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DEFORMATION ANALYSIS OF THE DOESEN ROCK GLACIER (AUSTRIA)

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Abstract

In the framework of a multidisciplinary research project on high-mountain permafrost in the Austrian Alps, a comprehensive deformation analysis of the active Doesen rock glacier (Hohe Tauern range) was carried out using various geodetic and photogrammetric methods. In 1995 a monitoring program was established in order to obtain geomorphometric parameters of the Doesen rock glacier for the past, present and future. Precise geodetic measurements within an observation network are acquired on a regular basis applying classical and also navigation satellite-based methods. Aerial photographs (1954, 1969, 1975, 1983 and 1993) were photogrammetrically evaluated. The flow vectors reveal that the horizontal velocity observed in the center of the rock glacier has decreased from 29 cm a^{-1}(1954-1975) to 17 cm a^{-1} (1975-1993), whereas recent measurements (1995-1996) indicate a significant increase in flow velocity (29 cm a^{-1}). Furthermore, this analysis also includes an evaluation of volumetric changes of the Doesen rock glacier.

Introduction

In order to get a better understanding of the genesis and the dynamics of active rock glaciers, various direct and indirect observation methods can be applied. The modelling of the flow of rock glaciers depends on numerous time-variant and often interrelated variables, e.g., geomorphometric parameters, air temperature, precipitation, debris supply, internal structure, physical and chemical processes, etc. In this respect the repeated mapping of the surface of the rock glacier in a three-dimensional co-ordinate system is of great importance. Surface flow velocities, volumes and superficial principal strain rates and changes thereof in the course of time have to be determined with high precision to describe the kinematics of a rock glacier. Detailed information on photogrammetric and geodetic methods and results of practical work are given in Haeberli (1985), Haeberli and Schmid (1988), Barsch (1996), Kääb (1996), and Zick (1996). Various authors, e.g., Whalley and Azizi (1994) and Barsch (1996), state that precise geometric measurements, especially long-term ones, are lacking.

A review of past and ongoing rock glacier mapping and monitoring projects in Austria is given by Kaufmann (1996). The outer Hochebenkar rock glacier (Figure 1) has the longest record of continuous photogrammetric and geodetic measurements, dating back to 1938. The derived displacement vectors have been analysed by many authors (e.g. Barsch, 1996), nevertheless some important questions concerning the flow process still remain to be answered. In 1995 a renewed terrestrial photogrammetric survey was carried out at this rock glacier. An evaluation is still pending (Kaufmann, 1996).

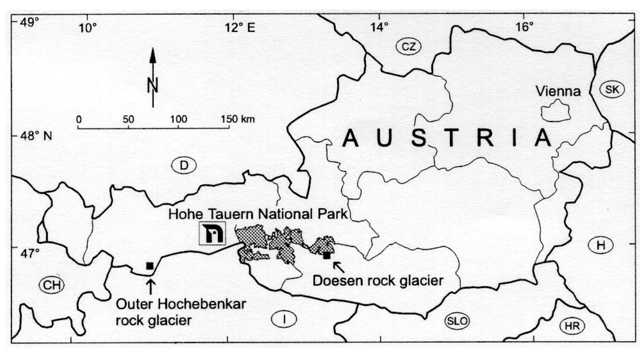

Figure 1. Location of main rock glacier study areas in the Austrian Alps.

In 1995, the Doesen rock glacier (Figure 1) was selected as a test site in the framework of a comprehensive study on permafrost in the Austrian Alps. The geographical location (inner Doesen Valley, Hohe Tauern range) and the main characteristics of the rock glacier have already been outlined by Lieb (1998, in this volume). An important issue of this study has been to set up a long-term monitoring program on the Doesen rock glacier based on photogrammetric and geodetic methods in order to derive time-series of precise surface flow velocities, volumetric changes and principal strain rates.

Photogrammetric approach

In this paper, only the evaluation of aerial and terrestrial metric photographs is considered. Until now, spaceborne remotely sensed data from non-military earth observation satellites are not applicable to the outlined tasks since their spatial resolution, which is not better than 1 m, is too limited.

