



Climate and glacier fluctuations in the Bavarian Alps



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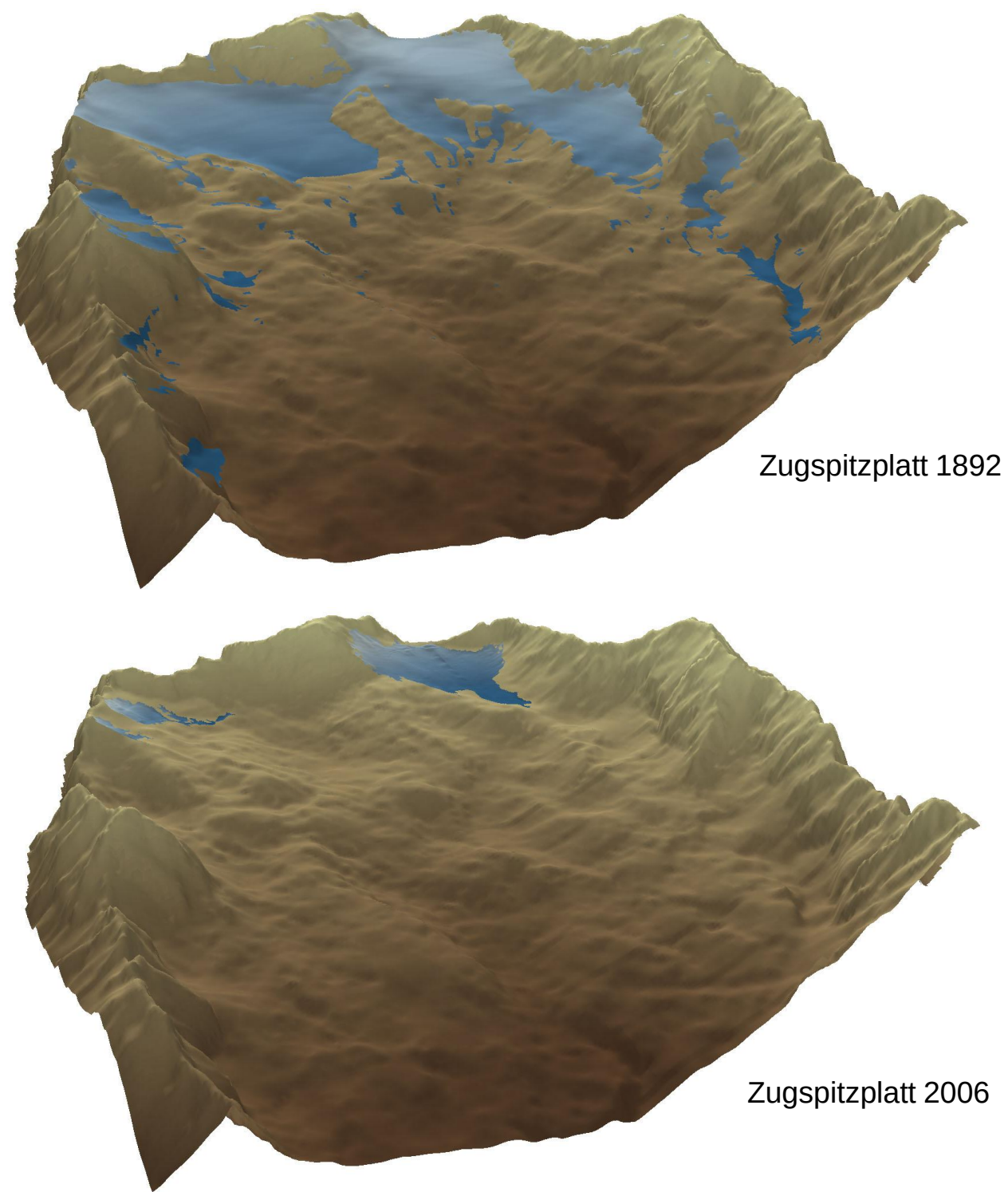


Fig. 1: 3D-perspectives of digital elevation models derived by the map of Finsterwalder and Jäger (1892) and by laser scanning (LVG 2006).

