Monitoring of Permafrost Creep on Two Rock Glaciers in the Austrian Eastern Alps: Combination of Aerophotogrammetry and Airborne Laser Scanning

Christoph Klug, Erik Bollmann, Rudolf Sailer, Johann Stötter
Institute of Geography, Innsbruck University, Austria

Karl Krainer
Institute of Geology, Innsbruck University, Austria

Andreas Kääb
Department of Geosciences, University of Oslo, Norway

Abstract

The aim of this study is to quantify vertical and horizontal surface changes of two rock glaciers (Reichenkar and Äusseres Hochebenkar) for a period of 56 years. The quantification of the surface changes is based on the comparison of multitemporal digital elevation models (DEM) and orthoimages over the period 1953/54–2003. By combining digital photogrammetry and airborne laser scanning (ALS) data from 2006 and 2009, the time series was extended to 2009. For the calculation of the vertical and horizontal changes, DEMs were generated from aerial photographs. The vertical changes were derived through subtraction of the multitemporal DEMs over the different periods. Additionally, the horizontal flow velocity was computed with the implementation of two image correlation programs. Furthermore the results were compared with dGPS-measured flow velocities. For different periods within 1953/54–2009, the surface displacements of the well-investigated rock glaciers Reichenkar and Äusseres Hochebenkar are reconstructed and analysed in this paper.

Keywords: active rock glaciers, aerophotogrammetry, airborne laser scanning; flow velocity; image correlation.

Introduction

Active rock glaciers, indicators of mountain permafrost, are lobate or tongue-shaped landforms composed of a mixture of perennially frozen rock debris and ice. They slowly creep downslope by inner deformation of ice and forces of gravity (Barsch 1996). As a result, the surface shows a typical topography of transverse or longitudinal ridges and furrows.

Most rock glaciers show average surface velocities of a few decimetres per year (Krainer & Mostler 2000), although higher velocities of more than 2 m a^{-1} have been observed throughout the Alps (e.g., Roer 2005, Haeberli et al. 2006, Avian et al. 2009). The highest flow velocities (5–7 m a^{-1}) in the Alps have been measured on the Äusseres Hochebenkar and Reichenkar rock glaciers discussed here (Schneider & Schneider 2001, Krainer & Mostler 2006). In the last 20 years, several alpine rock glaciers show increasing creep velocities (Roer et al. 2005). A relation may be supposed between the increasing flow velocity of rock glaciers and global warming.

According to Kääb & Vollmer (2000), a long-time survey of the distribution of rock glacier surface velocities, combined with terrestrial point measurements, can improve the understanding of the underlying processes.

Nevertheless, long-term measurements of flow velocities on active rock glaciers are rare. During the last few decades, a variety of methods for the quantification of rock glacier creep have been developed. Early approaches used field surveying and triangulation techniques (Pillewizer 1957). Recently, differential GPS (dGPS) has proved to be an effective direct method for studying rock glacier flow (Lambiel & Delaloye 2004). The main disadvantage of these methods is the lack of area-wide data coverage.

Airborne remote sensing techniques enable area-wide data acquisition. Aerial photogrammetry allows area-wide monitoring of rock glacier geometry, thickness changes, and surface creep (Kääb et al. 1997). Recently, techniques like space-borne differential synthetic aperture radar interferometry (DInSAR) (Strozzi et al. 2004) or terrestrial and airborne laser scanning have been used for surveying rock glaciers and measuring displacement rates (Bauer et al. 2003, Bollmann et al. submitted).

The objective of this paper is to reconstruct and analyse the surface displacements derived from aerial images and ALS data over the period 1953/54–2009 on two active rock glaciers in the Austrian Alps. Furthermore, the novel approach of using ALS data, especially for validating the photogrammetrical-derived DEMs, is pointed out.

Study Area and Data

Äusseres Hochebenkar rock glacier (AHK)

The Äusseres Hochebenkar (AHK) rock glacier (46°50′N, 11°01′E) is a tongue-shaped, talus-derived rock glacier about 2 km south of Obergurgl (Ötztal Alps, Austria). It expands from about 2830 m down to about 2360 m a.s.l. and reaches a length of up to 1.6 km. A detailed characterization of the physiognomy of AHK is given by Vietoris (1972) and Haeberli & Patzelt (1982). Since 1938, systematic terrestrial investigations on surface flow velocities, front advance rates, and surface elevation changes of AHK have been carried out on an annual scale (Schneider & Schneider 2001). Remote sensing methods, such as terrestrial and aerial photogrammetry, have also been applied (Kaufmann & Ladstätter 2002).

