WP 6 – Action 6.2 – State of the art report

Hazards related to permafrost and to permafrost degradation

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Editors

Philippe Schoeneich, Institut de Géographie Alpine, Université de Grenoble, France

Matteo Dall'Amico, Geological service, Autonomous Province of Trento, Italy

Philip Deline, EDYTEM, Université de Savoie, France

Andreas Zischg, Abenis Alpinexpert GmbH/srl, Bozen/Bolzano, Italy

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14 bis av. Marie-Reynoard

F-38100 Grenoble

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1. Rockglaciers

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Authors

Coordination : Philippe Schoeneich

Involved PPs and contributors :

- IGA-PACTE – Philippe Schoeneich, Jean-Michel Krysiecki, Xavier Bodin
- IGRS – Andreas Kellerer-Pirklbauer, Gerhard Karl Lieb

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Summary fo decision makers

Rockglaciers are the most prominent features of alpine permafrost. They are creeping accumulations of debris, moving usually at rates of cm/yr or dm/yr. The observed changes on rock glacier dynamics are all related to velocity changes, and show in most cases an increase in velocity.

Depending on the importance of the velocity increase, the five following types of reaction can be distinguished:

- Moderate positive and negative velocity changes, related to changes of MAGST with a time lag of one to two years.
- Acceleration of rock glacier displacement, with opening of crevasses on the rock glacier surface.
- Rupture and dislocation of the lower part of rock glaciers: in several cases, the lower part of the rock glacier starts to move significantly more than the upper part.
- Total collapse of the lower part of the rock glacier: the lower part of the rock glacier breaks down as a debris flow and is totally removed.
- Very strong acceleration of the rock glacier: the acceleration speeds up to very high values. One case is known so far, were velocities reached values as high as 80 m/yr !

The expected effects of velocity changes can be either local and limited to the rockglacier surface, or affect the downslope area:

- Veloctiy increase will induce increased damage to infrastructures built on rockglaciers.
- Strong acceleration will increase the surface instability, and the formation of scarps can lead to local rockfall hazard on the rockglacier surface.
- Velocity increase will induce increased rockfall activity on the rockglacier front, as well as a progression of the front.
- Partial or total rupture and collapse can occur in a few cases, and threaten potentially large areas downslope.
- Where rockglacier fronts are overhanging steep slopes or torrential catchments, secondary processes mobilizing the released debris can induce an increased hazard downslope.

The following recommendations can be made in order to reduce hazard due to rockglaciers :

- Infrastructures on rockglaciers should be avoided.
- The zones in front of active rockglaciers should be avoided.
- If the front of an active rockglacier is overhanging a steep slope, a security zone should be observed downslope of the rockglacier, with consideration of potential direct and indirect processes like rockfalls and debris flows.
- Paths and trails crossing rockglaciers or passing in front of rockglaciers should be regularly checked for security.

1. Introduction

Rockglaciers are the most prominent features in alpine permafrost. They are creeping landforms made of debris saturated by ice, and moving usually at a rate of a few cm/yr to dm/yr. Some rockglaciers are known to move faster.

Active rock glaciers are creeping permafrost phenomena. Therefore, their rate and mode of movement is strongly related to climatic conditions and as a consequence to the ground thermal regime at a given rock glacier site as pointed out by for instance Kääb et al. (2007) or Delaloye et al. (2008). Considering this, temperature and its change over time might be regarded as a good proxy for rock glacier velocity changes. 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 a later phase, the significant loss of ice content by permafrost degradation is able to reduce the deformation rate of the rock glacier towards its entire deactivation. Besides climate, however, factors such as slope, sub-rock glacier topography, thickness of the deforming layer, marginal friction, density, debris content, relative debris distribution, ice softness (as a function of temperature), water content and distribution (Ikeda et al. 2008) as well as layering influence the kinematics of rock glaciers (cf. e.g. Kääb et al. 2007).

In most cases, rockglaciers do not represent any serious hazard, except the instability of their surface and local rockfalls at the steep front. The surface movements, though moderate, can nevertheless cause damages to sensible infrastructures like cableways or buildings.

Recent observations show that changes are occurring and that some rockglaciers may experience drastic changes in their dynamic. Thus hazards related to rockglaciers could become more important in the future. It is therefore important to understand how rockglaciers react to changes in air and ground temperature. The latter appears to be the driving factor of rockglacier creep variations.

2. Reaction typology

The observed changes on rock glacier dynamics are all related to velocity changes, and show in most cases an increase in velocity.

Depending on the importance of the velocity increase, the five following types of reaction can be distinguished:

1. Moderate positive and negative velocity changes: these can be related to changes of MAGST with a time lag of one to two years. The running mean of the ground surface temperature (12 to 24 previous months, depending on the rock glacier) shows a good correspondance with the velocity changes (Delaloye et al. 2008, Bodin et al. 2009). The match with the MAAT is not as good (Buck & Kaufmann 2008, Kellerer-Pirklbauer et al. 2008). This is most probably due to the thermal offset induced between air and ground temperatures by the snow cover.
2. Acceleration of rock glacier displacement, with opening of crevasses on the rock glacier surface (Roer et al. 2008).
3. Rupture and dislocation of the lower part of rock glaciers: in several cases, the lower part of the rock glacier starts to move significantly more than the upper part. This leads to the formation of a scarp separating the two parts. In most cases, the lower part shows a disorganization of the surface topography, with perturbations of the initial ridge and furrow pattern and formation of crevasses, whereas the upper part keeps its “normal” shape (Roer et al. 2008).
4. Total collapse of the lower part of the rock glacier: the lower part of the rock glacier breaks down as a debris flow and is totally removed. A new front develops from the scarp. Only one

such case is known so far in the Alps (Krysiecki 2008, 2009), but potentially similar cases have been identified in the Chilean Andes (Iribarren & Bodin 2010).

5. Very strong acceleration of the rock glacier: the acceleration speeds up to very high values. On case is known so far, were velocities reached values as high as 80 m/yr ! The phenomenon started in summer 2009 and is followed since then, but one doesn't know how long it can last at such speeds before a total collapse (Delaloye et al. 2010).

Types 1 to 4/5 can be seen as a gradation, with increasing velocity. The two last types can be seen as two different end members of the evolution. The various possible evolution trajectories of rockglaciers in a warming climate can be summarized in the draft of figure 1.1.

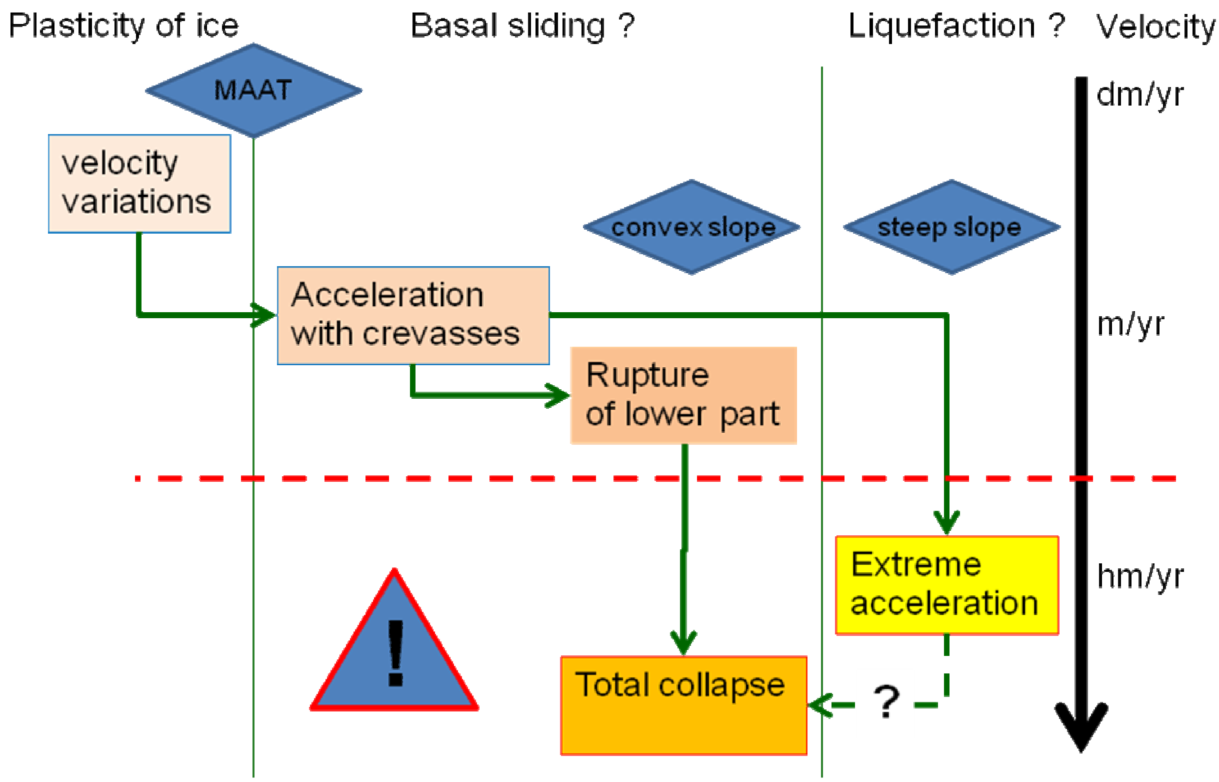

Fig. 1.1 – Evolution trajectories of rockglacier behavior with increasing temperature.

3. Processes involved

The movement of rock glaciers is usually explained as a cohesive flow due to the internal deformation of the ice-rock mixture constituting the permafrost body. It is admitted that no basal sliding is occurring at the rock glacier base, and that the whole movement is explained by the flow deformation. The few existing inclinometer data show that an important part of the deformation occurs at the base of the rockglacier in a shear horizon of limited thickness. This flow mechanism is very similar to that of a cold based glacier. The flow is made possible by the viscosity of the ice, but it supposes that the permafrost body is supersaturated with ice.

The viscosity is function of pressure. In pure glacier ice, the upper 30-50 m show brittle deformation, and it is only with a thickness higher than 30 m that the ice has a sufficient viscosity to allow flow deformations. Rock glaciers only rarely reach such thicknesses. But an ice-rock mixture has a lower viscosity than pure ice, and can therefore show deformations at lower pressure/thickness. Thus the viscous flow of rock glaciers is allowed: 1) by the overloading due to the thick rock cover of the active layer, and 2) by the impurities and rock fragments contained by the ice, which lower the viscosity of the ice.

