GLACIER-RELATED ASPECTS

QUANTIFICATION AND VISUALIZATION OF PERIGLACIAL SURFACE DEFORMATION IN THE INNERES HOCHEBENKAR CIRQUE, ÖTZTAL ALPS, AUSTRIA

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ABSTRACT

Inneres Hochebenkar is a glacial cirque (approx. 0.84 km^2) located in the Gurgl valley, Ötztal Alps, Tyrol. It holds not only a rock glacier (of the same name) but also a small glacier (Hochebenferner) in its root zone. During the Little Ice Age (last glacial maximum at around 1850) the Inneres Hochebenkar cirque was largely covered by the Hochebenferner Glacier, which has now receded to a small remnant (8.3 ha in 2006). The main focus of the present paper is to document the past and also more recent surface change of the periglacial environment of the Inneres Hochebenkar cirque. Remote sensing data, such as time-series of aerial photographs (1953-2010) and airborne laser scanner data (2006, 2010), were used to retrieve quantitative information on surface change, i.e. horizontal movement and/or surface height change. The results obtained are presented graphically (two separately moving rock glacier units connected by a small unit of inactive, but melting permafrost at the lower end of the cirque) and numerically (e.g. maximum mean annual creep velocities of up to 46.7 cm/year for the time period 2003-2010 and maximum surface lowering of -10.8 m for the time period 1953-2006). Special attention is also paid to proper visualization, i.e. computer animations, of areas of presumed surface change using time-series of both high-resolution orthophotos and shaded reliefs.

Keywords: permafrost, rock glacier, surface deformation, photogrammetry, Inneres Hochebenkar

1 INTRODUCTION

Glaciers are visible expressions of the cryosphere, which also includes permafrost. Mountain permafrost, i.e. alpine frozen ground, is present in the Austrian Alps and the focus of ongoing research (Krainer et al. 2012). In marked contrast to glaciers (frozen water), permafrost cannot be identified easily in the field. However, so called *rock glaciers*, which are creep phenomena of (discontinuous) mountain permafrost, can indicate permafrost conditions in the periglacial environment (Barsch 1996, Haeberli et al. 2006).

Climate change has significant influence on the cryosphere. Atmospheric warming during the last 150 years has caused strong glacier recession and also permafrost degradation. Recent studies focusing on rock glacier kinematics document ongoing environmental change, e.g. in the European Alps (Delaloye et al. 2008, Kellerer-Pirklbauer and Kaufmann 2012). Speed-up of rock glacier surface movement and, in some cases, strong changes in surface morphology, i.e. surface lowering and collapse, have been reported. Both processes destabilize the rock glaciers and may cause subsequent rapid mass movements (Schoeneich et al. 2014).

Recently, Krainer et al. (2015) carried out a study at the *Inneres Hochebenkar cirque* (‘*kar*’ is the German word for cirque) with special emphasis on its morphology and hydrology. The cirque holds not only a rock glacier (of the same name) but also a small glacier. Their study was supported by area-wide measurements of surface kinematics (1953-1997) carried out by other authors. The aim of the present paper, however, is to extend the observation period of change detection up to the year 2010. This will be facilitated by the combined analysis of new aerial surveys conducted in 2003 and 2010 and additional airborne laser scanning (ALS) data acquired in 2006 and 2010. Based on these new data we aim to answer the research question whether or not the surface kinematics of the Inneres Hochebenkar rock glacier have changed significantly. We will assess not only the horizontal flow velocity but also surface elevation change of the suspected rock glacier area in the periglacial part of the cirque.

The remainder of the paper is structured as follows: Section 2 gives a brief introduction to the study area. This is followed by a summary of previous work (permafrost studies, cartography, SAR interferometry, and photogrammetry) carried out in the study area. Section 3 presents the new data to be analyzed. Both image-based and DEM-based change detection will be addressed in Section 4. The results obtained are presented in Section 5. The paper concludes with a discussion and an outlook.

2 STUDY AREA

The study area of the Inneres Hochebenkar cirque (46°49'33" N, 11°00'33" E) is located in the Ötztal Alps, Tyrol, Austria (Figure 1). It can be accessed by foot (hiking trail no. 922) from the nearby village of Obergurgl (1,907 m, Gurgl valley). A detailed geomorphological map of the Inneres Hochebenkar cirque is given in Krainer et al. (2015). The cirque (approx. 0.84 km^2) is open to the west and its confining mountain ridges reach heights beyond 3,000 m. The main, central part of the cirque is covered by ground moraines deposited by Hochebenferner Glacier during the Little Ice Age (maximum glacial extent ca. 1850). The lower part of the cirque is occupied by the Inneres Hochebenkar rock glacier (Krainer and Ribis 2012) comprising two main tongue-shaped units (northern unit: from 2,694 m to 2,840 m, southern unit: from 2,650 m to 2,810 m). The root zone of the cirque holds the remnants of Hochebenferner and another small rock glacier (Figure 2).