Aerial Photogrammetric Method

Aerial photographs covering the area of interest were obtained from the Austrian Federal Office of Metrology and Surveying (Table 1). In a first step a geomorphometric study map at 1:5,000 scale and a primary digital terrain model (DTM) covering the inner Doesen Valley were evaluated. Further cartographic work comprised a stereo-orthophoto map at 1:30,000 scale, two combined image-line maps at 1:10,000 scale, i.e., an orthophoto map and a relief map, and various combined image-line maps of the Doesen rock glacier at 1:5,000 scale (Kaufmann, 1996). Figure 2 shows a computer-generated perspective view of the inner Doesen Valley.

Table 1. Aerial photographs covering the Doesen rock glacier

Year	Date	Image scale	Film type
1954	unknown	1:13,600-1:18,500	B/W
1969	29.9.-12.10.	1:26,000-1:32,000	B/W
1975	17.9.	1:16,100-1:22,800	B/W
1983	15.8.	1:30,500-1:35,200	CIR
1993	15.8	1:8,700-1:13,500	CIR

Three-dimensional displacement vectors were obtained by photogrammetrically tracking prominent boulders of the surface layer of the rock glacier using the photographs given in Table 1. The stereomodel dating from 1993 was selected as a reference model for the absolute orientation of the other stereomodels using

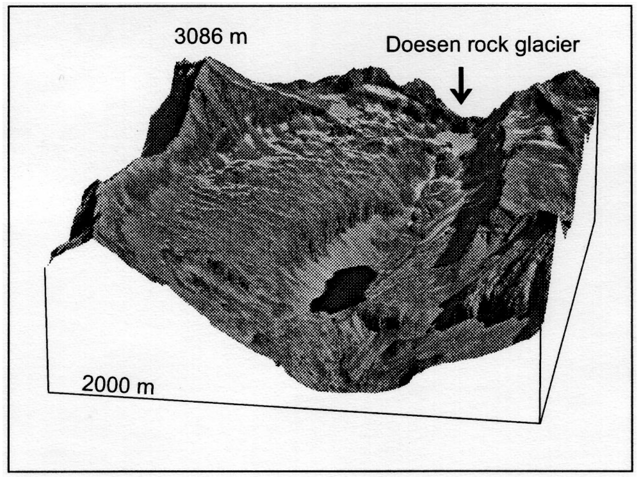

Figure 2. Perspective view of the study area from W direction. The rectified aerial photograph (1975) has been draped on the DTM.

homologous control points. In time-consuming work, 581 individual boulders, evenly distributed over the whole rock glacier, were identified and measured using the DSR-1 analytical stereoplotter. These points were remeasured in the older stereomodels, i.e., 372 points for 1983, 382 points for 1975, 297 points for 1969, and 305 points for 1954. Due to the small scales and sometimes very bad image quality of the photographs, even the identification of larger boulders was quite troublesome and tedious. As a final result mean annual flow velocities, flow lines, principal strain rates and changes of the surface height of the rock glacier were computed and presented in numerical and graphical (color-coded) form.

The basic idea of deriving changes of surface height has been published by Barsch (1996) and Zick (1996). The proposed geomorphological model assumes that the vertical displacement of a point on the surface of the rock glacier is an arithmetic sum of a "topographic" and a "glacial" component (Figure 3). In order to facilitate computation, horizontal and vertical displacements were interpolated with respect to the given grid spacing of the high-resolution DTMs. The topographically induced component was estimated using the local

