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Glacier changes in the Bavarian Alps from 1989/90 to 2006/07

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In memory of Hermann Rentsch († 19.03.2009).

Abstract

The five glaciers in Bavaria which today cover a total area of less than one square kilometer were frequently monitored by geodetic methods from the mid of the 20th century. In this paper, the record is extended by new surveys in 1999 and 2006. The glaciers show a prolonged surface lowering, which is intensified compared to the 1980s and reaches maximum rates from 1999-2006. Moreover, the ice thickness of four glaciers was determined in 2006 and 2007 by geophysical field techniques and allows the calculation of ice volumes. First simple extrapolations of observed volume losses indicate that the two Berchtesgaden glaciers and Südlicher Schneeferner could disappear by 2016, while the ice of Nördlicher Schneeferner endures until 2027. Ice thicknesses and surface changes are visualized in five annexed maps.

Zusammenfassung

Die fünf bayerischen Gletscher, die heute insgesamt eine Fläche von weniger als einem Quadratkilometer bedecken, wurden seit der Mitte des 20. Jahrhunderts regelmäßig geodätisch aufgenommen. Diese Reihe wird hier um zwei Neuvermessungen in den Jahren 1999 und 2006 erweitert. Alle Gletscher zeigen in dem Zeitraum eine fortgesetzte Erniedrigung ihrer Oberfläche, die im Vergleich zu den 1980er Jahren verstärkt ist und in der Periode 1999-2006 Maximalwerte aufzeigt. Außerdem wurden in den Jahren 2006 und 2007 die Eisdicken von vier Gletschern durch geophysikalische Messungen bestimmt, was erstmalig die Ermittlung des verbleibenden Eisvolumens erlaubt. Erste einfache Extrapolationen der beobachteten Volumenverluste in die Zukunft deuten an, dass die beiden Gletscher in den Berchtesgadener Alpen sowie der Südliche Schneeferner bis zum Jahr 2016 verschwinden könnten, während der Nördliche Schneeferner noch bis 2027 überdauern würde. Eisdicken und Oberflächenänderungen werden anhand von fünf Karten im Anhang verdeutlicht.

Introduction

Although the Bavarian part of the Alps is rather small and constricted to relatively low altitudes below 3000 m a.s.l., five small glaciers in favourable locations below the climatic snow line could survive the warming and the consecutive rise of the equilibrium line altitude since the Little Ice Age. Three of these glaciers can be found in the Wetterstein mountain range (Nördlicher Schneeferner, Südlicher Schneeferner, Höllentalferner), while two small glaciers remain in the Berchtesgaden Alps (Watzmannletscher, Blaueis).

The first systematic survey which delivered accurate height information from all Bavarian glaciers was conducted in 1949 (Finsterwalder 1951). Watzmannletscher was found to be dissolved into several firn patches then and therefore was ignored in this first investigation. Ten years later the rejoined firn bodies were again recognized as a glacier and included in the studies. The photo flights by the Bavarian Surveying Agency in 1959 opened up the era of aerial photogrammetry in this region

and provided a new benchmark for glacier geometry. From the 1960s onwards, the glaciers are surveyed regularly and at least once per decade by the Commission for Glaciology of the Bavarian Academy of Sciences and Humanities in collaboration with the Institute for Photogrammetry and Cartography of the Technical University in Munich. Based on these repeated surveys, changes in volume and elevation have been published for the periods 1949 to 1970 (Finsterwalder and Rentsch 1973) and 1970 to 1989/90 (Finsterwalder 1992).

Within the DFG-funded project “Bavarian Glaciers”, which was conducted from 2005 to 2007 (Hagg 2008), 32 historic maps of the Bavarian glaciers were digitized and reprojected into the common coordinate system UTM (Zone 32 North for the Wetterstein, Zone 33 North for the Berchtesgaden Alps). Shapefiles of the glacier boundaries as well as digital elevation models derived from these contour maps are available through the internet (www.bayerische-gletscher.de).