The cirque located north of Inneres Hochebenkar holds the Äußeres Hochebenkar rock glacier, Austria's prime rock glacier. It is well-known for its long record of continuous photogrammetric and geodetic measurements (Kaufmann 2012, Nickus et al. 2013). A virtual overflight of the study area showing both Äußeres and Inneres Hochebenkar rock glacier can be accessed through Kaufmann (2016).

Our research work presented in this paper covers a rectangular mapping area as outlined in Figure 1.

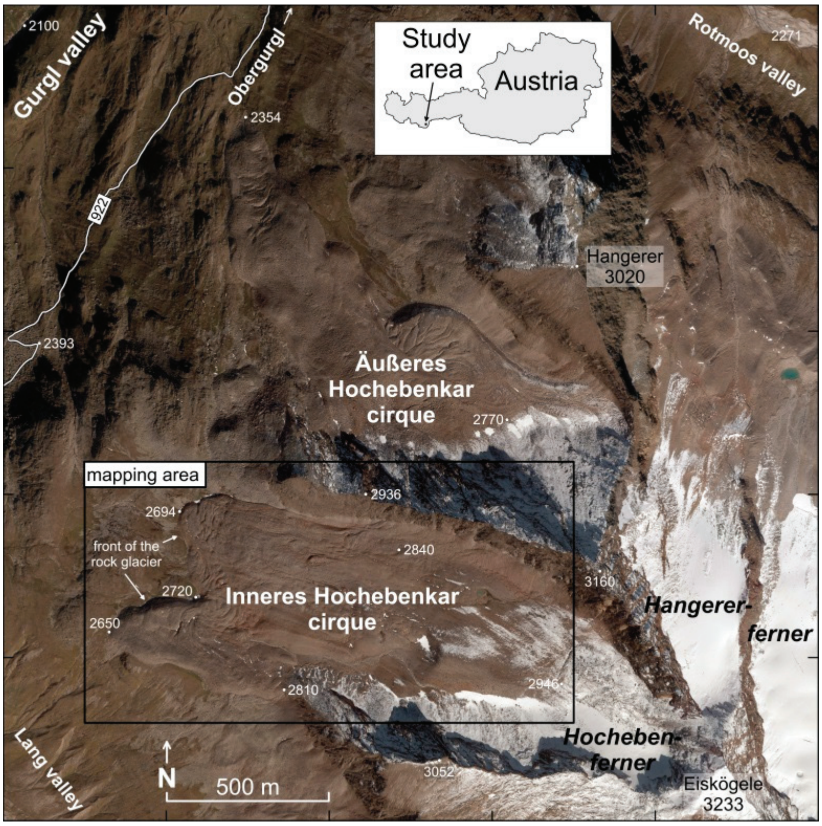

Figure 1: Location map showing both cirques of Äußeres and Inneres Hochebenkar. The mapping area is outlined by a box. Orthophoto of 11 September 2010. Orthophoto © Land Tirol.

Figure 2: Terrestrial view of the Inneres Hochebenkar cirque as seen from Ramolhaus (alpine hut, 3,005 m) in easterly direction. Photo taken on 31 August 2015 by A. Kleb.

3 PREVIOUS WORK

This section includes background information/material which helped us in carrying out our study and, most importantly, all previous work on the detection and mapping of surface movement/deformation of the Inneres Hochebenkar rock glacier.

3.1 PERMAFROST STUDIES

Permafrost-related studies at the Inneres Hochebenkar cirque were carried out by Haeberli and Patzelt (1982), and more recently by Krainer et al. (2015). Haeberli and Patzelt prepared, e.g. two separate maps indicating the occurrence of permafrost and active layer thickness. Both maps are based on field observations, such as basal temperature of the winter snow cover, refraction-seismic profiles, and summer temperature variations of springs. The work of Krainer et al. focuses on the hydrology of the cirque measuring the electrical conductivity and nickel concentration of spring water.