The AHK is characterized by very high surface velocities of up to several meters per year. According to Schneider & Schneider (2001), maximum displacement rates (6.6 m a^{-1}) were measured below a terrain edge at about 2570 m a.s.l. in the 1960s. Following Haeberli & Patzelt (1982), these high values are most likely a result of a significant increase of slope steepness below the terrain edge. The related velocity gradients result in deep cross cracks in the rock glacier body.

Reichenkar rock glacier (RK)

The Reichenkar (RK) rock glacier (47°02′N, 11°01′E) is located in the western Stubai Alps (Tyrol, Austria). It is situated in a small, northeast-facing valley called Inneres Reichenkar. RK is a tongue-shaped, ice-cored rock glacier 1400 m long with widths that reach 260 m near the head and 170–190 m near the front. The rock glacier covers an area of 0.27 km^2 and extends in altitude from 2750 m to 2310 m a.s.l.

Detailed information about this rock glacier can be found in Krainer & Mostler (2000) and Hausmann et al. (2007). Investigations on surface flow velocities have been carried out in the period 1997–2003 with dGPS measurements (Chesi et al. 2003). These data are used to validate the derived horizontal displacement rates.

Data acquisition

The basic data applied in the presented analysis are greyscale aerial photographs, provided by the Austrian Federal Office of Metrology and Survey (BEV), with a scale from 1:16.000 to 1:30.000. For the study sites, analogue aerial stereoscopic pairs are available for the years (Table 1), taken with Wild/Leica-Cameras of different types. Additionally, the federal province of Tyrol provided high-resolution orthoimages from the years 2003 and 2009.

To best pursue the objective target, the recording date and time are important, because snow cover or topographic shadowing make DEM generation impossible. For that reason, only aerial photographs with a certain standard were used.

ALS data acquisition campaigns at AHK and RK were carried out in 2006 (by the federal province of Tyrol) and 2009 (within the project C4AUSTRIA). A summary on the exact data acquisition dates is given in Bollmann et al. (submitted). DEMs out of these ALS flight campaigns were generated and integrated in the analysis.

Methods

Generation of DEM & orthoimages

For the photogrammetric analyses, the analogue data were provided as scanned aerial photographs (~1600 dpi) with the required calibration reports. Image orientation, automatic DEM extraction, and digital orthophoto generation were the first steps in this study. For a detailed description of the methods, see Baltsavias et al. (2001). The DEMs were generated from the mono-temporal stereo models with 1 m spacing. Additionally, the orthoimages were calculated with the cubic convolution resampling method with 0.2 m ground resolution.

Table 1. Calculated RMSE for the generated DEM vs. 2009. (-) Aerial images not available for acquisition in winter.

DEM	RK - RMSE	AHK -RMSE
2009 (ALS)	ref	ref
2006 (ALS)	0.13 m	0.10 m
1997	-	0.41 m
1994	0.22 m	-
1989 /1990	0.26 m	0.42 m
1977	-	0.25 m
1973	1.29 m	-
1971	-	0.55 m
1969	-	0.29 m
1953 / 1954	0.78 m	0.58 m

Accuracy assessment

In a first step, the quality of the used ground control points, as well as the calculated exterior orientation, were checked and evaluated by an automatic residual error tool to minimize processing errors and to improve accuracy.

Afterwards, an accuracy assessment was performed by comparing the generated DEM with the high-quality DEM of the ALS flight campaign of 2009. Therefore, 3 areas that represent the surface structure (slope, aspect, height) of the rock glaciers are detected in stable regions. On the basis of this analysis, the root mean square error (RMSE) could be calculated. The computed RMSE figures (Table 1) show values of 0.2–1.3 m.

For the analyses of the RMSE, it has to be kept in mind that the accuracy is strongly influenced by systematic errors such as shadowing, steep terrain, and low image contrast. According to Kääb (2010), a vertical RMSE for automatic generated DEM corresponding to 1–3 times the image pixel size is possible in relatively flat areas (e.g., alpine meadows). For slopes and ridges, a RMSE of 5–7 times the image pixel size can be expected. Steep slopes with shadowed areas reveal RMSE on the order of 60–100 times the image pixel size. This assessment is reflected in the results of this study. For detailed information on automatic photogrammetric-derived DEM vertical error analysis, see Baltsavias et al. (2001).

