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CLIMATE AND GLACIER FLUCTUATIONS IN THE BAVARIAN ALPS IN THE PAST 120 YEARS

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With 12 figures, 7 tables and 5 maps (appendix I–V)
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Summary: Five small glaciers in the Bavarian Alps have been surveyed repeatedly since the late 19th century. This enables the calculation of geodetic glacier mass balances, which are known to be key indicators for climate fluctuations. In this paper, the record is extended by the analysis of additional historical maps and by a new survey of the glacier surfaces in 2009/2010. After the 1960s and 1970s, when positive mass balances could be observed, the glaciers experienced severe mass losses, which is consistent with observations from the vast majority of mountain glaciers worldwide. Although the glaciers show individual behaviour which can be explained by topographic peculiarities, the overall trend is an intensified surface lowering during the past decades. To identify the local causes and triggers, homogenized climate data from stations near the glaciers have been analyzed. All records show an extensive warming in summer, but no increase over the altitudinal gradient. Winter precipitation shows little variation on a decadal time scale and reveals no significant trends over time. An analysis of snow height and winter precipitation measurements at Zugspitze proved that the precipitation measurements are not capable to explain glacier behaviour due to gauge undercatch and redistribution of snow by wind. Correlations between geodetically derived glacier mass balances and mean seasonal meteorological conditions indicate that mass losses are mainly caused by increased summer air temperatures. However, mean seasonal values cannot take into account fluctuations of the temporary snow line, which are crucial for the mass balance of small glaciers and which can only be considered using a daily time-step model.

Zusammenfassung: Die fünf existierenden Gletscher in den Bayerischen Alpen wurden seit dem späten 19. Jahrhundert wiederholt vermessen. Dies ermöglicht es, die Gletschermassenbilanz mit der geodätischen Methode zu bestimmen. In dieser Arbeit wird die bestehende Messreihe durch die Auswertung bisher unberücksichtigter historischer Karten sowie durch eine Neuvermessung der Gletscher in den Jahren 2009/2010 verlängert. Nach den 1960er und 1970er Jahren, als zuletzt positive Massenbilanzen registriert wurden, erfuhren die Bayerischen Gletscher deutliche Massenverluste, was sich mit der Mehrzahl der weltweiten Beobachtungen an Gebirgsgletschern deckt. Obwohl die bayerischen Gletscher durchaus individuell auf Klimaschwankungen reagieren, was zumeist mit lokalen topographischen Bedingungen zu erklären ist, zeigt der generelle Trend eine Verstärkung des Massenschwunds während der letzten Jahrzehnte. Um die Ursachen der Gletscherschwankungen zu identifizieren, wurden klimatologische Messreihen von nahe gelegenen Stationen analysiert. Die Daten zeigen über den Beobachtungszeitraum eine deutliche Erwärmung im Sommer, aber keine signifikante Veränderung des Winterniederschlags. Korrelationsanalysen deuten darauf hin, dass der Massenhaushalt der kleinen Gletscher hauptsächlich von der Lufttemperatur im Sommer gesteuert wird. Ein Vergleich mit Schneehöhenmessungen auf dem Nördlichen Schneeferner zeigt allerdings, dass Niederschlagsmessungen vom Gipfel der Zugspitze nicht repräsentativ für die Akkumulation auf dem unmittelbar benachbarten Gletscher sind.

Keywords: Climate fluctuations, glacier fluctuations, Bavarian Alps, geodetic glacier mass balance

1 Introduction

The climate change we are observing at the moment is not proceeding synchronously over the whole planet. Magnitude and impact of climate fluctuations vary considerably from one region to another. When estimated over a linear trend, the global mean surface temperatures have increased over the past 100 years (1906–2005) by 0.74 °C (Trenberth et al. 2007). Land surfaces have warmed at a faster rate than oceans. Temperatures in Europe (1901–2005) have risen by 0.9 °C (updated from Jones and Moberg 2003), with highest trends in central and north-eastern Europe and in mountains (Böhm et al. 2001). The greater Alpine region reveals a 20th century temperature increase of 1.2 °C, the warming since the late 19th century was twice as much as the mean for the northern hemisphere (Auer et al. 2007).

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The most obvious and evident effect of this pronounced warming in high mountain environments is the downwasting and retreat of glaciers. Glaciers are recognized as key indicators for climate change (Oerlemans 1994), because their mass changes represent the direct and unfiltered response to changes in the local climate. The glacier mass balance at any time is defined as the sum of mass gains (accumulation) and mass losses (ablation) per unit area, expressed as water equivalent (Paterson 1994). In addition to direct measurements on the glacier (glaciological method), mass changes can be derived from volume changes by comparing surface elevation changes using geodetic surveying techniques and assuming mean densities for firn and ice (photogrammetric or geodetic method). Despite their strong relation to climate, mass balance fluctuations also depend on glacier size and topographic effects and can differ significantly between neighbouring glaciers (Huss et al. 2010; Winkler et al. 2010). The mass balance of glaciers is mainly controlled by accumulation of snow and melting of snow and ice. In climates where these processes generally do not occur simultaneously, the determining meteorological factors are winter precipitation and summer temperature. In the Alps, glaciers have lost almost half of their area from the end of the Little Ice Age (1850) until 2000 (Zemp et al. 2007). This recession was not linear, but it was divided into faster and slower periods and even interrupted by periods with glacier advances in the 1890s, 1920s, and 1970–1980s (Patzelt 1985; Pelfini and Smiraglia 1988). On Swiss glaciers, the melt rates in the 1940s were even higher than from 1998–2006, which is explained by reduced winter snowfall (Huss et al. 2008) and by enhanced solar radiation (Huss et al. 2009).

For a climatological interpretation of glacier fluctuations it is of crucial importance to have long-term glacier observations from different regional climate zones, topographic glacier types and size classes. Most monitoring programs are installed on relatively large glaciers, which are not necessarily representative for the high number of very small glaciers in their region. The Austrian Glacier Inventory 1998 (Lambrecht and Kuhn 2007) lists 911 ice bodies, 90% of which are smaller than 1 km² and 43% even smaller than 0.1 km². This means that an important fraction of total glacier area is built up by the enormous number of small glaciers and glacierets. 34% of the Austrian glacier area is formed by glaciers smaller than 1 km². Very similar size distributions can be found in the western Alps and in other mountain regions of the mid latitudes like Caucasus or Altay (Hagg 2008).

Although underrepresented in the literature, a number of investigations of small glaciers can be found, especially from mountain ranges where no large ones exist, like those on the Iberian Pensinsula (Trueba et al. 2008; Chueca et al. 2007) or the Balkan (Hughes 2007; Grunewald and Scheithauer 2010).

The Bavarian Alps have a high potential for comparing climate and glacier fluctuations due to the availability of both long-term climate and glacier observations, which is rarely the case for small glaciers. Moreover, these glaciers are the only ones with mass balance observations from the Northern rim of the Alps, which is the zone of highest precipitation sums due to orographic uplift of air masses, making those glaciers particularly interesting for climatological interpretations. In this paper, geodetic mass balances were derived from historical maps and from a new survey. Additionally, temperature and precipitation series of meteorological stations closest to the glaciers are analyzed and correlated with the glacier mass balance record.

2 Investigation sites and datasets

Although the German part of the Alps is rather small and limited to relatively low altitudes below the regional climatic snow line (3200 m a.s.l. according to Glazirin and Escher-Vetter 1998), five small glaciers in favourable locations could so far survive the temperature increase since the end of the Little Ice Age (about AD 1850). Three of these glaciers (Nördlicher Schneeferner, Südlicher Schneeferner, Höllentalferner) can be found in the Wetterstein massif below Zugspitze (2962 m a.s.l.), the highest peak in Germany. Two more glaciers (Watzmanngletscher, Blaueis) remain in the Berchtesgaden Alps (Fig. 1).

The first theodolite measurements were carried out from 1885–1887, when Waltenberger surveyed the Berchtesgaden Alps on behalf of the German and Austrian Alpine Club, resulting in a 1:50 000 map (Waltenberger, 1887). This map already contain contours, but they have a large vertical distance of 100 m. One year later, the originals of Waltenberger were published in 1:25 000 (Schmidt et al. 1888), being the first map of the Alpine Club using this important scale (Figs. 2a, 3a).

The first maps of the Berchtesgaden glaciers that contain enough height information for quantitative analysis were produced by the Bavarian Topographic Office (Topographisches Bureau des königlich bayerischen Generalstabs) by interpolating contours