A photogrammetric survey in 1999 (Steglich 2004) and airborne laser scanning of the Wetterstein group in 2006 (both conducted by the Bavarian Office for Surveying and Geoinformation, LVG) are the basis for the surface changes reported in this paper. Moreover, the ice thickness of four glaciers was determined by ground penetrating radar (GPR) in 2006/2007 which for the first time enabled to calculate total ice volumes.

Methods

Geodetic survey 1999

Aerial images from overflights by the LVG in 1999 were the basis for analytical photogrammetric processing on a ZEISS Planicomp P1 and a subsequent DEM generation using the HIFI software (Ebner et al. 1980). While the Wetterstein images from 15 September 1999 showed almost snow free glacier surfaces with good contrast, the Berchtesgaden Alps were surveyed earlier in the year (5 July 1999) when Blaueis and Watzmannletscher were still snow covered due to an exceptionally high accumulation in the preceding winter. To assess the thickness of the snow pack, the elevation of 30 points on a contour line in the vicinity but outside the glacier boundaries of 1989 was measured in the 1999 stereo model. From the height difference between the bare ground model of 1989 and the snow covered model of 1999, the mean snow thickness on Blaueis was inferred as 2 m, on Watzmannletscher as 2.5 m. The DEM altitudes were reduced by these snow thicknesses and the results were regarded as 1998 autumn surfaces. This method introduces certain errors due to spatial variations of the snow pack, unknown summer ablation and inaccuracies of the stereo models, but when differences over longer time spans are investigated, the total surface changes are larger than these errors. Another problem introduced by the presence of snow is that glacier boundaries could not be identified in the 1999 images. For lack of better options, the glacier extent of the last survey (1989) was used for the calculation of elevation differences.

Surface differences 1989/90-1998/1999

For the Wetterstein glaciers, DEMs from the year 1990 already existed in the archive of the Commission for Glaciology. For the Berchtesgaden glaciers, analogue contour maps based on the survey of 1989 were digitized by Steglich (2004). Surface differences were calculated using the GLEKA software developed analysing the Austrian glacier inventory (Würländer and Eder 1998, Würländer and Kuhn 2000) at the Institute of Photogrammetry and Cartography of the Technical University Munich. This software was especially designed for deriving topographic information of glaciological interest from raster data following the mathematical fundamentals of Finsterwalder (1953).

Surface differences 1999-2006

An airborne laserscanning survey of the Wetterstein region was conducted by the LVG in several flights during winter 2006/2007. Survey dates cannot be given for specific locations, but the operators of the skiing resort could confine the survey period for the glaciers by the track pattern of snow groomers to the first half of November. Snow thickness during this period was 0.5-1 m according to the same sources (M. Hurm, pers. comm., 2008). For this reason a constant value of 0.75 m was subtracted from the original elevation data to obtain a glacier elevation model for the autumn of 2006. The resulting DEMs of the three glaciers were compared with the 1999 survey in order to calculate topographic changes, again using GLEKA.

Error analysis for the different methods and for the resulting differences.

Considering the scale of the images and the local conditions on the Bavarian glaciers, Finsterwalder and Rentsch (1973) estimated that the mean vertical error of terrestrial and airborne photogrammetry is within a range of few decimeters. The maximum error is 1 m (H. Rentsch, pers. comm., 2003).

Geist and Stötter (2007) evaluated the accuracy of airborne laser scanning and found maximum vertical errors of ca. 0.5 m on a non-glaciated test field. The method was also quality checked by differential GPS profiling on Engabreen in Norway, where mean discrepancies of 0.1 m \pm 0.1 m standard deviation were observed. More than 99.5% of all measured points were within an error range of 0.3 m (Geist et al. 2005).

For height differences in the 1989/90-1998/99 period, a maximum error of 2 m results from the two photogrammetric surveys, for 1999-2006 the value is only 1.5 m due to a higher accuracy of the laser technology. Regarding the minimum elevation differences of 2.67 m for the earlier and 3.25 m for the later period (table 2), the maximum point error adds up to 75% and 46% of the results, respectively. The mean error is considerably lower (\approx 0.4 m and 0.2 m for the two periods) and amounts to 15% and 6% of the minimum elevation differences, respectively. Since the error is randomly distributed, it is at least partly cancelled out when the integral is formed.