Calculation of horizontal displacements

The horizontal displacement rates from the orthoimages were calculated with the Correlation Image Analysis (CIAS) Software (Kääb & Vollmer 2000). CIAS has already been applied to a variety of glaciers and rock glaciers to calculate flow velocities from orthoimages or satellite images (Kääb 2004). CIAS identifies displacement rates as a double cross-correlation function based on the grey values of the used input images (Kääb 2010). The correlation algorithm searches via block matching a predefined corresponding reference section in the image of acquisition time 1 (t_1) in a sub-area of image of acquisition time 2 (t_2). If the reference block is successfully matched, the differences in central pixel coordinates show the horizontal displacement between t_1 and t_2. The output file consists of the x- and y-coordinates of the reference block, the displacement rates in the x- and y-direction, as well as the Euclidean distance, the direction, and the correlation

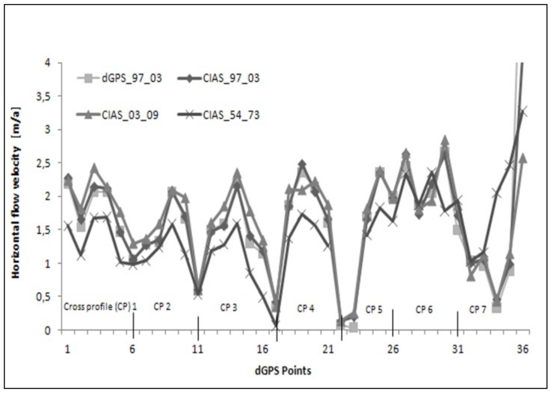

Figure 1. Comparison of the measured (dGPS) and computed (CIAS) flow velocities for the periods 1997–2003, 2003–2009, and 1954–1973.

coefficient. Matching errors can be detected and eliminated by analyzing the correlation parameters, the expected range for surface velocity, and direction. Because of the varying lengths of the periods, CIAS was run with different parameter combinations regarding the size of the reference and search area, as well as the window spacing.

For measuring changes in geometry, relative accuracy is more important than the absolute position of the images (Kääb 2010). Therefore, the multitemporal orthoimages have been co-registered using tie points in addition to the initial georeferencing.

Additionally, the horizontal displacement rates are calculated from shaded reliefs of ALS DEM with the open source image correlation software Imcorr (Scambos et al. 1992), which has been applied to calculate flow velocities of glaciers using different input data acquired from aircraft or satellites. Detailed information about this software is given in Bollmann et al. (submitted).

Accuracy assessment

The accuracy of the calculated horizontal displacement rates was evaluated using dGPS data from the 1997–2003 RK record. The original CIAS output point files were compared to the dGPS displacement rates using a buffer of 3 m around the dGPS points.

For the time period 1997–2003, an absolute mean deviation of 0.4 m (Std 0.46 m) between the dGPS values and the corresponding nearest CIAS point measurements was calculated. Figure 1 shows the computed and the 36 dGPS measured flow velocities within the investigated period. Additionally, the dGPS points were used as reference for the periods 1954–1973 and 2003–2009. In contrast to the latter epoch, the velocities between 1954 and 1973 were slower in evidence, but there is still a good relative correlation within the profiles.

Table 2 presents the calculated differences by CIAS, considering the mean absolute error (Amean) in combination with the standard deviation (Std) to be the most appropriate accuracy indicators.

Table 2. Comparison between horizontal displacement rates calculated from CIAS and measured by dGPS (CIAS – dGPS).

CIAS - dGPS	Mean [m]	Amean [m]	Std [m]	Max [m]	Min [m]	RMSE [m]	R^2
1997/2003	0.24	0.4	0.46	1.28	0.02	2.05	0.91

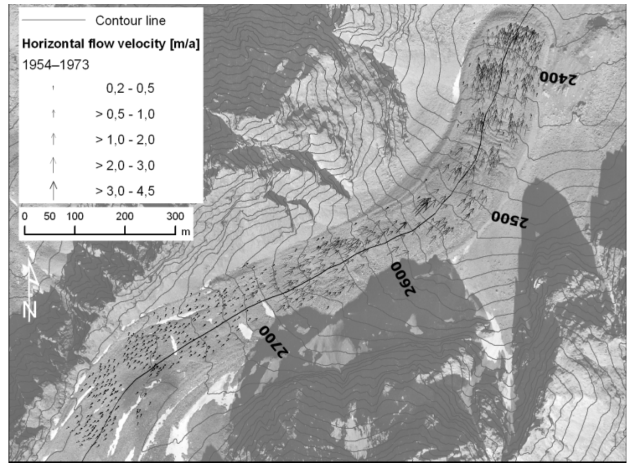

Figure 2. Mean annual horizontal flow velocity on RK 1954–1973. Contour lines indicate the steep midsection.

