Band 41 (2007), S. 147–167

ZEITSCHRIFT FÜR
GLETSCHERKUNDE
UND GLAZIALGEOLOGIE

Analysis of surface elevation changes on Kesselwand glacier – comparison of different methods

JAKOB ABERMANN, HERALT SCHNEIDER AND ASTRID LAMBRECHT, INNSBRUCK

With 12 figures

Abstract

Kesselwandferner is an interesting and well investigated glacier in the Ötztal Alps, the glaciological parameters of which have been measured annually for more than forty years. Within this timeframe a period of strong advance (from 1970 to 1985) could be observed.

An analysis of surface elevation changes revealed interesting features, especially during the advance period when the accumulation area responded with a surface elevation decrease due to downward mass transport. At the same time there was a strong increase in the ablation area. During the last two decades an opposite tendency has been observed. Today, the altitude of the glacier surface in the major part of cross-profile B (at around 3200 m) is about 7 m higher than it was in 1983, when the lowest values were recorded. It is still increasing although a strong setback was observed after the very hot summer of 2003.

The dataset gained by groundbased surveying was compared with a digital elevation model of 1997 based on aerial photogrammetry and with three digital elevation models based on airborne laser-scans taken between 2001 and 2003. A three-dimensional coordinate transformation was necessary to compare the different datasets.

It was found that due to its sensitivity to blinding, the digital elevation model of 1997 produced significant errors especially in the firn-area. In large parts of the glacier it agrees satisfactorily with the data provided from the theodolite measurements.

The laser scanning method proved very accurate and sensitive to small features (e.g. crevasses). However, compared with the theodolite measurements there is a systematic error of 1 to 1.5 m of altitude.

Analyse der Änderung der Gletscheroberfläche am Kesselwandferner – Vergleich verschiedener Methoden

Zusammenfassung

Der Kesselwandferner ist ein interessanter und viel erforschter Gletscher in den Ötztaler Alpen, dessen glaziologische Parameter in einem einzigartigen Datensatz seit mehr als vierzig Jahren gemessen werden. Innerhalb dieser Zeit wurde eine starke Vorstoßperiode (1970–1985) beobachtet.

In diesem Artikel werden die Oberflächenhöhenänderungen betrachtet, deren Entwicklungen besonders in der Vorstoßperiode einige interessante Details beinhalten: Im Akkumulationsgebiet des Gletschers konnte in dieser Zeit eine Oberflächenhöhenverringerung aufgrund des Massentransports nach unten festgestellt werden. Umgekehrt nahm die Höhe der Oberfläche im Ablationsgebiet zu. Während der letzten beiden Jahrzehnte konnte man einen entgegengesetzten Trend beobachten. Die Höhe der Oberfläche in weiten Teilen des Profils B (in etwa 3200 m) ist heute um ungefähr 7 m höher als 1983, als sie den geringsten Wert in diesem Bereich zeigte. Sie nimmt noch immer stetig zu, allerdings hat der außergewöhnlich heiße Sommer 2003 einen Einbruch dieser Tendenz hervorgerufen.

In einem weiteren Schritt wurden in diesem Artikel die Daten aus der Feldarbeit mit jenen aus dem digitalen Geländemodell von 1997, das auf digitaler Photogrammetrie basiert, und jenen aus verschiedenen Laserscanüberflügen der Jahre 2001 bis 2003 verglichen. Es war notwendig, eine dreidimensionale Koordinatentransformation durchzuführen, um die Datensätze vergleichen zu können.

Folgende Aussagen über die Vergleichbarkeit sind zu treffen: Das photogrammetrisch bestimmte Höhenmodell von 1997 stimmt über weite Teile gut mit den Daten aus den Theodolitenmessungen überein, jedoch ist diese Methode empfindlich in Bezug auf Überblendungen besonders im Firngebiet. Laserscanning liefert sehr hochaufgelöste und fein strukturierte Oberflächenmodelle, allerdings tritt im Vergleich mit den Feldmessungsdaten ein systematischer Fehler von etwa 1 bis 1.5 m auf, der auf die dreidimensionale Koordinatentransformation zurückzuführen sein könnte.

1. Introduction

Kesselwandferner is situated in the southernmost Ötztal at 10.8°E and 46.8°N (Fig. 1). The glacier measures 3.9 km^2 at a length of about 4.1 km (source: Institute of Meteorology and Geophysics, Innsbruck, 2006). Fluchtkogel (3496 m) marks its highest elevation, its lowest point is at around 2800 m.a.s.l.

Climatically, the glacier is situated between the dry and central alpine valleys of Vinschgau in the south and Ötztal in the north (approx. 500 mm and 600 mm annual precipitation, respectively, Fliri 1975).

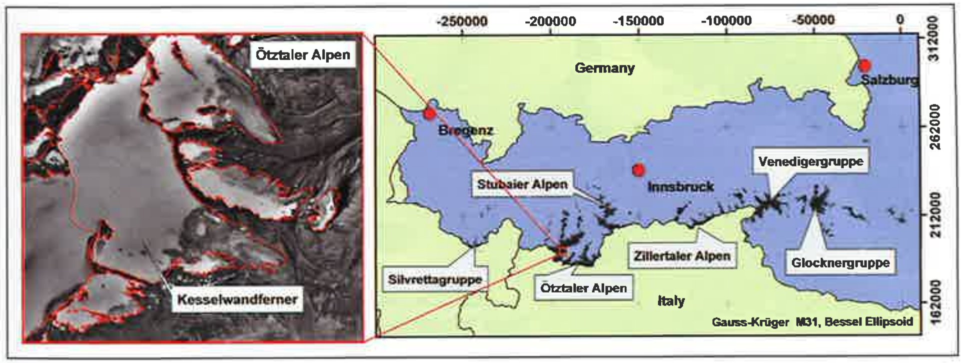


Figure 1. Location of the Kesselwandferner, orthoimage of the Austrian Glacier Inventory taken in September 1997.

