for HLC-U-mean, one for HLC-L-mean, and finally four for DOE-mean. All 13 significant pairs of variables are shown in Figure 8 also indicating simple regressions. Regarding different annual data series of movement and climatic parameters, two correlations where calculated for more or less identical one-year periods (A), and six, two and three correlations where the beginning of the one-year climatic data period was shifted to, respectively, six (B), twelve (C) or 24 (D) months earlier in relation to the one-year data of rock glacier velocity. Strong direct correlation (≥0.8) was calculated twice, whereas modest direct or inverse correlation (r=±0.8 to ±0.5) ten times.

The comparison of rock glacier movement and air temperature as well as derivatives of it (i.e. MAAT, FDDair, and TDDair) revealed only for the TDDair of the Sonnblick Observatory statistically significant results with mostly modest correlation. Thereby, the calculated TDDair values of the identical one-year period or the one-year shifted to six months earlier showed that the warmer a year is in terms of cumulative value of positive daily mean air temperature, the faster the rock glaciers move. For WEI for instance, a value of TDD=100 at SON during the period March to February would theoretically cause a mean velocity of 3.3 cm a^{-1}, whereas TDD=600 would cause 8.0 cm a-1. For HLC-L, the same TDDair values at SON as above would cause mean velocities of 102.8 and 223.0 cm a^{-1}.

The comparison of rock glacier movement with snow data (SNOWsum and SNOWmean) shows only for the maximum velocities at WEI a significant positive correlation. This means for WEI that the more snow is available, the faster the rock glacier moves two years later. Mathematically, this means for WEI that a mean monthly snow depth of 1 m would cause a maximum velocity of 7.2 cm a^{-1}, whereas 5 m would cause 13.5 cm a^{-1}. However, in the cautious interpretation here one should not forget that the snow data used here are not directly from the rock glacier site. No correlation was detected between rock glacier movement and snow in early winter (SNOWdec) as well as snow during spring (SNOWapma). Only for HLC-U a weak but statistically insignificant correlation (r = 0.52, p=0.087) was established between SNOWdec and rock glacier movement.

The combination of rock glacier movement with ground surface temperature and its derivatives reveals that there seems to be no direct link between ground surface temperature and rock glacier velocity. Our time series on ground surface temperature are generally short hampering correlation analysis. However, at least for the mean velocities at WEI the results show that the cooler a year was (i.e. higher FDDsurf), the slower a rock glacier moves half a year to one year later. At WEI, a cumulative value of negative daily mean ground surface temperature in one year of -1000 causes a mean velocity of 4.1 cm a^{-1}, whereas a FDDsurf of -250 about 1.5 times more (6.7 cm a^{-1}). In contrast, a surprise in the correlation analysis was the statistical significant negative correlation of mean and maximum velocities at WEI with the TDD at the ground surface 6, 12 and 24 months earlier compared to the geodetic measurement periods. This would indicate at first glance for WEI that the lower the cumulative value of positive daily mean ground surface temperature in one year the slower moves the rock glacier.

The correlation results between rock glacier movement with ground temperatures at one meter depth and derivatives of it showed in general very little correlation. This was mainly – and as partly previously mentioned – due to lack of long time series as well as non normal distribution of data. However, where the ground temperature data at one meter depth were relatively good (only at DOE), correlation was strong. The mean