Considering this general theoretical knowledge, how can we explain the various observed reaction patterns ?

3.1 Moderate velocity variations

The velocity variations related to air and ground temperatures are possibly due to viscosity changes with temperature. The viscosity of ice becomes smaller when the ice temperature is close to the melting point. So a rise of temperature induces an increase of flow deformations, and a drop of temperature induces a decrease of the deformations. Significant velocity changes occur only when several positive/negative seasonal deviations cumulate over more than one year. Data clearly show the cumulative effect of, for instance consecutive snow rich winters and hot summers, inducing acceleration, or snow poor cold winters and cool summers, inducing cooling of the ground and deceleration. The observed time lag of the order of 1-2 years can then be considered as the thermal diffusion time through the permafrost body.

Another factor may be the presence of melt water. When the permafrost temperature becomes close to the melting point, meltwater will be available not only on the permafrost table, but possibly also within the permafrost body, and percolate through it. This water could allow internal sliding along ice grain boundaries, inducing enhanced deformation rates.

3.2 Acceleration

The transition from moderate velocity variations to acceleration possibly needs a process change.

The opening of crevasses means that at least in surficial ice layers the tension forces exceed the viscous accommodation capacity of the ice. This means also that the acceleration doesn’t take place in the surface layers but at a certain depth in the permafrost body, or even at its base.

One hypothesis is that a basal sliding takes place, due to an increase in melt water availability. Thus the motion mode would change to a type very similar to that of temperate based glaciers. No deformation profile is available on rock glaciers showing this type of evolution, so the question cannot be answered. It has to be noted too, that according to borehole data, many rock glaciers do not lie directly on bedrock, but on unfrozen debris. In such cases, it is unlikely that sufficient water pressure could build up to allow basal sliding.

In any case, a threshold seems to be crossed between normal creep of rock glaciers and onset of surficial dislocation features due to acceleration.

3.3 Rupture and dislocation of lower part

In these cases, the lower part of the rock glaciers clearly changes to a different flow mechanism than the upper part. The onset of basal sliding is probable.

But local conditions are involved too. All reported cases show a convex long profile, and a scarp located at the knickpoint. The slope gradient appears therefore as an important factor favoring the rupture of rock glaciers (Avian et al. 2009).

3.4 Total collapse

The total collapse appears as the paroxysmic case of the rupture. In the only reported case of the Alps, it could be shown that the process started with the formation of a scarp and the acceleration of the lower part, characteristic features of the rupture in two parts induced by the acceleration of the lower part of the rock glacier. The scarp is located on the knickpoint to a steep slope. The collapse occurred three years after the formation of the scarp, as a rapid slide or mud-flow (Krysiecki 2008, 2009).

Why the Berard rock glacier collapsed, and why the other cases remain stable is unknown. One possible reason could be the nature of material. The collapsed Berard rock glacier is built of fine debris of schists, whereas the other cases are made of coarse blocky debris. In presence of water, fine schists are prone to liquefaction, whereas blocky material will drain. But it has to be mentioned that only the surface material is observable, and that in most cases we don't know the kind of material building the internal permafrost body.

3.5 Extreme acceleration

The rock glacier of Grabengufer reached velocities that scientists considered previously as impossible for rock glaciers. Whether there is still ice and how much is unknown, as is the mechanical process allowing such speeds on a steep slope without total collapse so far. The geometry of scarps and backtilting of terrain indicate rotational failures. Geophysical investigations suggest a total thickness of 15-25 m with a basal layer containing much fine-grained material and unfrozen water (Delaloye et al. 2010). Fast sliding on an unfrozen or even liquefied basal layer seems therefore to be a possible explanation.

The life-time and death of a rock glacier

Rock glaciers are classically classified as active/inactive/relict rock glaciers. An active rock glacier contains ice and shows movements, an inactive rock glacier still contains ice but shows no down-slope movement, and a relict rock glacier contains no ice anymore.

In warming conditions, active rock glaciers can become inactive. It was usually assumed that rock glaciers in boundary conditions should be less active than rock glaciers in full permafrost conditions, and that a degrading rock glacier will progressively slow down until it stops moving and becomes an inactive rock glacier. This assumption proves to be wrong.

Recent observations seem to show that in degrading permafrost conditions, a rock glacier will first experience a velocity increase, as the permafrost temperature becomes close to the melting point, and it is only in a second phase, when the ice content diminishes and the permafrost is no longer supersaturated by ice, that the movements will decrease and finally stop. Whether all rock glaciers show this evolution is unknown yet. Whether the velocity increase leads to an acceleration or even a rupture and possibly a collapse depends on local conditions (rock type, “grain-size”, ice content, nature of bed, topography, …).

4. Induced hazards

Hazards induced by rock glaciers and their evolution can be distinguished according to different criteria:

- Normal effects, that occur on all rock glaciers independent from climate change, vs new effects due to degradation.
- Local effects on the rock glacier itself, vs downslope effects.
- Proximal effects due the rock glacier itself, vs more distant effects due to process chains reworking debris originating from rock glaciers.

Distant effects due to debris flows reworking periglacial material will be treated in a special chapter. So we will concentrate here on the direct effects of rock glaciers.

Surface movements

Surface movements can be split into 1) lateral down-slope movements, due to the creep of the permafrost body, and 2) vertical movements due to the melting of ice.

Down-slope movements are a normal feature on rock glaciers, even in a stable or cooling climate, and have to be expected on any active rock glacier. As shown by numerous case studies, surface movements are subjected to increase in warming conditions, either temporally after a series of warm years, or more drastically after crossing of some thresholds. On most rock glaciers, down-slope movements are in the order of cm/yr to dm/yr. But the velocities can increase up to several meters/yr, without considering the very rare case of collapse.

Vertical settling movements are due to the melting of the ice content of the permafrost body, and can be considered as a consequence of permafrost degradation. They induce either a localised settling or a general lowering of the surface topography. The importance of the vertical movements will depend on the ice content and the rate of melting. As many rock glaciers contain thick lenses of nearly pure ice, in case of a total melting of the ice content the final settling of the surface could be very important.

Surface movements threaten only infrastructures built on or crossing rock glaciers, like cableways, roads or pipes. If movements in the dm/y range can be more or less easily accommodated by annual maintenance, movements of several dm or more are usually not sustainable anymore and can even lead to the total destruction of the infrastructure. The problem of infrastructures will be treated more in detail in a separate chapter.

Surface instability

The continuous movement of rock glaciers induces a general instability of the surficial coarse block cover. This instability probably increases with velocity.

In case of foot paths crossing a rock glacier, this could be an issue, as unstable blocks can cause accidents. In accelerating rock glaciers, showing crevasses or scarps, the hazard due to rockfalls from scarps and overhanging blocks has to be considered, especially in steep parts of the rock glaciers.

Proximal effects

The front of an active rock glacier is always an unstable area, due to the fall of stones and boulders from the top of the frontal talus. In case of a velocity increase, the instability of the front will normally increase too. This hazard is usually limited to a few meters in front of the rock glacier. But in the case where the front is or becomes overhanging over a steep slope, the reach distance of falling boulders can be much longer.

The down-slope movement of a rock glacier is associated with a progression of its front over the pre-existing topography. This progression is usually very slow. But in the case of a strong acceleration, the rock glacier front may move forward by several meters or even tens of meters. This can override and destroy infrastructures built too close to the front of the rock glacier.

Here again, if the front moves to a position overhanging a steep slope, the dynamics of the front may evolve and lead to a significant rockfall hazard.

As a general rule, foot paths and moreover infrastructures should be avoided just in front of a rock glacier, and should be kept in a safe distance below the front of very active or accelerating rock glaciers.

Distant direct effects

Total collapse or extreme acceleration with dislocation of the front have been observed only in isolated cases yet. In these cases however, important rockfalls or sudden debris flows can reach far from the rock glacier front, depending on the local topography.

Reported cases of collapse or rupture most occur when a rock glacier progresses over a convex slope and becomes overhanging over a steep slope. So the possibility of a collapse, or at least of increased rockfall activity should be considered in any case of rock glacier hanging over a steep slope (as it would be the case for hanging glaciers !).

5. Case studies

5.1 Velocitiy changes and collapse of rock glaciers in France

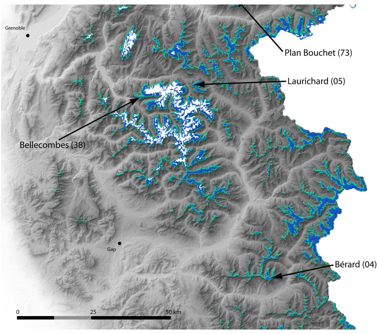

Fig. 1.2 – Location of the French case studies Laurichard and Bérard. Laurichard is situated Est of Grenoble, on the N slope of the Combeynot massif. Le Bérard is situated N of Barcelonnette, in a tributary of the Ubaye valley. The map shows the permafrost probability : dark blue colors indicate probable occurrence, green color corresponds to the uncertainty range. Both case studies are situated in the lower range of permafrost distribution.

Laurichard rock glacier

Latitude	N 45.0181°
Longitude	E 06.3997°
Elevation [m a.s.l.]	2440-2630 m
Slope	Variable: moderate on top and toe, steep (50%) in middle part
Aspect	N
Type of rockglacier	talus; lobate to tongue shaped; active
Evidence of permafrost	Observation of ground ice, ground surface temperature, geoelectric
Evidence of movement	Aerial photograph, geodetic, Lidar
Typology of movement	Velocitiy changes
Mean velocity range	From 0.3 to 1.6 m/yr
Change in velocity	20% increase 2000-2004, decrease 2004-2006
Year of first data	(1979) 1985

The Laurichard rock glacier is situated in the granitic Combeynot massif at 2500 to 2600 m asl. It is a well developed bouldery rock glacier, with distinct compression ridges and a steep frontal and lateral slope. The rock glacier has a three stepped long profile, with moderate slopes in the upper part, a steep median part, and again a moderate slope in the frontal part.