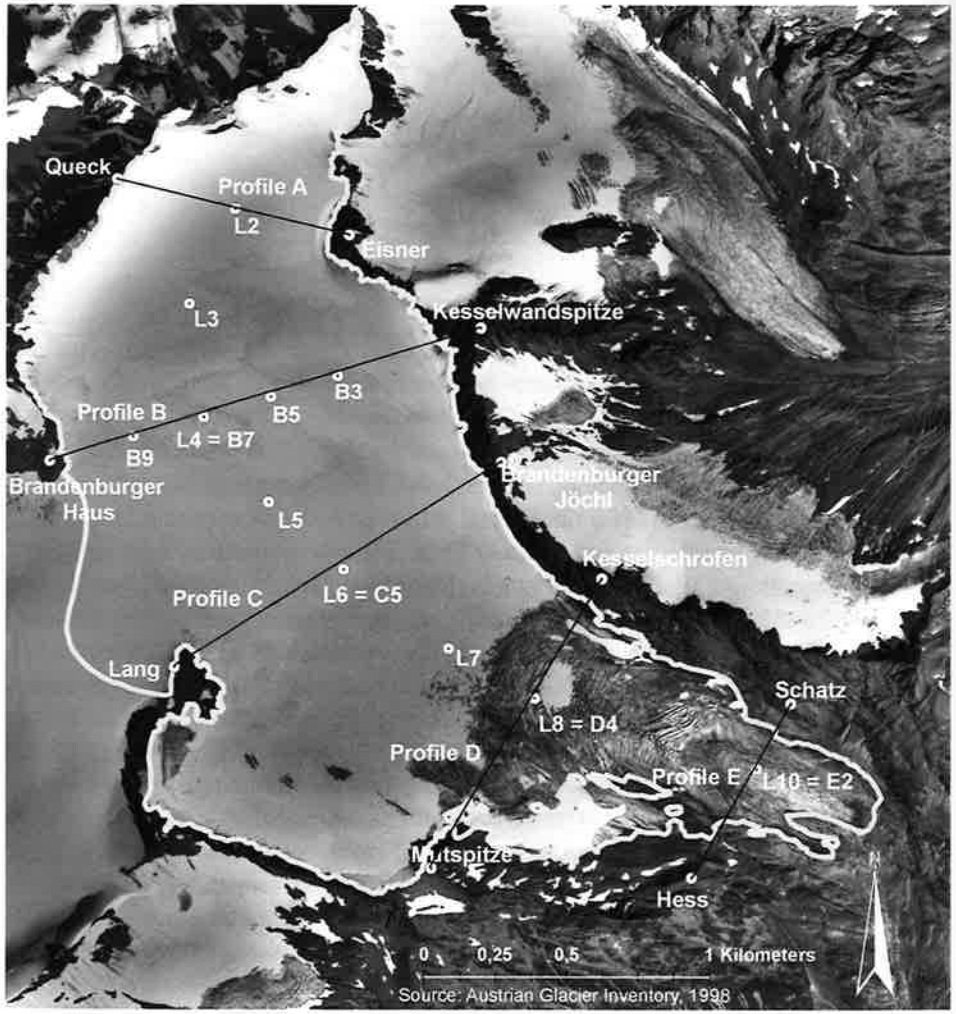
Over the past century, Kesselwandferner responded to climate with two advances: In 1922 the glacier reached its maximum extent, followed by years of retreat. In 1931, the margins of Kesselwandferner and adjacent Hintereisferner separated, with the period of retreat lasting until 1965. Following this, Kesselwandferner remained more or less stationary for the next five years. As a result of some years of positive mass balance in the 1960s, the tongue advanced by about 320 m between 1970 and 1985. Interestingly, neighbouring Hintereisferner did not advance during the same time period. This very different dynamic response was mainly due to the different orographic circumstances of the two glaciers (Kuhn et al. 1985). Contrary to the typical valley glacier Hintereisferner, Kesselwandferner has a high and large accumulation area but a short and steep glacier tongue that is exposed towards the southeast. Thus, a comparatively large accumulation area means a greater gain of mass in years with positive mass balance which makes Kesselwandferner a climatically very sensitive glacier.

2. Data and methods

2.1 Field measurements

There is a very valuable dataset of glaciological parameters on Kesselwandferner. Since 1965 H. Schneider of the Institute of Mathematics at the University of Innsbruck has been carrying out annual campaigns, in which the most important parameters of ice flow as well as mass balance are measured by means of terrestrial photogrammetry.

The profiles shown in Fig. 2 are surveyed by a theodolite, combined with an electro-optical rangefinder (Kern, DM501). A network of stakes has been established for mass balance and velocity measurements; the stakes are annually set back to their original positions.



Source: Austrian Glacier Inventory, 1998

Figure 2. Orthoimage of the Kesselwandferner (11.9.1997) containing the glacier boundary of the Austrian Glacier Inventory and the names of the signals, stakes and cross profiles.

Fig. 3 shows the schematic movement of a stake and the change of the surface altitude in the accumulation and ablation area between two dates of measurements, t_1 and t_2. *s* refers to the horizontal distance of the base points of the stakes (length of the horizontal velocity vector), *v* to the vertical movement relative to the surface, Δa to the relative elevation change due to accumulation or ablation, Δz to the altitude difference of the base points of the stakes (length of the vertical velocity vector), Δh to the altitude difference in the flowpath of the stake and Δd to the absolute elevation change (Schneider 1970).

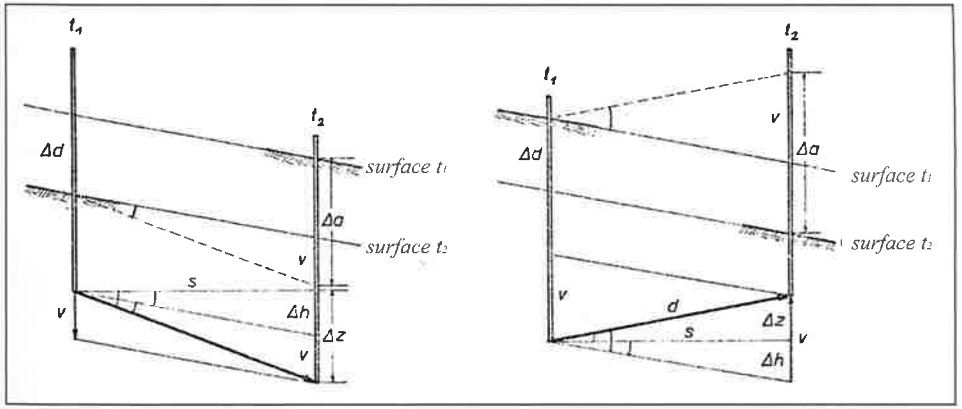


Figure 3. Schematic concept of stake movements left, in the accumulation area and right in the ablation area (Schneider 1970).

With the exact positioning of the stake, the distance from its upper end down to the surface and the comparison of the previous year's position all mentioned parameters can be calculated. Every year the stakes are relocated to their initial positions in the cross-profiles.

The field measurements yield the entire velocity-vector (horizontal and vertical components), the absolute surface altitude in five cross-profiles (point measurements at approximately 30 m-intervals) and at the stakes (see Fig. 2), the surface slope as well as the position and shape of the glacier tongue (Span 1999). For single spot measurement an accuracy of 2 cm in x-, y,- and z-direction within the grid of the "Münchner" coordinates is achieved (see 2.4.1.; Schneider 1976).

2.2 Data from the digital elevation model 1997

The Digital Elevation Model (DEM) 1997 has been established through photogrammetric methods from stereo images of aerial photographs taken on 11.9.1997. The vertical accuracy of this method is 0.7 m for a single spot measurement (Würländer and Eder 1998). This DEM has been produced as part of the new Austrian Glacier Inventory (Eder et al. 2000, Würländer and Eder 1998, Lambrecht and Kuhn 2007).

2.3 Laser-scans

Laser scanning is an active remote sensing technique at which a laser beam is emitted and the reflected beam is recorded (Wehr and Lohr 1999, Bucher 2005). This method is very accurate and not particularly influenced by weather circumstances (Wever 1999).

In this article three out of the ten DEMs that have been gained through laser scanning flights within the EU-Project OMEGA (Operational Monitoring System for European Glacial Areas) are used.

The horizontal accuracy of the used laser-scan technology is 1 m, the vertical accuracy 0.3 m (Geist and Stötter 2006). The following flight dates have been used for comparison with the field measurements:

11.10.2001 (flight No. 1)
19.08.2002 (flight No. 6)
12.08.2003 (flight No. 9)

Flight No. 1 and flight No. 6 were evaluated using the System ALTM1225, Flight No. 9 with ALTM2050, which provides a higher number of spot measurements and therefore a higher resolution as well (Geist and Stötter 2006).

2.4 Comparability of the data

The different origin of the data caused various problems when attempts were made to compare them with each other. First, the coordinate systems in which the data had been gained had to be adjusted and transformed. Another problem lay in the different dates upon which the measurements were taken.

2.4.1 Coordinate systems

The "Münchner" coordinates, in which the field measurements have been evaluated, are Gauß-Krüger coordinates that, unlike the Gauß-Krüger "Landesvermessung" coordinates, are apparently not reduced to sea level in x-y-location (Schneider 1976, Schimpp 1959). The difference between these systems is rather equally distributed around 0.5 m in x- (west-east) and 4 m in y-direction (north-south) as Fig. 4 suggests where a test data set around Profile E has been transformed through Helmert-Transformation with four identical signal points (Kahmen 1993). This horizontal differences are sufficient for many glaciological applications (e.g. mass balance or velocity measurements), but in this study exact altitudes out of different data sources are compared. Thus a more accurate positioning is necessary.

An arithmetic mean of the deviation between these two similar systems has been calculated from all available transformed points and used for a least square root regression adaptation of the two different datasets (Tab. 1). Regarding the values of the standard deviation in Tab. 1 a satisfactory approximation has been achieved.