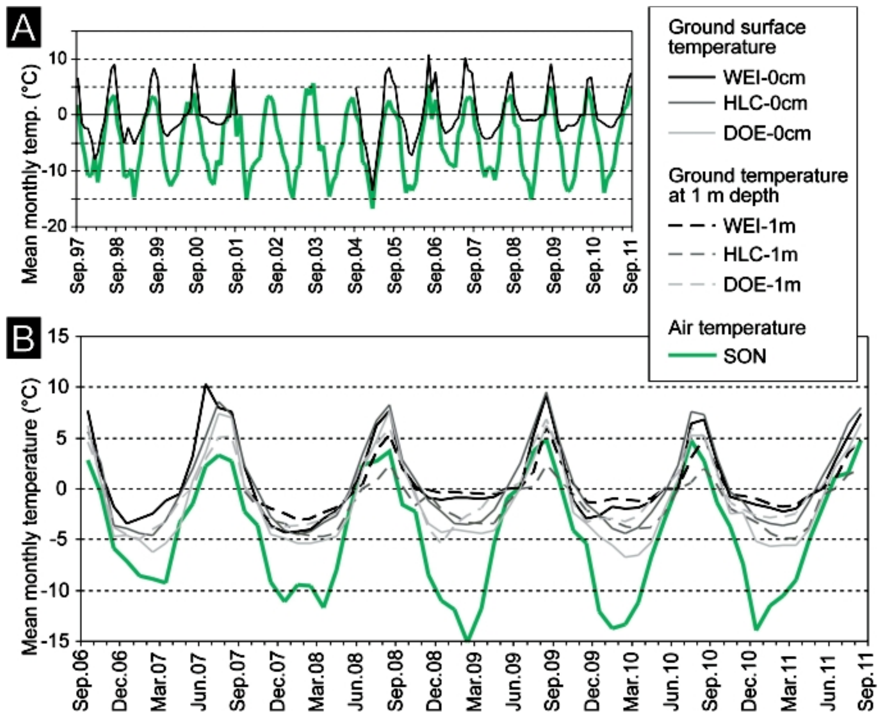


Figure 7: Mean monthly temperatures during the period 1997-2011 at the ground surface at WEI (A) as well as at the ground surface and at 1 m depth at the three rock glaciers WEI, HLC and DOE during the period 2006-2011 (B). Additionally, the mean monthly air temperature for SON is plotted for the relevant periods for comparison.

velocity of DOE is strongly related to the FDDdepth of the same year. Thermal conditions of FDDdepth of -400 would cause a mean velocity of 37.2 cm a-1, whereas -800 only 24.7 cm a-1. Finally, the MAGT at one meter depth of a period 6 months earlier in relation to the geodetic measurement year shows strong correlation. Here, a MAGT value of -2°C causes a mean velocity of 18.0 cm a-1. A decrease in temperature by 1°C would cause an increase in velocity to 26.4 cm a^{-1}.

5. Discussion

Our results show that there is generally a strong but at the same time not a simple relationship between rock glacier velocity and climate if looking on the results from the monitored