Movements have been measured since 1979 and regularly repeated since 1985. Thus it represents one of the longest displacement measurement record on a rock glacier in the Alps. Classical geodetic measurements are made under supervision of the Parc National des Ecrins on two transverse and on one longitudinal line of points. They have been performed every 2-3 years from 1985 to 1998, and annually since 1999.

Measured velocities range from 0.2 to 1.6 m/yr (fig. 1.4). The highest velocities are measured in the steep median part. The rock glacier shows an increase in flow velocities from 1985 to 1999, culminating in the early 2000's, a decrease from 2004 to 2006, and again a moderate increase since 2007. Accelerations of 2001 and 2003-4 and decelerations thereafter show a good correspondance with the MAGST (mean annual ground surface temperature), averaged over the previous 12 months (data from Valais and on site, fig. 1.5). This shows that creep rates are strongly dependant on ground surface temperatures, which appear as the main controlling factor. The warming of 2006-7 however was too short and had almost no effect. Previous to 2000, mean velocities on periods of 2 to 3 years don't show significant variations, except the mentionned acceleration trend from 1985 to 1999.

Fig. 1.3 – The Laurichard rock glacier. Left : general view (photo P. Schoeneich). Right : Lidar DTM and location of the lines for surface displacement measurements (from Bodin et al 2009).

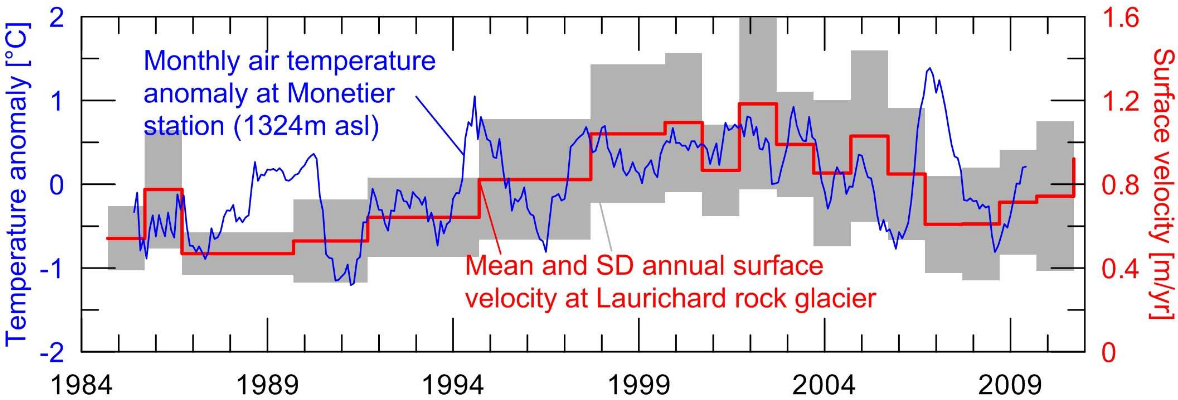

Fig. 1.4 – Mean surface velocity of the Laurichard rock glacier (RGL1) and 1σ range (grey band) from 1986–2006 (based on points L1 to L3, L5 to L8, L10 to L12), and 12-month running mean air temperature anomaly (relative to the 1960–91 average) at the Monêtier station (Meteo France data)(from Bodin et al. 2009).

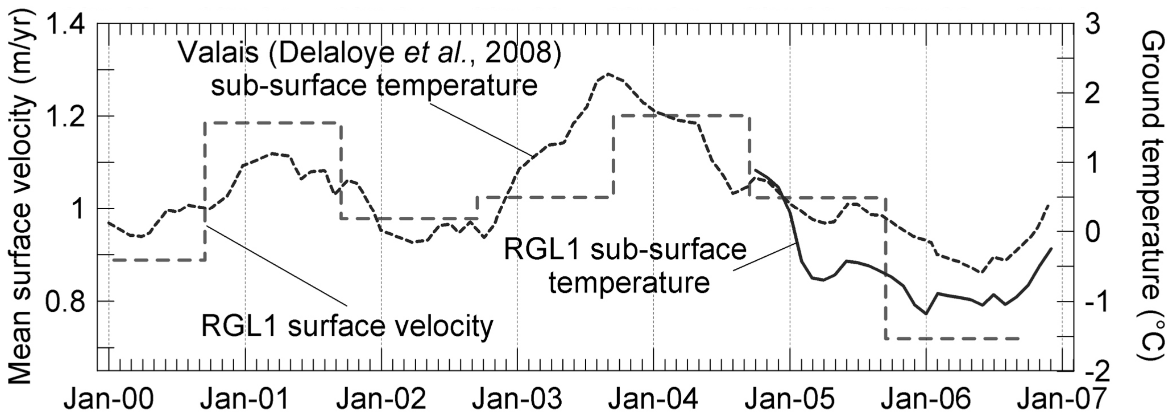

Fig. 1.5 – Ground surface temperatures and rock glacier movement, 2000–06: mean surface velocity (profile L) of the Laurichard rock glacier (RGL1), and 12-month running mean of ground surface temperatures on RGL1 (2003–06, average of four dataloggers) and in the Valais region (2000–06; western Swiss Alps; about 2500m asl, data Delaloye et al., 2008)(from Bodin et al. 2009).

Bérard rock glacier

Latitude	N44°26'
Longitude	E6°40'
Elevation [m a.s.l.]	2670-2850
Slope	Moderate in upper part, steep in lower part, overhanging front
Aspect	N-NW
Type of rockglacier	talus; lobate; pebbly rock glacier
Evidence of permafrost	Observation of ground ice, ground surface temperature, geoelectric
Evidence of movement	Aerial photograph, DGPS
Typology of movement	collapse
Mean velocity range	From 0.1 to 4.5 m/yr, locally up to 20 m/yr
Change in velocity	Strong acceleration probably in 2006, deceleration since 2007
Year of first data	2007

The Bérard rock glacier is located in the Parpaillon range at N44°26' and E6°40' between 2670 and 2850m a.s.l. (between 2650 and 2850m a.s.l before the collapse). It is a pebbly rock glacier, composed by flysch and schist debris. Due to its lithology, the Bérard rock glacier is smaller than most bouldery rock glaciers. Currently, the rock glacier is approximately 250m long and 100m wide.

At the end of the summer 2006, the frontal part totally collapsed, within a few weeks, and triggered a mud flow. No observation is available before the event, but changes on the rock glacier surface were detected on an orthophotography from 2004: a scarp developed at the place of the future rupture and closed depressions seem to have developed (Krysiecki 2008). These features strongly ressemble those identified on other accelerating rock glaciers. Thus the acceleration would have begun at least in 2004, and the very hot summer of 2003 could be the inital trigger. The collapse of the lower part occured in september 2006. The summer of 2006 was caracterized by a very hot July and a rainy August. It is assumed that the combination of a strong melting in July with the rainwater of August could have triggered the collapse (Krysiecki 2008, 2009).

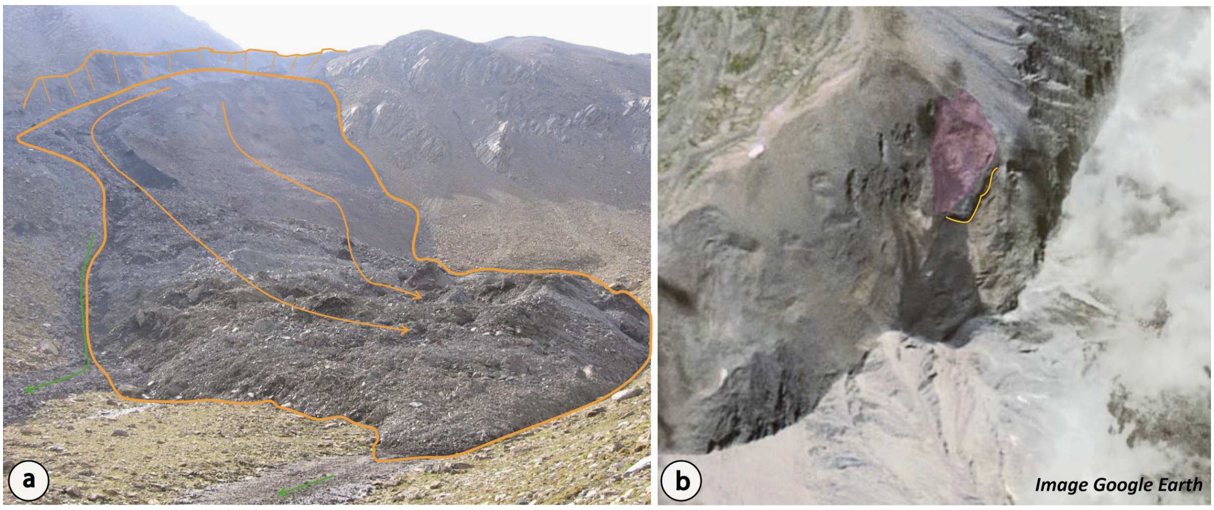

Fig. 1.6 – The collapsed Bérard rock glacier. Left: the collapsed frontal part of the rock glacier end of August 2006. The scar overhanging the steep frontal slope is clearly visible (photo Michel Peyron RTM 04). Right: satellite image from July 2006 (image form Google Earth archive). The detachement scar began to form at least since 2004 and is well developped ca one month before the collapse. The collapsing part is outlined.

At this rock glacier, a comprehensive set of methods has been initiated during the start of the summer 2007, such as geodetic survey, ground surface temperature, meteorological measurements, geomorphic mapping and geophysical survey.

The combination of the thermal and geodetic data, allows a distinction of three areas:

- The collapsed mass, characterized by strong morphological changes (rapid downwasting of ice/debris packets) just after the deposition, but no visible signs of evolution since 2007 and which displays surface velocities below 0.1 m/yr and WEqT around 0°C.
- The highly unstable but non-collapsed median part, characterized by destabilization signs like wide fractures and which displays surface velocities between 0.8 and more than 20 m/yr (no ground temperature available).
- The unstable but non-collapsed upper part of the rock glacier, characterized by creeping signs and which displays surface velocities between 0.1 and 4.5 m/yr and WEqT (Winter Equilibrium Temperature) values < - 2°C in 2008 and 2009.