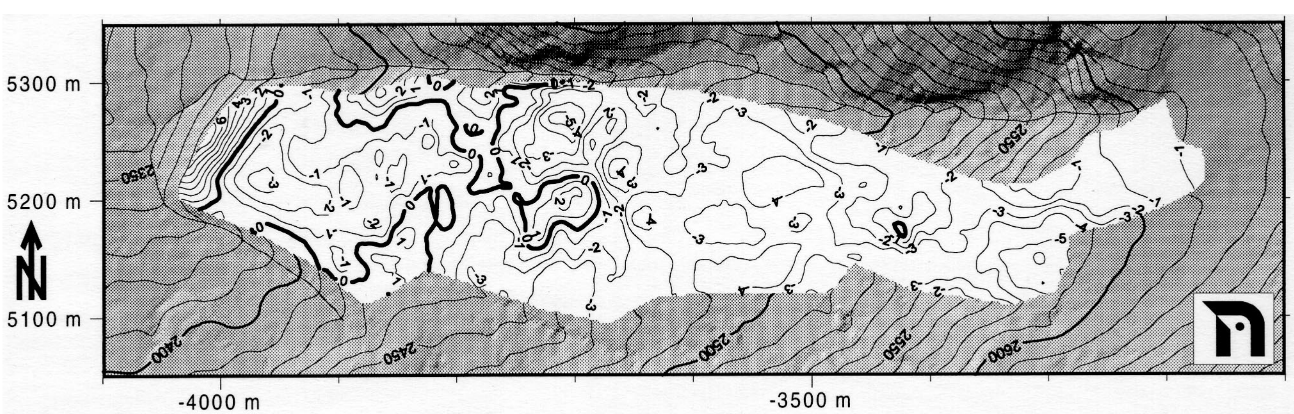

Figure 3. "Glacial" component (cm a^{-1}) of the vertical displacement for the time period 1954-1993.

gradient of the DTM, which itself was smoothed to a great extent in order to reduce the influence of micro-relief, i.e., ridges and furrows.

Based on dense three-dimensional relief data, i.e, contour lines, drainage lines, ridge lines, break lines and spot heights, three high-resolution DTMs covering the area of the Doesen rock glacier were generated representing the situations of 1954, 1975 and 1993. Unfortunately, it was not possible to derive proper height information for the whole catchment area. The slopes in the S and SE of the rock glacier, which have been identified as the main regions for debris supply, were almost always in shadow. As a matter of fact, the area of interest was restricted to the area indicated in Figure 3. Since mass balance computations could not be performed, relative volumetric changes within the outlined area only were assessed. By dividing the relative volumetric change by the respective planimetric area a general trend towards a lowering of the surface level was derived. But due to the topography of the rock glacier and its intrinsic downslope movement, the result obtained is slightly lower than the actual value.

TERRESTRIAL PHOTOGRAMMETRIC METHOD

Aerial photographic surveys are generally very expensive. In order to study the applicability of terrestrial photogrammetry in the monitoring program of the Doesen rock glacier, a feasibility study (Kaufmann, 1996) was carried out. In 1994, 1995 and 1996, terrestrial photogrammetric surveys (Figure 4) were conducted using a Rolleiflex 6006 metric réseau camera equipped with two interchangeable objectives (f=50 mm and f=150 mm). Spherical targets (Ø 14 cm) were deployed on the rock glacier as precise control points. Since the annual movements of the Doesen rock glacier are in the range of several centimeters, the time period between two surveys should be at least two or more years to get significant results. Because of the great number of terrestrial photographs needed to cover the whole rock glacier and the importance of treating all sources of systematic errors in the evaluation process, the application of digital photogrammetric methods has been found to be a prerequisite.

Figure 4. Terrestrial photograph taken with a Rolleiflex 6006 metric réseau camera. View in NW direction onto Doesen Lake and Doesen rock glacier. Photograph taken by R. Kostka on 27 July, 1995.

Geodetic approach

CLASSICAL METHOD

Independently of the photogrammetric approach, a geodetic network was installed at the Doesen rock glacier in 1995. The network consists of 7 reference points (Figure 5, points S1-S4 south of the rock glacier and points N1-N3 north of the rock glacier) permanently fixed in the bedrock by brass bolts, and assumed to be stable. In addition, 34 object points were selected on the rock glacier (Figure 6). These points were stabilized preferably on large boulders in the same way as the reference points, the bolts allowing targets and retroreflectors to be mounted. Additionally, two transverse and two longitudinal profile lines (Figure 6), consisting of 72 painted points on smaller boulders, completed the points to be monitored on the rock glacier. In 1996 all geodetic measurements (distances and directions) were repeated. The stability of the reference points was checked using statistical tests. In total, 106 displacement vectors were computed. Figure 6 shows the horizontal components (flow vectors) for further visual analysis. Surface height changes were computed for the profile lines and the individual points following the model previously given.