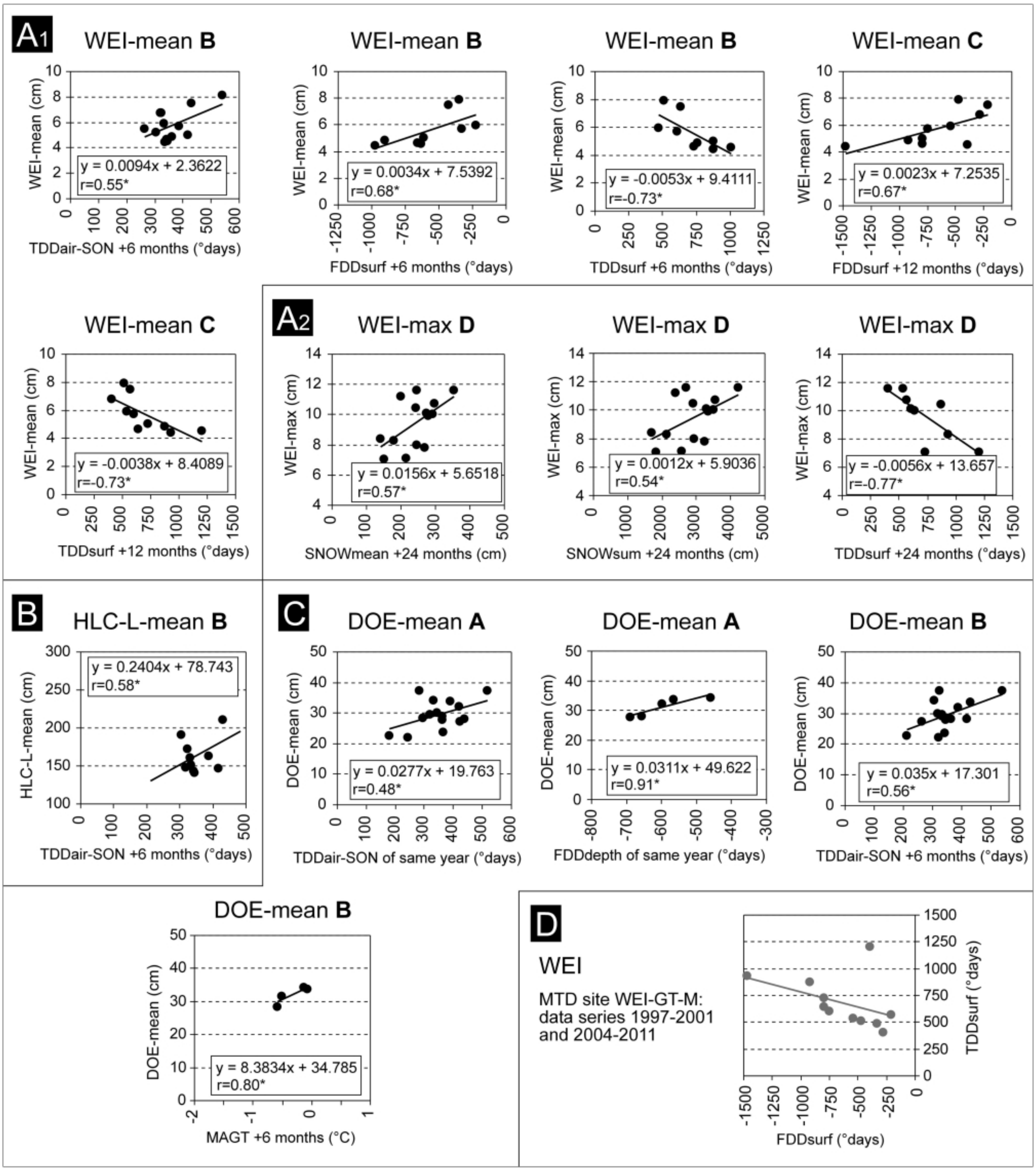


Figure 8: Linear simple regression plots of all 13 statistically significant pairs of variables. The results of relevant climatic parameters with mean velocities of WEI (A1), maximum velocities of WEI (A2), and mean velocities of the lower part of HLC (B) and DOE (C) are presented. Linear functions, correlation coefficients and significance (all at the p<0.05 level/*) are indicated. In (D) the relationship between FDD and TDD for the surface sensor at the MTD site WEI-GT-M with data from 1997-2001 and 2004-2011 is indicated.

rock glaciers. It seems to be doubtless that air and consequently ground surface and ground temperatures at depth are the most important factors in controlling relative changes in the velocity. This circumstance is regardless to even large differences in the absolute velocities as shown here with mean velocities of up to between 8 cm a^{-1} at WEI in contrast to 262 cm a^{-1} at the lower and faster part of HLC. This relative homogeneity in rock glacier behaviour is not only valid for the Hohe Tauern region with our three studied rock glaciers, but also for rock glaciers elsewhere in the European Alps (Delaloye et al., 2008).

Going further back in time before the mid-1990s was accomplished by applying photogrammetry. Results of this allow the probable conclusion that the maximum velocities during the measurement years 2003-2004 and 2010-2011 were by far the fastest one of the last 5.5 decades (Fig. 4). The three rock glaciers moved slower around the wetter, cooler and glacier friendlier years in the 1970s and 1980s (Fig. 4C), compared to the years since annual geodetic measurement initiation. This observation is also confirmed from long-term monitoring of rock glacier movement in Western Austria (Schneider and Schneider, 2001) and to some extent from the French Alps (Bodin et al., 2009). At faster moving rock glaciers where the debris supply is smaller in relation to the debris transport by the moving rock glacier, cracks might form, the rooting zone depression might enlarge or the rock glacier could even turn to dynamically inactive (Barsch, 1996) due to debris starvation. At HLC the lower part is faster compared to the upper part one forming cracks during the last decades (Avian et al., 2005). Figure 5 shows well that the faster, lower part reacted more intense to the warm temperature in 2007 compared to the upper one further enhancing the tearing apart of the upper part of the rock glacier from the lower part.