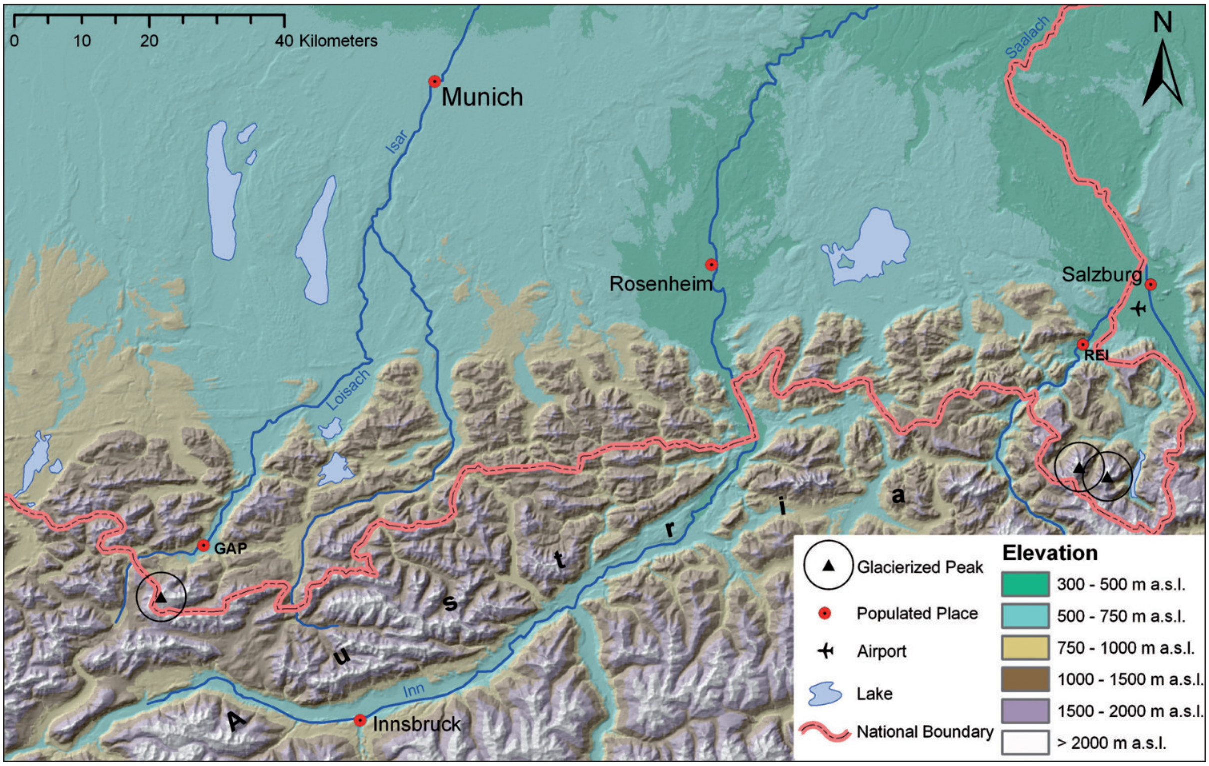

Fig. 1: Location of the glacierised peaks (from west to east: Zugspitze, Watzmann, Hochkalter) in the Bavarian Alps (GAP: Garmisch-Partenkirchen, REI: Bad Reichenhall). Elevation is based on SRTM-3 (Shuttle Radar Topography Mission) data (courtesy NASA/JPL-Caltech)

with an equidistance of 10 m from tachymetric and barometric point measurements. The mapping was based on the cadastral land register in the scale 1:5 000 and published as "Positionsblätter" in the scale 1:25 000. At the Institute of Photogrammetry and Cartography of the Technical University of Munich, a copy of the original 1:5 000 map of Blaueis from 1889 (Fig. 2b) was found and used for this study. For Watzmanngletscher, a scan of the respective "Positionsblatt", based on a survey in 1897 was provided by the Bavarian State Office for Surveying and Geoinformation (Fig. 3b). An additional map from Blaueis (1924) was discovered in the storage of the Technical University of Munich. This map was produced by Thiersch using terrestrial photogrammetry and has never been used to calculate area or volume changes before.

In the Wetterstein mountains, the earliest useable map is the one by Finsterwalder and Jäger (1892), also surveyed by photogrammetry and covering Nördlicher and Südlicher Schneeferner at the scale 1:10 000 (Fig. 4).

The glacier extent during the first half of the 20th century, however, is only documented by some photographs (see www.bayerische-gletscher.de).

A new survey in 1949 (Finsterwalder 1951) covered all glaciers except for Watzmanngletscher, which was found to be dissolved into several firn patches and therefore was excluded from this first inventory. From the 1960s onwards, the glaciers were 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 glacier area, volume and thickness have been published for the period 1892–2007 (Finsterwalder and Rentsch 1973; Finsterwalder 1992; Hagg et al. 2008a; www.bayerische-gletscher.de).

For this contribution, three maps of Watzmanngletscher (1897) and Blaueis (1889, 1924) were newly added to the geodetic observations. A new survey of all glaciers in 2009/10 provides a benchmark for the most recent state of the glaciers and extends the period of glacier observations to 120 years.

Zugspitze weather station (2962 m a.s.l.) is operated by the German Meteorological Office (DWD) and has been running continuously since 1901. It

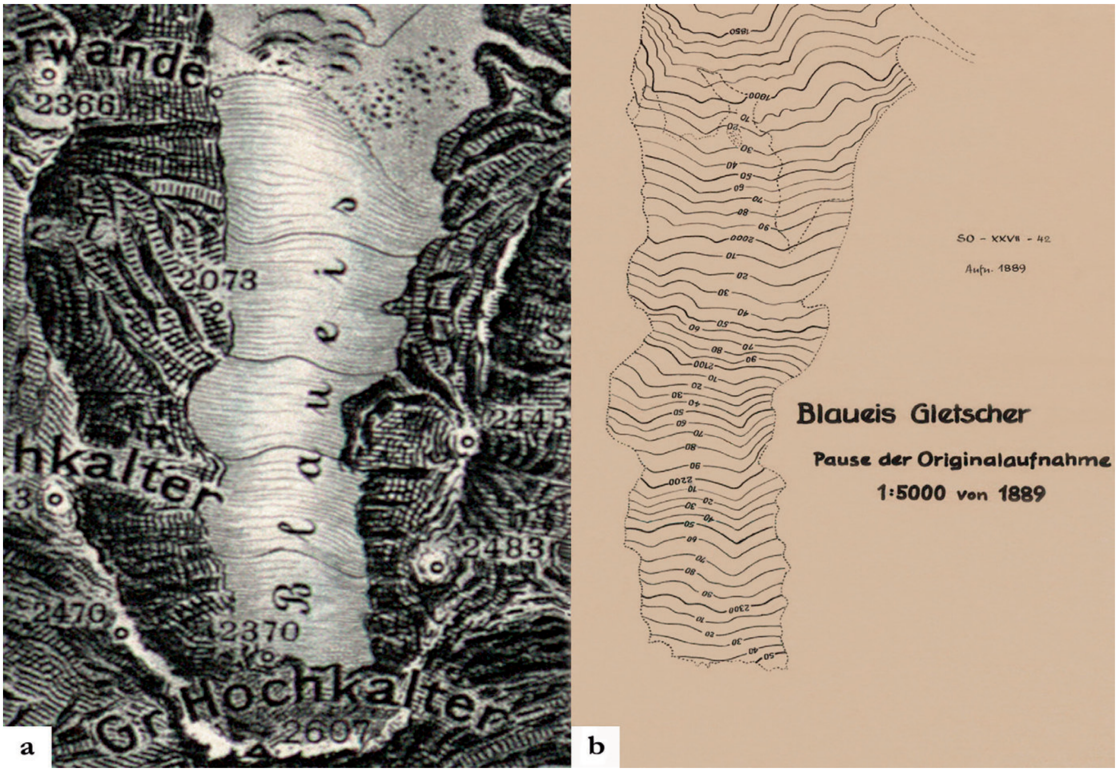

Fig. 2: Early maps of Blaueis. a) Detail from the "Topographischer Plan vom Watzmann und Umgebung", 1:25'000, based on the survey by Waltenberger 1885–1887 (Schmidt et al. 1888), b) copy of the 1:5'000 original survey by the Bavarian Topographic Office in 1889 (© Bavarian State Office for Surveying and Geoinformation)

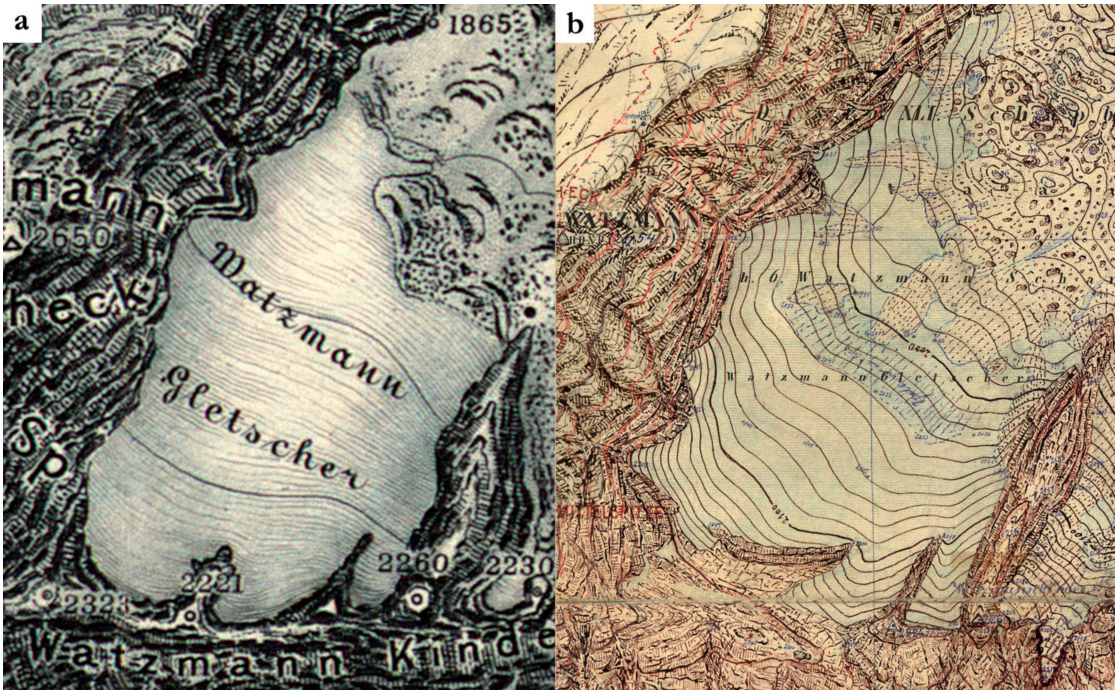

Fig. 3: Early maps of Watzmanngletscher. a) Detail from the "Topographischer Plan vom Watzmann und Umgebung", 1:25'000, based on the survey by Waltenberger 1885–1887 (Schmidt et al. 1888), b) detail from the 1:25000 "Positionsblatt" SO.028.44 of the Bavarian Topographic Office from 1897 (© Bavarian State Office for Surveying and Geoinformation)