NAVIGATION SATELLITE-BASED METHOD

In the framework of the monitoring program the applicability of the satellite-based Global Positioning System (GPS) was investigated as well. Applied studies have shown that the reference points can be determined with equal accuracy compared to classical methods. Thus GPS could be used to check the stability of the reference points from time to time. Monitoring of the numerous points on the rock glacier by means of the time-saving reoccupation and rapid static methods, however, is not recommended. The observation time for each point is still too long and the surrounding mountains considerably hamper reception of proper satellite signals, which makes positioning difficult or even impossible.

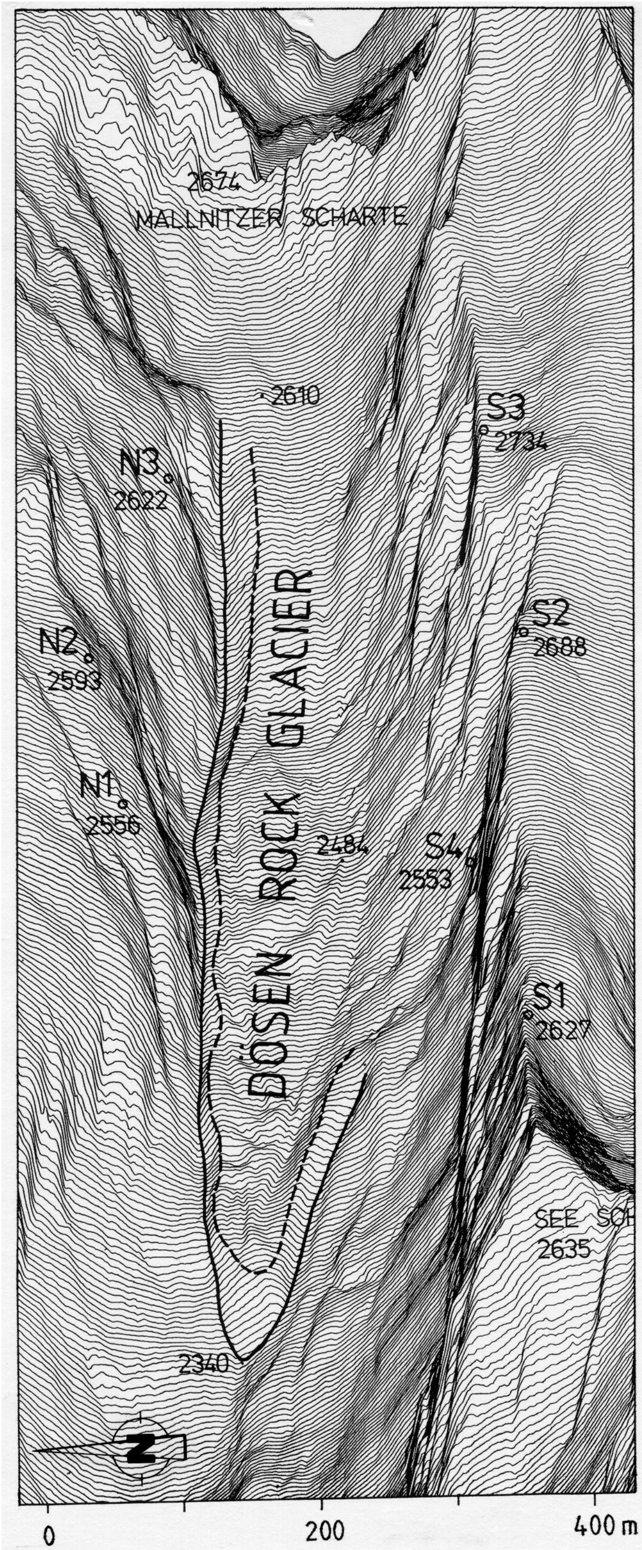

Figure 5. Axonometric view of the Doesen rock glacier showing vertical profiles. N1-N3 and S1-S4 are the reference points of the geodetic network.