Generally, a time lag of one to more years for acceleration can be observed after a rock glaciers reacts to warm air temperatures. The analyses of the geodetic data reveal the differentiation of six different main phases: (a) low velocities in the mid-1990s, (b) faster velocities at the end of the 1990s, (c) again low velocities in 1999-2000, (d) steady acceleration peaking in 2003-2004 with very high rates, (e) steady deceleration in velocities until 2007-2008 with values partly even lower than 1999-2000, and finally (f) steady but faster increase compared to the period 2000-2004 until 2011. Combining these phases with air temperature data shows that fast accelerations can be explained in two ways. Either this acceleration is related to very high air temperatures (as in 2007-2008) or by constant higher air temperatures over a longer time period. In the latter case, the acceleration was rather gradually from year to year. An explanation for this might be gradual warming of the ice in the permafrost body accompanied by relatively high content of liquid water compared to cooler periods. These effects might increase gradually creep velocities to such a state where they accelerated even more (Buck and Kaufmann, 2008). Based on our results it is not possible to conclude that faster rock glaciers also react faster or more intense to warming or cooling if comparing the lower part of HLC (very high rates) with the ones of WEI (very low rates).

Deceleration seems to be slightly different to acceleration in terms of response time. Strong cooling causes a faster deceleration in comparison to strong warming and acceleration as for instance in 1999-2000 and 2004-2006. Possibly this is related to the availability of liquid water within the rock glacier. Cooler temperatures – particularly in terms of cooling intensity in winter – cause refreezing of pore water causing a deceleration in rock glacier deformation and surface movement (Ikeda et al., 2008).

Judging from the air temperature-velocity relationship in the period mid-1990s to 2011, it seems to be feasible that the peak in surface velocity was reached in 2010-2011. An exception might be the lower part of HLC and its steep front. At HLC the specific topographic situation with the steep frontal part might trigger faster velocities with enhanced tearing-apart of the rock glacier during periods of warmer temperatures. In contrast, during cooler periods gravitational forces still act on the moving mass impeding deceleration. Either this might lead to tearing-apart and rock glacier disintegration at the frontal part (as at the Bérard rock glacier in France; Krysiecki, 2009) or the rock glacier will decelerate again and therefore adapt to the new thermal conditions as happened after the peak in 2003-2004 at HLC-L.

The correlation analysis between the movement parameter (rock glacier velocity) and the different climatic parameters (air temperature, snow depth, ground surface temperature and ground temperature at 1 m depth and derivatives of them) revealed strikingly one of the most important problems in permafrost research; the shortage of longer time series. Particularly ground temperature data are the main limitation here and continuation of permafrost monitoring is of crucial importance. Gaps in data series make interpretations even more difficult as for instance the missing geodetic campaigns at WEI in 2002 or at DOE in 2003. At DOE we therefore probably missed the year with the highest movement rates of the entire period 1995-2011.

Studies on the seasonal variations of rock glacier velocities showed that seasonal changes are very much related to rock glaciers where the permafrost base is above bedrock, whereas such changes are less important where permafrost reaches bedrock (e.g. Haeberli et al., 1998; 2006; Krainer and Mostler, 2006; Hausmann et al., 2007; Delaloye et al., 2010). In some cases also basal sliding could take place along a water-saturated, fine-grained layer below the rock glacier body if water conditions are suitable during summer (Hausmann et al., 2007). No seasonal velocity measurements exist for the three rock glaciers WEI, HLC and DOE. However, judged from the warm MAGT at one meter depth at the three rock glaciers (<-2°C) it seems to be very likely that the permafrost base is above bedrock and therefore seasonal variations are very likely.