3.2 OTHER MAPS

The area was covered by several topographical mappings which provide the information on the historical glacier extent. The glaciation of the Inneres Hochebenkar cirque during the 19th century can be assessed based on old maps (tiris 2016). A good example is the map of the survey '*Dritte Landesaufnahme*' 1864-1887, which shows that Hochebenferner Glacier was already receding (Figure 3). The maximum extent of glaciation was reached around 1850, which marks the end of the Little Ice Age. Thus, most probably the Inneres Hochebenkar cirque was not completely glaciated at that time.

In 1936 the Inneres Hochebenkar cirque was surveyed by terrestrial photogrammetry in preparing a 1:25,000 map (sheet Gurgl) of the Ötztal Alps (Pillewizer 1957). The map was published in 1949 by the Austrian Alpine Club (Figure 4).

The 1:10,000 map 'Gurgler Ferner 1981' also comprises the Inneres Hochebenkar cirque (Figure 5). The above mentioned maximum glacial extent is indicated in the map in red color (solid line = confirmed by field evidence, dashed line = vague). For explanatory notes on the 'Gurgler Ferner 1981' map, see Patzelt (1986).

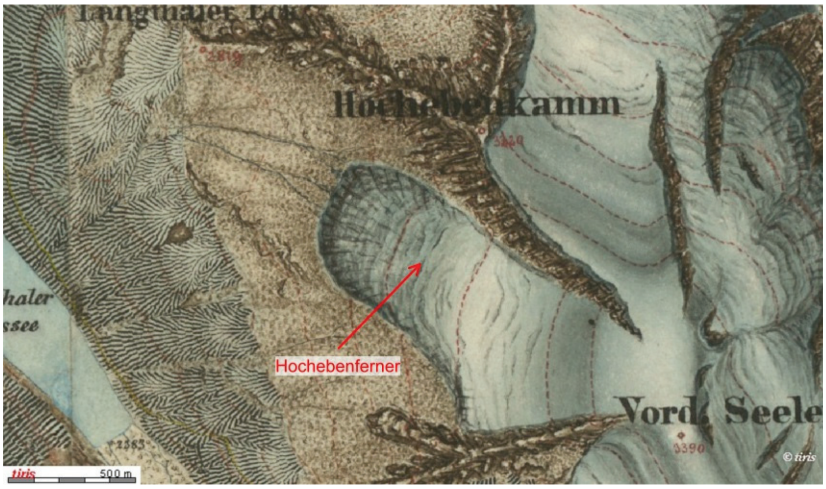

Figure 3: The Inneres Hochebenkar cirque with Hochebenferner Glacier (survey 1870-1873). 'Dritte Landesaufnahme' survey 1864-1887, source: tiris (2016).

Figure 4: The Inneres Hochebenkar cirque (terrestrial photogrammetric mapping, 1936). Clip from the map 'Ötztaler Alpen, Blatt Gurgl' 1:25,000, published in 1949. The location of two terrestrial photogrammetric profiles is indicated in red color.

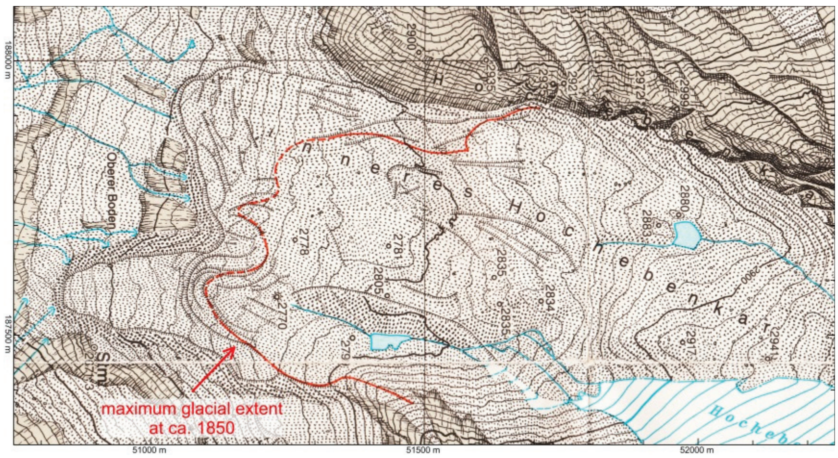

Figure 5: The Inneres Hochebenkar cirque (aerial photogrammetric mapping, 1981). Clip from the map 'Gurgler Ferner 1981' 1:10,000, published in 1986.