Results and discussion

In the following, the main findings for rock glacier research are reported. The upper edge of the snout of Doesen rock glacier has advanced almost 7 m from 1954 to 1993. The horizontal directions of the flow vectors highly correspond to the low frequencies of the topographic relief. The micro-relief composed of furrows and ridges seems to ride passively on top of the inner permafrost body, at least for the short observation period of 39 years considered. Furthermore, the graphical representation of Figure 6 seems to reveal that the main debris supply is coming from the adjacent steep slopes in the S and SE of the rock glacier, and that the area of the upper orographic right side of the rock glacier does not show any significant horizontal movements. The movement of the outer orographic right side, between 2450 m and 2600 m altitude, has turned out to be far less distinct than in the other areas of the Doesen rock glacier. The maximum flow velocities, i.e., 29.4 cm a^{-1} (1954-1974), 17.2 cm a^{-1} (1975-1993) and 29.6 cm a^{-1} (1995-1996), were all measured in the center of the rock glacier near the position of point No. 15 (see Figure 6). According to the transverse profiles in this area, the flow velocities decrease towards the outer edges of the rock glacier. Table 2 lists the statistical mean values of horizontal flow velocity and surface height change derived for the whole area of interest (117,500 m^2) for the given time periods. These numerical results suggest that the flow velocities decreased significantly from 1954 to 1975, then remained steady until 1993. For the time period 1995-1996, a significant acceleration of movement (over 50% compared to the time period 1975-1993) can be observed, as far as this value which is valid for only one year, can be compared with the data from the photogrammetric approach. The present flow velocities correspond to those of the 1950s and 1960s. In the past few years, increasing flow velocities have also been observed at the Macun I rock glacier (Swiss Alps) by Zick (1996).

Numerical values that reflect the change of thickness of the Doesen rock glacier were twice derived from photogrammetric measurements (see Table 2 and 3) and a third time using the classical method (i.e., mean surface lowering for all 106 points with -4.3 cm a^{-1} and -5.9 cm a^{-1} for the two transverse profiles). Despite the limitations of the applied model - e.g., the snout always shows a "false surface uplift" as can be seen in Figure 3 - and the lack of sufficient measurements, a continuous reduction of the thickness of the Doesen rock glacier is obvious. From 1969 to 1983 statistics showed a non-significant uplift of the surface, whereas surface lowering was most distinct in the time period 1995-1996. The reason for the observed surface lowering may be either extending flow or decay of ice, or both. The interrelationship between (horizontal) flow velocity and surface height change on the one hand, and the dependence of both parameters on climatic conditions on the other hand, are questions of special interest which have yet to be answered. Principal strain rates did not show significant results because the photogrammetrically derived