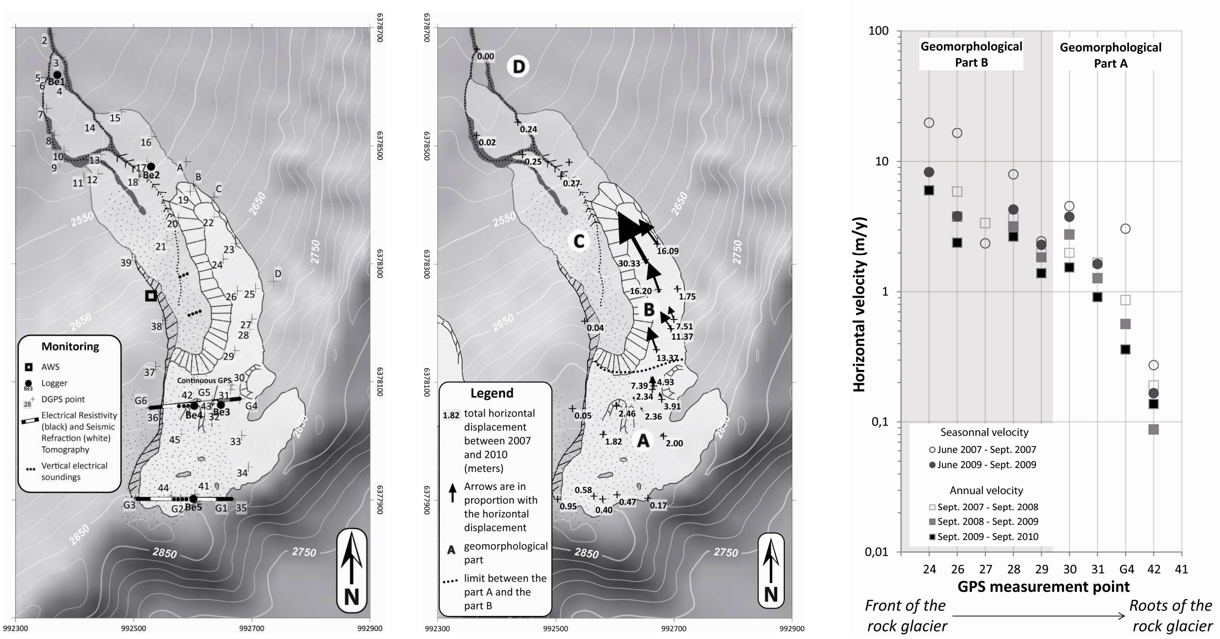

Fig. 1.7 – Evolution of the Bérard rock glacier after the collapse (from Krysiecki et al. submitted). Left: monitoring actions undertaken on the lower collapsed and on the upper remaining part (light gray) of the rock glacier. Middle: total surface displacements measured from 2007 to 2010. Right: seasonnal and interannual variations of the velocity of selected points. A decrease is clearly visible.

The Berard rock glacier is so far a unique case of total collapse of the frontal part. The question arises, on which factors could have favoured this evolution (Krysiecki 2009):

- The rock glacier front was overhanging a steep slope, and the convexity of the topography favoured the detachment and the long runout distance of the mud flow.
- The collapse occured mainly on the central and left sided part of the rock glacier front, which is made of fine debris of black shists, whereas the right sided blocky part remained in place. The former lithology is very prone to sliding when saturated with water.
- Except a lense of massive ice that was exposed after the collapse, the fine grained shist debris were cemented by ice, but with a relatively low ice content. Low resistivity values in the ERT profiles seem to confirm this point.
- GST measurements indicate only moderately cold WeqT. The permafrost was probably already a "warm" permafrost, close to the melting temperature.

5.2 Recent rock glacier velocity behaviour and related natural hazards in the Hohe Tauern Range, central Austria

1. Introduction

Climate warming was quite substantial during the last decades in central Austria as monitored at the high mountain meteorological observatory Hoher Sonnblick. This meteorological observatory is the highest permanently staffed meteorological observatory in the European Alps at 3105 m a.s.l. providing a record of climate data since 1886. The observatory is located relatively near the three rock glaciers of interest (cf. Fig. 1.9). The long time series provides also a basis for comparison of kinematic and climate parameters of the three rock glaciers. Fig. 1 illustrates the evolution of the mean annual air temperature (MAAT) during the period 1948-2009 clearly showing a significant warming. Note for instance in this figure the extremely high MAAT in 2006-2007 caused by the warm swell between summer 2006 and summer 2007. Seeing this obvious change in temperature, the question arises how this influences creeping permafrost phenomena such as rock glaciers.

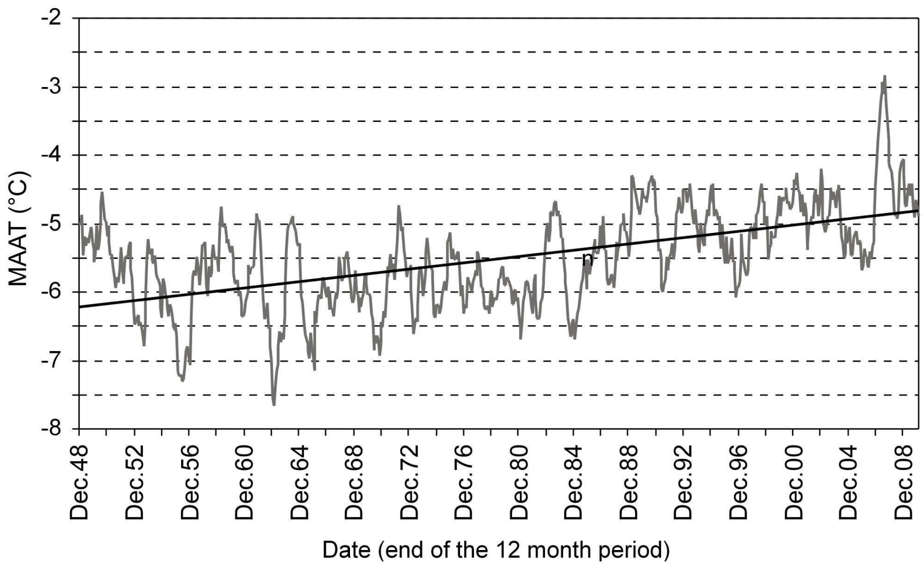

Fig. 1.8 – Mean annual air temperature (12-month running mean) at Mt. Hoher Sonnblick (3105 m a.s.l.) during the period 1948-2010. The linear trend is indicated. Note the extremely high MAAT in 2006-2007 caused by the warm swell between summer 2006 and summer 2007. For location see Fig. 2. Data kindly provided by Central Institute for Meteorology and Geodynamics/ZAMG.

In this contribution we focus on the recent movement behaviour of three active rock glaciers in alpine central Austria based on photogrammetric and in particular geodetic data and its relation to temperature and temperature changes as illustrated in Fig. 1.8. The three rock glaciers are located in the Hohe Tauern Range and are some of the best studied rock glaciers in Austria. The rock glaciers are namely the Hinteres Langtalkar (HLC), Weissenkar (WEI) and Dösen (DOE) Rock Glaciers. Photogrammetric and geodetic velocity data cover the periods 1969-2008 for HLC, 1974-2008 for WEI and 1954-2008 for DOE. Due to its annual and therefore high temporal resolution, focus within the study was laid on the geodetic data. The rock glacier velocity data of all three rock glaciers, partly also previously published (see below), as well as the orthophotographs depicted in this contribution were kindly provided by Dr. Viktor Kaufmann, Institute of Remote Sensing and Photogrammetry, University of Technology, Graz.

2. The study region and the selected rock glaciers

Hohe Tauern Range

The Tauern Range is an extensive mountain range in the Central Alps of the Eastern Alps covering some 9500 km² 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 two subgroups Hohe Tauern Range and the smaller Niedere Tauern Range. The former covers c.6000 km² and reaches with Mt. Großglockner almost 3800 m a.s.l.. All three rock glaciers of interest here are located in the Hohe Tauern Range (Fig. 1.9), two in the sub-unit Schober Mountains and one in the sub-unit Ankogel Mountains.

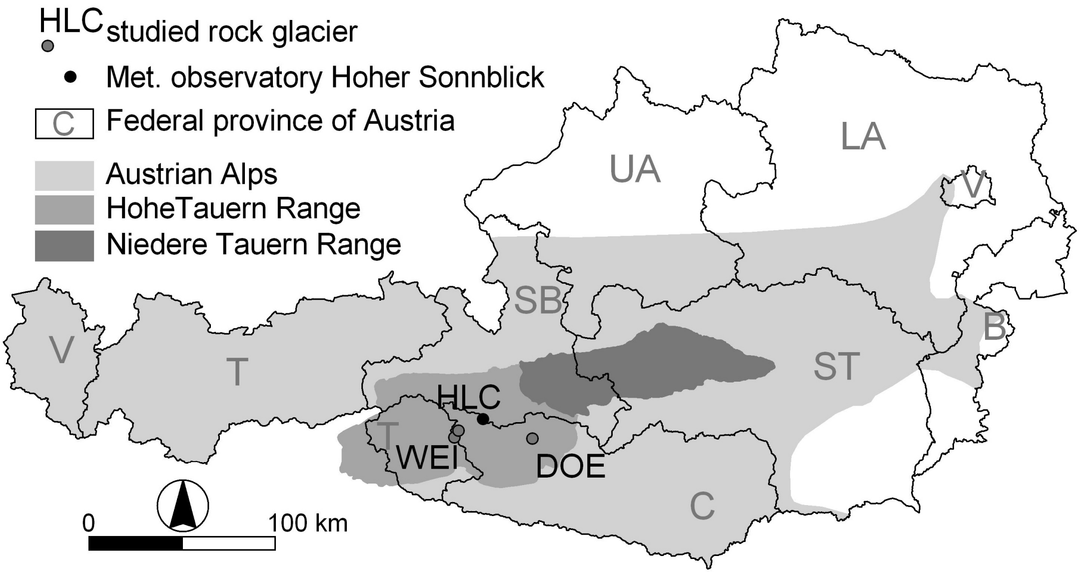

Fig. 1.9 – Location of the three rock glaciers Weissenkar (WEI), Hinteres Langtalkar (HLC) and Dösen (DOE) located in the Hohe Tauern Range, central Austria. WEI is located in the Federal Province of Tyrol (Eastern Tyrol). The other two rock glaciers are located in Carinthia. Location of the meteorological observatory at Mt. Hoher Sonnblick is indicated. Abbreviations of Federal Provinces: V=Vorarlberg, T=Tyrol, SB=Salzburg, UA=Upper Austria, LA=Lower Austria, V=Vienna, B=Burgenland, ST=Styria, C=Carinthia.