3.3 MEASUREMENT OF FLOW VELOCITY

Wolfgang Pillewizer was the first to measure surface flow velocity at the Inneres Hochebenkar rock glacier (Pillewizer 1957). In 1953 he set up a terrestrial photogrammetric baseline at 2,686 m north of the southern unit of the rock glacier in order to measure flow velocity by repeat photography (Figure 4). A second survey was carried out by the same author in 1955. The horizontal displacements of five points located at the upper edge of the frontal slope were determined. Pillewizer calculated a mean annual flow velocity of 1.10 m a^{-1} for the period 1953-1955.

Another terrestrial photogrammetric profile at the Inneres Hochebenkar rock glacier was set up and re-visited by Egon Dorrer in the framework of the course '*Kurs für Hochgebirgs- und Polarforschung*' held in Obergurgl (Vietoris 1972). The baseline had been installed in 1959 on a stable rock outcrop at 2,800 m as indicated in Figure 4 (drawn after Vietoris 1972). The profile extends across the supposed rock glacier flow direction and covers only morainic surface points of the central part of the cirque. This baseline was re-visited in 1966. No movements were detected, and the northern unit of the rock glacier was thus considered as inactive.

The velocity field of the Inneres Hochebenkar cirque was mapped for the first time applying satellite radar interferometry (Rott and Siegel 1999, Nagler et al. 2002). Their work was based on ERS-1 and ERS-2 synthetic aperture radar (SAR) images. Comparative motion fields were obtained for two interferometric pairs in July/August 1995. The analysis clearly showed two separate moving units, a northern and a southern one. Calculated displacement rates were several centimeters within the 35 days repeat cycle.

High-resolution surface velocity fields were derived from interannual aerial photographs (several epochs between 1953 and 1997) acquired from the Austrian Federal Office of Metrology and Surveying (Kaufmann and Ladstädter 2002a, 2002b, 2003). Kaufmann and Ladstädter computed 3D displacement vectors following a stringent photogrammetric approach based on preliminary (quasi-)orthophotos. Image matching was not done in image space using the raw image data, but in object space using this special type of quasi-orthophoto. The results obtained confirm the earlier findings of Rott and Siegl (1999). The flow patterns of the two moving units of the rock glacier could be retrieved with high spatial and also good temporal (multi-year) resolution. Maximum mean annual flow velocities of up to 55 cm a^{-1} for the northern unit and 49 cm a^{-1} for the southern part were measured for the time period 1953-1969.

4 DATA ACQUISITION

The present study is based on aerial photographs and airborne laser scanning (ALS) data. Aerial survey data from five epochs (1953, 1969, 1981, 1990, and 1997) were taken from a previous project. Additional, more recent data stem from aerial surveys carried out in 2003 and 2010. Image data and elements of exterior orientation of both surveys were provided by the Office of the Tyrolean Regional Government. Some characteristic parameters of the aerial surveys are given in Table 1. Change detection analysis was carried out using grayscale images (Figures 6 and 7).

Table 1: Aerial surveys 1953-2010.

Date	Flying height above ground (m)	Camera type	Scale/ GSD*	Remark
31.08.1953	3,250	analog	1 : 15,450	B&W
07.10.1969	4,430	analog	1 : 29,150	B&W
07.09.1981	2,930	analog	1 : 19,150	B&W
10.10.1990	5,240	analog	1 : 34,300	B&W, snow cover
11.09.1997	5,580	analog	1 : 36,550	B&W
05.09.2003	5,360	analog	1 : 17,650	color-positive
11.09.2010	2,810	digital	17* cm	R, G, B, NIR

*… ground sampling distance

Multi-temporal digital terrain models (DEMs) of the study area were made available for the epochs 1953 and 1997 (see above) and additionally for 2006 and 2010 (Table 2). The latter also included the digital surface models (DSMs). ALS data were provided by the Office of the Tyrolean Regional Government.

Table 2: Digital elevation/surface models 1953-2010.

Date	Grid spacing	Origin	Remark
31.08.1953	2.5 m × 2.5 m	photogrammetric mapping	DEM
11.09.1997	2.5 m × 2.5 m	photogrammetric mapping	DEM
23.8.2006	1 m × 1 m	ALS	DEM and DSM+
09.10.2010	1 m × 1 m	ALS	DEM and DSM

+… see Figure 8

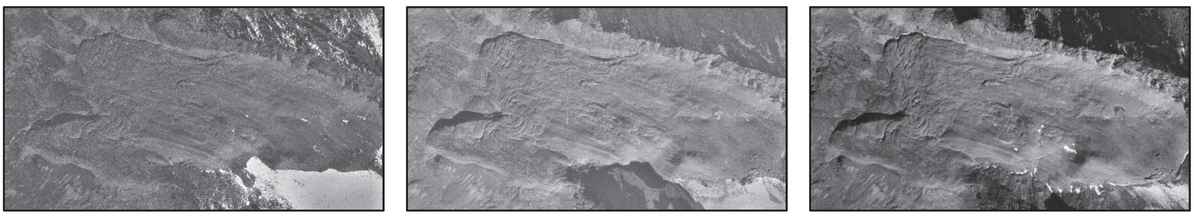

Figure 6: Aerial surveys of 1953 (left), 1969 (middle), and 1997 (right).