Table 1. Arithmetic mean of the deviations between the "Münchner" coordinates and the "Landesvermessung" coordinates and the respective standard deviations.

	x-Direction	**y-Direction**
arithmetic mean	3.73984	–0.47824
standard deviation	0.59521	0.19975

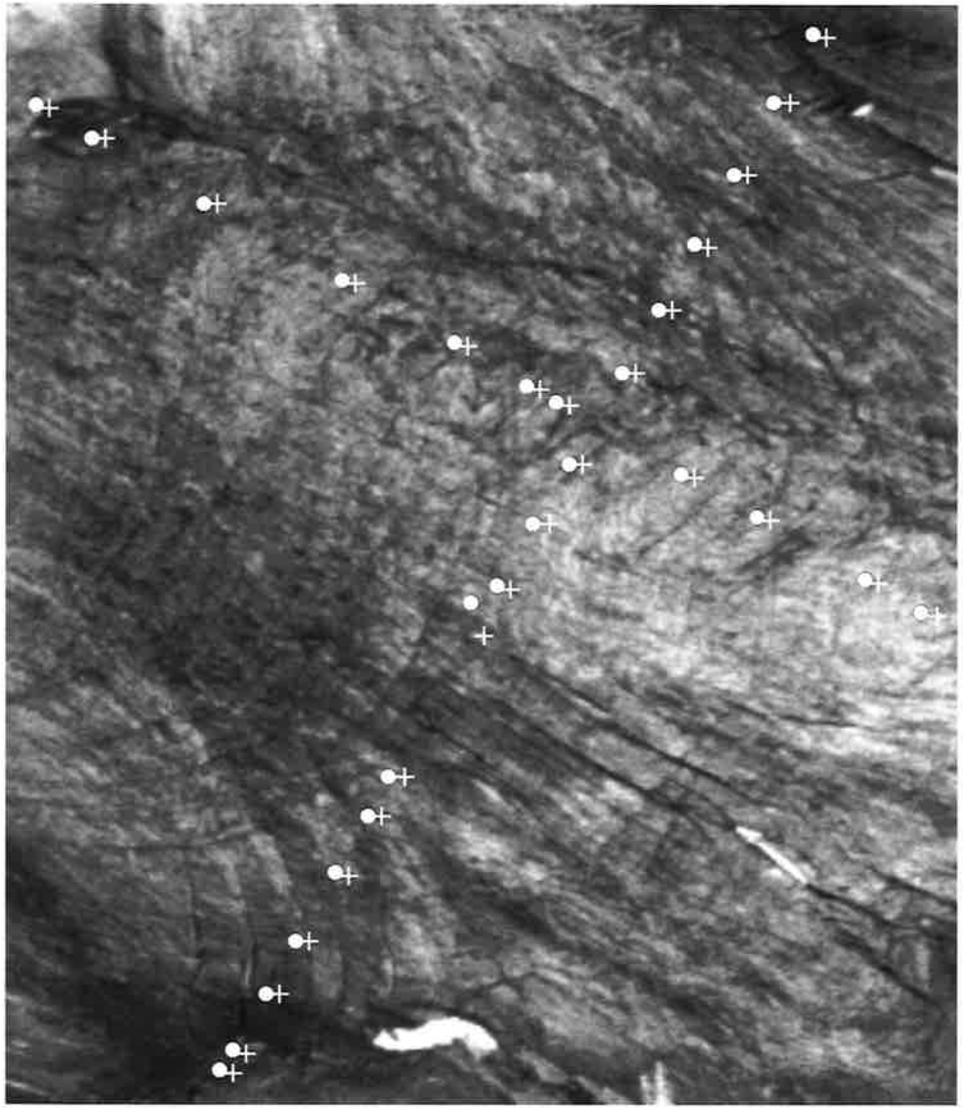


Figure 4. Comparison of the "Münchner" (crosses) with the "Landesvermessung" coordinates (circles) around profile E.

The vertical differences, calculated for all eight signal points available in both systems are between 0.08 m and 0.27 m, the "Landesvermessung" coordinates being generally higher. These differences have not been taken into account because of their unequal distribution over the glacier and because of their low values.

For the comparison of the field measurement data with the laser scanner data (2001, 2002 and 2003) it was necessary to transform the modified Gauß-Krüger coordinates into UTM-WGS84 using the transformation software *Easytrans*. The reason for choosing this system lay in the fact that the laser scanner data have been evaluated in UTM-WGS84. A three-dimensional transformation was necessary because Gauß-Krüger M28 refers to orthometric, whereas UTM-WGS84 refers to ellipsoidal heights (Reigber and Schwintzer 2003). The difference between these systems is about 50 m for the area of Kesselwandferner, the ellipsoidal altitude values being higher.

If not explicitly mentioned, all figures in this article show orthometric height values. Only in 3.2.2., where the field measurements are directly compared with the laser scanner data, have transformed ellipsoidal heights been used.

2.4.2 *Estimates of accumulation and ablation for date adjustment*

In order to compare the different datasets it was necessary to estimate accumulation and ablation between the dates of measurement. The emergence velocity that also influences the surface altitude development, as Fig. 3 suggests, has been neglected because the maximum time between the measurements is approximately 6 weeks. This time period is too short to influence the surface altitude changes significantly, because the annual emergence velocity values are less than ±1 m a^{-1} (Abermann 2006). As a basis for an estimation of accumulation, the precipitation and temperature data of the nearest weather station Vent (1900 m) have been used. In a first step the total amount of precipitation in the required period has been evaluated. According to Hoinkes and Steinacker (1974) a threshold temperature has been estimated, for which the snow/rain transition is at 3200 m (snow in the accumulation area) and another one for which the whole glacier would be snow covered. For Vent, these threshold temperature values are 7.8°C for the accumulation area and 5.4°C for the whole glacier, both calculated with a lapse rate of –0.006 K/m. All precipitation that has fallen at temperatures below these threshold values between the dates of measurement has been summed up. The increase in precipitation concomitant with altitude was estimated from a comparison of the ombrometer at "Proviantdepot" (2737 m) with that of Vent (1900 m). This comparison led to an amplification factor that slightly varies for each period (Tab. 2). Finally, the precipitation that has fallen below the respective threshold value has been multiplied with the described factor and builds the base for the accumulation estimation in water equivalent.

Table 2. Summary of the correction factors used for date-adjustments in accumulation and ablation area. t_1 refers to the date of the field measurement in the accumulation area, t_2 in the ablation area and t_3 is the date of the flight. F is the amplification factor for precipitation at "Proviantdepot" in comparison to Vent and Δz is the resulting surface elevation change between the respective measurement dates.

year	**t_1**	**t_3**	**F**	**Corrections Accumulation Area (Acc. A.)**						
				Precipitation (P) between t_1 and t_3			Ablation (DDM)	Δz (DDM)		
				P Vent [mm]	P in Vent at T < 7.8°C [mm]	P (Acc. A.) as snow [mm w.e.]	[mm w.e.]	[mm w.e.]	[m]	
1997	11.9.	11.9.	1.32	–	–	–	–	–	–	
2001	15.9.	11.10.	1.34	34	29	39	–34	5	0.02	
2002	15.9.	19.8.	1.25	42	13	16	–185	–169	–0.2	
2003	13.9.	12.8.	1.3	94	22	29	–263	–234	–0.3	
year	**t_2**	**t_3**	**F**	**Corrections Ablation Area (Abl. A.)**						
				Precipitation (P) between t_2 and t_3			Ablation (DDM)	Δz (DDM)		Δz (stake comparison)
				P Vent [mm]	P in Vent at T < 5.4°C [mm]	P (Abl. A.) as snow [mm w.e.]	[mm w.e.]	[mm w.e.]	[m]	[m]
1997	27.8.	11.9.	1.32	34	6	8	–490	–482	–0.5	–0.5
2001	28.8.	11.10.	1.34	108	50	67	–375	–308	–0.3	–0.3
2002	30.8.	19.8.	1.25	25	0	0	–454	–454	–0.5	–0.3
2003	27.8.	12.8.	1.3	286	0	0	–772	–772	–0.8	–0.8

The ablation that took place between the respective measurement dates was estimated using two different methods:

First the ablation for the required time interval was taken from comparable stakes at neighbouring Hintereisferner (Abermann 2006). This method only works for the ablation area where corresponding stakes at Hintereisferner can be found.