Volume determination

In November 2006 (Nördlicher and Südlicher Schneeferner) and October 2007 (Watzmannletscher and Blaueis), glacier ice thicknesses have been determined using a ground penetrating radar system (GPR) with 200 MHz antennas. To locate the profiles, simultaneous kinematic GPS tracking using a single frequency, differential system was carried out. On the radargrams the bedrock could mostly be identified clearly. To convert time into depth, a mean radar wave velocity of 0.15 m/ns was assumed, based on the known velocity of electromagnetic waves in temperate ice (0.159 m/ns after Murray et al. 2000) and a correction for the overlying snow cover. In a Geographic Information System, point shapefiles containing ice thickness along the profiles have been created and the glacier outlines have been determined based on digital orthoimages (© Bavarian Office for Surveying and Geoinformation) from the same year. The thickness information together with the glacier boundaries has then been interpolated on a raster with a spatial resolution of 2 meters, using a spline function (type: tension, weight: 1).

Results

Changes in area, thickness and volume

The evolution of glacier areas from the mid of the 20th century is displayed in figure 1. During the last decades, the glaciers can be divided into two size classes: the two bigger glaciers with extents above 20 ha and the three smaller glaciers with almost identical areas around 10 ha.

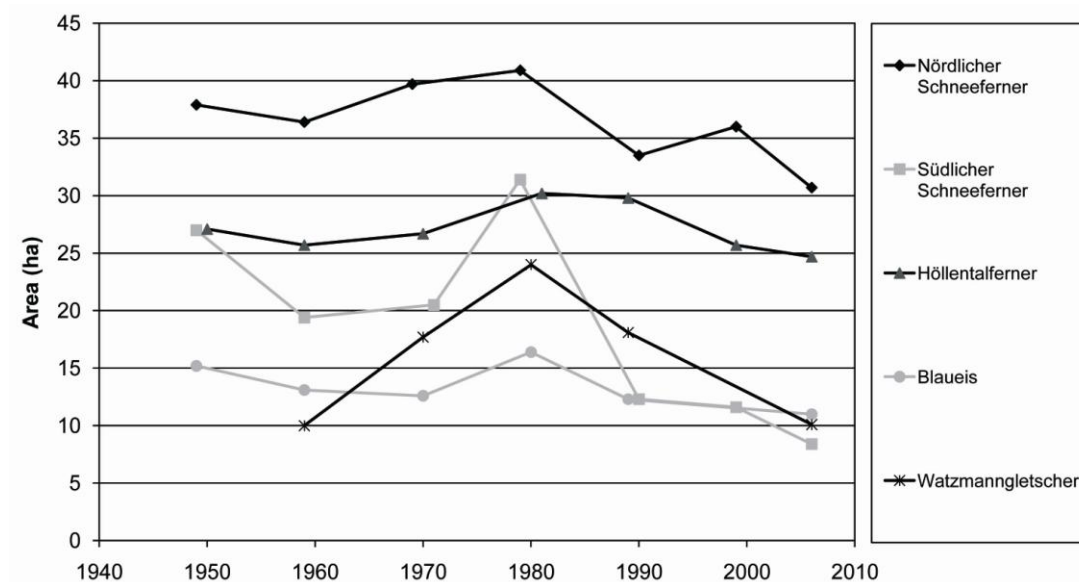


Figure 1: Area changes of the Bavarian glaciers 1949-2006.

Numerical values for the glacier areas are given in table 1 for the last three surveys.

Table 1: Glacier areas (ha).

	1989	1990	1999	2006
N Schneeferner	-	33.5	36.0	30.7
S Schneeferner	-	12.3	11.6	8.4
Höllentalferner	29.8	-	25.7	24.7
Watzmangletscher	18.1	-	-	10.1
Blaueis	12.3	-	-	11.0

The enlargement of Nördlicher Schneeferner between 1990 and 1999 is probably due to human activities which make it difficult to trace the glacier boundary everywhere. Artificial snow accumulation from nearby snow fields, or artificial debris covers are common especially close to the ski lifts. Thus, especially in the lower parts of the glacier, the delineation of the glacier boundary is difficult.