Hinteres Lantalkar Rock Glacier

Hinteres Langtalkar Rock Glacier (HLC) is located in the Schober Mountains at N46°59´ and E12°47´ between 2450 and 2720 m a.s.l. The Schober Mountains are characterized by crystalline rocks and a continental climate 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).

HLC is a very active, monomorphic tongue-shaped rock glacier with two rooting zones facing generally towards NW (Fig. 1.10). The rock glacier is approximately 850 m long, 200 to 350 m wide and consists of mica-schist and amphibolites. Distinct changes of the rock glacier surface were detected on aerial photographs from 1997 on. Its frontal part is heavily influenced by disintegration through active sliding processes since 1994 (e.g. Avian et al. 2005, 2008, 2009). The current movement pattern differentiates a slower upper part (HLC-U) and a substantially faster lower part (HLC-L) with maximum horizontal displacement rates up to 250 cm a-1 (Kaufmann & Ladstädter 2008). At this rock glacier, a comprehensive set of methods is applied (in particular since 2006) such as LiDAR, geodetic survey, aerial photogrammetry, ground surface temperature and near ground surface temperature monitoring, meteorological measurements, geomorphic mapping and observations and continuous monitoring of cirque processes by using an automatic digital camera (cf. Kellerer-Pirklbauer et al. 2009).

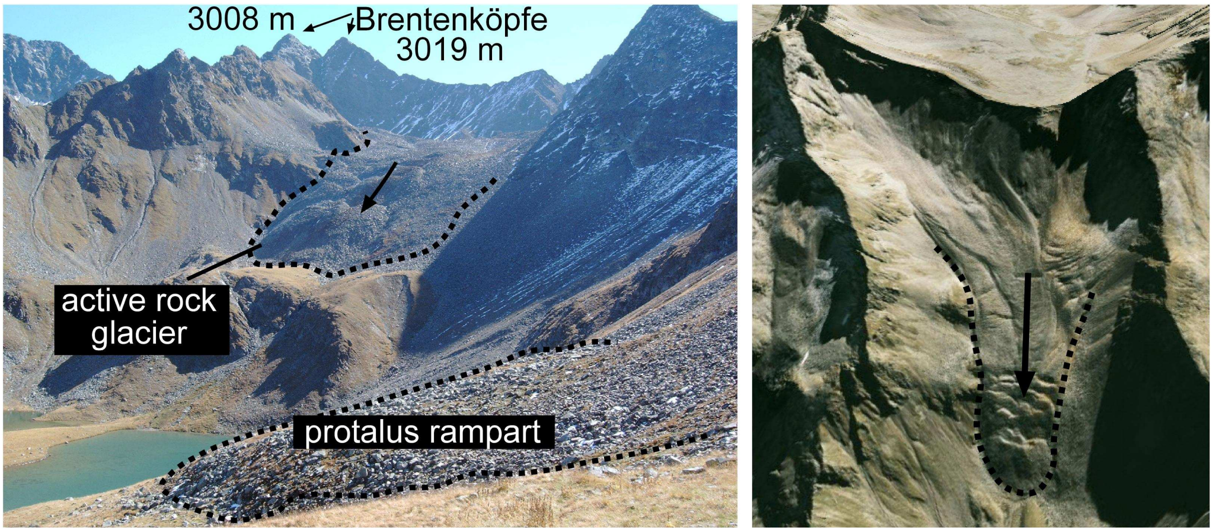

Fig. 1.10 – Hinteres Langtalkar Rock Glacier (HLC) with its length of about 850 m and its surrounding on terrestrial image and as seen from space. Photograph viewing direction towards E. Photograph A. Kellerer-Pirklbauer. Satellite image source Google Earth.

Weissenkar Rock Glacier

Weissenkar Rock Glacier (WEI) is also located in the Schober Mountains at N46°57´ and E12°45´ between 2615 and 2870 m a.s.l. WEI is located some 3.8 km SW of HLC facing towards W. WEI is a slowly moving tongue-shaped rock glacier consisting of an active upper lobe overriding an inactive lower lobe (Fig. 1.11). The landform is fed by active scree slopes and characterized by well developed furrows and ridges at its lower half, a length of 500 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 (Kaufmann et al. 2006), thus this rock glacier is substantially slower compared to HLC. Recent research at WEI was carried out by applying geodetic survey, aerial photogrammetry, ground surface temperature and near ground surface temperature monitoring, meteorological measurements, rock glacier dating as well as geomorphic mapping and observations (cf. Kellerer-Pirklbauer et al. 2009).

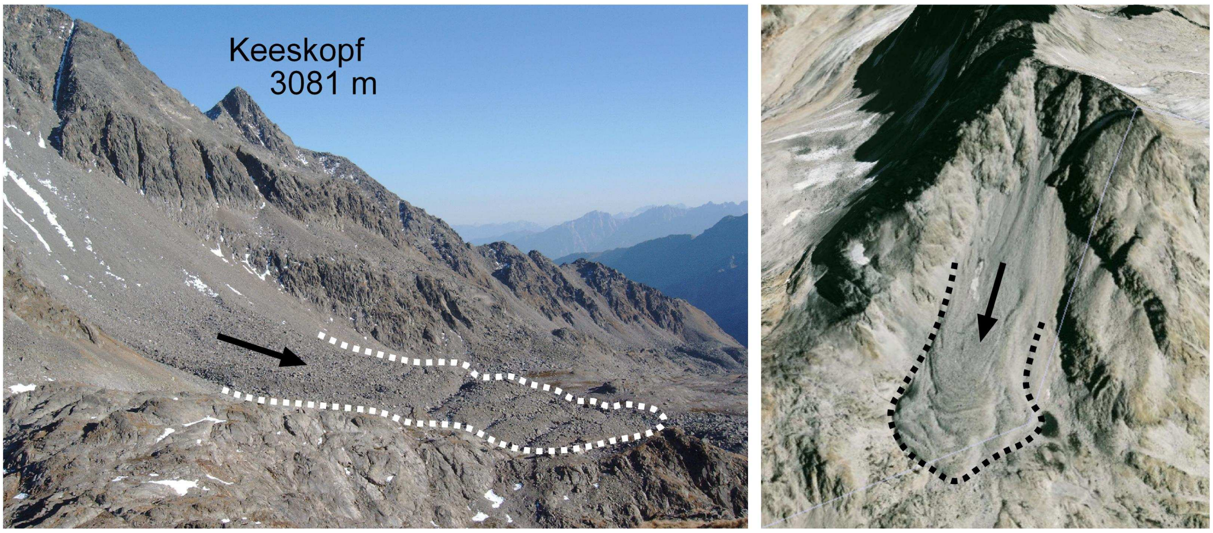

Fig. 1.11 – Weissenkar Rock Glacier (WEI) with its length of about 500 m and its surrounding on terrestrial image and as seen from space. Photograph viewing direction towards S. Photograph A. Kellerer-Pirklbauer. Satellite image source Google Earth.

Dösen Rock Glacier

Dösen Rock Glacier (DOE) is located at the inner part of the glacially shaped, E-W trending Dösen Valley, Ankogel Mountains, at N46°59´ and E13°17´ between 2355 and 2650 m a.s.l. (Fig. 1.12). 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 (Kellerer-Pirklbauer 2008). The four rock glaciers predominantly consist of granitic gneiss. The largest of the four rock glacier is DOE, an active monomorphic tongue-shaped rock glacier with a length of 950 m, a width of 150 to 300 m and a surface area of 0.19 km². Mean surface velocities during the last decades were below 40 cm a-1 (Kaufmann et al. 2007). 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) including geodetic survey, aerial photogrammetry, ground surface temperature and near ground surface temperature monitoring, meteorological measurements, geomorphic mapping and observations and continuous monitoring of cirque processes by using an automatic digital camera.

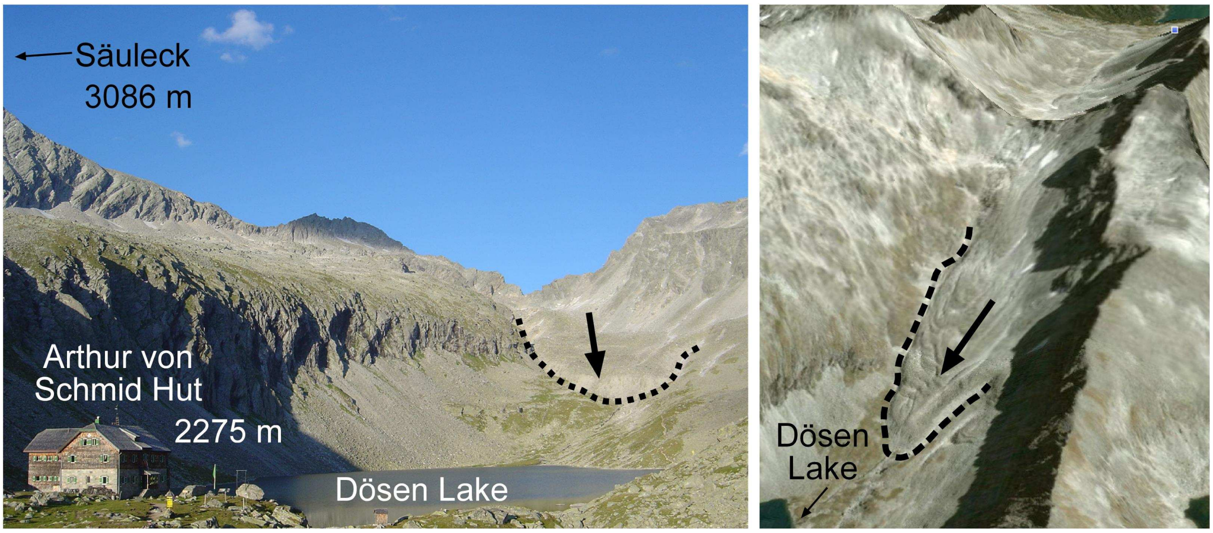

Fig. 1.12 – Dösen Rock Glacier (DOE) with its length of about 950 m and its surrounding on terrestrial image and as seen from space. Photograph viewing direction towards E. Photograph A. Kellerer-Pirklbauer. Satellite image source Google Earth.