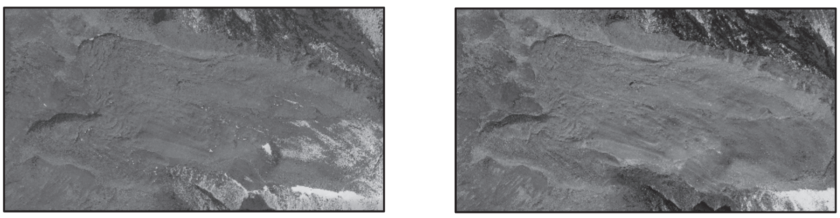

Figure 7: Aerial surveys of 2003 (left) and 2010 (right).

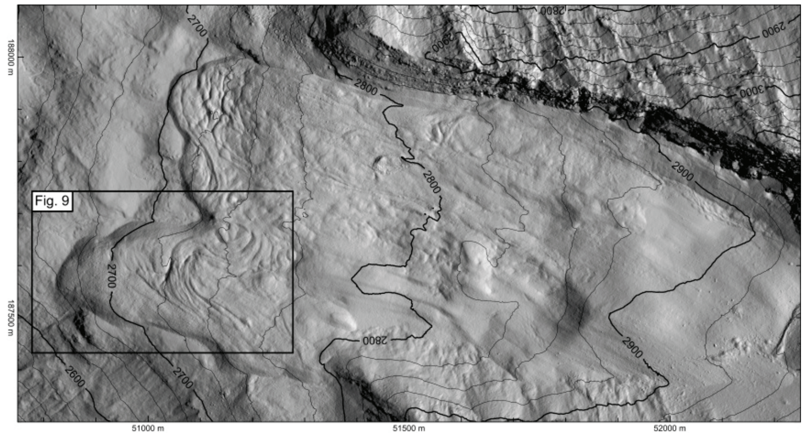

Figure 8: Shaded relief of the Inneres Hochebenkar cirque. Source: ALS-based digital surface model (DSM) 2006.

5 METHODS

Surface deformation can be best described by a dense field of 3D displacement vectors. These vectors can only be determined by observing identical surface points in space and time. Different remote sensing techniques and computational methods are available to solve this task (Kääb 2005). As already mentioned in Section 3.3, Kaufmann and Ladstädter (2002a) have developed a photogrammetric method for deriving these 3D displacement vectors in a stringent way. Under special conditions, i.e. if the DEMs of the multi-temporal stages are known, the 3D problem can be reduced to a 2D one. Image matching of the multi-temporal orthophotos will thus provide the correct 2D, i.e. horizontal, component of the displacement vector. Subsequently, the third, i.e. vertical, component of the displacement vector can be retrieved indirectly from the Z-values interpolated from the respective DEMs.

3D displacement vectors of the Earth's surface can also be deduced from surface geometry only, i.e. through matching of multi-temporal DEMs or DSMs (Bollmann et al. 2015).

However, in many applications the vertical component of the displacement vector is of secondary importance. Instead, surface elevation change is computed by simply subtracting multi-temporal DEMs.

5.1 IMAGE BASED CHANGE DETECTION

The computation of 2D (horizontal) displacement vectors is based on orthophotos. We have developed a toolbox of Matlab routines to highly automate the computation. Orthophotos of all epochs were computed on an Intergraph digital photogrammetric workstation (ImageStation) at a ground sampling distance (GSD) of 20 cm. The proper DEM for epochs for which no contemporary DEM was available was selected in such a way as to best approximate the topographic situation at the time of acquisition of the aerial photographs to be rectified.

Displacement vectors were computed for a regular grid (5 m × 5 m) of points. Image matching is based on the computation of the normalized cross-correlation coefficient (valid solutions ≥ 0.4) and applying back matching (threshold ≤ 1 pixel) for consistency check. The correlation window size was set to 31 × 31 pixels, which corresponds to 6.2 m × 6.2 m in object space. Subpixel accuracy was achieved by parabolic interpolation in the neighborhood of the correlation maximum in x and y direction.