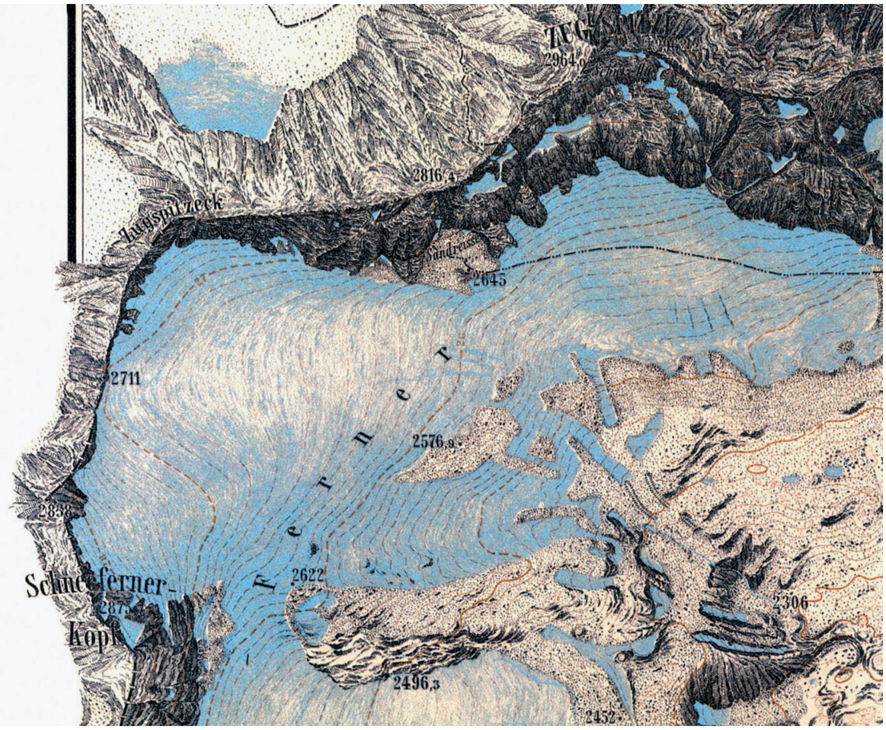

Fig. 4: Detail from the 1:10'000 map "Zugspitze" by FINSTERWALDER and JÄGER (1892) (© Bavarian State Office for Surveying and Geoinformation)

provides a very valuable and rare high altitude dataset, measured at a distance of 0.5–2.4 km from the three glaciers. Not only standard meteorological data is measured, but also snow height at a location directly on Nördlicher Schneeferner (2600 m a.s.l.). A meteorological station at Watzmannhaus (1923 m a.s.l.) in the Berchtesgaden Alps was in operation from 1948-1953, but no long-term series of a mountain station exists. The closest valley stations with a long record are those in Schönau (616 m a.s.l., 7–10 km northeast of the glaciers, 1948-1998) and in Bad Reichenhall (470 m a.s.l., 17 km north, 1945–2006). Salzburg airport (450 m a.s.l., 25 km north) has a record back to 1842.

3 Methods

3.1 Analysis of meteorological records

For Zugspitze station, the DWD has produced homogenized monthly series of temperature and precipitation to account for location changes of the sensors (KOELTZSCHY 2008, pers. comm.). This series deviates from the raw data mainly in the first half of the 20th century. The long-term record of Salzburg airport was homogenized within the HISTALP (historical instrumental climatological surface time series of the Greater Alpine Region) project, where a total of 557 series was gap-filled and outlier corrected (AUER et al. 2007). Since the whole time series of glacier variations should be correlated with climatic conditions, data from Salzburg airport had to be used for this purpose. To test its representativeness for the glacier locations, correlation coefficients between Salzburg and Bad Reichenhall have been determined (Fig. 5). Since the Schönau data series is interrupted by numerous gaps, it was omitted from this analysis. There is a strong correlation between temperatures, which can be expected over a horizontal distance of 17 km. Even winter precipitation, which has a stronger spatial variation than air temperature, shows a distinct interdependence. Temperature and precipitation trends were derived by linear regression analysis.

Glacier changes in the Wetterstein group between 1892 and 1949 were correlated with the climate record from Zugspitze, although this station began operation only in 1901. The remaining 8 years were assumed to have the same average meteorological conditions as the 49 years with observations. This is at least confirmed by data of Hohenpeißenberg meteorological station, located in the alpine foothills about 40 km north of Zugspitze. Here, the summer (5–9) mean temperature 1892–1901 and 1901–1949 is

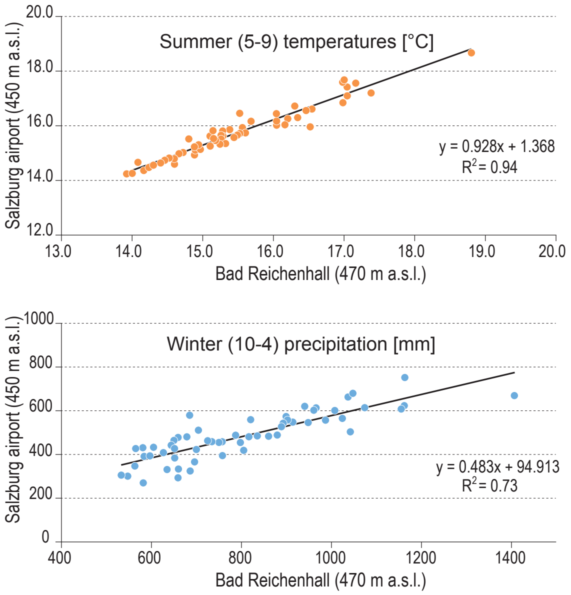

Fig. 5: Correlation of summer temperatures and winter precipitation between Bad Reichenhall (data from DWD) and Salzburg airport (HISTALP database, Auer et al. 2007)

12.2 °C and 12.4 °C, respectively. The corresponding total winter (10–4) precipitation is 400 mm and 418 mm, respectively.

3.2 Determination of geodetic mass balances

3.2.1 Analyzing additional historical maps

A historical research in different archives yielded contour maps that had not been used for volume change calculations before. The oldest maps are those of Watzmanngletscher (1897) and Blaueis (1889), which were produced at the Bavarian Topographic Office.

Since no technical details about the surveys are known, the accuracy of these maps remains unclear. It is estimated that the maps are less accurate than those by terrestrial photogrammetry and include errors of about 2–5 meters. The subsequent surveys have vertical accuracies of approximately 1 m (see below), yielding a total error of height changes between the surveys of 6 meters. Since the time span is quite large (Blaueis: 35 years, Watzmanngletscher: 62 years), the error of the mean annual height change is reduced to 0.17 m/a and 0.10 m/a, respectively.

The Blaueis map of 1924 was discovered in the archives of the Technical University of Munich. The map had been generated by Thiersch using terrestrial photogrammetry.

An investigation of the accuracy of early photogrammetric maps of glaciers shows that the in the ablation zone it is usually higher than 1m, whereas in the accumulation zone the error can be up to a few meters in dependence of the baseline and the possibilities of target identification (Haggren et al. 2008). Geo-referencing the scanned version of the map introduces an additional error. The digitization of the contour lines, the TIN calculation and the subsequent DEM generation was tested against the original scan. The elevation contours derived by this method are almost identical with the original scan, which indicates that this error is below the accuracy of four pixels (less than 1 m) in horizontal location. However, the geo-location of the maps depends on the quality of the ground control point identification. This is estimated to be better than 2 m. This uncertainty translates to a maximum vertical error of 1.6 m for the steepest parts of the glaciers (around 40°). For the flat parts of the glaciers (slope of up to 10°), the error is up to 35 cm. This corresponds to the mean elevation accuracy of 1 m estimated by H. Rentsch (pers. comm.) for the photogrammetrical maps of the second half of the 20th century. Between two surveys, the maximum error sums up to 2 m. Since the measurements were carried out on a decadal time scale, the error of the mean annual height change is 20 cm.

The three maps were geo-referenced by identifying points with known coordinates such as peaks or buildings. This was a difficult task for the 1889 Blaueis map, because the two most striking landmarks have changed their coordinates since then: the peak of Hochkalter collapsed in a land-slide in 1908, where 240000 m^3 of rock were moved (Mühlberger 2007) and the Blaueis alpine hut was rebuilt at a different location after it was destroyed by an avalanche in 1955.

3.2.2 Survey 2009/2010

In September 2009 and, in the case of Höllentalferner, in October 2010, the surface of all glaciers was surveyed by different methods. Nördlicher Schneeferner was captured by a terrestrial laser scanner (Riegl LMS-Z429i), the Berchtesgaden glaciers and Höllentalferner were mapped using an electronic tachymeter (Leica TPS1200-TCRM1205) and Südlicher Schneeferner was measured using a Leica SR 20 L1 kinematic GPS (Mayr 2010).

Terrestrial laser scanners and electronic tachymeters both operate using laser distance measurements. A laser emits a light beam, which is reflected diffusely at a surface. Part of the dispersed radiation returns to the station and is registered by a photo diode. While the laser scanner samples the target area automatically line by line, measuring in the order of ten thousands of points, the view angle of the tachymeter has to be changed manually after every measured point. Within a few hours, several hundred points can easily be recorded this way. This is sufficient to model the surface of small glaciers precisely enough for mass balance calculations. The maximum range of the laser beam of typically 1–2 km restricts the method to small glaciers. The results of both surveying methods are point clouds with very high accuracy (a few cm), which have to be georeferenced and interpolated to a DEM.

Kinematic GPS profiling requires direct contact of the surveyor with the object. The GPS device has to be carried across the glacier, which limits application to relatively small glaciers with overall accessibility. The use of differential GPS technology ensures high horizontal and vertical accuracies of few dm, as long as enough satellites are visible, which can be a problem on cirque-type glaciers with high rock cliffs. On Südlicher Schneeferner, a large portion of the sky is visible due to the relatively flat topography. The position was recorded every second as a GPS track which could be interpolated directly to a DEM.

The uncertainty of the horizontal resolution is below 10 cm (for all methods: GPS, Tachymetry and Laser scanning). This translates into a vertical error of less than 8 cm. In addition, the measurement uncertainty varies from a few centimeters for Tachymetry and Lasercanning to about 20 cm for L1 GPS positions. Therefore the total error in elevation of the point measurement is less than 30 cm. The interpolation of the point measurements into digital elevation models introduces additional uncertainty. The error between our gridded results and the point measurements has a standard deviation of 10–40 cm on the individual glaciers. Thus, the total elevation error for the new glacier maps is about 70 cm.