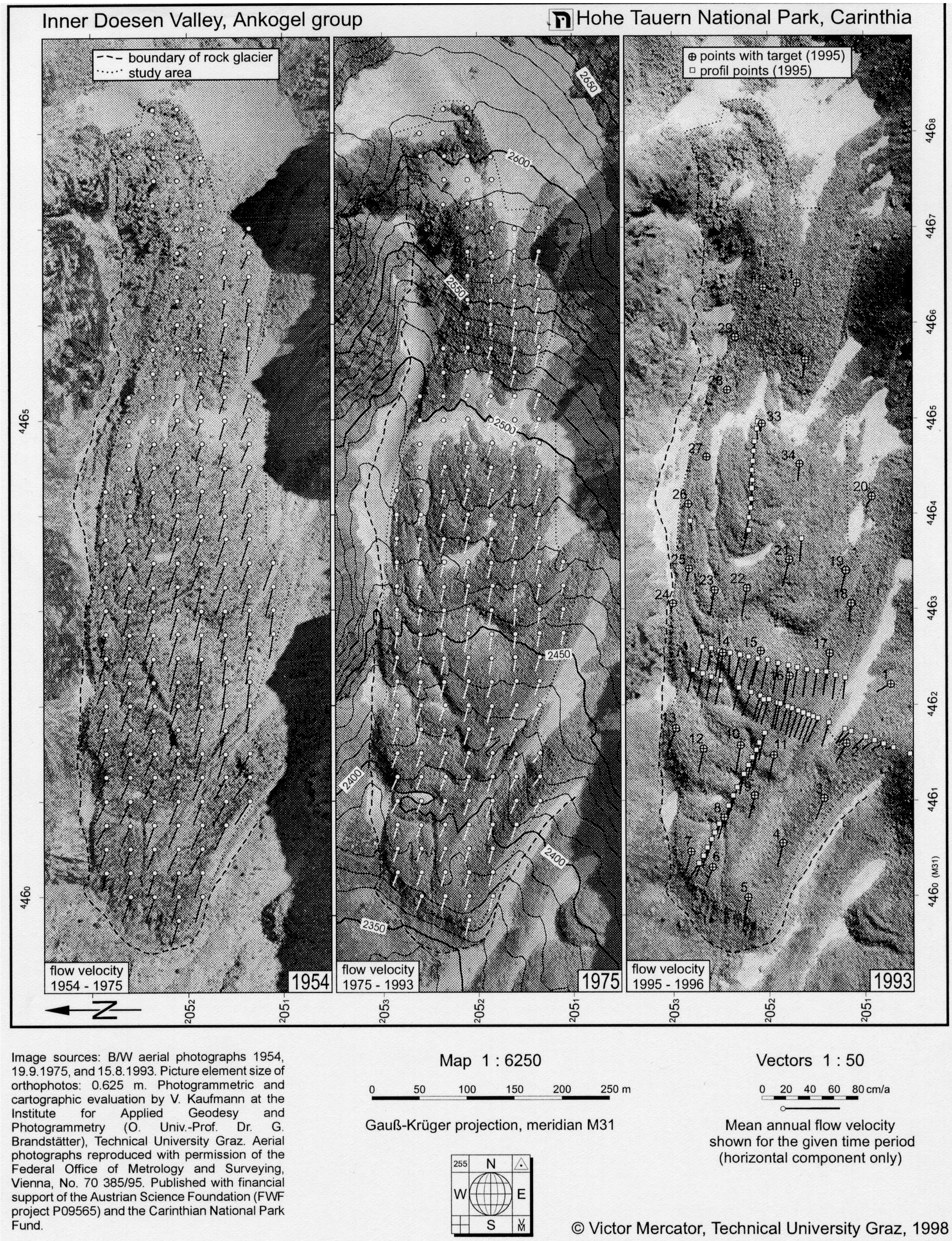

Figure 6. Cartographic representation of the mean horizontal flow velocities at the Doesen rock glacier for the time periods 1954-1975, 1975-1993, and 1995-1996.

points were too close together and not sufficiently accurate. The point density has to be reduced.

In September 1997, large-scale black-and-white aerial photographs were acquired over the Doesen rock glacier and the geodetic measurements were repeated. The latter will be done annually, provided that the necessary funds are available. The quality and speed of the photogrammetric evaluation will be increased by means of digital photogrammetry, a relevant methodology having already been proposed by Kaufmann (1997). To overcome obvious problems in gathering pre-

Table 2. Statistical parameters derived from photogrammetric measurements of selected points

Time period	Mean horizontal flow velocity (cm a^{-1})	Mean surface height change (cm a^{-1})
1954-1969	19.4	-5.5
1969-1975	13.0	8.8
1975-1983	11.9	2.3
1983-1993	10.6	-5.7
1954-1975	17.2	-1.7
1975-1993	10.9	-2.1
1954-1993	14.3	-1.9

Measurements of 1969 and 1983 are subject to greater uncertainty and therefore results obtained are not significant.

Table 3. Evaluation of the high-resolution digital terrain models

Time period	Relative mass balance (m^3 a^{-1})	Mean surface height change (cm a^{-1})
1954-1975	-727	-0.6
1975-1993	-3071	-2.6
1954-1993	-1808	-1.5

Surface area considered: 117,500 m^2.

cise data, other remote sensing methods, e.g., radar interferometry using ERS-1/2 satellite data or airborne laser scanning, may be worth investigating.

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