Results and Discussion

Reichenkar

The horizontal surface velocity fields (cf. Figs. 2 and 3) and the thickness changes on RK (Fig. 4) varied between the individual investigated epochs. From 1954–2009, an average vertical loss of the rock glacier of nearly 3.2 m (~ -6 cm a^{-1}) can be observed. In the rooting zone surface, lowering of up to -0.5 m a^{-1} in various periods indicates massive loss of ice. The average elevation change in this zone lies within the range of -0.10 m a^{-1}.

The increase in thickness at the front of individual flow lobes suggests that elevation changes are influenced by mass advection. Over the investigated periods, the surface of RK was creeping with average rates of 0.9 m a^{-1} (Table 3). Maximum creep rates occur in a transition zone (2540–2660 m a.s.l.), a steeper mid-section before the flat tongue, where compressive flow with development of transverse ridges and furrows can be observed. The measured surface displacements depict acceleration since the late 1990s from the middle to the front part of the rock glacier. The displacement rates in the root zone seem to be constant over the whole period (0.2–0.5 m a^{-1}), whereas flow rates at the tongue, which were consistent over the periods from 1954 to 1997 with average rates of 1–2 m a^{-1} along the central axis, increased to 2.0–3.0 m a^{-1} since 1997. The increasing velocities cannot be explained by the gradient of the slope, which measures only 11–12° on the lower part of RK.

The front of RK advanced 53 m from 1954 to 2009 (0.76 m a^{-1}). Figure 5 depicts the mentioned acceleration, which increased from an average of 0.6 m a^{-1} to 1.55 m a^{-1} during the last 20 years. The measurements show displacement rates at the front of up to 3 m a^{-1}. At the orographic left part of the flat

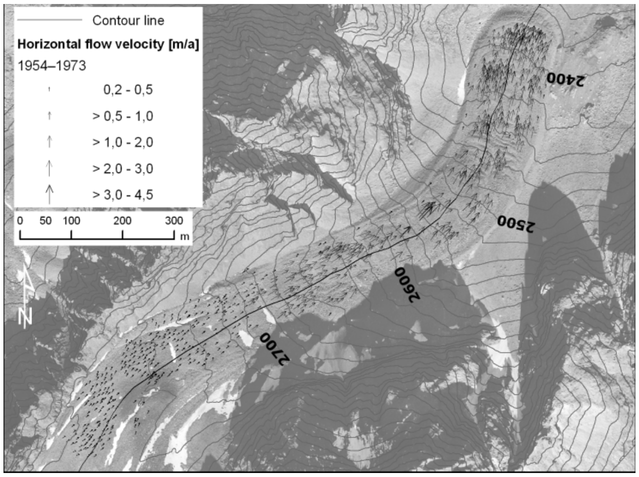

Figure 3. Mean annual horizontal flow velocity on RK 1997–2003. Points indicate 36 dGPS points measured along seven cross profiles.

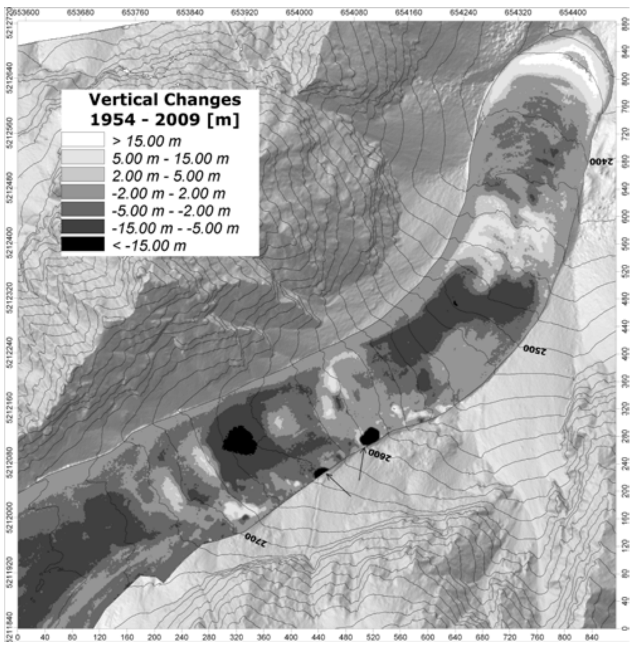

Figure 4. Cumulated vertical changes of RK between 1954 and 2009. Arrows indicate errors because of bad contrast.