3. Surface displacement and climate data

Rock glacier movement data

Temporal information regarding available geodetic and photogrammetric rock glacier movement data used in this study is summarised in Table 1. Furthermore, the numbers of measurement points used for calculating the mean values for each rock glacier are given. Note that only mean horizontal surface displacement values of the three rock glaciers were used for the present analysis. For HLC, the slow upper part (HLC-U) and the substantially faster lower part (HLC-L) were further differentiated. The velocity data of all three rock glaciers discussed in this chapter and the orthophotographs from Hinteres Langtalkar Rock Glacier depicted in Fig. xx were kindly provided by Dr. Viktor Kaufmann, Institute of Remote Sensing and Photogrammetry, University of Technology, Graz.

Table 1.1 – List of the geodetic and photogrammetric data and dada sources used in the present study. HLC-U and HLC-L=upper and lower parts of Hinteres Langtalkar Rock Glacier, WEI=Weissenkar Rock Glacier, DOE=Dösen Rock Glacier.

Rock glacier	Geodetic measurements	Number of measurements points[1]	Photogrammetric measurements	Data source
HLC-U	annually since 1998	9	1969, 1991, 1997	Kaufmann & Ladstädter (2008) and unpublished data
HLC-L	annually since 1998	6	1969, 1991, 1997	Kaufmann & Ladstädter (2008) and unpublished data
WEI	annually since 1997 (in 2002 no measurements)	18 (16 for 1997/8)	1974, 1998, 2002	Kaufmann *et al.* (2006) and unpublished data
DOE	annually since 1995 (in 2003 no measurements)	11	1954, 1969, 1975, 1983, 1993, 1997	Kaufmann *et al.* (2007) and unpublished data

Climate Data

Two meteorological stations have been installed in 2006 at the site HLC and DOE at the beginning of the Project ALPCHANGE (funded by the Austrian Science Fund/FWF; mainly carried out by University of Graz and University of Technology, Graz). At both stations climate data including air temperature, air humidity, wind speed, wind direction and global radiation are continuously logged (Fig. 1.13). For the present study, data were available for Sept. 2006 to Sept. 2008 at DOE and for Sept. 2006 to Aug. 2008 at HLC. No meteorological station exists at site WEI. However, due to its close distance to HLC (less than 4 km) and the same elevation rane, the temperature data collected at HLC might be also regarded as valid for WEI.

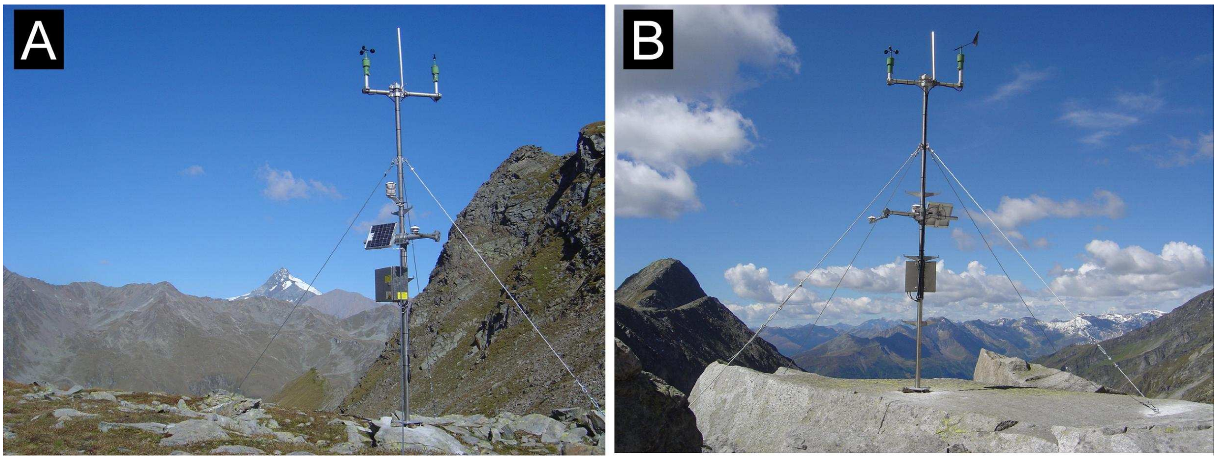

Fig. 1.13 – The meteorological station at site HLC (A) and DOE (B) installed in 2006 within the Project ALPCHANGE. The station at HLC is located on bedrock at 2655 m a.s.l. in close vicinity to the rock glacier. The station at DOE is located on a large boulder on the rock glacier surface at 2600 m a.s.l. Photograph viewing directions towards NW (A) and W (B). Photographs A. Kellerer-Pirklbauer.

In order to compare the rock glacier velocity changes with the temperature evolution, it was necessary to extend the time series of the temperature data at sites HLC and DOE from the two years of measurement (2006-2008) to a longer period. This was accomplished by correlation analysis with temperature data from the nearby meteorological observatory Hoher Sonnblick, 15 km NE of HLC, 19 km NE of WEI and 26 km ESE of DOE.

The correlation of the mean monthly temperature between Hoher Sonnblick and DOE for the 23 months period Oct. 2006 to August 2007 is high and significant ($r=0.998$, $p<0{,}01$). The mean difference in the mean monthly temperature is 2.72K. Considering the different elevations of the two stations (Sonnblick 3105 m a.s.l.; DOE 2600 m a.s.l.), a theoretical mean vertical lapse rate of 0.54°C/100 m can be calculated.

The result of the correlation analysis between Hoher Sonnblick and HLC for the 22 months period Oct. 2006 to July 2007 is again high and significant ($r=0.997$, $p<0{,}01$). The mean difference in mean monthly temperature is 3.17K, which yields a theoretical vertical lapse rate of 0.70°C/100 m between the two sites (HLC 2655 m a.s.l.). These results also indicate that despite the fact that the meteorological station at HLC is located higher in elevation (+55 m), the mean temperature is 0.45K warmer at HLC. Considering this elevation difference and a mean lapse rate of 0.65°C/100 m, the temperature difference at the same elevation between the two sites is 0.81K. In the next step, the two calculated mean difference values for DOE and HLC were combined with data from Hoher Sonnblick to calculate the mean annual air temperature (12 months running mean) for both sites for the period 1990-2009 (Fig. 1.14).

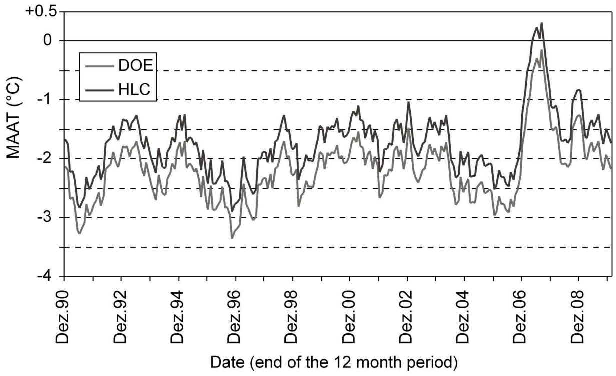

Fig. 1.14 – The measured (autumn 2006 to summer 2008) and calculated (remaining period) mean annual air temperature (MAAT) (12-month running mean) at the two sites DOE (for 2600 m a.s.l.) and HLC (for 2655 m a.s.l) for the period 1990-2009. The data of HLC are regarded as representative for the nearby site WEI. Note for instance the effects of the cooler summers 2005 and 2006 and the exceptional warm winter 2006/7 causing even a positive MAAT at site HLC. The heat wave in summer 2003 was not as effective in causing higher MAAT values as in the Western Alps (cf. Delaloye et al. 2008).

4. Recent surface velocities of the three rock glaciers

The mean horizontal surface velocity and its change over time for all three rock glaciers of interest during similar periods are depicted in Fig. 1.15. For HLC, the slower upper part was separated from the substantially faster lower part. Hence two graphs are shown for this rock glacier. The graphs show that during the period where only photogrammetric data is available (max. 1954 to mid 1990s) it is not possible to recognize a homogeneous and/or synchronous behaviour of the three rock glaciers. The main limitation in the 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 glacier were substantially lower compared to the highest values measured in the later period where geodetic measurements were carried out annually therefore providing high quality data. Regarding the geodetic data period, it is striking to see that despite variable flow complexity, morphology, mean annual surface velocity, the compared three rock glaciers show a quite homogenous and synchronous flow behaviour. Table 1.2 lists the coefficients of correlation between the three rock glaciers HLC, WEI and DOE. Again, for HLC the slower upper and the faster lower part were differentiated. The results indicate a strong and highly significant positive correlation between the three rock glaciers. The weakest correlation is between WEI and the lower faster part of HLC. This strong relationship clearly demonstrates that the interannual variations of the rock glaciers are caused by external climatic factors and is not related to local conditions.