The degree-day-method is another way of estimating ablation. In a first step 7.8°C for the accumulation area and 5.4°C for the ablation area have been subtracted from a daily mean temperature of Vent and the positive values summed up. This value has been multiplied by 4 mm d^{-1} K^{-1} for the accumulation area and 6 mm d^{-1} K^{-1} for the ablation area, respectively (Paterson 1994). The value for the ablation area is higher because of the significantly lower albedo. The result is an estimation of the ablation in mm water equivalent. The difference between the snow precipitation in water equivalent and the estimated ablation value yields to Δz in mm w. e. Divided by the ice density (900 kg m^{-3}), the resulting value shows the ice ablation Δz in m.

The summary of the date adaptation in Tab. 2 shows that the results fit together well for 1997, 2001 and 2003, only in 2002 the degree-day-method leads to a higher value (Δz (DDM): –0.5 m whereas Δz (stake comparison): –0.3 m).

3. Results and discussion

3.1 Surface elevation changes in field measurement data

Changes in surface elevation of a glacier occur as a result of the vertical motion of ice and mass balance (Paterson 1994). The detailed distribution of these components for Kesselwandferner can be found in Abermann (2006). In this article, only the resulting altitude changes are observed.

Fig. 5 shows the surface altitude changes along the longitudinal profile since 1965, standardized for the value of 1968 because that was the first year to yield a complete stake dataset. An obviously different reaction between the accumulation and ablation area can be noted. Between 1970 and 1983 (advancing period) the surface in the accumulation area (L2 to L5) lost altitude whereas it has continuously increased since the mid-eighties, the only exception being the unusually warm summer of 2003 (Schär et al. 2004). Some of the stakes of the accumulation area (e.g.: L3 and L4) have today reached a higher surface altitude than they had in 1968.

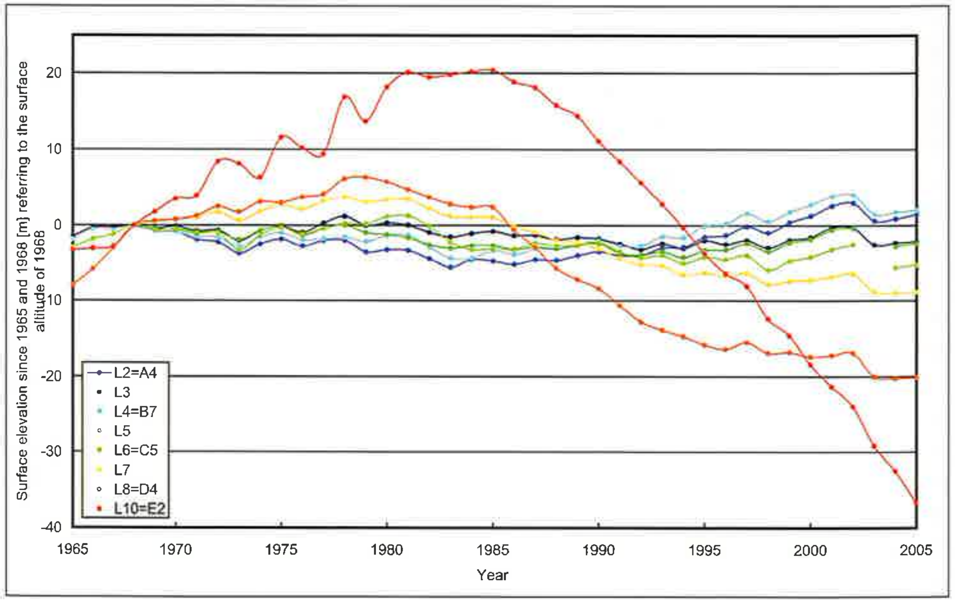


Figure 5. Surface elevation changes at the stakes in the longitudinal profile since 1965, referring to the value of 1968. The stakes in the accumulation area (L2 to L5) gain altitude in the past decade.

The data pertaining to the ablation area show a different result: The closer to the tongue the stake is situated, the more obvious is the advancing period in the surface altitude data. Stake E2 for example gained approximately 25 m of ice thickness up until 1985, since then it has lost more than 60 m. The undulating pattern of E2 during the advance period is a result of ice avalanches from the serac zone immediately above that have later been transported through Profile E.

The surface elevation along profile B which runs from Brandenburger Haus to Kesselwandspitze (see Fig. 2) has been measured at approximately 20 m-intervals since 1965. Additionally, a stake set of at least four stakes that have been placed back every year, has been recorded up until 2003. Profile B displays interesting details concerning local differences and general tendencies of surface altitude changes.

Fig. 6 shows the surface elevation development of profile B over the last 40 years, looking against the flow direction. On its western part (left in this figure) the profile is very close to the ice divide of Gepatschferner. It is obvious that the depression we observe today has not always been there. Up to 1980 the surface elevation has increased in this area but since the end of the advance period (1985) the depression is growing. It is very probable that Gepatschferner and Kesselwandferner influence each other here. However, in the remaining part of the profile, from approximately 200 m from Brandenburgerhaus towards Kesselwandspitze, an opposite trend can be observed. During the advancing period surface elevation has decreased with a minimum ice thickness in 1983 (see also Fig. 7).

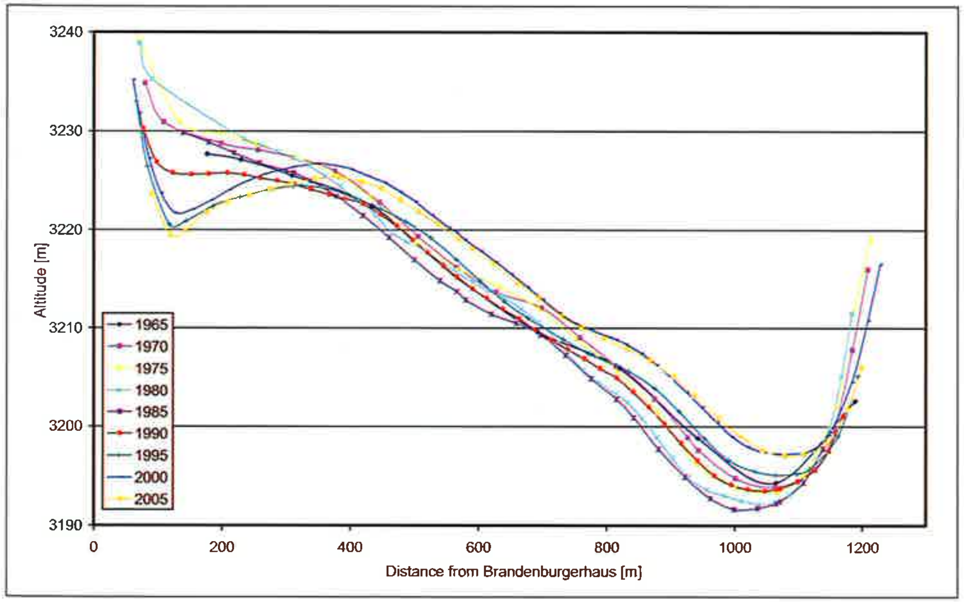


Figure 6. Development of the surface elevation in profile B from 1965 to 2005 looking up against the flow direction.