The climate change we are observing at the moment affects the whole planet, allowing us to speak of “global” warming. However, magnitude and impact of climate fluctuations vary considerably from one region to another. When estimated over a linear trend, 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). The most obvious and evident effect of this pronounced warming in high mountain environments is the downwasting and retreat of glaciers. The mass balance of glaciers is mainly controlled by accumulation of snow and melt of snow and ice and therefore is controlled by winter precipitation and summer temperatures. Glaciers are recognized as key indicators for climate change. In the Alps, they have lost almost half of their area from the end of the Little Ice Age (1850) until 2000 (Zemp et al. 2007). The Bavarian Alps are a worthy region for comparing climate and glacier fluctuations, because there exist both long-term climate observations and glacier monitoring. In this contribution, temperature and precipitation series of meteorological stations nearest to the glaciers are analysed and correlated with an extended glacier mass balance record.



Fig. 2: Chalk lithograph by Posselt (1875)



Fig. 3: Blaueis 2007 (Photo: M. Obermeier)

REGIONAL SETTING AND HISTORY OF GLACIER OBSERVATION

The glaciers in Bavaria were surveyed for the first time in the late 19th century with theodolite measurements and terrestrial photogrammetry in the Wetterstein (Finsterwalder and Jäger 1892). The first maps containing enough height information for a quantitative analysis are from Blaueis (1889, Fig. 4), the two Schneeferners (1892, Fig. 5) and Watzmanngletscher (1897, Fig. 4). The photo flights by the Bavarian Surveying Agency (LVG) 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 were surveyed regularly and at

least one 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. In 2006, the LVG conducted an airborne laser scanning campaign in the Wetterstein range, applying the most modern and sophisticated geodetic method up to date. Based on these repeated surveys, changes in volume and elevation have been published for the periods 1949 to 1970 (Finsterwalder and Rentsch 1973), 1970 to 1989/90 (Finsterwalder 1992) and 1989/90 to 2006 (Hagg et al. 2008). For this contribution, three historic maps of Watzmanngletscher (1897) and Blaueis (1889, 1924) were newly added to the series of geodetic observations.