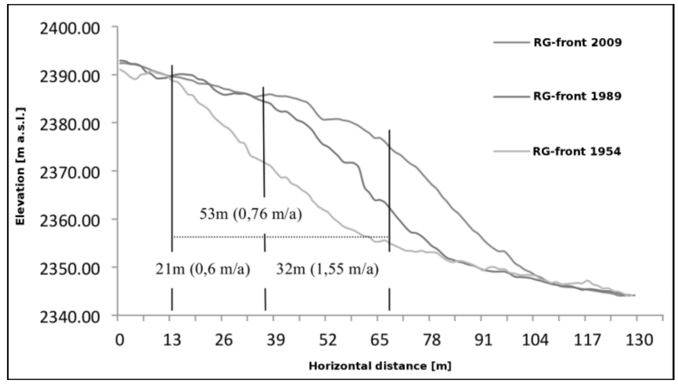

Figure 5. Front advance depicted by longitudinal profiles.

Table 3. Calculated horizontal velocities (mean, maximum, and acceleration dv) on RK and AHK. The rock glaciers were separated into three sections (root zone, transition zone, and tongue), and in every zone the same amount of measured blocks was used for calculation of the annual mean.

Period	Measured blocks	Mean velocity [m/a]	Max. velocity [m/a]	dv [%]
Reichenkar				
1954 - 1973	841	0.75	3.4	-
1973 - 1989	871	0.73	3.5	- 2.7
1989 - 1994	909	0.73	4.2	0.0
1994 - 1997	987	0.76	5	+ 3.2
1997 – 2003	830	1.12	4.9	+ 47.4
2003 - 2009	811	1.3	4.1	+ 16.1
Hochebenkar				
1953 – 1969	2438	0.84	5.2	-
1969 - 1971	2479	0.64	6.9 (?)	- 14.3
1971 – 1977	2711	0.42	4.1	- 34.4
1977 – 1990	2283	0.54	1.85	+ 28.6
1990 – 1997	2865	0.63	1.7	+ 16.7
1997 - 2003	2308	0.77	2.3	+ 22.2
2003 - 2009	2439	0.86	2.5	+ 11.7

tongue (2520–2460 m a.s.l.), one portion features relatively high movement rates (~ 3.3 m a^{-1}) since 1994. In combination with the general topography, the distinct speed gradients indicate that the lower part of the frozen body is overridden from above by a new lobe.

Hochebenkar

The rock glacier is characterized by a comparatively high flow velocity of several meters per year and periodically changing flow rates between 1953 and 2009 (Table 3). A transverse terrain edge at an altitude of about 2580 m a.s.l. divides the rock glacier into a lower steep part and an upper flat part. Within all periods, the rooting zone shows constant velocities (0.2–0.5 m a^{-1}), whereas in the adjacent zone toward the terrain edge displacement rates differ during the investigation periods.

In the period from 1953 to 1969, high movement rates (1.0–2.5 m a^{-1}) were measured in this zone. At the same time, the upper part of the tongue showed the development of massive transverse cracks, where the loss of mass was extremely high. From the early 1970s to the beginning of the 1990s, a phase with relatively slow average annual velocity rates (0.5–1.0 m a^{-1}, Table 3) could be observed. From the 1990s onward, the movement rates increased, showing velocities (1.0–2.5 m a^{-1}) similar to those of the late 1960s (Fig. 6). On the terrain edge, creep velocities increased to about 2.5 m a^{-1}. Maximum creep rates (6.9 m a^{-1}) have been measured in this transition zone from 1953 to 1969, although rockfall may be a significant process here and cannot be attributed to permafrost creep exactly.

The measurements show elevation changes within the range of -0.10 m a^{-1} in the upper part, whereas the changes increase to nearly -0.6 m a^{-1} at the zone below the terrain edge (Fig. 7). Thinning of the frozen debris at the terrain edge of around 2580 m a.s.l. is compensated to a large extent by corresponding thickening in the lowest part. Below 2580 m, which marks the