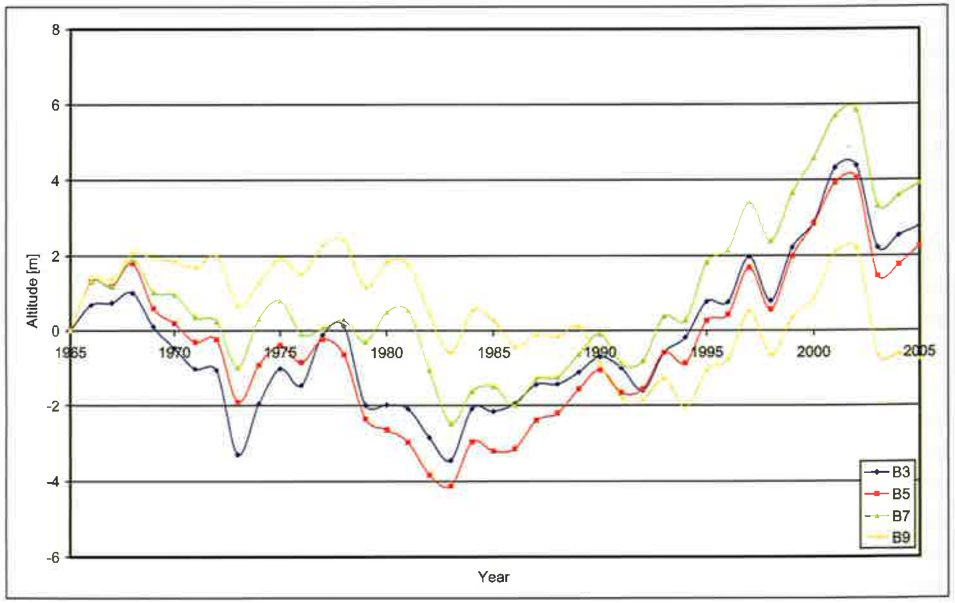


Figure 7. Surface elevation development of the stakes in profile B referring to the values of 1965. Note the different development of B9 compared to B3, B5 and B7 that used to be higher than the other stakes during the advancing period and is lower now.

Since then a growth of more than 10 meters has continued up to now. The reason for this can be found in the glacial dynamics. The vertical transport of the past 20 years in this area is very small and the horizontal velocities especially in the ablation area have decreased considerably (Span 1999; Abermann 2006). Today, the horizontal and vertical motion is very slow and therefore the downward ice transport is small. Due to this, it can build up mass in the accumulation area even though we observe a period of negative mass balance years.

Fig. 7 shows the relative surface altitude changes of the four stakes in Profile B relative to the value of 1965. Here the relatively constant ice thickness of stake B9 and the increase of B7 to B3 since 1983 can be clearly seen.

3.2 Comparison of altitude changes among the different data sources

Having adjusted the coordinate systems in 2.4.1. and estimated the amount of accumulation and ablation between the different measurement dates in 2.4.2., it is now possible to compare the field measurement data with the DEM 1997 that has been produced with digital photogrammetry (see 3.2.1.) and with those DEMs that have been gained through laser-scan technology (see 3.2.2.), respectively.

3.2.1 Field measurements and DEM1997

Fig. 8 shows the comparison in Profile A. At the left part of the profile (near signal Queck), altitude differences of about 10 m can be seen, the field measurement values being higher in this area. In the right half of the profile the data fit together much better. The orthoimage (see Fig. 2) that has been used provides an answer vis-à-vis the discussed discrepancy: The area in the northwestern part of the accumulation area shows a strong blinding due to the solar insolation and the high albedo values of the snow cover. No surface features are detectable as common points for the generation of the elevation model. This strongly affects the accuracy of the photogrammetric method (Würländer and Eder 1998).

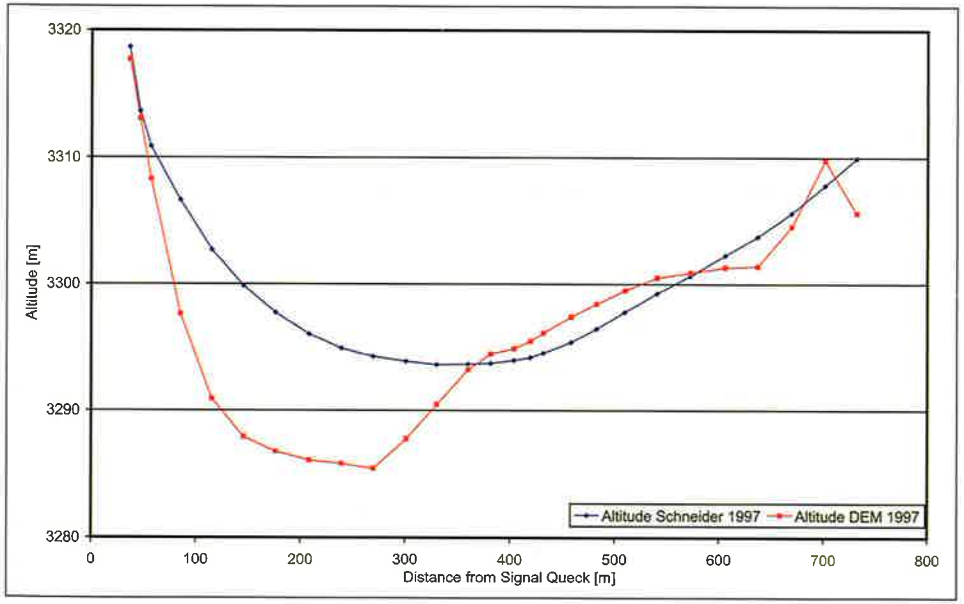


Figure 8. Comparison of field ground based surveying (altitude Schneider) and DEM 1997 for profile A. Note the big differences at its western part that are due to blinding.

The altitudes in the remaining four profiles fit together better, as Fig. 9 displays exemplarily for Profile D, wherein the DEM1997 is on an average around 0.7 m higher. However, the date adjustment considerations of 2.4.2. would suggest the DEM surface being 0.5 m lower.

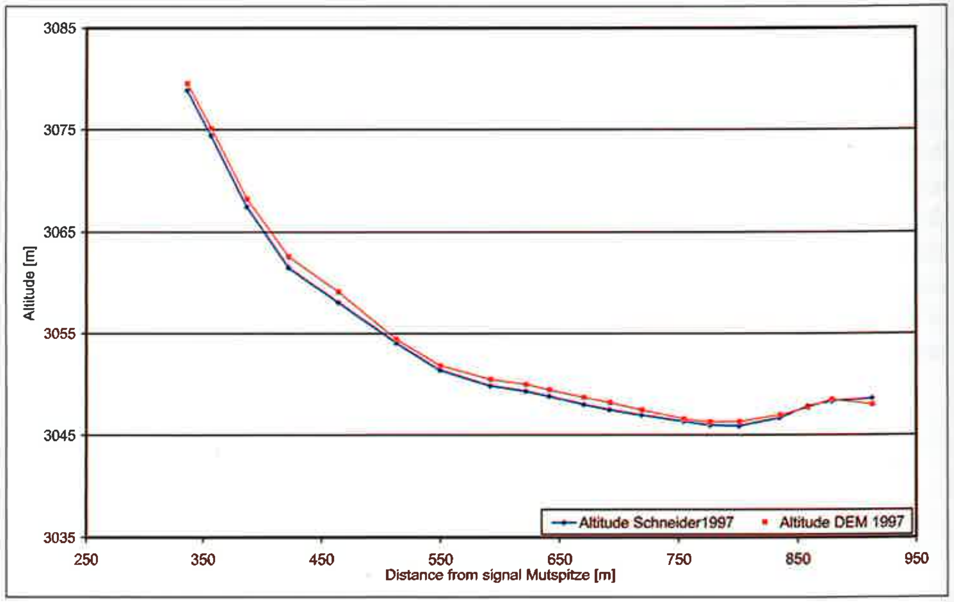


Figure 9. Comparison of field measurement data (altitude Schneider) and DEM 1997 for profile D.