Only 13 out of 270 pairs of variables show statistical significant correlations (Fig. 8). Eight of the correlating pairs of variables support the observation that warmer air temperatures (in terms of a high value of TDD), warmer ground surface temperatures (in terms of a low value of FDD), and warmer ground temperatures at 1 m depth (in terms of MAGT as well as low value of FDD) favour faster rock glaciers and rock glacier acceleration. This, as well as the findings by Buck and Kaufmann (2008), indicates that warmer temperatures favor higher velocities at all three studied rock glaciers with a delay of up to two years reflecting the delay in propagation of the temperature signal deeper into the rock glacier body. Higher temperatures cause higher deformation rates of the ice contained in the rock glacier as well as influencing the quantity and sources for liquid water lubricating rock glacier movement (Ikeda et al., 2008). However, the coupling between air and ground temperature due to conductive and non-conductive heat transfer processes is complex. Haeberli et al. (2006) pointed out that numerical modelling of energy fluxes through rock glacier surfaces requires parameterisation of for instance solar radiation, sensible heat, surface albedo, heat conduction and advection, latent heat transfer. Therefore, this would need correspondingly large amount of precisely measured or computed data and different types of numerical models (Mittaz et al., 2000; Hoelzle et al., 2001). Furthermore, coarse blocks generally building up the surface layer of rock glaciers cause further complications in heat transfer between the atmo- and the lithosphere (e.g. Humlum, 1999; Herz et al., 2003; Haeberli et al. 2006, Gruber and Hoelzle, 2008).

The interpretation of the results on the relationship between snow cover and rock glacier movement must be done cautiously. The snow data used here are not local data from the rock glacier site therefore interpretations regarding the significance of snow on the rock glacier movement is difficult if thinking about the strong spatial and temporal changes of the winter snow cover in the Schober Mountains (Rieckh et al., 2011). However, possibly the correlation results with SNOWmean and SNOWsum for DOE still indicates some sort of a rather long-term delay in velocity caused by snow melting, percolation of the melted snow into the rock glacier body, and storage of this water for weeks to months favouring faster rock glacier movement. Such long travel times of groundwater in rock glaciers are feasible if looking on studies on a relict rock glacier in Eastern Austria (Pauritsch et al., 2012). Furthermore, there was no clear correlation found out in our analysis between the snow cover in December (SNOWdec) and rock glacier movement as found out by Bodin et al. (2009) for one rock glacier in the French Alps. However, our results still confirm (although not statistically significant) the results by these authors where higher snow depths in December cause faster annual movement rates.

The negative correlations between the mean and maximum velocities of WEI and the cumulative value of positive daily mean ground surface temperature in one year seem to be abnormal. The established correlations would indicate that the less warmer a summer is, the faster moves the rock glacier. This is generally contradictory to our other results (as well as to earlier studies as e.g. Delaloye et al., 2008) where it is shown that warmer/less cold temperatures are related to faster movement and not vice versa. Three possible explanations for this might be that, first, only the data of one MTD site at the surface of the rock glacier (site WEI-GT-M) were compared with data of 16-18 stabilized observation points. The site specific situation (e.g. snow and thermal properties) might cause lower TDDsurf values compared to the mean situation at the rock glacier surface hence is not representative for the entire rock glacier. Second, Figure 8D shows for the site WEI that years with a high value of TDDsurf are generally also years with a high FDDsurf value. This suggests that the moderate cold temperatures during one year are more important for higher velocities than warmer summers. Third, a further reason for slower velocities after periods with higher TDD might be higher rates of water loss and hence less water availability in the rock glacier itself reducing possible lubrication of the rock glacier body.

The best correlation results were achieved by combining the movement data with the ground temperature data at one meter depth. Here linear regression models for DOE show us that in case the cumulative value of negative daily mean ground surface temperature in one year is -400, the mean surface velocity of the rock glacier in the same year is about 37.2 cm a^{-1}. In contrast, during a year twice as cold with a FDD value of -800, the velocity is only 24.7 cm a^{-1} hence causing a deceleration by one third. One of the most useful result on a regional scale was achieved by correlating the mean annual values of DOE with the MAGT where the beginning of the one-year data period was shifted to six months earlier. Results showed here that a warming of ground temperatures at one meter depth by 1.9°C (from -2.2°C to -0.3°C) at DOE would cause a doubling in mean surface velocities. However, the temperatures at one meter depth are close to melting conditions and the local lower limits of discontinuous permafrost are at the fronts of the rock glaciers (Lieb, 1998). Therefore, it might be in this century that the inversion from velocity increase due to warming of permafrost to decrease due to substantial melting of permafrost will occur at DOE but also at many other rock glaciers in central and eastern Austria located near at the lower boundary of permafrost occurrence.