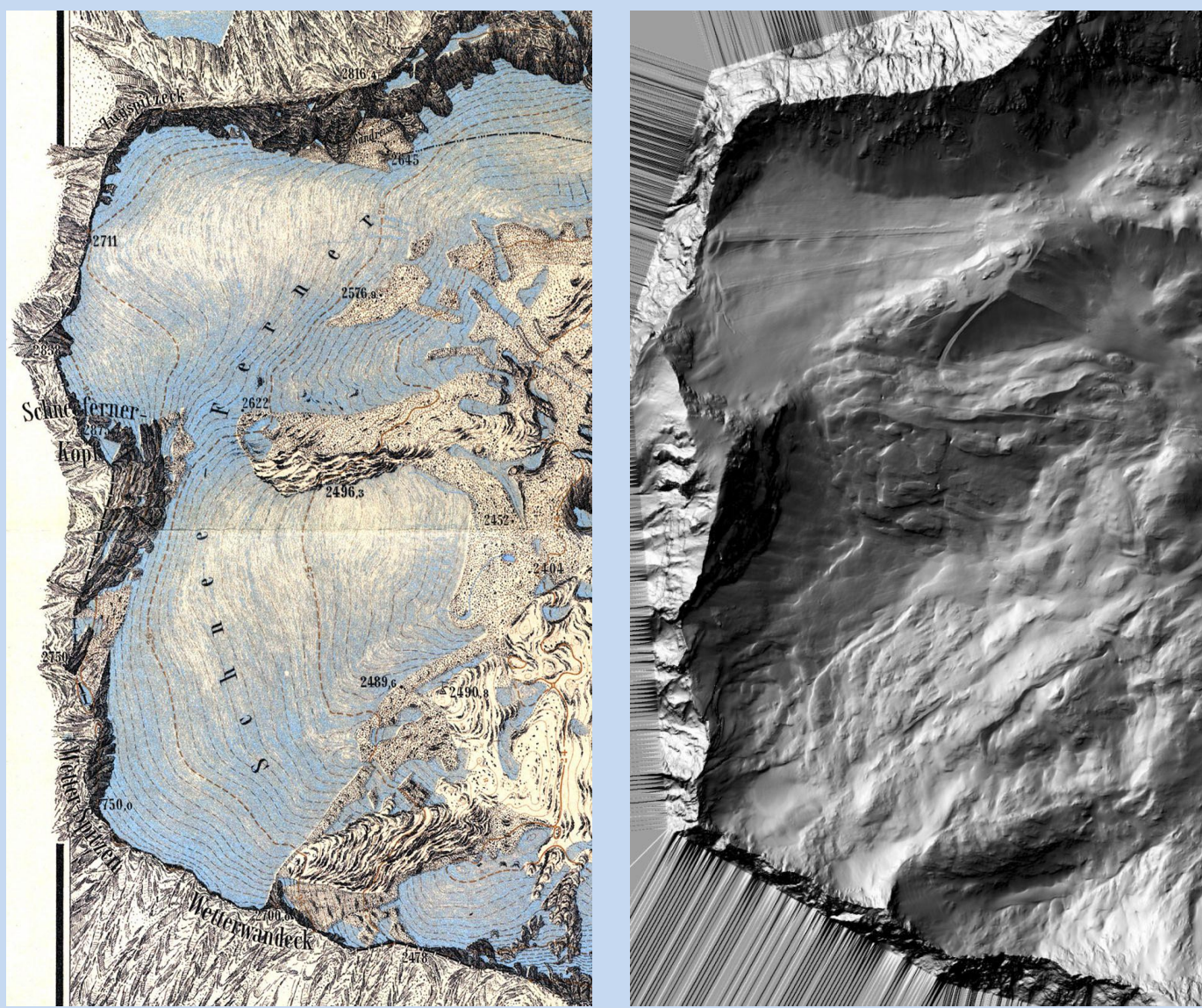


Fig. 5: Detail of the map „Zugspitze“ by Finsterwalder and Jäger (1892, left) and hillshade of the digital elevation model derived by airborne laser scanning (LVG, right).