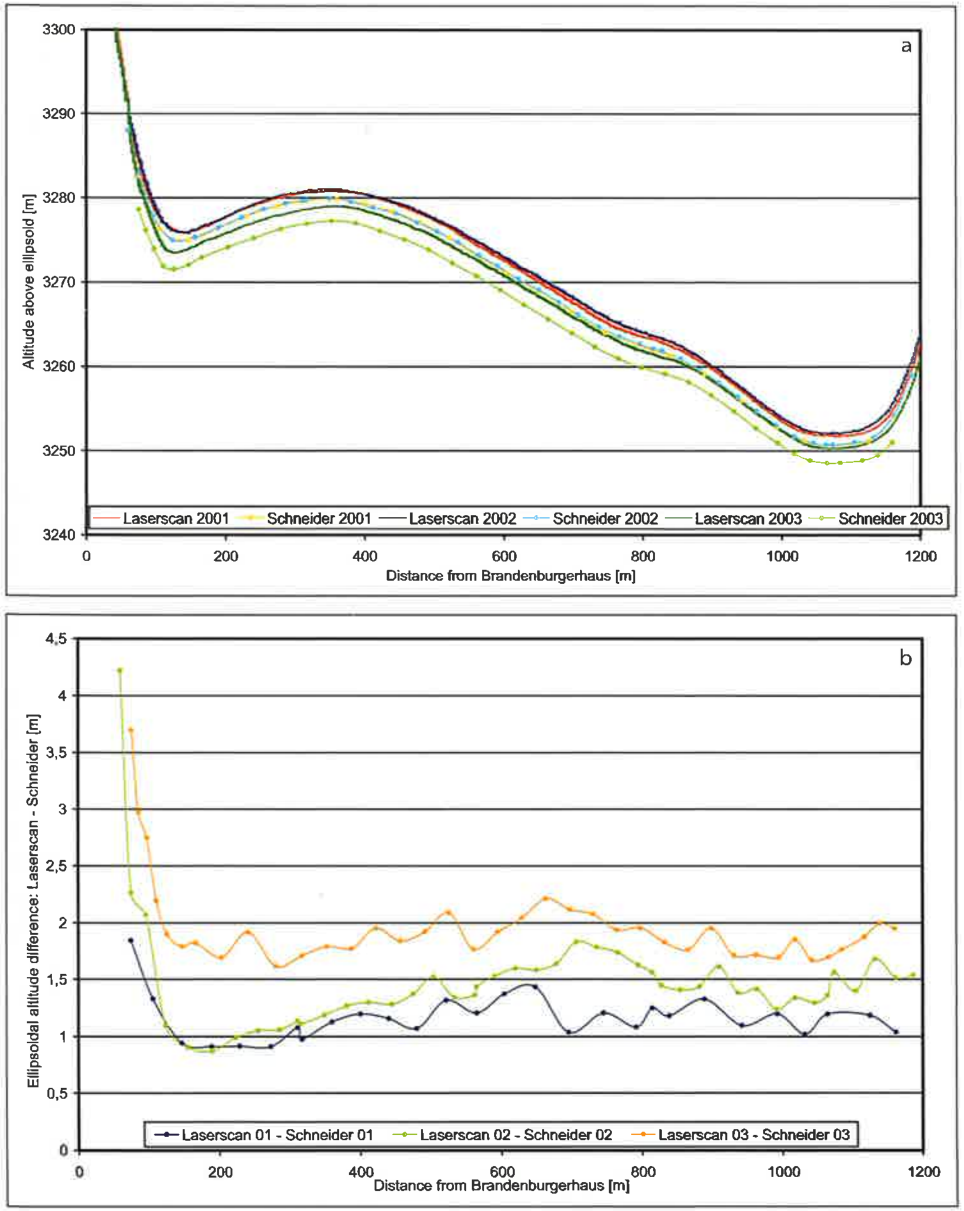
3.2.2 Field measurements and laser scanner data

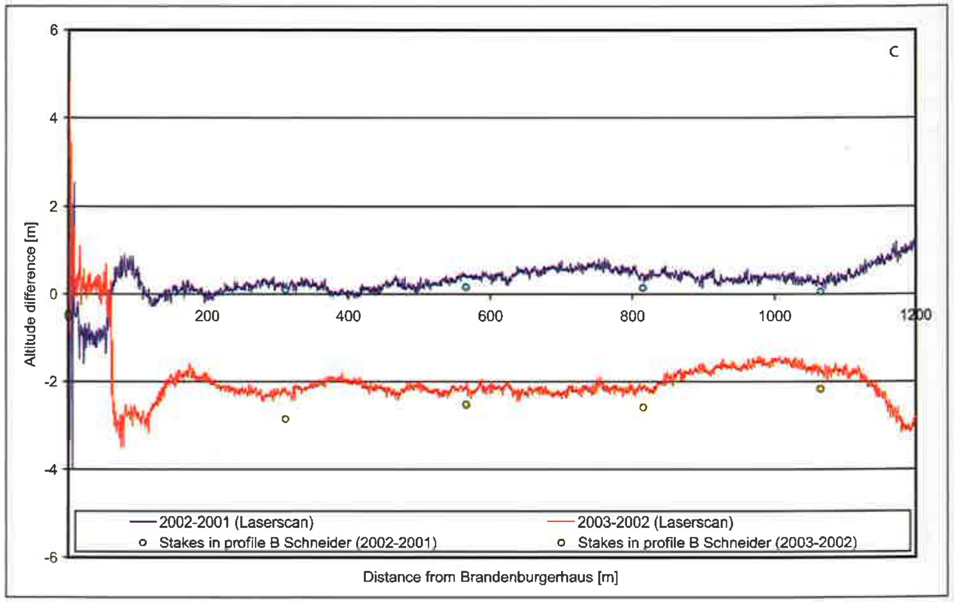
In order to compare the field measurements with laser scanner data the coordinate transformed data of the field measurements had to be used. While this comparison has been done all over the glacier, in this article only the results for profile B as an example of an accumulation profile and D of an ablation profile are shown (Abermann 2006).

Fig. 10 (a) shows the profile altitude of profile B for the ground based surveying (altitude Schneider) and laser scanner data for the years 2001 to 2003. The surface altitudes of 2001 and 2002 are very similar within each method, 2003 is distinctly lower. In general, the data gained through laser scanning appear to be higher than the field measurement data, which is clearly indicated in Fig. 10 (b) where the differences between the methods in the surface altitudes for each individual year are displayed. For 2001 and 2002 the laser scanner data is around 1.5 m higher, in 2003 the difference is around 2 m. These differences can not be explained through ablation or accumulation between the measurement dates because the previous estimations would suggest a 30 cm higher (see Tab. 2) surface of the laser scanner data at most. There seems to be a systematic error caused by the coordinate transformation.

To investigate how well the data fit together within one measurement method, the relative altitude changes between two years have been compared in Fig. 10 (c).

Figure 10. Comparison of the surface elevation in profile B between laser scanner data and field measurement data (2001 to 2003) (a); Altitude difference between the laser scanner data and the field measurement data for the respective years (2001, 2002 and 2003) (b); Altitude differences between the respective years (2002–2001 and 2003–2002) for the laser scanner data (solid lines) and the stakes in the profile (dots). Note the larger negative values in the field measurement differences of 2003–2002 (c).