Blunder detection of erroneous measurements is based on smoothness constraints of the vector field. The direction and magnitude of each displacement vector is statistically tested considering *a priori* measurement precision. A further consistency check (optional) compares the direction of the displacement vector with the aspect of the terrain derived from a coarse DEM (2006) at 5 m grid spacing. Spatially singular displacement vectors without control of neighboring measurements are removed. The number of remaining blunders/outliers will vary depending on the acuity of the thresholds selected for the various consistency checks, but will still be low. Remaining blunders are removed interactively using an appropriate editing tool.

The precision of the displacement vectors obtained is evaluated in stable areas in the forefield of the rock glacier, where the displacements should be zero (cp. Figure 9). The statistics, i.e. mean value and standard deviation (SD/σ), provide information about systematic shifts and measurement precision. Systematic effects are rectified in the final result. The significance level for horizontal movement was always set to 3-times of SD/σ.

All relevant information of the computation was stored in an ASCII table for further analysis and visualization. We used SURFER (Golden Software) as a flexible tool for the tasks addressed. Figure 9 depicts the mean annual horizontal flow velocity as interpolated isolines (isotachs). The local pattern of surface movement is revealed by a displacement vector overlay. Shaded relief and orthophotos as a backdrop and/or terrain contour lines as an overlay may support further interpretation (Figure 9).

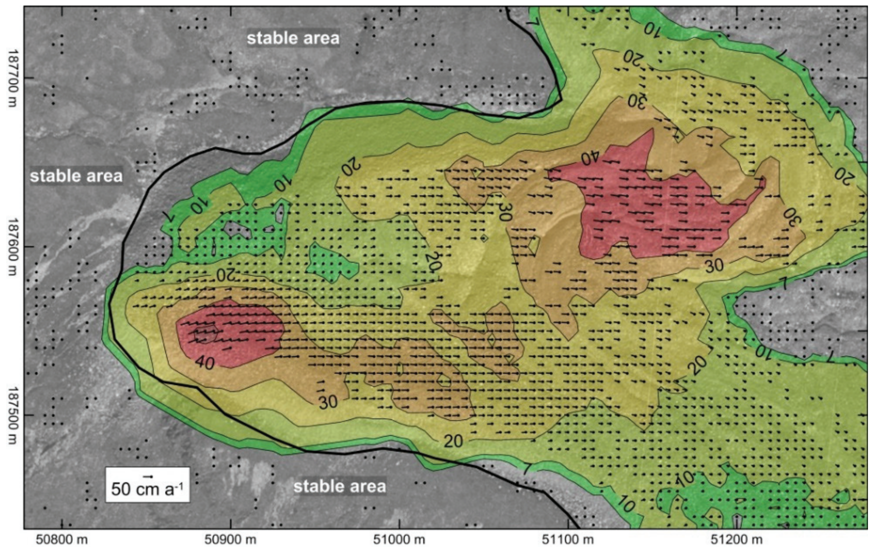

Figure 9: Mean annual horizontal flow velocity of the southern unit of the Inneres Hochebenkar rock glacier for the time period 1953-1969. For location see Figure 8.The significance level of movement is at 7 cm a-1 (3 σ).

5.2 DEM/DSM-BASED CHANGED DETECTION

In this case the computation of 2D (horizontal) displacement vectors is based on multi-temporal elevation data only. The investigations were restricted to the ALS datasets because of resolution and accuracy aspects. The processing workflow outlined above for orthophotos as base data for change analysis did not need to be changed at all. The image matrices (orthophotos) were simply replaced by the respective height/elevation matrices (DSMs). The grid spacing of the measuring points was 10 m and the correlation window size remained the same, i.e., 31 × 31, corresponding to 31 m × 31 m in object space. Accuracy analysis was carried out in the same way as outlined in the previous section.

The temporal change in surface elevation was computed using all available DEMs by simply subtracting the respective datasets at a common grid spacing of 2.5 m. Systematic shifts in horizontal and vertical direction of the DEMs relative to each other need to be corrected (Kääb 2005). This can be accomplished in stable areas. The statistical analysis provides insight into the achievable measurement precision of surface height change.

6 RESULTS

In this paper we focus on the horizontal flow velocity of the Inneres Hochebenkar rock glacier and we only look at surface elevation change for supporting information.