3.2.3 Calculating geodetic glacier mass balances

The gridded elevation data were used to calculate surface changes by subtracting subsequent DEMs. This step was performed using the "Gletscherkataster" (GLEKA) software, which follows the geometric principles of Finsterwalder (1953) and was developed in the frame of the Austrian Glacier Inventory (Würländer and Eder 1998; Würländer and Kuhn 2000) for quick DEM-comparison in glaciological applications. The resulting volume changes were linked to ice thickness measurements gathered from radar measurements in 2006 and 2007 (Hagg et al. 2008a), which allows the reconstruction of total ice volumes for each survey and the respective changes relative to the initial volume. Divided by the mean glacier area between two surveys, volume changes were converted into height changes of the glacier surface. To convert ice volume into water equivalent, a mean ice density of 0.9 g/cm^3 was assumed.

4 Results and discussion

4.1 Climate change

The complete monthly series of summer temperatures and winter precipitation from all stations considered is displayed in figures 6 and 7. The 10-year running mean of temperature clearly shows well-known features of sub-recent climate history. The general warming trend is interrupted from the 1880s to the 1910s and in the 1960s–1970s, in both periods glacier advances are reported in the Alps (Zemp et al. 2007). In the most recent period since 1980 the temperature increase is enforced. The three graphs run predominantly parallel, but the magnitude of fluctuations differ. Bad Reichenhall is starting on a very high level around 1950, meets the other curves around 1980 and shows the strongest increase since then. Salzburg and Zugspitze picture the same anomalies during most periods, but started to divert in the 1990s. The lowest increase in the past years is observed at Zugspitze.

Mean precipitation amounts differ by more than a factor of 2 between the stations, mostly due to elevation. Zugspitze reveals the strongest year-to-year variation, winter sums range from 600 mm to 1800 mm, approximately. This station shows very low winter precipitation around 1920 and in the 1940s. The second anomaly is in agreement with the strong melt rates observed on Swiss glaciers in this decade (Huss et al. 2008). The glacier advances in the 1920s were the delayed response to the cold and wet 1910s, in the 1920s the mass balances were already negative again.

Numerical values of annual and seasonal temperature and precipitation trends are listed in table 1.

In general, the warming is significantly stronger in more recent periods. Between 1976 and 2005, the rates exceed the 20th century value by a factor of 3–5.

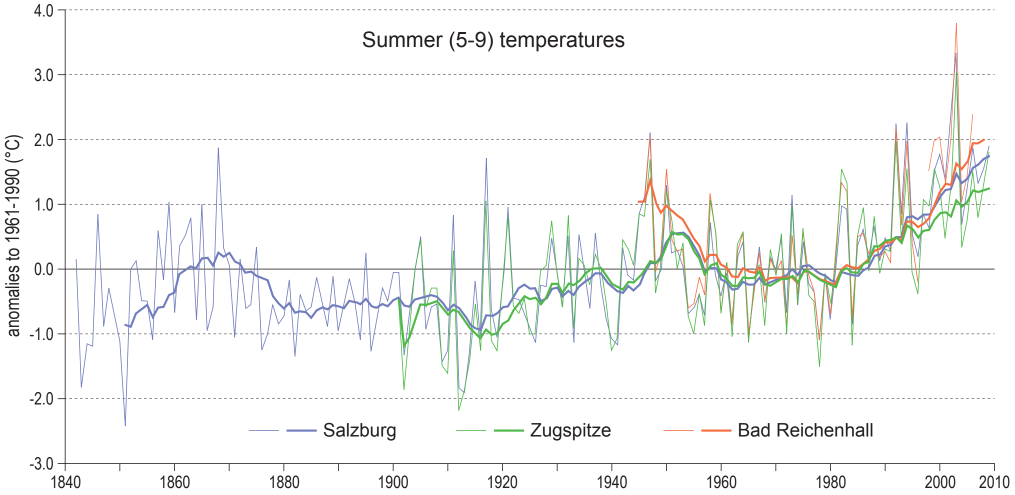

Fig. 6: Summer temperature anomalies of three relevant meteorological stations, relative to the standard period 1961–1990. Thin lines represent annual values, thick lines the 10-year running mean. Data source: DWD (Zugspitze, Bad Reichenhall) and HISTALP (Salzburg airport, Auer et al. 2007)

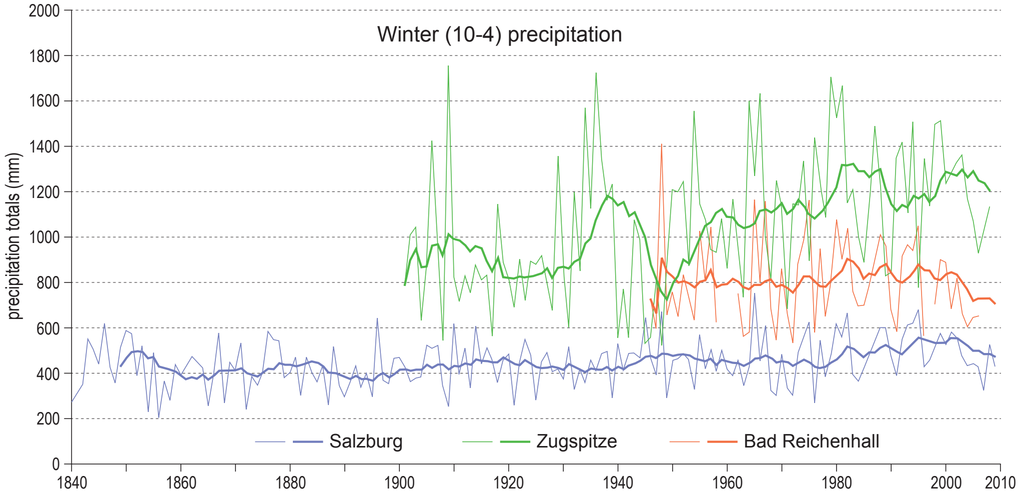

Fig. 7: Winter precipitation of three relevant meteorological stations. Thin lines represent annual values, thick lines the 10-year running mean. Data source: DWD (Zugspitze, Bad Reichenhall) and HISTALP (Salzburg airport, Auer et al. 2007)

In almost all cases, warming is more pronounced in summer when compared to the annual mean. The most recent warming since 1976 is less pronounced at Zugspitze when compared to the valley stations of the Berchtesgaden area. According to findings of the project "KLIWA" (Climate change and consequences for water management), summer (5–10) temperatures in elevations of 1400–1500 m a.s.l. in the western and eastern Bavarian Alps revealed trends of 0.11 °C and 0.10 °C per decade, respectively. With increasing altitude, the positive temperature trends at alpine stations between 500 and 1500 m a.s.l. decreased or remained stable. In the Bavarian Alps, a stronger warming in higher altitudes could only be verified in October and January (KLIWA 2005a).

Precipitation trends are weak and mostly positive. There is no significant difference between annual and winter sums and there is no clear pattern between the stations or towards more recent periods. The KLIWA study (2005b) revealed insignificant trends of basin precipitation in catchments originating in the Bavarian Alps between 0.2% and 2.1% per decade during the winter season (12–2) in the period 1931–1997. This is in accordance to Auer et al. (2007), who find no general difference in warming rates between high and low altitude stations, but a very slight difference between the four sub-regions defined in

Tab. 1: Linear temperature and precipitation trends in long-term records close to the glaciers. Trends have been calculated as linear regression coefficient multiplied by 10, all values are mean trends in units per decade. Data source: DWD (Zugspitze, Bad Reichenhall) and HISTALP (Salzburg airport, Auer et al. 2007)

		Zugspitze (2963 m a s.l.)	Bad Reichenhall (470 m a.s.l.)	Salzburg airport (450 m a.s.l.)
Annual temperature (°C)	1901–2000	0.14	–	0.12
	1951–2000	0.22	0.35	0.26
	1976–2005	0.40	0.84	0.57
Summer (5–9) temperature (°C)	1901–2000	0.14	–	0.14
	1951–2000	0.23	0.27	0.29
	1976–2005	0.58	0.85	0.80
Annual precipitation (% of 1961–1990)	1901–2000	2.4	–	1.1
	1951–2000	1.6	-0.5	1.8
	1976–2005	3.1	-3.1	1.5
Winter (10–4) precipitation (% of 1961–1990)	1901–2000	2.2	–	2.1
	1951–2000	1.9	2.0	4.7
	1976–2005	2.3	-0.1	3.9

the HISTALP project. The Wetterstein belongs to the subregion Northwest, whereas Berchtesgaden is situated in the northeastern sector. Corresponding decadal trends of annual temperatures are 0.14 °C (NW) and 0.12 °C (NE) for 1900–2000 and 0.55 °C (NW) and 0.47 °C (NE) for 1975–2000 (Auer et al. 2007). The annual trends for the 20th century are identical to Zugspitze and Salzburg airport, which also served as input to the HISTALP database. In the more recent period the HISTALP trends diverge from the station data in table 1, but since the periods do not match completely they can only be compared to a limited degree. In any case, the sub-region mean trends of the HISTALP database confirm the increase in warming rates.

4.2 Glacier changes

The two glaciers on Zugspitzplatt (Nördlicher and Südlicher Schneeferner) have experienced the strongest areal retreat (Fig. 8). This is due to the fact that they formed a plateau type glacier with little vertical extent during the Little Ice Age and were strongly affected by the rise of the equilibrium line. The other glaciers, in contrast, were already restricted to their cirques around 1850. Watzmanngletscher was dissolved into several firn patches and not considered as a glacier any more in the 1940s. Then again, it shows the largest mass and area gains from 1960 to 1980, indicating that it is especially sensitive to climate fluctuations.

The complete record of geodetically derived mass balance is displayed in figure 9, numerical values can be taken from tables 4–7.

Blaueis reveals a slight mass gain from 1889 to 1924, followed by strong mass losses until 1949. The overall mass balance 1889-1949 is similar to the other glaciers, but since Blaueis is the only case where a survey from the first half of the 20th century is available, the question arises if other glaciers in Bavaria had balanced or even positive budgets during this period, too. This is not unlikely since enforced glacier re-advances are reported in the Alps in the 1890s and from 1915–1930 (WGMS 2008). In the past three decades, the rate of surface lowering is declining at Blaueis, revealing an opposite trend to the other glaciers. This is probably due to debris accumulation on the lower glacier part after the extraordinary high melt rates from 1980–1989. The supraglacial moraine has an isolating effect and reduces ice melt as soon as a critical thickness of few centimeters is reached (Nakawo and Young 1981; Nicholson and Benn 2006; Hagg et al. 2008b). The upper glacier part has a very shaded location and shows only small surface changes.