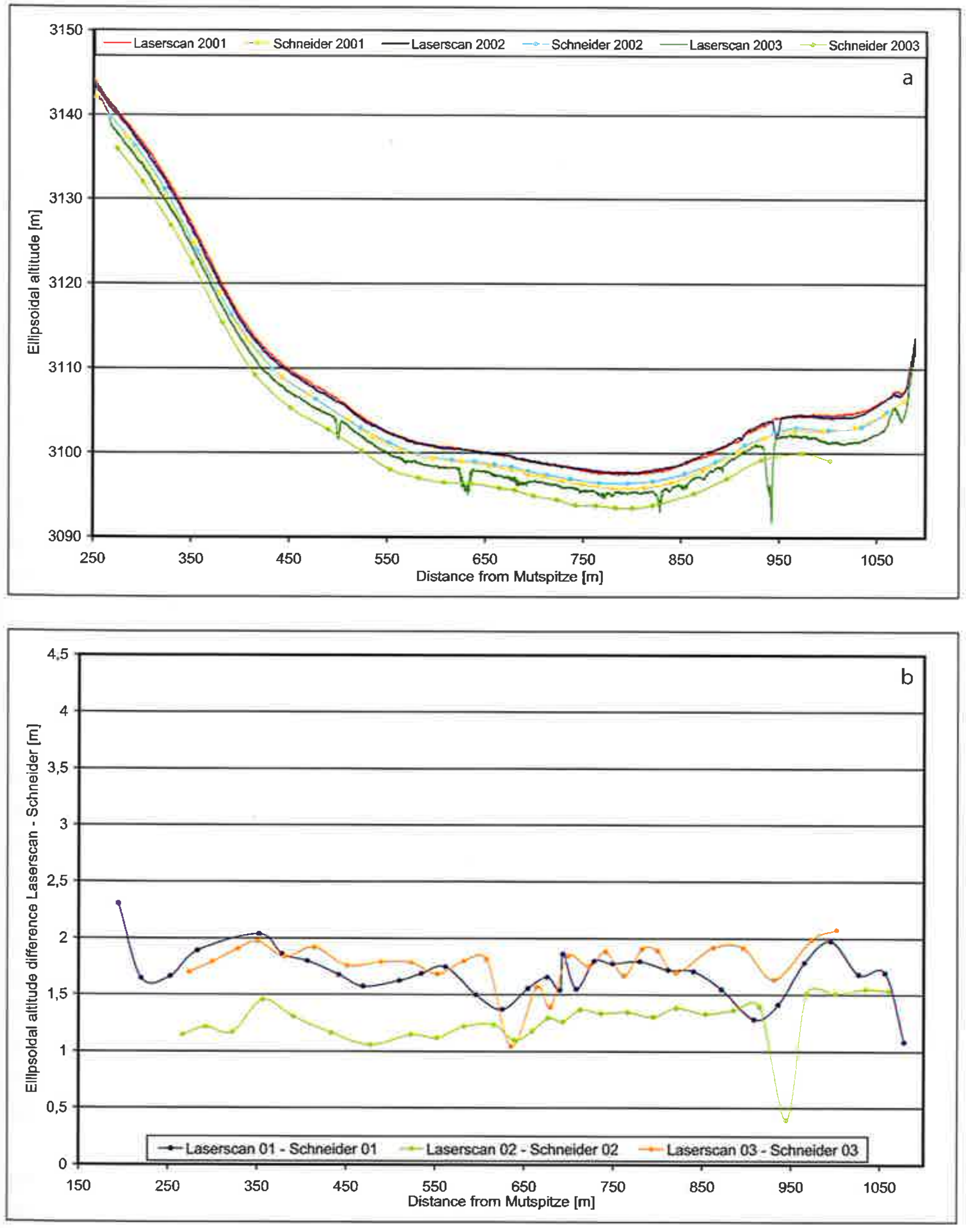


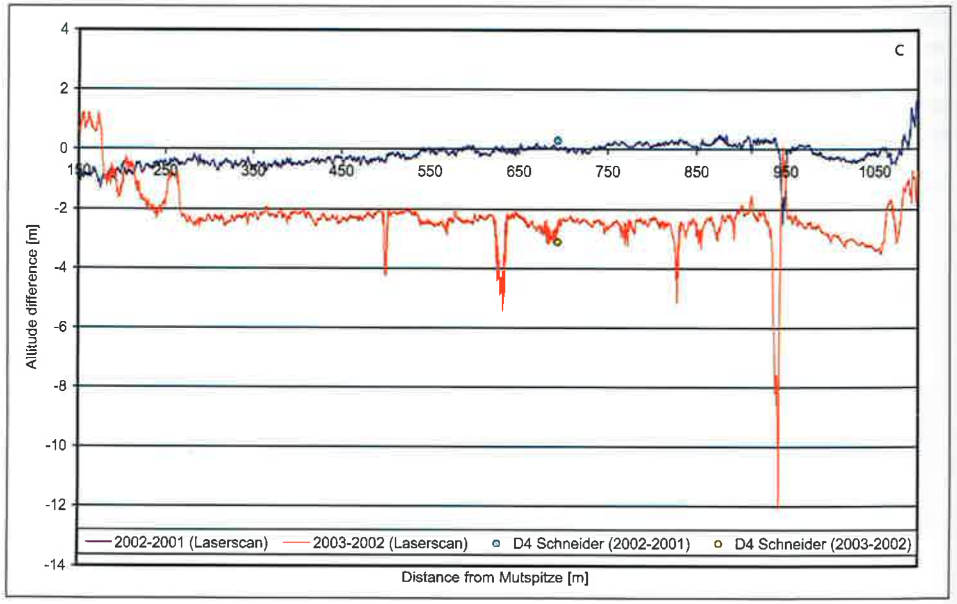
The solid lines show the differences between the laser-scan surfaces (blue: 2002–2001, red: 2003–2002). The dots show the four respective stake values. For 2002–2001, both methods fit together very well. For 2003–2002 however, there is a bigger difference in the field measurement data. This can easily be explained by taking a brief glance at the dates of the measurements: In the unusually warm summer of 2003 (Schär et al. 2004) there was approximately 0.3 m ablation in this area between the date of the flight and the field measurement (Tab. 2).

A propos of the ablation area, Fig. 11 (a) shows the development of profile D in the different data methods. Again, 2001 and 2002 lie very close to each other within each method, a strong mass loss caused a much lower surface altitude in 2003. The more accurate sensor that was used for the laser scanning in 2003 (see 2.3.) led to a higher resolution. Thus the crevasses can be shown remarkably well. An interesting detail is the displacement of the deep crevasse that was situated at 950 m from Mutspitze from 2002 to 2003 around 10 m towards west the reason being the local topography and the slope of the glacier in this area. These details can of course not be seen in the field measurement data because of the lack of a high number of measurements.

The altitude difference between the laser scanner data and the field measurement data can be seen in Fig. 11 (b). The largest differences can again be seen in 2003, where the values reach almost 2 m, in 2001 the differences are around 1.2 m. Regarding the estimated values of ablation adaptation not even the half of these deviations can be explained by the different measurement dates (Tab. 2). Fig. 11 (c) shows again the altitude changes between the laser-scan surfaces 2002–2001 and 2003–2002, and the altitude change at the stake D4.

Figure 11. Comparison of the surface elevation in profile D between laser scanner data and field measurement data (2001 to 2003) (a); Altitude difference between the laser scanner data and the field measurement data for the respective years (2001, 2002 and 2003) (b); Altitude differences between the respective years (2002–2001 and 2003–2002) for the laser scanner data (solid lines) and the stake D4 (dots) (c).





In both periods the different methods correspond very well. The slightly higher difference in the stake D4 from 2002–2001 compared to the laser-scan flight could be attributed to fresh snow that fell during the interval between the field measurement and the flight in 2001 (see Tab. 2).

4. Conclusion and outlook

This purpose of this article is to show a comparison of the surface altitude data of the well investigated Kesselwandferner gained by employing three different methods. A very valuable dataset consisting of velocity and surface altitude measurements taken over more than 40 years, a DEM from aerial photogrammetry of 1997 and laser-scan DEMs for 2001 to 2003 have been used.

The field measurement data include the full advance period from 1970 to 1985. Some interesting features could be pointed out: While the surface elevation in the accumulation area decreased during the advancing period, since then it has been increasing continuously, the only exception being the very warm year 2003. Today, the surface altitude in profile B is about 6 m higher than it used to be at its minimum in 1983. The opposite trend has been observed in the ablation area, where at stake E2 for example the surface altitude decreased at around 60 m between 1986 and 2005.

A comparison of the field measurements with other data sources shows the following: The DEM 1997 based on digital photogrammetry fits together well with the field measurement data in large parts of the glacier but it is sensitive to blinding due to the solar insolation that caused errors of about 12 m in certain areas.