6.1 HORIZONTAL FLOW VELOCITY

Older image data (aerial surveys 1953-1997) were re-processed applying the procedure outlined in this paper. Table 3 lists all evaluations based on the same statistical parameters. Selected results showing the mean annual horizontal flow velocity of the Inneres Hochebenkar rock glacier are shown in Figures 10-14.

Table 3: Computation of horizontal flow velocity for the Inneres Hochebenkar rock glacier.

Time interval	No. of valid measurements	Significance level♣ of flow velocity (cm a^{-1})	Max. flow velocity (cm a^{-1}) – northern unit	Max. flow velocity (cm a^{-1}) – southern unit
1953-2010	12,009	±2.5	36.4	36.7
1953-1969	10,625	±7.0	56.5	52.7
1969-1981	10,390	±10.0	34.0	37.8
1981-1997	19,456	±6.5	31.8	39.8
1981-1990	9,921	±8.5	26.2	39.5
1990-1997	too few points	---	---	---
1997-2010	24,293	±7.0	33.1	40.1
2003-2010	29,279	±10.0	32.9	46.7
2006-2010♦	10,556	±8.5	24.6	57.2

♣… 3 σ, ♦… evaluation of DSMs

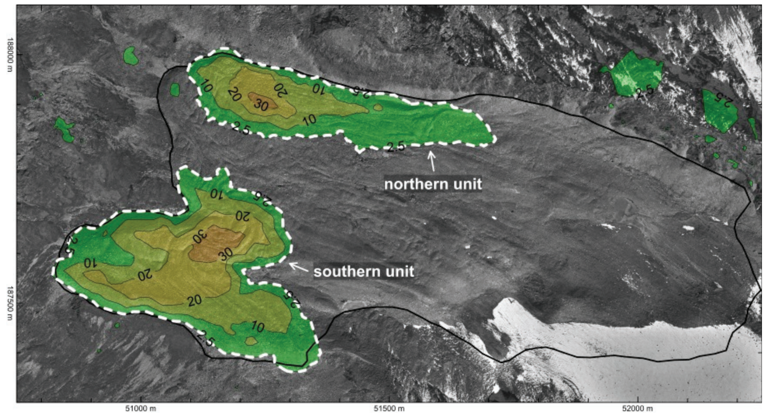

Figure 10: Mean annual horizontal flow velocity for the time period 1953-2010, isotachs (cm a^{-1}), significance level at 2.5 cm a^{-1} (3 σ).

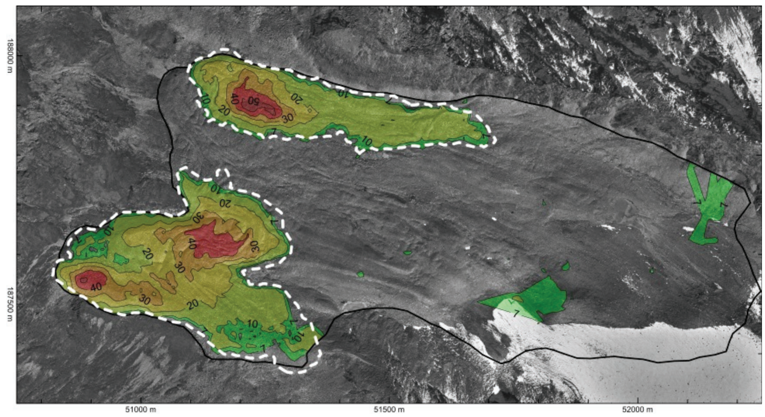

Figure 11: Mean annual horizontal flow velocity for the time period 1953-1969, isotachs (cm a^{-1}), significance level at 7 cm a^{-1} (3 σ).

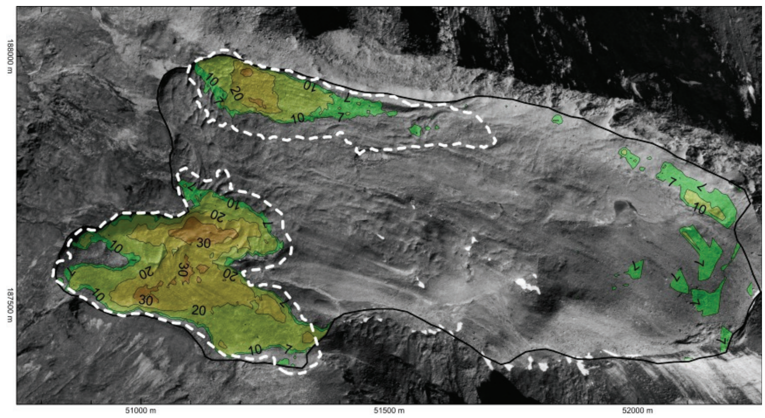

Figure 12: Mean annual horizontal flow velocity for the time period 1997-2010, isotachs (cm a^{-1}), significance level at 7 cm a^{-1} (3 σ).