From 1989/90-2006, all glaciers reduced their areal extent. The strongest relative reduction of -44% was observed on Watzmangletscher, which has lost all its protuberances and is constricted to its most central part (see Map 5). Given the facts that this glacier was considered as diminished in the 1940s and that it showed the largest mass and area gains from 1960 to 1980, Watzmangletscher seems to be the most sensitive and vulnerable of Bavarian glaciers to climate fluctuations.

The changes in area, thickness and volume for the periods 1989/90-1998/99 and for 1999-2006 are shown in tables 2a and 2b, respectively. Changes versus altitude for 20 m elevation bands can be obtained from www.bayerische-gletscher.de.

Table 2a: The changes in area, thickness and volume for the period 1989/90-1998/99.

	Period	Area changes (1000 m ²)	Thickness changes (m)	Volume changes (1000 m ³)
N. Schneeferner	1990-1999	25.546	-6.45	-2123.75
S. Schneeferner		7.367	-2.67	-273.22
Höllentalferner	1989-1999	-40.223	-5.93	-1645.49
Watzmangletscher	1989-1998	-	-3.75	-678.61
Blaueis		-	-3.56	-429.04

Table 2b. The changes in area, thickness and volume for the period 1999-2006.

	Period	Area changes (1000 m ²)	Thickness changes (m)	Volume changes (1000 m ³)
N. Schneeferner	1999-2006	-50.435	-6.08	-1859.49
S. Schneeferner		-31.101	-3.25	-284.05
Höllentalferner		-10.321	-6.72	-1685.37

The total thickness change divided by the number of years gives mean rates of surfaces changes (m/a) which can be compared with earlier periods (Figure 2).