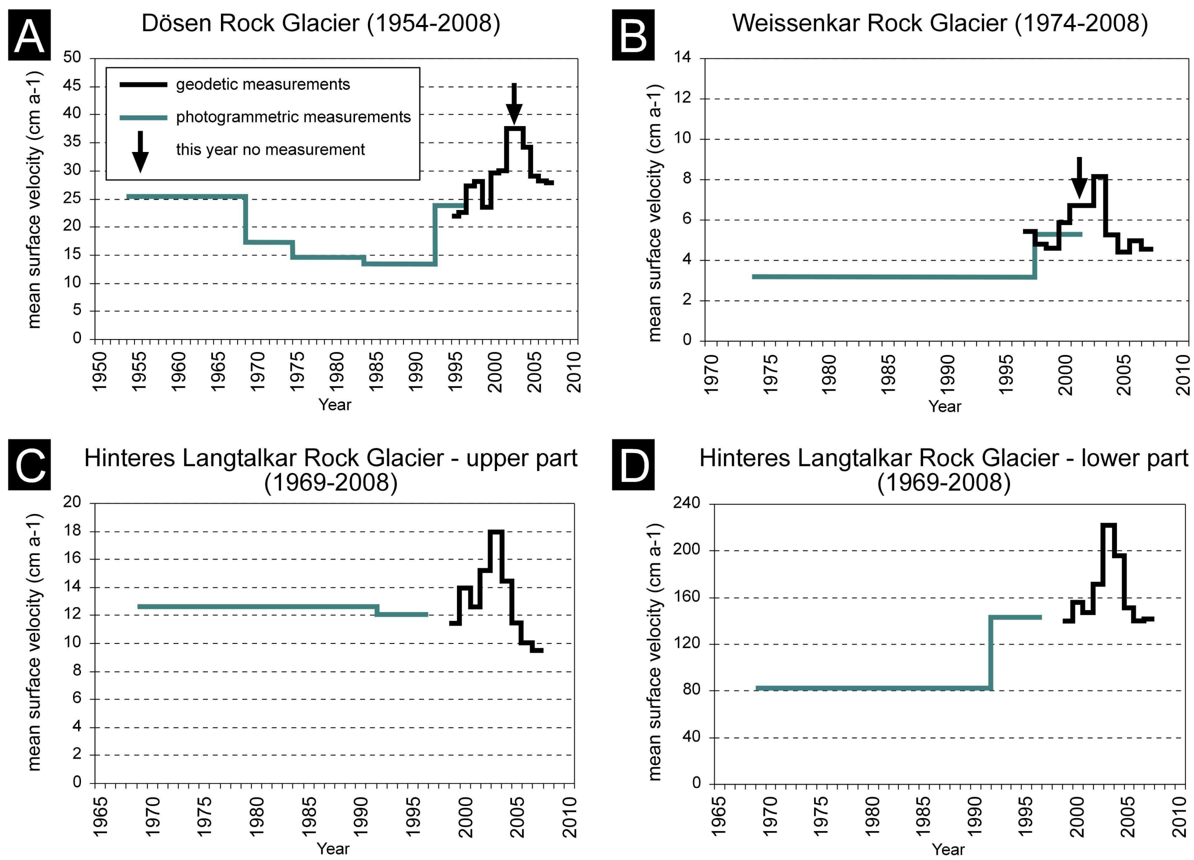

Fig. 1.15 – Mean annual horizontal surface velocities of the three rock glaciers (A) Dösen (DOE), (B) Weissenkar (WEI) and (C-D) Hinteres Langtalkar (HLC) for different periods based on geodetic and photogrammetric measurements. At HLC the slower upper and the faster lower part were differentiated. DOE – mean of 11 measurement points; WEI – mean of 16 (only first year) to 18 points; HLC-U – mean of 9 points; HLC-L – mean of 6 points. For data source refer to text.

Table 1.2 – Correlation matrix between the mean horizontal surface displacement of the three rock glaciers HLC (slow upper and fast lower parts differentiated), WEI and DOE. Correlation is significant at the 0.01 (**) or 0.05 (*) level. Number in brackets gives number of value pairs (measurement years).

Correlations	HLC-lower	WEI	DOE
HLC-U	0.895** (9)	0.841** (9)	0.836** (9)
HLC-L		0.677* (9)	0.836** (9)
WEI			0.752** (11)

Fig. 1.16 shows the relative flow velocity for all three rock glaciers for the period of geodetic data. HLC was the last of the three rock glaciers where annual geodetic measurements were initiated (in 1999). Therefore, the velocity of the measurement period 1999-2000 was taken here as 100%. This figure clearly shows that the velocity during 1999-2000 was lower compared to the two years of measurements before (1997-1999) and preceded a period of at least five years with partly substantially higher values. A first phase of higher velocity occurred in 2000-2001 (only at HLC), followed by several years of accelerating annual flow rates peaking in 2003-2004 at all three rock glaciers. In 2003-2004, the velocity was about 1.6 to 1.8 times higher compared to 1999-2000. After this peak, 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 2006-2007. Summarising, the observed behaviour at the three rock glaciers matches quite well with the results obtained elsewhere in the European Alps (Delaloye et al. 2008).

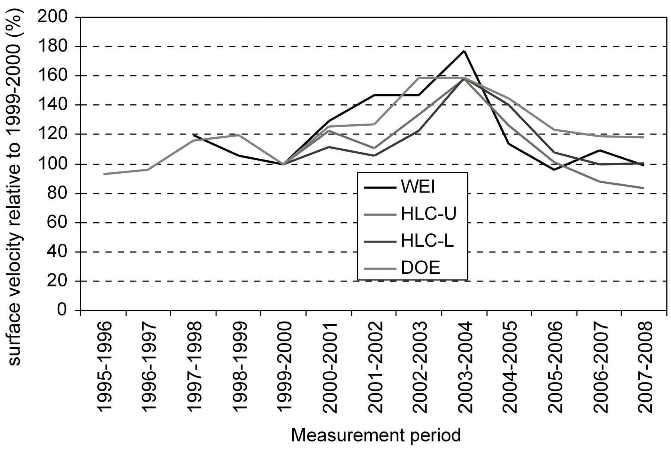

Fig. 1.16 – Relative mean velocity changes compared to 1999-2000 at all three rock glaciers DOE=Dösen, WEI=Weissenkar and HLC=Hinteres Langtalkar upper and lower parts. Note the remarkable peak in 2003-2004.

HLC is a special rock glacier due to its highly active lower part caused by topographic and climatic reasons. A remarkable movement over a prominent bedrock ridge starting most likely in 1994 (reported by M. Krobath in Avian et al. 2005) was the scientific reason for initiating geodetic, photogrammetric, LiDAR – and later – ground temperature and meteorological measurements. Fig. 1.17 depicts the morphological changes of the rock glaciers in the 52-year period 1954 to 2006. Besides the formation of crevasses-like cracks at the central part of the rock glacier (Avian et al. 2005; Roer et al. 2008), the partial break and disintegration at the front through active sliding processes since 1994 is astonishing and unusual (cf. Avian et al. 2009; Kaufmann & Ladstädter 2008a). This partial break is caused by enhanced strain due to movement of HLC over a terrain ridge into steeper terrain. This increasing strain caused morphological changes similar to landslides with indications for potential shear zones causing the process of sliding (Avian et al. 2009).

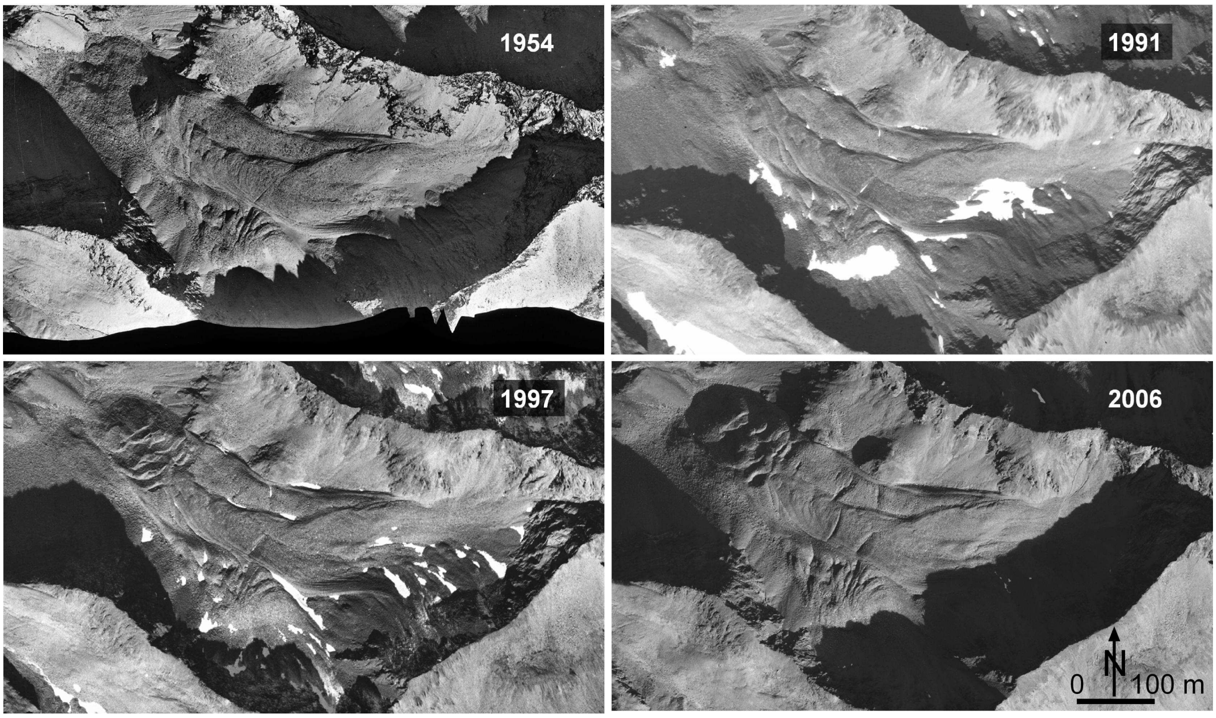

Fig. 1.17 – Aerial photographs of the Hinteres Langtalkar Rock Glacier (HLC) between 1954 and 2006 indicating the formation of crevasses and in particular the disintegration through active sliding processes since 1994 at its frontal part. All aerial photographs were taken by the Austrian Federal Office of Metrology and Surveying, Vienna (BEV) in the month of September (cf. Kaufmann & Ladstädter 2008a).

5. Rock glacier velocity and air temperature relationship

Measured geodetic data were combined with the measured and calculated air temperature data of the three rock glacier sites. To allow comparison, the MAAT was taken from September until August of the consecutive year because the geodetic measurements at the three rock glacier are carried out between mid August and at the beginning of September at the latest. No statistical significant relationship was calculated for all three rock glaciers between the mean surface velocity and the MAAT of the same year as well as the mean surface velocity and the MAAT of the previous year. This seems to be in slight contrast to the findings by Buck & Kaufmann (2008), who found out that a certain relationship exists between velocity of the three rock glaciers discussed here and MAAT of the previous year taken from climate stations of the region. However, they were able to establish this relationship if looking specifically on certain parts of a given rock glacier and not on the mean velocity value. Regarding mean velocity values, we found out that a weak positive correlation – although not significant in all cases – can be observed between the mean surface velocity and the MAAT of two years before (Fig. 1.18). For WEI and HLC-U the coefficient of correlations between these two parameters is >0.5. This, as well as the findings by Buck & Kaufmann (2008), indicates that warmer temperatures favour higher mean surface 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 existence and quantity of liquid water lubricating rock glacier movement.