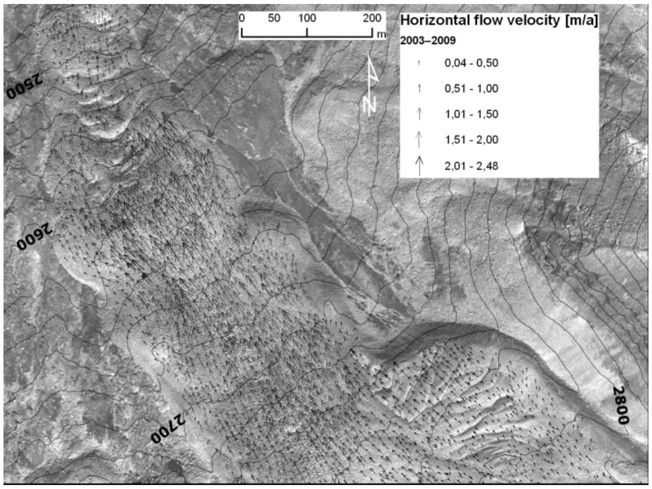

Figure 6. Mean annual horizontal flow velocity on AHK 2003–2009. Contour lines indicate the terrain edge at 2580 m a.s.l.

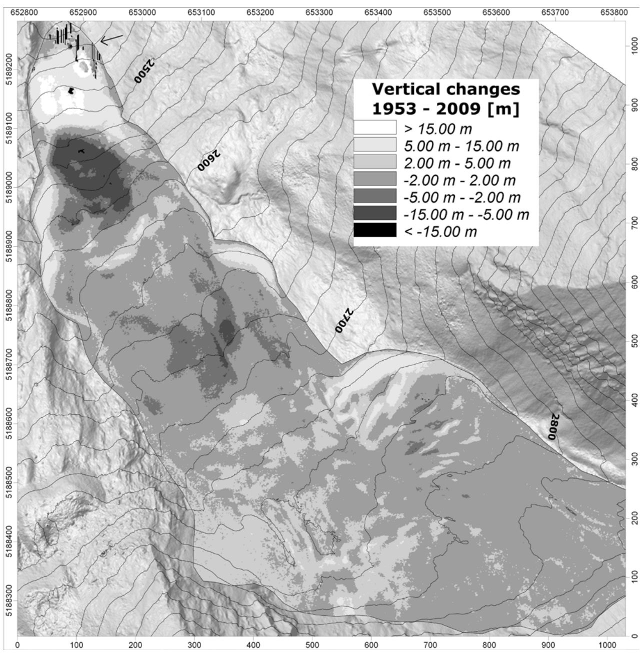

Figure 7. Cumulated vertical changes of AHK between 1953 and 2009. Arrow at the front indicates errors because of bad contrast.

end of the steady-state creeping zone, the tongue has moved into very steep terrain. In this area, landslides have occurred due to the specific topographic situation and make image correlation nearly impossible. The front of AHK advanced 135 m (2.4 m a^{-1}) from 1953 to 2009. Since 1969, the rates of front advance decreased from 4.1 m a^{-1} to 1 m a^{-1} in the 1990s, and since that time an increase could be observed to the current 1.6 m a^{-1}.

Conclusion

In the case of RK and AHK, permafrost creep is the most important factor governing surface elevation changes. Computer-based aerial photogrammetry in combination with ALS allows detailed determination and analysis of surface elevation changes in, and horizontal displacements on, the investigated rock glaciers over a period of 56 years. These calculations build an important analytical component for identifying the state of activity of rock glaciers.

Using ALS data in rock glacier research, especially for validating the photogrammetrical-derived DEMs and for calculating flow velocities, has proved to be a useful data source for area-wide investigations on rock glaciers. The results show the potential of the method combination to quantify spatio-temporal variations of rock glacier surface changes.

The obtained spatial patterns agree with the dGPS measurements and the existing knowledge about the flow behavior of the two rock glaciers. Furthermore, the length of the time series allows the investigation of temporal variations of flow velocities, on which little has been previously done for fast creeping types like RK and AHK. The study reveals an acceleration of the rock glaciers since the late 1990s. In contrast to AHK, where the displacement rates in the 1950s and 1960s have been similar to current rates, the RK shows acceleration over all periods from 0.75 to 1.3 m a^{-1} currently. In addition to the temporal variation, spatial variation in the velocity field of RK could be detected. The orographic left portion in the middle and lower section shows higher velocities.

Although some regional-scale studies have been conducted (e.g., Roer 2005), most investigations are still concentrated on single rock glaciers, and meso-scale information on this topic is limited. Area-wide data about the flow behavior of rock glaciers provide useful input for understanding rock glacier dynamics. In order to obtain detailed information of rock glacier dynamics, more data about the internal structure are needed. Furthermore, the temporal resolution of temperature and velocity measurements has to be increased to get more detailed information about the interrelation of rock glacier creep and global warming.

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