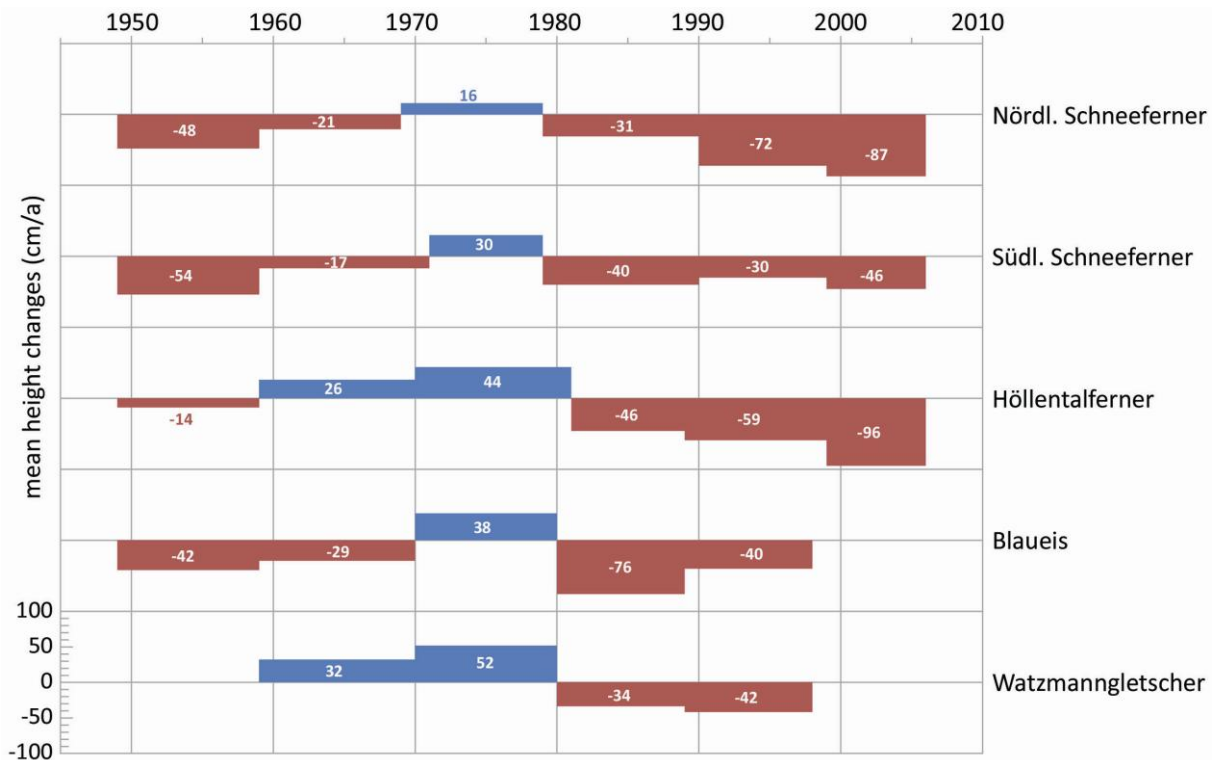


Figure 2: Surface changes of the Bavarian glaciers between geodetic surveys.

Figure 2 was already published in similar form several times (e.g. Finsterwalder 1992) for different time periods. For this updated version, the values were recalculated from the digital archive created within the “Bavarian glaciers” project (Hagg 2008), extended by new survey results (1989/90-1998/99-2006). In some cases, the mean surface changes strongly depart from earlier calculations. This is partly due to differing methods in processing. In former studies, analogue contour maps have been analysed by manually planimetering areas between contour lines. For the digital archive, the same analogue contour lines and glacier boundaries have been scanned, georeferenced, projected into UTM, digitized, interpolated into a raster and then analysed by the GLEKA software. As described above, the manual method based on Finsterwalder (1953) is the basis for this software. Some discrepancies from older results are due to the fact that geodetic surveys from other years have been chosen, while small errors can be related to digitization and projection methods. Nevertheless, the

largest aberrations cannot be explained by differing methods. The data source, however, is the same and interpolation of contour lines and subtracting gridded data are standard methods in GIS analysis. The discrepancies are almost certainly not due to the digital processing of the original maps, but probably originate from inaccuracies in the earlier manual interpretation methods.

Ice Volumes

Table 3 shows mean and maximum ice thicknesses as well as the total volume of the four examined glaciers.

Table 3. Mean thickness, maximum thickness and volume of investigated glaciers.

	Observation Date	Mean thickness (m)	Maximum thickness (m)	Volume (mio. m ³)
N. Schneeferner	7.11.2006	16.8	52	5.16
S. Schneeferner		4.6	16	0.4
Watzmannletscher	2.10.2007	5.9	16	0.6
Blaueis	3.10.2007	3.8	13	0.4

The spatial distribution of ice thicknesses is depicted in the attached maps.

Discussion and Conclusion

The three glaciers in the Wetterstein group experienced reinforced mass losses from 1999-2006. Nördlicher Schneeferner and Höllentalferner show the fastest surface lowering in the whole observation period. Südlicher Schneeferner also revealed intensified downwasting compared to the 1990s.

Nördlicher Schneeferner is by far the thickest glacier examined by radio sounding and its maximum depth of 52 m was higher than the authors expected. Unfortunately, the radiosounding of Höllentalferner yielded no results and its volume can only be estimated. Regarding the comparable size of the glaciers and the identical geological situation, the total volume will not differ much from that of Nördlicher Schneeferner. Assuming equal volumes of these two, the total Bavarian ice volume in 2006/2007 would amount to 11.7 mio. m³. The other glaciers are thin ice covers with a rather short life expectancy. If the most recent mass losses are prolonged into the future, they disappear within 9-10 years (from the date of volume determination). The last ice remnants of Nördlicher Schneeferner would disappear in 2027 under such a linear retreat. This kind of extrapolation is object to strong simplifications and inaccuracies, since changes in surface geometry which influence incoming radiation are not considered. Moreover, the velocity of deglaciation changes with the occurrence of rock outcrops or debris covers. Nevertheless, these results deliver first hints and the spatially distributed ice thicknesses can serve now as input to energy- and ice flux models to create more sophisticated scenarios of glacier retreat and disappearance.