At Südlicher Schneeferner, the mass losses from 1990–2006 were moderate compared to the other glaciers. This can be explained by the area-volume relation of this glacier. The many hollows and sinks in the rough terrain around the glacier quickly filled with firn during the positive mass balances in the 1970s. In only 8 years (1971–1979), the glacier area increased by 53%, which is by far the highest increase of all five glaciers in this decade. The new glacier parts were not very thick and quickly disappeared again in the 1980s. From 1990 to 2006, the protuberances in the lowermost parts and connection between the two main ice bodies melted out. Since these glacier parts were relatively thin, the melt

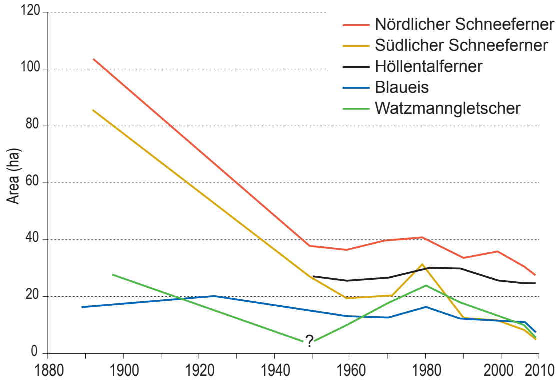

Fig. 8: Area changes of Bavarian glaciers 1889–2009

rates were limited by the melt out of bedrock. Since 2006, the glacier area is restricted to the depressions of the upper cirques and both melt rates and areal retreat is again comparable to the other glaciers.

The main topographic features and the glacier areas and ice volumes are given in tables 2 and 3.

4.3 Correlation of climate and glacier changes

The geodetic mass balances were related to mean summer temperatures and winter precipitation of the respective periods. These correlations are depicted in figure 10, the numerical values are given in tables 4–7.

A clear dependence of the mass balance on summer temperature (Fig. 10, upper graphs) is visible in most cases and confirmed by coefficients of

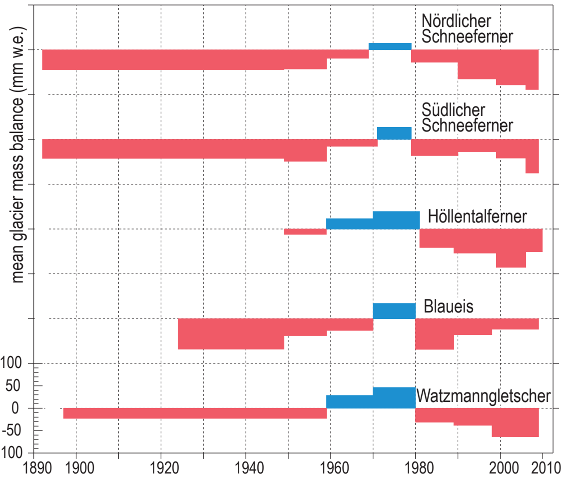

Fig. 9: Geodetically derived mass balance changes of the Bavarian glaciers. A mean density of 0.9 g/cm³ was assumed to transfer volume changes into water equivalents. Values are annual means between two geodetic surveys. Note that the balanced state of Blaueis between 1889 and 1924 (+2 mm/a) is hardly visible

variation between 0.34 and 0.66. Only for Blaueis, the coefficient of determination is very low (0.04). This is caused by three data points (see table 7): the strong negative mass balance of -68 cm w.e./a between 1924 and 1949 cannot be explained by summer temperatures which were 0.1 °C below the baseline mean. This also holds for the equally strong mass losses in the 1980s, when summer temperatures were 0.3 °C above baseline mean, which is still a cold period compared to the ones that follow. The positive mass balances in the 1970s are hard to relate to the temperature anomaly of -0.2 °C, especially

Table 2: Location, area and main topographic features of the Bavarian glaciers

	Nördlicher Schneeferner	Südlicher Schneeferner	Höllentalferner	Blaueis	Watzmann-gletscher
latitude (N)	47° 24.8‘	47° 24.0‘	47° 25.4‘	47° 34.3‘	47° 33.3‘
longitude (E)	10° 58.4‘	10° 58.4‘	10° 59.5‘	12° 52.0‘	12° 55.8‘
year of survey	2009	2009	2010	2009	2009
area (ha)	27.8	4.8	22.3	7.5	5.6
max. elev. (m a.s.l.)	2792	2665	2564	2368	2119
min. elev. (m a.s.l.)	2556	2557	2203	1937	1998
mean elev. (m a.s.l.)	2628	2592	2356	2163	2034
historical glacier extents ha (year)	30.7 (2006)	8.4 (2006)	24.7 (2006)	11.0 (2006)	10.1 (2006)
	36.0 (1999)	11.6 (1999)	25.7 (1999)	–	–
	33.5 (1990)	12.3 (1990)	29.8 (1989)	12.3 (1989)	18.1 (1989)
	40.9 (1979)	31.4 (1979)	30.2 (1981)	16.4 (1980)	24.0 (1980)
	39.7 (1969)	20.5 (1971)	26.7 (1970)	12.6 (1970)	17.7 (1970)
	36.4 (1959)	19.4 (1959)	25.7 (1959)	13.1 (1959)	10.0 (1959)
	37.9 (1949)	27.0 (1949)	27.1 (1950)	15.2 (1949)	–
	–	–	–	20.2 (1924)	–
	103.6 (1892)	85.5 (1892)	–	16.4 (1889)	27.9 (1897)

Tab. 3: Volumes and thicknesses of the Bavarian glaciers

	Nördlicher Schneeferner	Südlicher Schneeferner	Höllentalferner	Blaueis	Watzmann-gletscher
year of survey	2006	2006	2010	2007	2007
volume (mil. m³)	5.2	0.4	2.4	0.4	0.6
max. thickness (m)	49.0	12.8	48.0	13.0	16.0
mean thickness (m)	16.8	4.6	11.7	3.8	5.9

since the same mean temperatures coincide with a negative mass balance between 1959 and 1970.

For all five glaciers, the correlations between winter precipitation and glacier mass balance are negative. This means that in periods with above average winter snowfall, the glaciers experience above average mass losses. Winter snow pack has a twofold impact on glacier mass balance: in most cases it represents the most important accumulation source and it determines the date when ice ablation sets in, which means that it controls the duration of the melting season. Both effects support a positive correlation with winter precipitation sums. On cirque glaciers, avalanches can be the major contribution to accumulation, but their activity is also positively correlated with winter precipitation. The negative correlation determined here is contradictory to the concept of glacier mass balance. The only solution we can suggest is that there is no correlation at all and the negative dependence is a spurious correlation. This assumption is supported by the low precipitation variability and the very low correlation coefficients.

For Nördlicher Schneeferner, also measured snow heights are available. From this record, the snow height on 1 May was taken as an index for winter accumulation. Regression analyses for the three Zugspitze glaciers (Fig. 10) show that glacier mass balances are more closely related to snow height on 1 May (mean R^2: 0.56) than to winter precipitation (mean R^2: 0.17). Moreover, the correlation with snow heights is positive and therefore consistent with the concept of glacier mass balance. This means that winter precipitation and snow height behave inversely proportional, the cross correlation between the two parameters varies between R^2=0.40 and R^2=0.59. The most likely explanation for this apparent contradiction is redistribution by wind. For solid precipitation, most of the systematic measurement error is attributed to wind (Yang et al. 1999). Ostrem and Tvede (1986) have shown that wind-blown snow can strongly influence accumulation distribution and that changes in the wind field can modify the spatial pattern of glacier mass balance. This topic is also discussed in very recent research (Lehning et al. 2011), including the persistency of drift features (Schirmer et al. 2011) as well as the role of preferential deposition in the survival of small glaciers (Dadic et al. 2010).

While the Zugspitze meteorological station on the crest is certainly subject to wind-induced gauge undercatch, the concave terrain below the leeward slope at Nördlicher Schneeferner supports deposition of wind-blown snow. This illustrates the problems connected with precipitation measurements in mountains. Even a very close proximity of a high-standard long-term meteorological station does not guarantee that measured winter precipitation is representative for the location under investigation. Capturing the redistribution by wind and avalanches in a complex topography is the greatest challenge if snow packs of relatively small areas are calculated. Thus, snow measurements are essential for an accurate determination of the snow water equivalent in alpine environment.

According to Kuhn (1993), the mass balance of glaciers in the northern Alps is strongly controlled by accumulation, whereas central Alpine glaciers are more influenced by summer temperatures. This theoretical concept could not be confirmed by precipitation data, which might be due to the fact that the measured precipitation is not representative for the local accumulation on the glaciers. The closer relation of the Bavarian glaciers to air temperature is in accordance with the findings of Schöner et al. (2000), who further state that during periods of mass gain, the opposite correlations can be observed. Although most of the energy for melting is provided by direct solar radiation, air temperature is generally a good melt indicator, as it also correlates with radiation: high air temperatures occur on days with high radiation sums. High summer air temperatures also correlate with the number of hot (and cloudless) days, which is an important value for glacier mass balance. In a warmer climate, glacier melt is not only more intense, but also occurs on more days per year. The most important factor, which cannot be accounted for by long-term mean air temperatures is the albedo effect of summer snowfalls.