6. Conclusions

The combination of geodetic and photogrammetric velocity data allowed us to go back in time for up to 5.5 decades until 1954. With this it was possible to show that the rock glacier movement between the mid-1950s and mid-1990s was generally lower compared to the period afterwards. Either the measurement year 2003-2004 or 2010-2011 was the fastest during the last 5.5 decades related to climatic conditions. During these two measurement years, mean velocity was about 1.5 to even 3.2 times faster compared to lowest mean velocities during the older periods measured photogrammetrically.

The comparison of the three rock glacier velocity time series showed strong and highly significant positive correlations.

This demonstrates that the relative interannual variations of the rock glaciers are caused by external climatic factors and are not related to local conditions which are quite different at the three studied rock glacier sites. This is in accordance to rock glacier behaviour elsewhere in the European Alps.

Measurements from the geodetic period revealed six different main phases: (a) low velocities in the mid-1990s, (b) faster velocities at the end of the 1990s, (c) low velocities in 1999-2000, (d) steady increase in velocity peaking in 2003-2004, (e) steady deceleration in velocities until 2007-2008 with values partly even lower than 1999-2000, and (f) steady but faster increase compared to the period 2000-2004 until 2011. The exceptional fast accelerations are either related to very high air temperatures over a short period or by constant higher air temperatures over a longer time period causing gradual warming of the ice in the permafrost body accompanied by relatively high content of liquid water compared to cooler periods.

Generally, a time lag of one to more years for acceleration can be observed when a rock glacier reacts to warm air temperatures. Strong cooling causes a faster deceleration in comparison to strong warming and acceleration.

By correlating rock glacier velocity with different climatic parameters (air temperature, snow depth, ground surface temperature and ground temperature at 1 m depth and derivatives of them) it was shown that the relationships are complex and only in few cases statistically significant. Most of the correlating pairs of variables support the observation that warmer air temperatures, warmer ground surface temperatures, and warmer ground temperatures at 1 m depth (or derivatives of the three parameters) favour faster rock glaciers and rock glacier acceleration. The most striking problem in the analysis were short time series in particular of ground temperature (surface and at one meter depth).

The combination of rock glacier movement with ground surface temperature and derivatives of it reveal for instance for WEI that the cooler a year was (in terms of cumulative value of negative daily mean ground surface temperature/FDDsurf), the slower a rock glacier moves half a year to one year later. For WEI it was shown that a FDDsurf of -1000 causes a mean velocity of 4.1 cm a^{-1}, whereas a FDDsurf of -250 (one fourth) a velocity of 6.7 cm a^{-1}, hence about 1.5 times faster. This indicates that a milder winter causes a substantial increase in velocity.

The established statistical significant relationship between snow cover and rock glacier movement hint some sort of a rather long-term delay in velocity caused by snow melting, percolation of the melted snow into the rock glacier body, and storage of this water for weeks to months favouring faster rock glacier movement with a substantial time lag. However, due to the fact that snow depth data are not directly from the rock glacier sites, interpretations must be done cautiously.

The correlation results between rock glacier movement with ground temperatures at one meter depth and derivatives of it showed in general very little correlation caused by data series restrictions. However, where the ground temperature data of sufficient length were available (as for the rock glacier DOE), correlations were strong and highly significant. A reduction by 50% of the FDD at one meter depth (FDDdepth) causes a velocity increase by 1.5 times.

All three rock glacier fronts are close to the local lower limits of discontinuous permafrost. Therefore, the inversion from velocity increase due to warming of permafrost to decrease due to substantial thawing of permafrost is feasible within this century at the three studied rock glaciers, but also possibly at many other rock glaciers in central and eastern Austria.

Finally, the results of our study clearly showed that there is a need for long-term continuous data series (e.g. PermaNET for the European Alps; Mair et al., 2011) to try establishing relationships between rock glacier velocity and climate parameters. On the one hand, annual velocity data from the three studied rock glacier exist since about 1.5 decades in high quality. On the other hand, air and ground temperature data series directly from the rock glacier sites are substantially shorter and none of the three rock glaciers are equipped with a permafrost borehole. Ongoing geophysical measurements at all three rock glaciers studied here (Erich Niesner, pers. comm. 2011) will help to better understand the three landforms. Therefore, the data used here allowed a first estimation of the relationship between rock glacier and climate but longer time series and additional future data will certainly improve the results presented here.

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