To compare the laser scanner data with the field measurement data it was necessary to transform the latter three-dimensionally from “Gauß-Krüger/M28” to “UTM/WGS84”. The resulting data show a very similar course but there is an approximate 1.5 m discrepancy between them. Most probably this error has its source in the co-ordinate transformation. The compared differences within each dataset that are not influenced by the transformation process fit together very well (Figs. 10 (c) and 11 (c)).

The big advantage of the laser-scan technology is its very good resolution all over the glacier. This advantage is illustrated in Fig. 12 where the surfaces of 2001 and 2002 are shown on top of each other. A rise of the surface in the major part of the accumulation area can be seen within this period whereas approximately below profile D the surface altitude is decreasing. Thus, given that operational monitoring through laser scanning could prove very interesting, it seems feasible that field measurements will continue to maintain this extraordinary dataset in future.

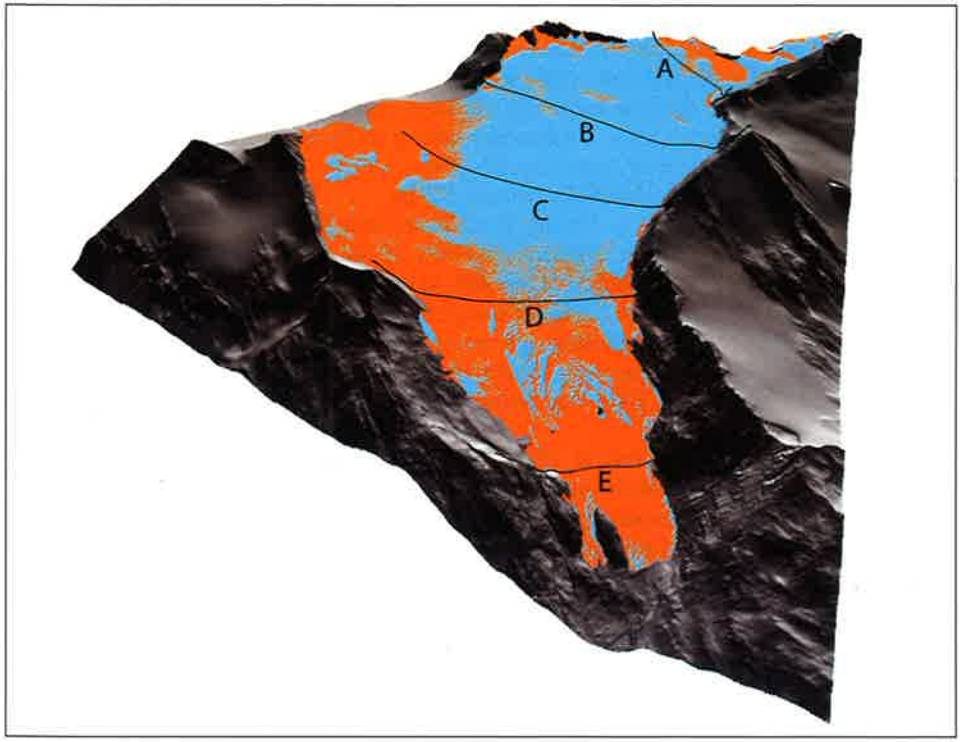


Figure 12. 3-D image of the surface of Kesselwandferner with the cross-profiles A to E for 2001 (blue) and 2002 (red). The colours show which of the surfaces is higher.

5. Acknowledgements

The authors would like to thank Univ.-Prof. Dr. Michael Kuhn for his advices and discussions, Univ.-Prof. Dr. Johann Stötter and Dr. Thomas Geist for providing the laser scanner data and especially Dr. Thomas Geist for his help with the use of the software Easytrans. Thanks also to Dr. Estelle Dryland for proof-reading the English version of this article.

6. References

Abermann, J., 2006: *Glaziologische Analyse der Höhe der Gletscheroberfläche am Kesselwandferner*. Unpublished diploma thesis at the Institute of Meteorology and Geophysics, University of Innsbruck, 66 pp.

Bucher, K., 2005: *Ableitung der horizontalen Gletscherbewegung aus multitemporalen Laserscanner-Daten*. Unpublished diploma thesis at the Department of Geography, University of Innsbruck, 69 pp.

Eder, K., R. Würländer, and H. Rentsch, 2000: Digital photogrammetry for the new glacier inventory of Austria. *IAPRS International Archives of Photogrammetry and Remote Sensing* 33, pp. 1–15.

Fliri, F., 1975: *Das Klima der Alpen im Raume von Tirol*. Universitätsverlag Wagner, Innsbruck–München, 454 pp.

Geist, T., and J. Stötter, 2006: Documentation of glacier surface elevation change with multi-temporal airborne laser scanner data – case study: Hintereisferner and Kesselwandferner, Tyrol, Austria. *Zeitschrift für Gletscherkunde und Glazialgeologie*, in Press.

Hoinkes, H., and R. Steinacker, 1974: Zur Parametrisierung der Beziehung Klima–Gletscher. *Rivista Italiana di Geofisica e Scienze Affini* 1, pp. 97–104.

Kahmen, H., 1993: *Vermessungskunde*. De Gruyter, 589 pp.

Kuhn, M., G. Markl, G. Kaser, U. Nickus, F. Obleitner, and H. Schneider, 1985: Fluctuations of climate and mass balance: Different responses of two adjacent glaciers. *Zeitschrift für Gletscherkunde und Glazialgeologie* 21, pp. 409–461.

Lambrecht, A., and M. Kuhn, 2007: Glacier changes in the Austrian Alps during the last three decades, derived from the new Austrian glacier inventory. *Annals of Glaciology* 46, accepted.

Paterson, W. S. B., 1994: *The Physics of Glaciers*. Butterworth-Heinemann, 472 pp.

Reigber, C., and P. Schwintzer, 2003: Das Schwerefeld der Erde. *Physik in unserer Zeit* 34, 206–212.

Schär, C., P. Vidale, D. Lüthi, C. Frei, M. Häberli, A. Liniger, and C. Appenzeller, 2004: The role of increasing temperature variability in european summer heatwaves.*Nature* 427, 332–336.

Schimpp, O., 1959: Der Haushalt des Hintereisferners (Ötztal). Akkumulation, Ablation und Gletscherbewegung in den Jahren 1952/53 und 1953/54. *Veröffentlichungen des Museum Ferdinandeum* 39, 66–138

Schneider, H., 1970: *Die Grundlagen der Vermessungen am Kesselwandferner (Ötztaler Alpen) und die Bewegung dieses Gletschers in den Haushaltsjahren 1965/66, 1966/67 und 1967/68*. Unpublished dissertation, University of Innsbruck, 206 pp.

Schneider, H., 1976: Die Karte des Kesselwandferners 1971 und die Grundlagen der Vermessungen. *Zeitschrift für Gletscherkunde und Glazialgeologie* 11, 229–244.

Span, N., 1999: *Zur Dynamik des Kesselwandferners*. Unpublished dissertation at the Institute of Meteorology and Geophysics, University of Innsbruck, 214 pp.

Wehr, A., and U. Lohr, 1999: Airborne laser scanning – an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 68–82.

Wever, C., 1999: Laserscannermessungen – ein Verfahren setzt sich durch. *GIS Geoinformationssysteme* 2, 12–17.

Würländer, R., and K. Eder, 1998: Leistungsfähigkeit aktueller photogrammetrischer Auswertemethoden zum Aufbau eines digitalen Gletscherkatasters. *Zeitschrift für Gletscherkunde und Glazialgeologie* 35, 167–185.

Manuscript received 1.4.2007, revised 4.6.2007.

Authors' addresses: Jakob Abermann
Astrid Lambrecht
Institute of Meteorology and Geophysics
Innrain 52
A–6020 Innsbruck, Austria
Jakob.Abermann@uibk.ac.at

Heralt Schneider
Institute of Mathematics
Technikerstraße 15
A–6020 Innsbruck, Austria