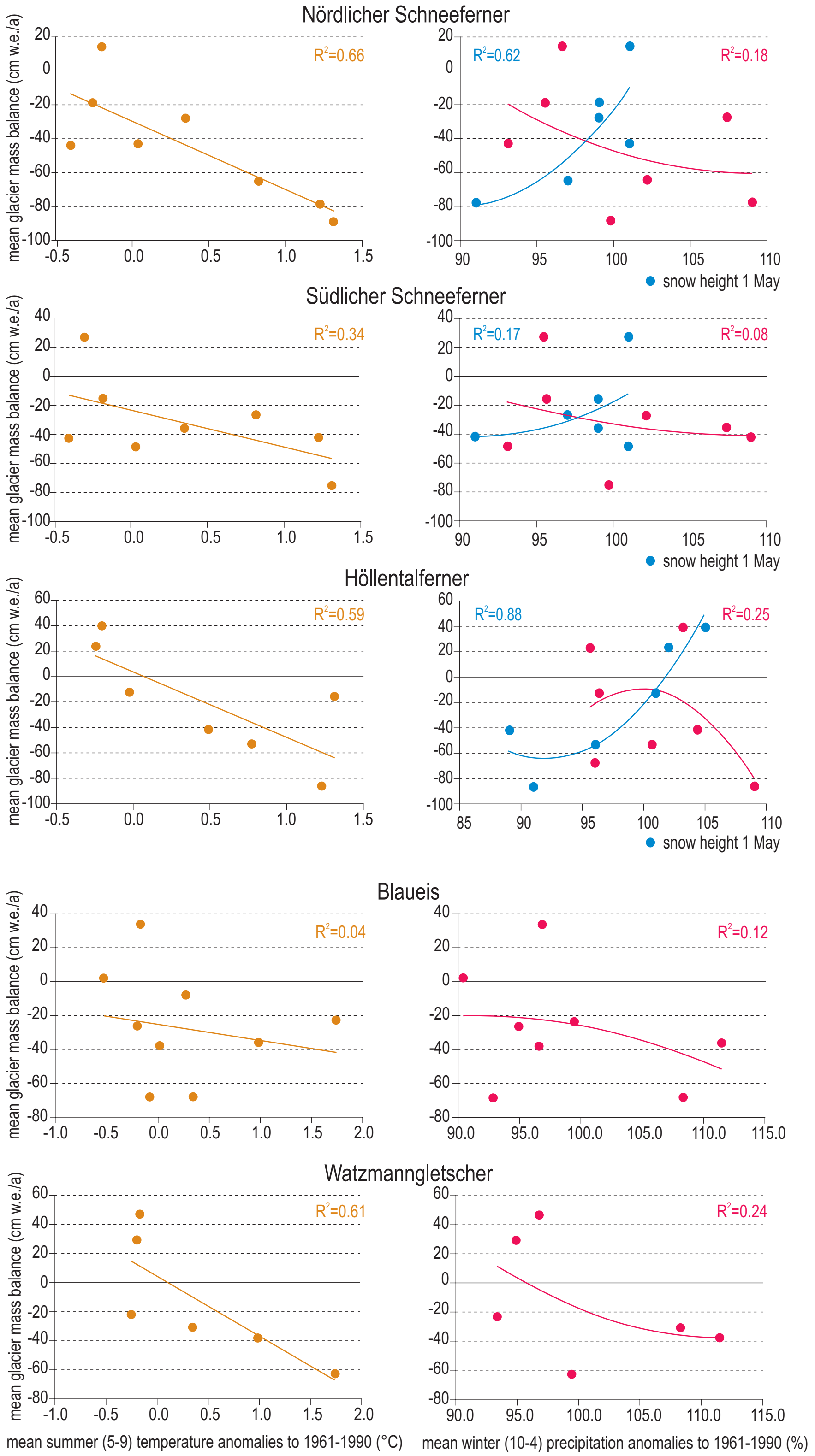

Fig. 10: Relation between geodetically derived glacier mass balances and mean summer temperatures and winter precipitation in the corresponding periods. For the Zugspitze glacier, also the measured snow height on 1 May is depicted (unfilled dots and dashed trendline)

Tab. 4: Geodetically derived glacier mass balances for Nördlicher Schneeferner (cm w.e. per year) and mean anomalies to 1961-1990 of summer (5-9) temperatures, winter (10-4) precipitation and snow height on 1 May at Zugspitze in the corresponding periods

	Nördlicher Schneeferner			
Period	Summer temperature anomalies (°C)	Winter precipitation anomalies (%)	Snow height anomalies (1 May) (%)	Glacier mass balance (cm w.e./a)
1892–1949	-0.4*	-21*	–	-44
1949–1959	0.0	-7	1	-43
1959–1969	-0.3	-5	-1	-19
1969–1979	-0.2	-3	1	14
1979–1990	0.4	7	-1	-28
1990–1999	0.8	2	-3	-65
1999–2006	1.3	9	-9	-78
2006–2009	1.5	-11	–	-89

*mean value for 1901-1949

Tab. 5: Geodetically derived glacier mass balances for Südlicher Schneeferner (cm w.e. per year) and mean anomalies to 1961–1990 of summer (5-9) temperatures, winter (10–4) precipitation and snow height on 1 May at Zugspitze in the corresponding periods

	Südlicher Schneeferner			
Period	Summer temperature anomalies (°C)	Winter precipitation anomalies (%)	Snow height anomalies (1 May) (%)	Glacier mass balance (cm w.e./a)
1892–1949	-0.4*	-21*	–	-42
1949–1959	0.2	-7	1	-48
1959–1971	0.0	-4	-1	-15
1971–1979	-0.1	-5	1	27
1979–1990	0.6	7	-1	-36
1990–1999	1.0	2	-3	-27
1999–2006	1.5	9	-9	-42
2006–2009	1.5	-11	–	-75

*mean value for 1901–1949

Tab. 6: Geodetically derived glacier mass balances on Höllentalferner (cm w.e. per year) and mean anomalies to 1961–1990 of summer (5-9) temperatures and winter (10–4 precipitation and snow height on 1 May at Zugspitze in the corresponding periods

	Höllentalferner			
Period	Summer temperature anomalies (°C)	Winter precipitation anomalies (%)	Snow height anomalies (1 May) (%)	Glacier mass balance (cm w.e./a)
1950–1959	0.2	-4	1	-13
1959–1970	0.0	-4	2	23
1970–1981	0.0	3	5	40
1981–1989	0.7	4	-11	-41
1989–1999	1.0	1	-4	-53
1999–2006	1.5	9	-9	-86
2006–2009	1.5	-11	–	-68

One should expect that using mean positive degree day sums (PDDS) instead of air temperature should yield higher coefficients of variation. PDDS is the sum of positive daily air temperatures and usually a better indicator for melt. Especially during spring and fall, when both negative and positive air temperatures occur, the two values have different information content: at the beginning of the melt season, e.g., the first half of a month might have temperatures below zero, while days with positive temperatures and melt might occur during the second half. A month like that can have mean temperatures slightly below zero, indicating no melt, while PDDS would be positive, describing melt more realistically.

Tab. 7: Geodetically derived glacier mass balances on the Berchtesgaden glaciers (cm w.e. per year) and mean anomalies to 1961-1990 of summer (5-9) temperatures and winter (10-4) precipitation at Salzburg airport in the corresponding periods

	Blaueis				**Watzmanngletscher**		
Period	Summer temperature anomalies (°C)	Winter precipitation anomalies (%)	Glacier mass balance (cm w.e./a)	Period	Summer temperature anomalies (°C)	Winter precipitation anomalies (%)	Glacier mass balance (cm w.e./a)
1889-1924	-0.5	-9	2	–	–	–	–
1924-1949	-0.1	-7	-68	–	–	–	–
1949-1959	0.0	-3	-38	1897-1959	-0.3	-7	-23
1959-1970	-0.2	-5	-26	1959-1970	-0.2	-5	29
1970-1980	-0.2	-3	34	1970-1980	-0.2	-3	47
1980-1989	0.3	8	-68	1980-1989	0.3	8	-31
1989-1999	1.0	11	-36	1989-1999	1.0	11	-38
1999-2009	1.7	0	-21	1999-2009	1.7	0	-51

At Zugspitze, PDDS were calculated for the periods between geodetic surveys and correlated with glacier mass balances. Surprisingly, the correlation did not improve compared to monthly air temperatures.

A better climate-glacier correlation could probably only be achieved using daily information. Summer snow falls are crucial for glacier mass balance. Fresh snow has a very high reflectivity (80–97%), whereas typical albedos of glacier ice range between 20 and 40% (Paterson 1994). Due to the high air content, snow is an effective isolator and prevents the conduction of sensible heat towards the underlying ice. Summer snowfalls therefore immediately reduce ice melt and, depending on the thickness of the snow pack, a considerable amount of energy and time is required to reach pre-snowfall conditions. Therefore, it is essential if precipitation occurs on warmer or colder days and such weather patterns can only be described with daily meteorological data. On Nördlicher Schneeferner, a 6 years series of direct mass balance observations using the glaciological method (1962/63–1967/68) exists. We applied a method after Hoinkes and Steinacker (1975) to reduce positive degree day sums after snowfall events, according to the amount of precipitation that falls below freezing point. Additionally, the snow height on 1 May is included as an index for the beginning of the ablation period. It could be shown that the so modified PDDS are more closely related to glacier mass balance than the traditional ones (Fig. 11).

5 Conclusions

The Bavarian glaciers are at a critical stage. Three glaciers have mean ice thicknesses of few meters only. If current melt rates continue in the future, these ice patches are likely to disappear within a few years, while the two larger ones have a somewhat longer life expectancy. The analysis of meteorological data revealed that the glacier degradation can be attributed to increased summer temperatures. The long-term mass balances show no correlation with mean winter precipitation from nearby stations, but fairly good correlations with snow heights in the case of the glaciers at Zugspitze. A sound estimate of accumulation conditions requires labour-intensive field campaigns over several years using a spatially dense net of observation and ideally ground-penetrating radar. This is particularly true for small glaciers below the regional snow line, because here, redistributed snow often remarkably contributes to total accumulation.

The glaciers in Bavaria owe their existence to very special, local conditions and thus show a very individual response to climate change. The larger the area of a glacier, the closer its link to regional climate conditions. Short-term variations of the snow line and consecutive albedo effects complicate the climate-glacier relation. Therefore, a proper reproduction of glacier mass balances requires modelling approaches on a daily time-step.