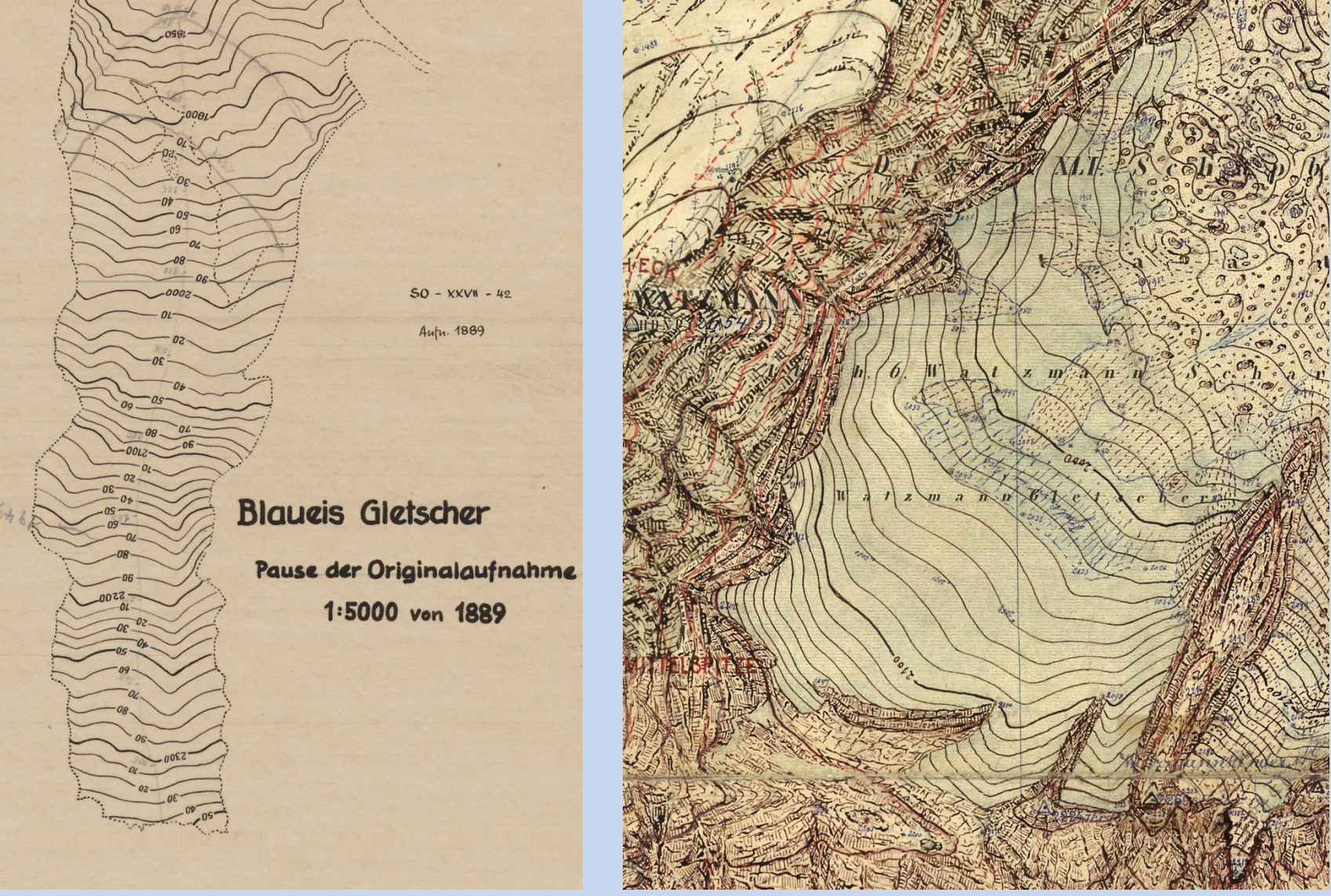


Fig. 4: Contour maps of Blaueis (1889, left) and Watzmanngletscher (1897, right) by the Topographic Bureau.

OBSERVED CLIMATE CHANGE AT STATIONS CLOSE TO GLACIERS

Climate stations

Zugspitze weather station (2962 m a.s.l.) is operating continuously since 1901 and provides a very valuable and rare high altitude dataset. In the Berchtesgaden Alps, there was a meteorological station at Watzmannhaus (1923 m a.s.l.) operating from 1948-1953, but no long-term series of a mountain station exists. The closest valley stations with a long record are Schönau (616 m a.s.l., 7-10 km northeast of the glaciers, 1948-1998) and 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.

Analyzing climate records

The climate records used are raw data as measured by the German Meteorological Office (DWD) only in the case of Schönau. 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). For correlations with glacier mass balances, Salzburg airport was used in order to cover also the earlier periods. This step was justified by a strong correlation between Salzburg and Schönau temperatures ($R^2=0.94$) and precipitation sums ($R^2=0.74$). To visualize the climate trends, the 10-years running mean was calculated. All values shown in Figures 6 and 7 are anomalies from the 1961–1990 average.