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References

- Ebner, H., B. Hofmann-Wellenhof, P. Reis, F. Steidler 1980: HIFI – ein Minicomputer-Programmsystem für Höheninterpolationen mit finiten Elementen, *Zeitschrift für Vermessungswesen* 105: 215-255.
- Finsterwalder, R., 1951: Die Gletscher der Bayerischen Alpen. Jahrbuch des Deutschen Alpenvereins 1951, Überbrückungsband der Alpenvereinszeitschrift 1943-1951: 60-66.
- Finsterwalder, R., 1953: Die zahlenmäßige Erfassung des Gletscherrückgangs an Ostalpengletschern, *Zeitschrift für Gletscherkunde und Glazialgeologie* 2: 189-293.
- Finsterwalder, R., H. Rentsch, 1973: Das Verhalten der bayerischen Gletscher in den letzten zwei Jahrzehnten. *Zeitschrift für Gletscherkunde und Glazialgeologie* 9 : 59-72.
- Finsterwalder, R., H. Rentsch, 1976: Die Erfassung der Höhenänderung von Ostalpengletschern in den Zeiträumen 1950-1959-1969. *Zeitschrift für Gletscherkunde und Glazialgeologie* 11: 29-35.
- Finsterwalder, R., H. Rentsch, 1980: Zur Höhenänderung von Ostalpengletschern im Zeitraum 1969-1979. *Zeitschrift für Gletscherkunde und Glazialgeologie* 16 : 111-115.
- Finsterwalder, R., 1981: Zur Höhenänderung der Zugspitzgletscher. *Mitteilungen der Geographischen Gesellschaft München* 66: 25-30.
- Finsterwalder, R., 1992: Die Veränderungen der bayerischen Gletscher im letzten Jahrzehnt (1980-1990). *Mitteilungen der Geographischen Gesellschaft München* 77: 5-12.
- Geist, T., J. Stötter, 2007: 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* 41: 77-106.
- Geist, T., H. Elvehøy, M. Jackson, J. Stötter, 2005: Investigations on intra-annual elevation changes using multitemporal airborne laser scanning data: case study Engabreen, Norway. *Annals of Glaciology* 42: 195-201.
- Hagg, W., 2006: Digitale Aufbereitung historischer Gletscherkarten in Bayern. *Mitteilungen der Geographischen Gesellschaft München* 88: 67-88.
- Hagg, W., 2008: Die Bedeutung kleiner Gletscher am Beispiel der bayerischen Alpen. *Geographische Rundschau* 3, 22-29.
- Murray, T., G.W. Stuart, M. Fry, N.H. Gamble, M.D. Crabtree, 2000: Englacial water distribution in a temperate glacier from surface and borehole radar velocity analysis. *Journal of Glaciology* 46 (154): 389-398.
- Steglich, C., 2004: Bestimmung, Dokumentation und Visualisierung der Veränderungen der bayerischen Gletscher im Zehnjahresvergleich (1989/90-1999). Diploma thesis, Fachbereich Vermessungswesen und Kartographie, Fachhochschule München, 100 pp., unpublished.
- Waltenberger, A., 1887: Ueber topographische Messungen und Terrainaufnahmen im Gebirge. Mit besonderer Bezugnahme auf die Mappirungs-Arbeiten im Berchtesgadener Gebiet. *Zeitschrift des DuÖAV* 17: 99-127.
- Würländer, R., K. Eder, 1998: Leistungsfähigkeit aktueller photogrammetrischer Auswertemethoden zum Aufbau eines digitalen Gletscherkatasters, *Zeitschrift für Gletscherkunde und Glazialgeologie* 34: 167-185.

Würländer, R., M. Kuhn, 2000: Zur Erstellung und Anwendung der Produkte des neuen Österreichischen Gletscherkatasters. Salzburger Geographische Arbeiten 36: 57-67.

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