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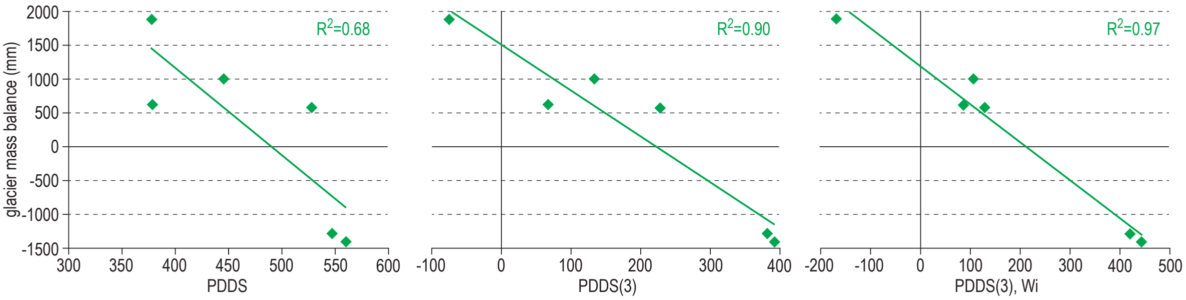

Fig. 11: Relation between glaciologically derived glacier mass balances on Nördlicher Schneeferner (1962/63–1967/68) and different temperature indexes according to Hoinkes and Steinacker (1975): positive degree day sums (left), positive degree day sums adjusted to summer snow falls (middle) and positive degree day sums adjusted to summer snow falls and winter accumulation (right)

ische Zugspitzbahn AG (M. Hurm) and the National Park Berchtesgaden offered logistic help. The German Meteorological Office very quickly provided precipitation and homogenized air temperatures of the Zugspitze station. Thomas Werz processed meteorological data for the degree-day model and Ines Schwenkmeier took care of map reprojections. The constructive comments of Stefan Winkler and two anonymous referees are greatly acknowledged. We thank Annelen Kahl for correcting the English.

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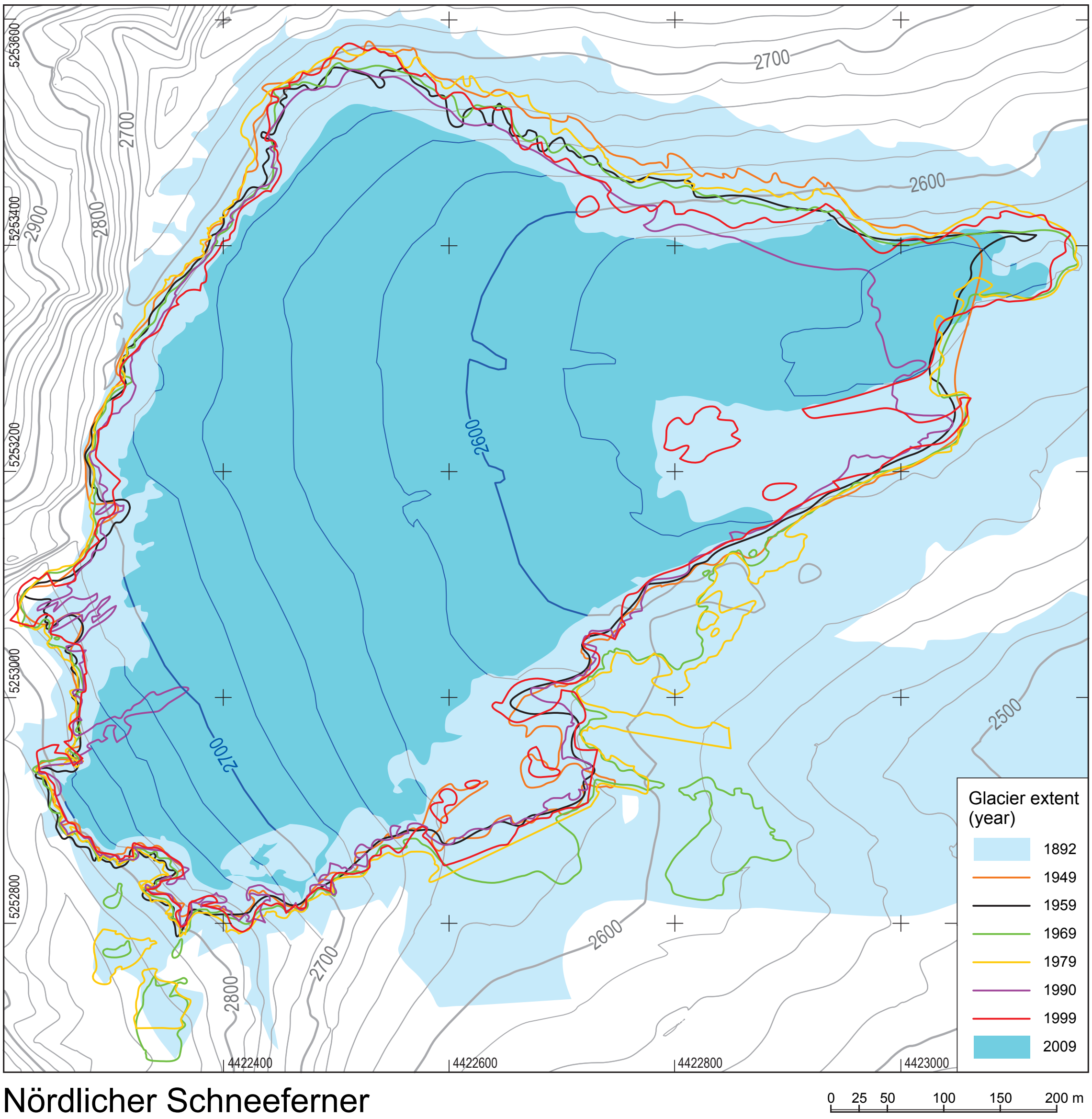
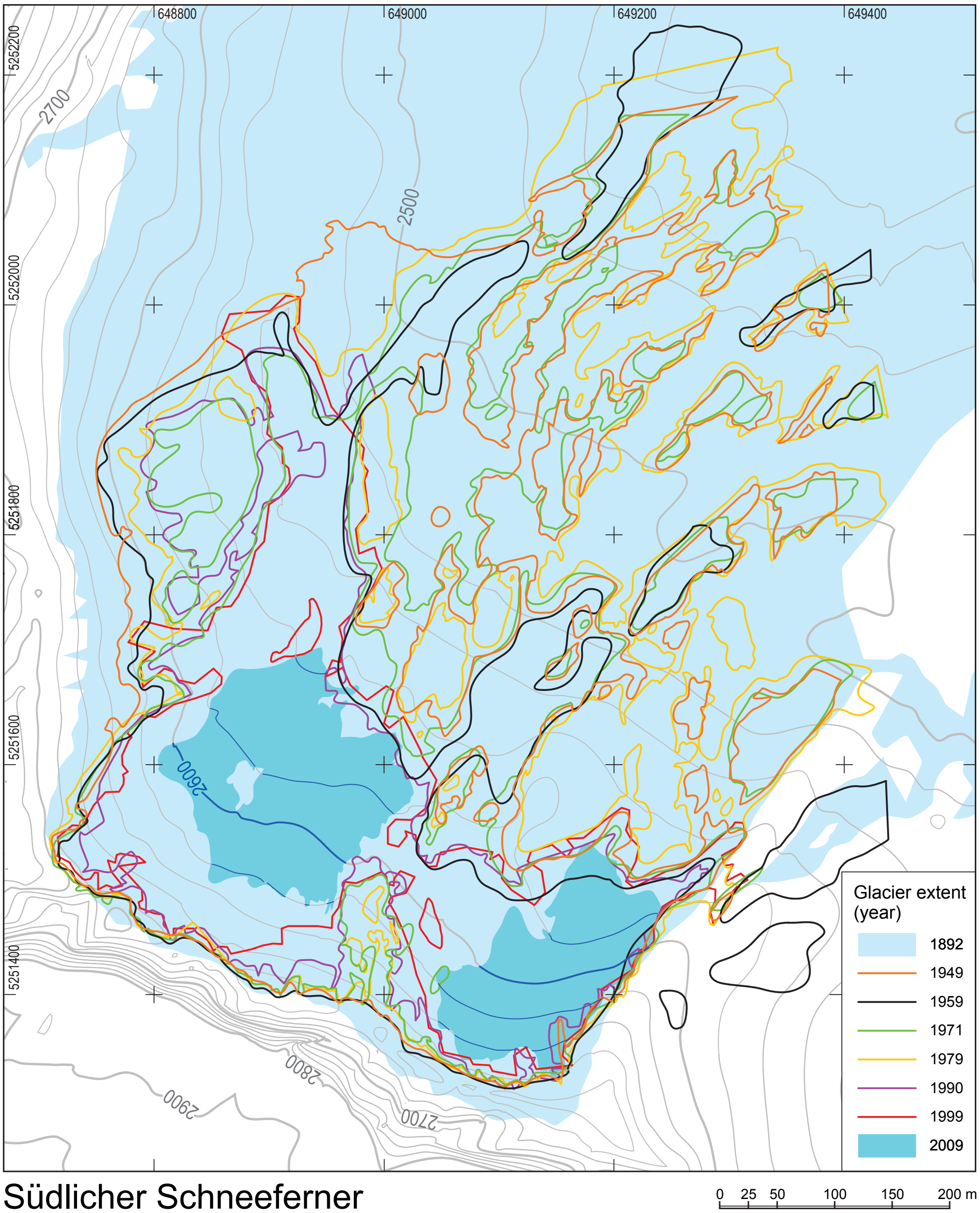
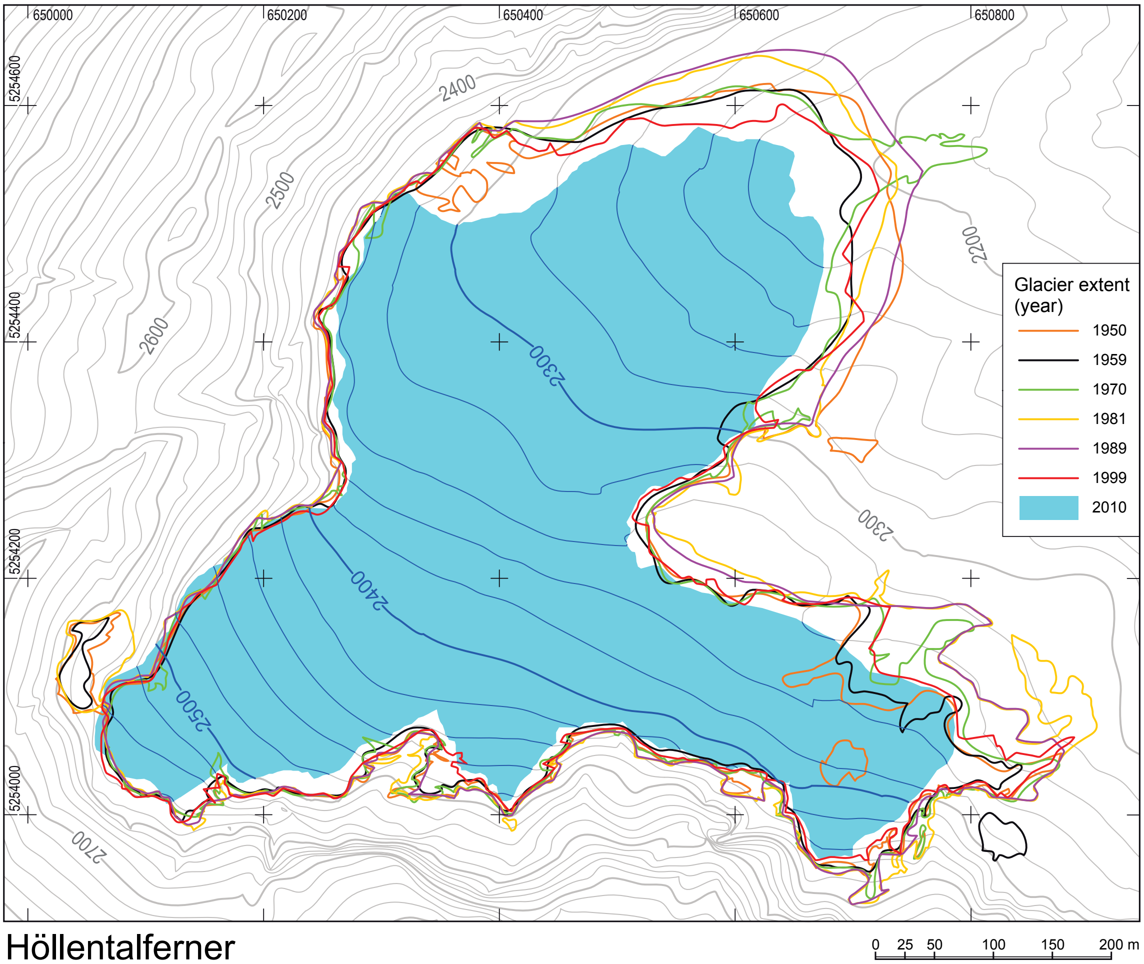
Appendices