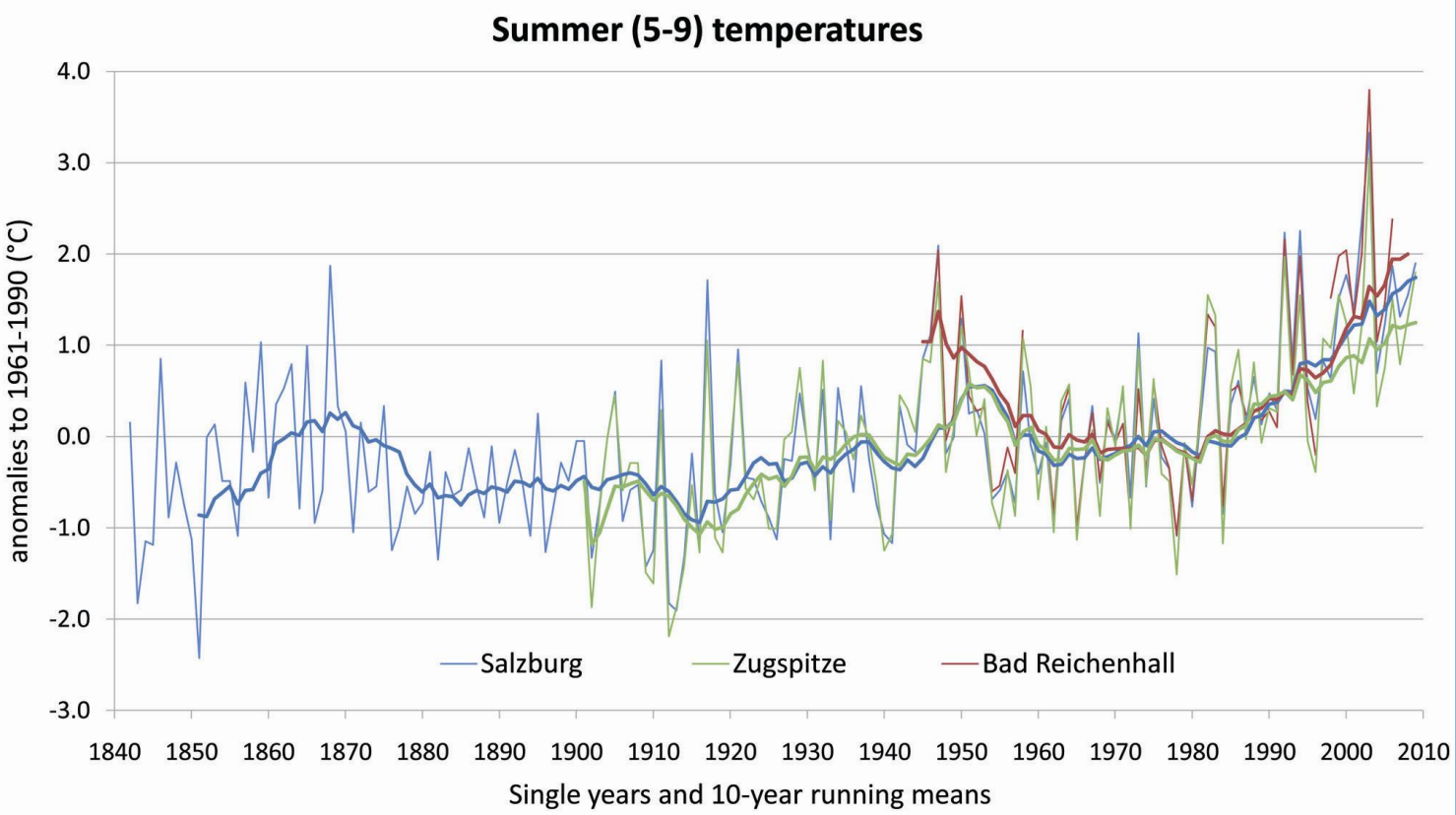


Fig. 6: Summer (May-Sep) temperatures at stations with a long-term record.