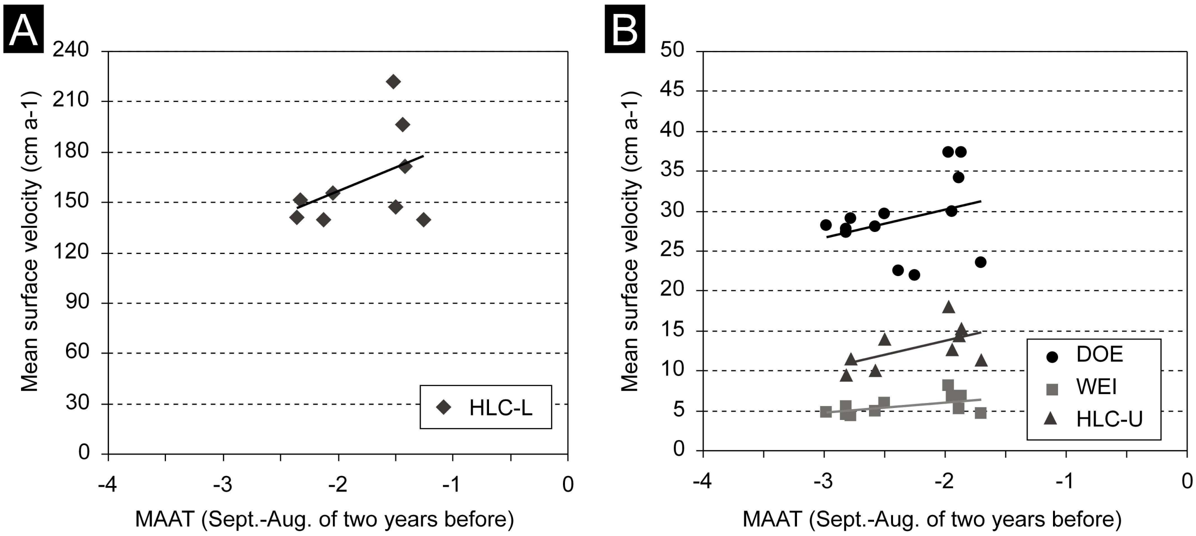

Fig. 1.18 – Mean surface velocity of the three rock glaciers Hinteres Langtalkar (HLC), Weissenkar (WEI) and Dösen (DOE) versus mean annual air temperature (MAAT; period Sept.-Aug) of two years before the rock glacier velocity measurement period (e.g. mean surface velocity of 2006/7 compared to MAAT (Sept.-Aug.) 2004/5. Trends for each rock glacier (all not significant) are indicated. At HLC the slower upper (U) and the faster lower (L) part were differentiated.

The evolution of the mean annual air temperature since 1990 and the mean annual surface velocities since geodetic measurement initiation for each of the three rock glacier are shown in Fig. 1.19. The graphs clearly show that the low 12-month running mean MAAT in 1998-1999 caused low velocities in 1999-2000. Furthermore, the time period from 2000 to mid 2004 shows relatively constant high MAAT values, but the rock glacier velocity gradually increased and reached its peak in 2003-2004. According to Buck & Kaufmann (2008), an explanation for this might be that the constant warming of the ice in the permafrost body as well as the constant development of water films as a result of high air temperatures have increased the respective creep velocities to such a state where they accelerated even more. The following period until late 2006 is characterised by generally decreasing 12-month running mean MAAT as well as decreasing velocities. Of special interest is the enormous double peak of MAAT in 2007 caused by the warm winter 2006-2007. So far, the data for the geodetic measurement period 2008-2009 are not available yet. However, according to the previous observations and established relationship one might expect again a substantial increase in surface velocity rates similar (or even higher) to the ones observed in 2003-2004.

First analysis regarding surface velocity and ground surface temperature have been partly carried out for WEI (Kellerer-Pirklbauer et al. 2008). More ground temperature and meteorological data are currently collected for WEI, HLC and DOE in order to allow more comprehensive analysis regarding relationship between rock glacier kinematics and climate and comparison to other sites (Delaloye et al. 2008).

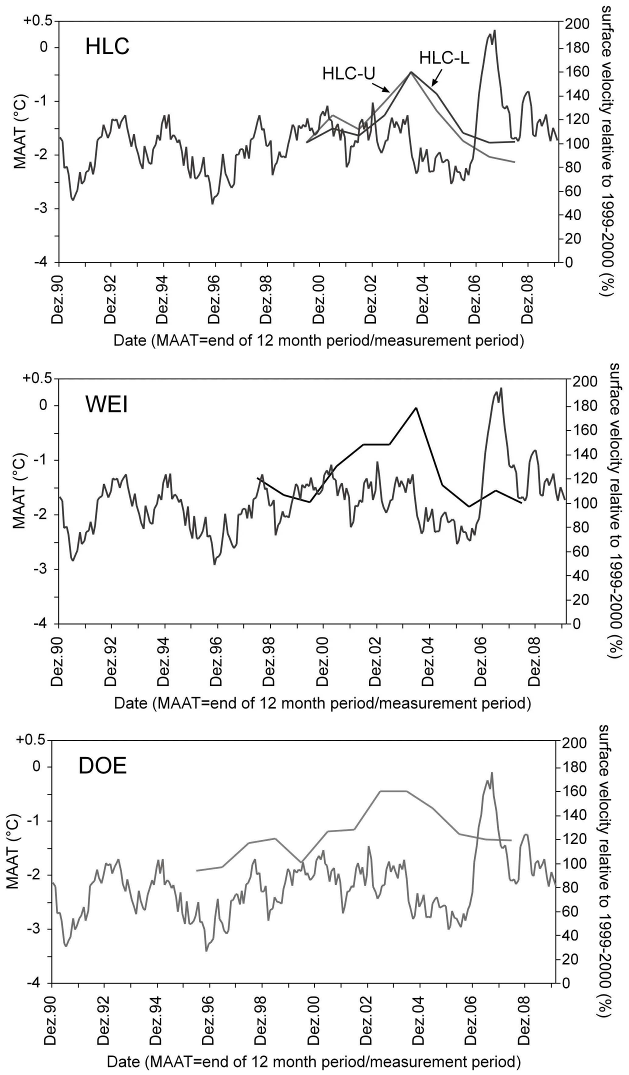

Fig. 1.19 – The MAAT (12-month running mean) and the mean surface velocity (relative to measurement period 1999-2000) at the three rock glaciers Hinteres Langtalkar (HLC), Weissenkar (WEI) and Dösen (DOE). Note that the rather constant temperatures between 2000 and summer 2003 caused a steady increase in surface velocity at all three sites.

6. Natural hazard potential at present and in the future

Generally, natural hazards at the three rock glaciers might be caused by (i) geometrical, velocity and hence stability changes of the rock glacier body, by (ii) the retreat of perennial snow and surface ice unrevealing unstable blocks and smaller-sized rocks on the surface of the rock glacier and at its rooting zone, and by (iii) debris from the rock walls behind the rock glaciers falling on the rock glacier.

Hinteres Lantalkar Rock Glacier

The lower part of the tongue of HLK is highly instable and partly disintegrating resulting in rock fall with single boulders rolling down a slope over a vertical distance of some 100 m (cf. Avian et al. 2005, 2009). No hiking trail or frequently used mountain route crosses neither this endangered area, nor the rock glacier body itself. A former plan to build a trail across the rock glacier to Brentenscharte has been given up because of these expected difficulties. The slope beyond the rock glacier front is covered by alpine meadows and therefore used as alpine pasture during summer. Therefore, at least sheep and cattle are potentially threatened by unstable rock masses. The hiking trail 920 (connecting the village Heiligenblut with the mountain hut Elberfelder Hütte) passes HLC in safe distance to the NW. It runs in alpine meadows on Lateglacial moraines and is divided from the area possibly influenced by mass wasting from the rock glacier front by the glacially shaped basin of Hinterer Langtal Lake. There is no other infrastructure in the vicinity of HLC.

Weissenkar Rock Glacier

WEI is a very slowly moving rock glacier and not dangerous to mountaineers and infrastructure at all. Hiking trail 915 (connecting the two mountain huts Lienzer Hütte and Elberfelder Hütte) runs to the W of the rock glacier across safe underground on stable rocks. No frequently used climbing route leads across the rock glacier itself due to heavily weathered rocks above the root zone. Because the rock glacier front is situated on a rocky plateau like (glacially shaped) landform, boulders or other material falling down from the rock glacier front cannot contribute to mass wasting processes affecting areas and infrastructure at lower elevations.

Dösen Rock Glacier

DOE is crossed by the hiking trail 533 connecting the two mountain huts Arthur-von-Schmidhaus and Gießener Hütte. At its western part is also used as an educational trail on which visitors can observe features of permafrost and climate change ("Blockgletscherweg Dösental"). The ascent to the rock glacier itself leads over the unstable marginal slope where rock fall and block movement might occur. Because the mentioned hiking trail crosses the entire length of the rock glacier body, mountaineers may also be prone to some threat resulting from unstable parts of the rock glacier surface which mainly consists of very coarse debris with diameters up to several meters. At the upper part of the rock glacier, mountaineers have to cross the rooting zone which was characterised in the last years by rapidly retreating and melting perennial snow patches, forcing the mountaineers to cross partly unstable terrain (Fig. 1.20). Furthermore the trail may be reached by rocks falling down the rock faces to the S. With the exception of this hiking trail, no infrastructure is threatened by DOE. Larger scale mass wasting processes at the rock glacier front (which are not likely to occur) cannot affect areas at lower elevations because all sediments are stored in the basin of Dösen Lake which is situated some 300 m to the W of DOE.

Fig. 1.20 – Large unstable block (ca. 4m x 1.2 m x 1 m) in close vicinity to the hiking trail 533 on the surface of DOE. Until recently the block was covered by perennial snow stabilising the block. The retreating snow patch released the large block which is only balancing on a second block. Even a single hiker is heavy enough to destabilise this heavy block (several tons) of granitic gneiss. Photographs A. Podesser.

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