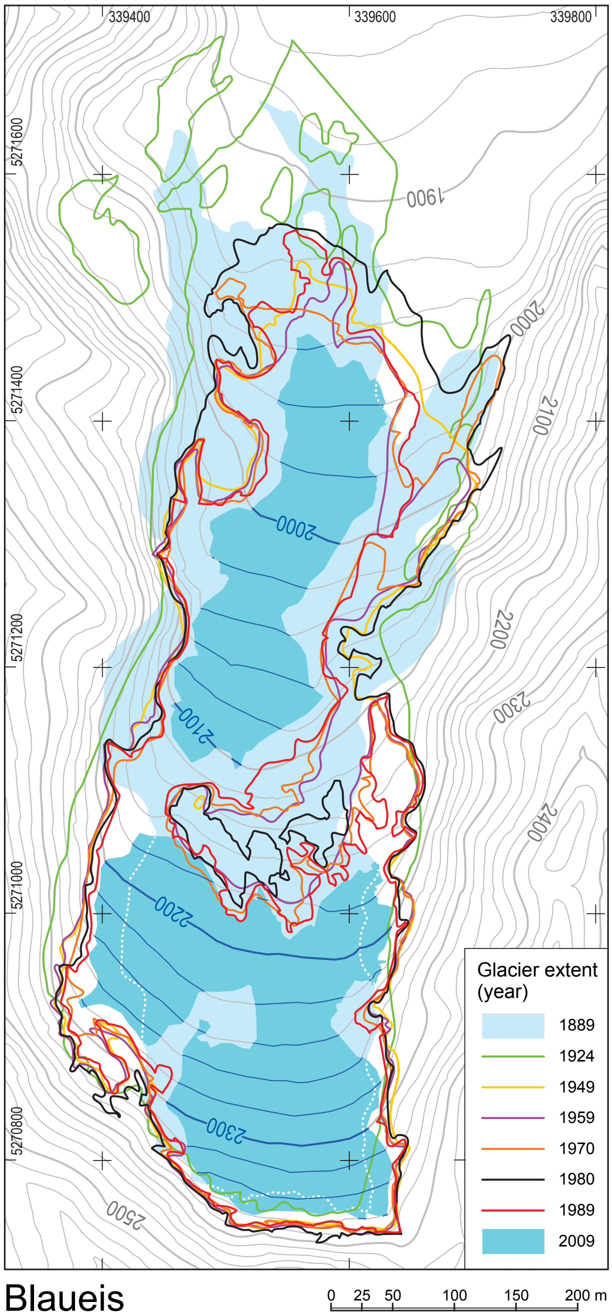
Appendix I: Contour map of Nördlicher Schneeferner 2009 (after terrestrial laserscanning in September 2009 by C. Breitung, C. Mayer and E. Mayr) and historical glacier extents (Projection: UTM zone 32 North, source: www.bayerische-gletscher.de)



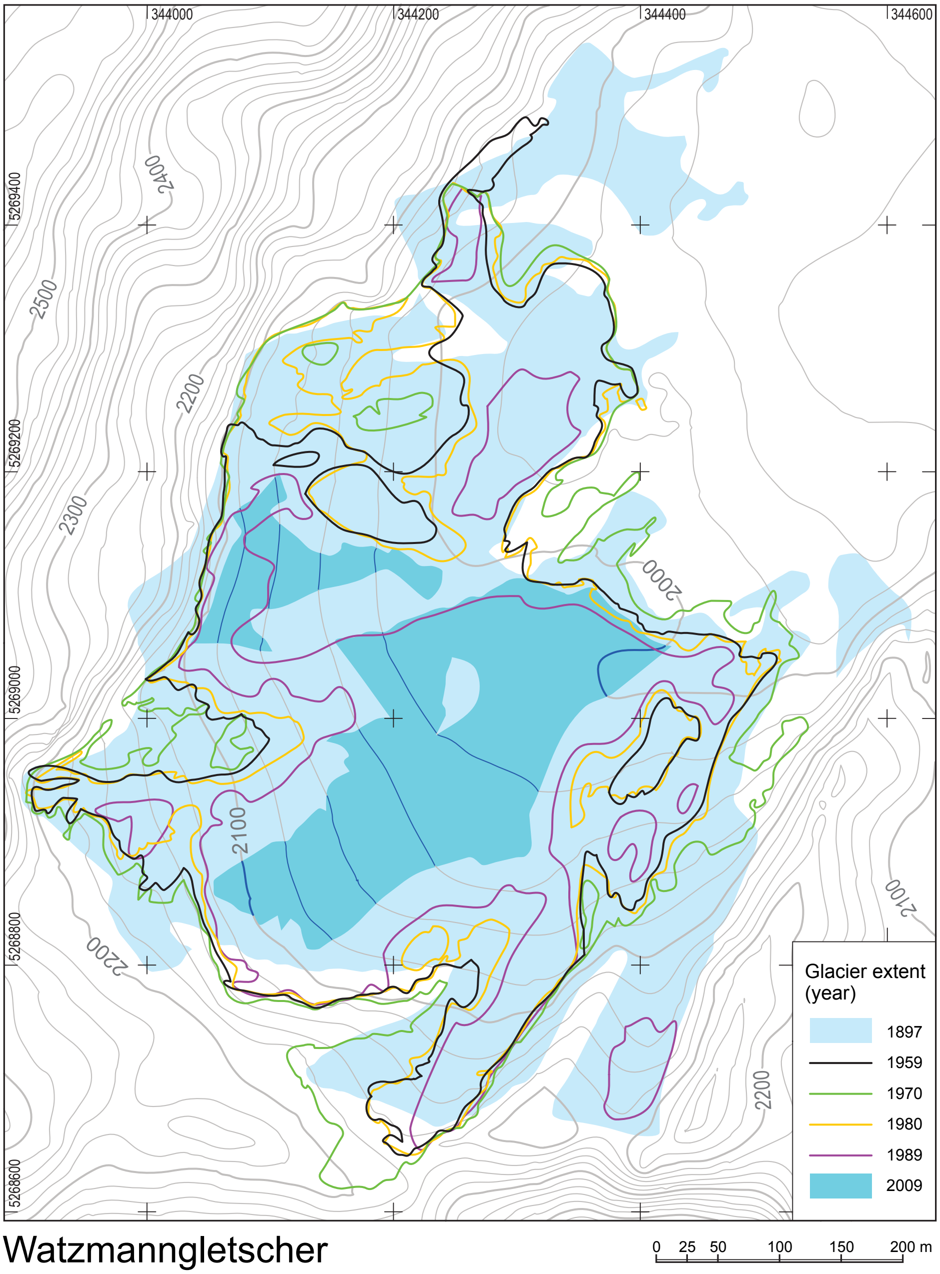
Appendix II: Contour map of Südlicher Schneeferner 2009 (after kinematic GPS-profiling in September 2009 by C. Mayer and E. Mayr) and historical glacier extents (Projection: UTM zone 32 North, source: www.bayerische-gletscher.de)



Appendix III: Contour map of Höllentalferner 2010 (after a tachymetric survey in October 2010 by C. Mayer, W. Hagg and A. Lambrecht) and historical glacier extents (Projection: UTM zone 32 North, source: www.bayerische-gletscher.de)



Appendix IV: Contour map of Blaueis 2009 (after a tachymetric survey in September 2009 by C. Mayer and E. Mayr) and historical glacier extents (Projection: UTM zone 33 North, source: www.bayerische-gletscher.de)



Appendix V: Contour map of Watzmanngletscher 2009 (after a tachymetric survey in September 2009 by C. Mayer and E. Mayr) and historical glacier extents (Projection: UTM zone 33 North, source: www.bayerische-gletscher.de)