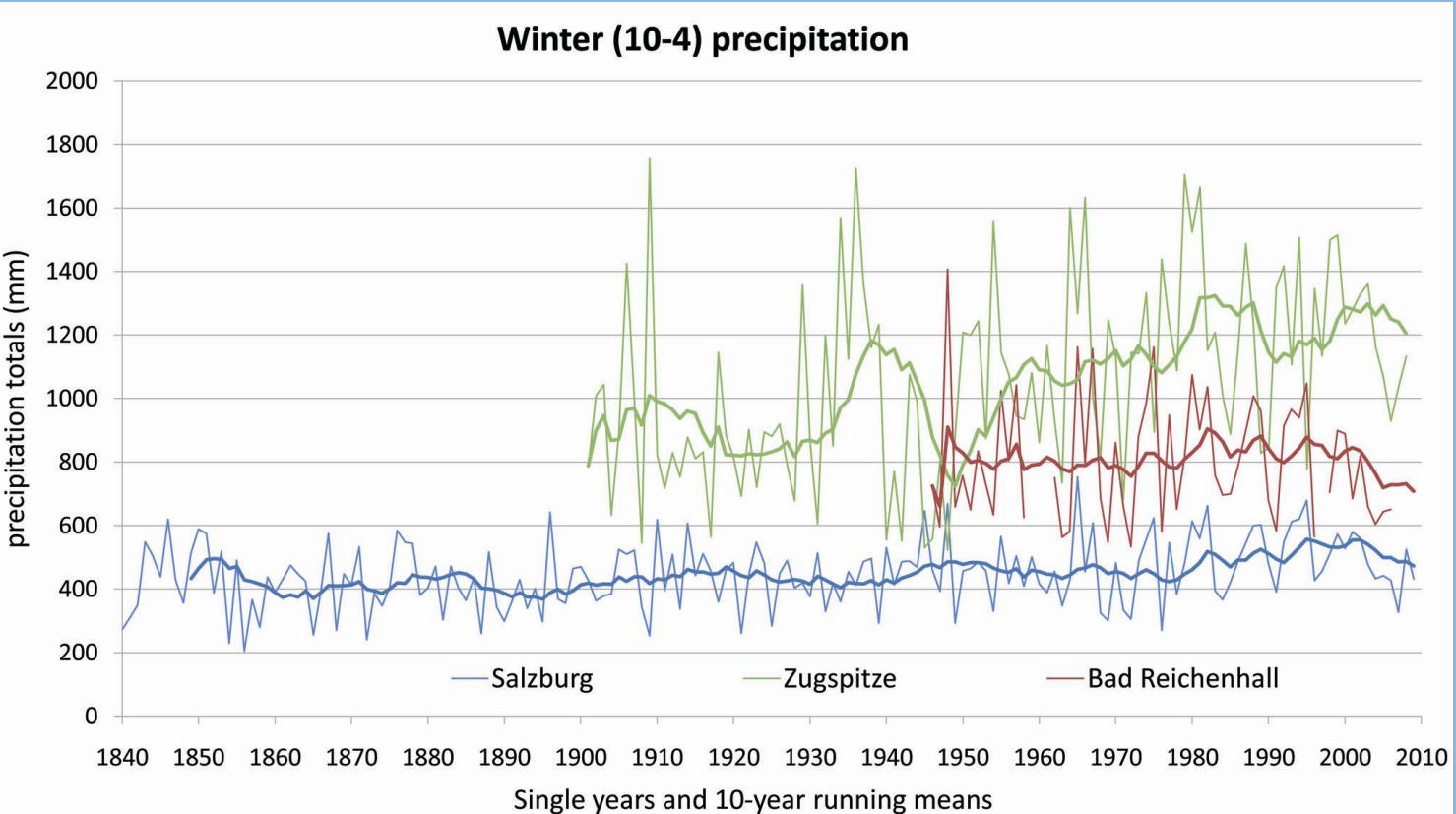


Fig. 7: Winter (Oct-Apr) precipitation at stations with a long-term record.

Linear trends have been calculated as linear regression coefficient multiplied by 10, all values shown in Table 1 are mean trends in units per decade.

Table 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

	Period	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 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 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

Results

- warming is stronger in more recent periods (1975-2005: 3-5 times higher than for the 20th century).
- in almost all cases, warming is stronger in summer.
- the most recent warming since 1976 is less pronounced at Zugspitze when compared to the lowland stations of the Berchtesgaden area. **It seems that climate warming is not generally stronger in high altitudes.** In the Bavarian Alps, this is only true for October and January (see KLIWA project).
- 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.