Figure 13: Mean annual horizontal flow velocity for the time period 2003-2010. Isotachs (cm a^{-1}), significance level at 10 cm a^{-1} (3 σ).

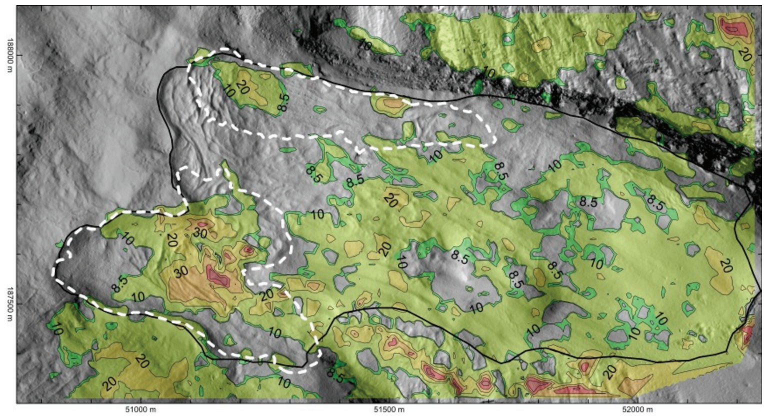

Figure 14: Mean annual horizontal flow velocity for the time period 2006-2010. Isotachs (cm a^{-1}), significance level at 8.5 cm a^{-1} (3 σ) for an area west of the northern unit.

6.2 SURFACE ELEVATION CHANGE

The mapping of significant surface height change is difficult because the photogrammetric DEMs are of low quality and the ALS-based DEMs show inhomogeneous systematic errors in elevation due to systematic errors in geo-referencing (Figure 14). This means that the quantitative analysis of the computed surface elevation change is rather difficult and interpretation can only be done qualitatively in combination with other information, e.g. flow velocity. The surface elevation change of the Inneres Hochebenkar rock glacier was always the highest in the wrinkled area of the southern unit: -9.0 ±1.7 m (3 σ) for 1953-1997 and -3.9 ±1.5 m (3 σ) for 1997-2006, respectively.

7 DISCUSSION AND OUTLOOK

The present study confirms the results obtained in previous studies by Kaufmann and Ladstädter (2002a, 2002b, and 2003): the lower section of the Inneres Hochebenkar cirque holds two independently moving parts, i.e., the northern and southern units of the Inneres Hochebenkar rock glacier. Both areas with statistically significant movement (1953-2010) are outlined in Figure 10 with a thick white dashed line. The activity of the southern unit over time was slightly higher compared to the northern unit. The wrinkled pattern of the surface topography of the southern unit is certainly caused by the special kinematics of this area (see Kaufmann 2016a). Surface deformation in this area goes along with marked surface lowering.

The highest flow velocities (1.10 m a^{-1}) for the Inneres Hochebenkar rock glacier were measured by Pillewizer at the southern unit in the time period 1953-1955. In the overlapping subsequent observation period 1953-1969 the flow velocity decreased significantly with maximum flow velocities hardly exceeding 50 cm a^{-1} at both units. The northern unit was initially moving faster than its southern counterpart, but also slowed down faster over time. A recent increase in flow velocity of the southern unit is speculative. The evaluation of a more recent photo flight (2015), which is not yet available for the public, will answer this question.

Permafrost degradation/melt at the Inneres Hochebenkar rock glacier is rather difficult to quantify since the error levels of the DEMs involved are too high. However, we found strong indications that the lower (non-moving) end part connecting both moving units has undergone substantial surface lowering (2.0-4.7 m in 1953-1997).

Aerial photogrammetry has proven to be a valuable tool for change detection analysis on a multi-annual/decadal time scale. Dense image matching will allow the automatic generation of high-resolution DEMs. Thus, *true orthophotos* can be obtained more easily. Precise orthophotos and high-resolution DEMs combined will allow more accurate 3D surface change detection.

The potential of the available multi-temporal ALS data could not be fully exploited because of obvious geometric problems in fusing the datasets of 2006 and 2010. These systematic registration errors can hardly be corrected by the user. Using the standard 1 m grid data we were (theoretically) able to compute horizontal flow velocities with a precision of 8.5 cm a^{-1} (3σ-level) for a time period of 4 years.

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