CLIMATE-GLACIER-CORRELATIONS

The dependance of glacier behaviour from mean summer temperatures and from mean winter precipitation (Fig. 10) is relatively low. Also by combining both climate factors, glacier fluctuations cannot be reconstructed in most cases. This is especially surprising at Zugspitze, where we benefit from a high altitude climate station in closest proximity to the glaciers. Here, also positive degree day sums yielded no better correlations with glacier mass balance than mean temperature anomalies. One reason may be that the albedo effect of summer snowfalls cannot be considered with monthly data. For this purpose, a mass balance model which distinguishes rain from snow has to be applied.

GLACIER CHANGES SINCE 1889

The two glaciers on Zugspitzplatt (Nördlicher and Südlicher Schneeferner) have experienced the strongest retreat. This is due to the fact that they formed a plateau type glacier during the little ice age and were strongly affected by the rise of the equilibrium line. The other glaciers, in contrast, were already cirque glaciers in 1850. Watzmanngletscher was considered as diminished in the 1940s and shows the largest mass and gains from 1960 to 1980, indicating that it is also especially sensitive to climate fluctuations.

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 also other glaciers in Bavaria had balanced or even positive budgets during this period.

This is not unlikely since enforced glacier re-advances are reported in the Alps around

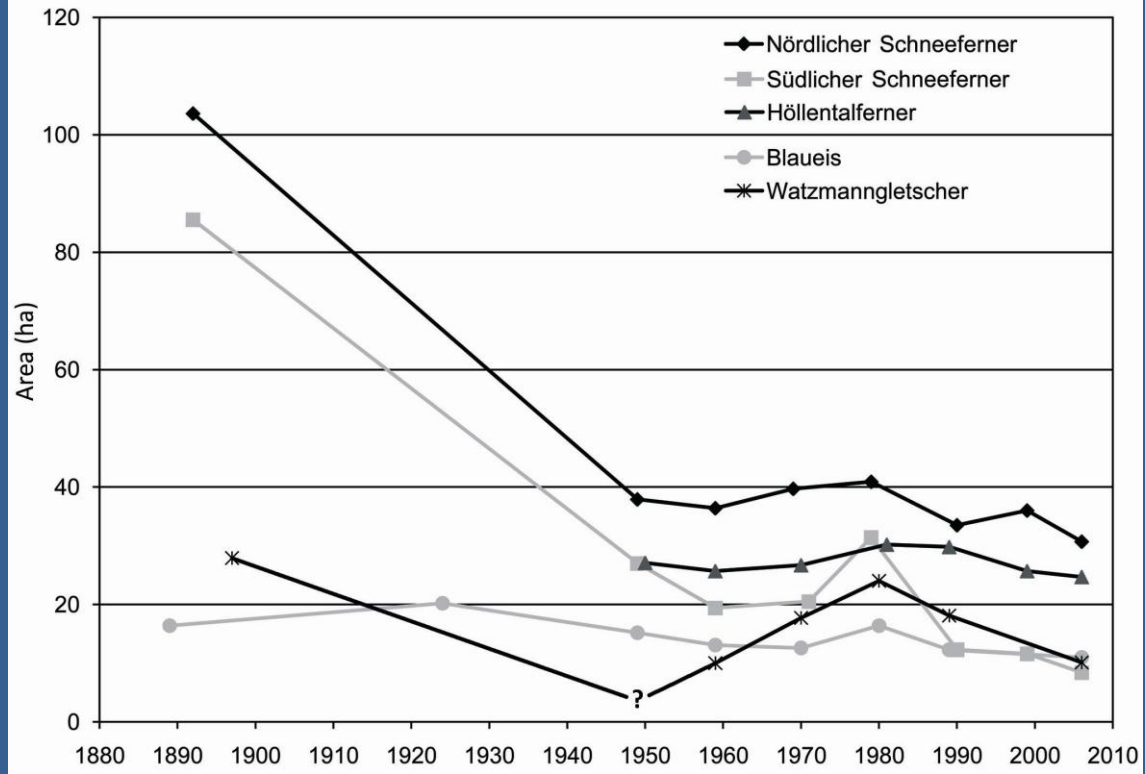


Fig. 8: Aerial evolution of the five glaciers.

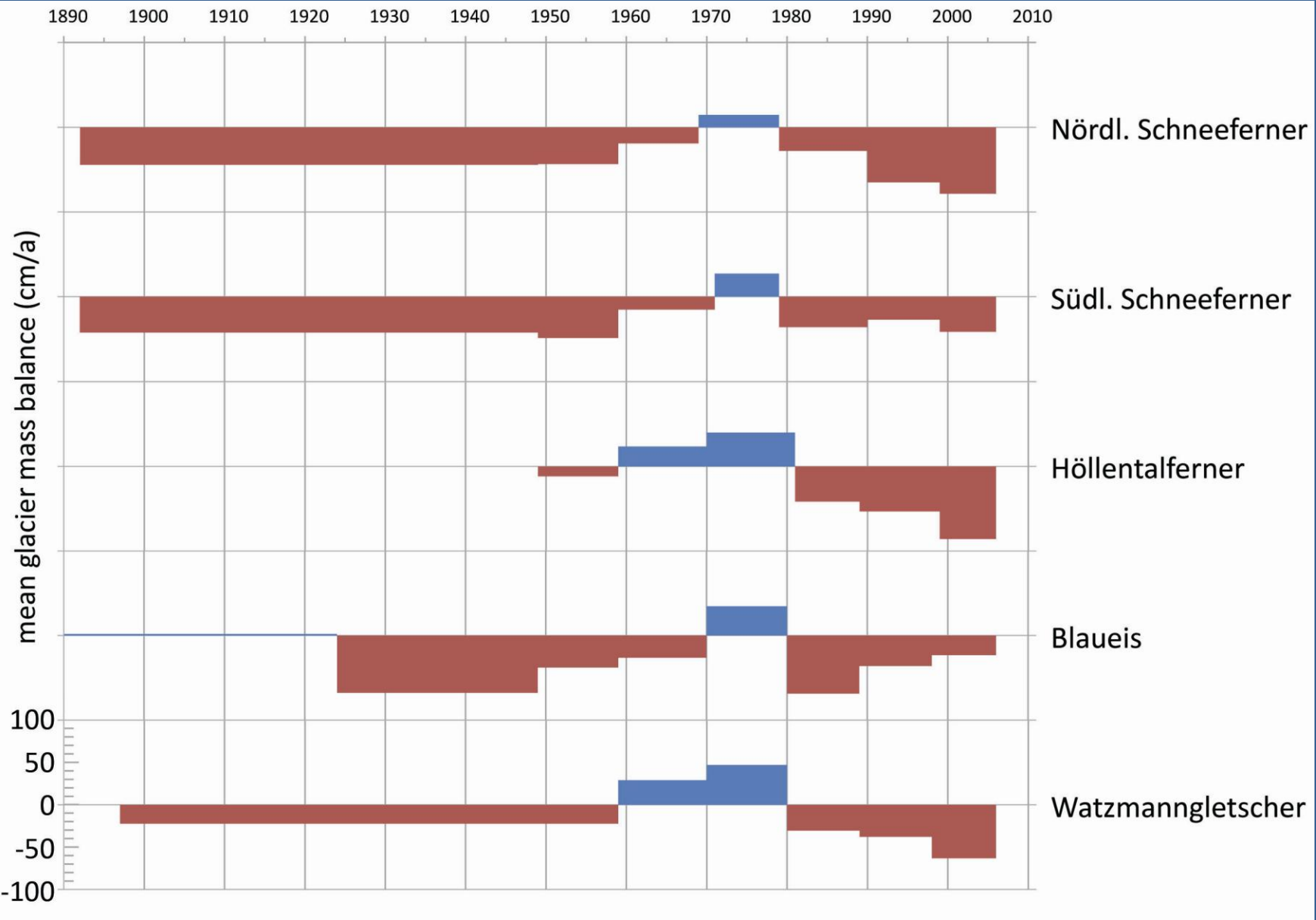


Fig. 9: Mean mass balances (cm water equivalent) of the Bavarian glaciers between geodetic surveys.

1915-1930. While Höllentalferner shows the smallest area changes, it suffers the largest mass losses in the latest period of observation (1999-2006).

