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How stable are twentieth-century calibration models? A high-resolution summer temperature reconstruction for the eastern Swiss Alps back to AD 1580 derived from proglacial varved sediments

Alex Blass,[1,2]* Martin Grosjean,[2,3] Andrea Troxler[3] and Michael Sturm[1]

([1]Eawag, Swiss Federal Institute of Aquatic Science and Technology, 8600 Dübendorf, Switzerland; [2]NCCR Climate, 3012 Bern, Switzerland; [3]Department of Physical Geography, University of Bern, 3012 Bern, Switzerland)

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Abstract: We found a significant *positive* correlation between local summer air temperature (May–September) and the annual sediment mass accumulation rate (MAR) in Lake Silvaplana (46°N, 9°E, 1800 m a.s.l.) during the twentieth century ($r = 0.69$, $p < 0.001$ for decadal smoothed series). Sediment trap data (2001–2005) confirm this relation with exceptionally high particle yields during the hottest summer of the last 140 years in 2003. On this base we developed a decadal-scale summer temperature reconstruction back to AD 1580. Surprisingly, the comparison of our reconstruction with two other independent regional summer temperature reconstructions (based on tree-rings and documentary data) revealed a significant *negative* correlation for the pre-1900 data (ie, late 'Little Ice Age'). This demonstrates that the correlation between MAR and summer temperature is not stable in time and the actualistic principle does not apply in this case. We suggest that different climatic regimes (modern/'Little Ice Age') lead to changing state conditions in the catchment and thus to considerably different sediment transport mechanisms. Therefore, we calibrated our MAR data with gridded early instrumental temperature series from AD 1760–1880 ($r = -0.48$, $p < 0.01$ for decadal smoothed series) to properly reconstruct the late LIA climatic conditions. We found exceptionally low temperatures between AD 1580 and 1610 (0.75°C below twentieth-century mean) and during the late Maunder Minimum from AD 1680 to 1710 (0.5°C below twentieth-century mean). In general, summer temperatures did not experience major negative departures from the twentieth-century mean during the late 'Little Ice Age'. This compares well with the two existing independent regional reconstructions suggesting that the LIA in the Alps was mainly a phenomenon of the cold season.

Key words: Late Holocene, varves, lake sediments, climate reconstruction, 'Little Ice Age', glacier, Alps.

Introduction

Long-term climate reconstructions are essential to place the recent, probably anomalous climate and environmental changes into a broader perspective. In this context, one particular quality of lake sediments is the potential to contain records over very long periods of time (eg, Leonard, 1997; Zolitschka *et al.*, 2000; Wick *et al.*, 2003) and the ability to record low-frequency climate signals (eg, Moberg *et al.*, 2005).

To date, very few sedimentary studies have revealed quantitative high-resolution climate reconstructions (Hughen *et al.*, 2000; Moore *et al.*, 2001), since lacustrine sediment parameters often respond in a complex way to climate signals (eg, Ohlendorf *et al.*, 1997). Also, dating at (near-)annual resolution is difficult or even impossible, and long local instrumental data series are rare in many areas.

Moreover, quantitative reconstructions are difficult as they are strongly dependent on the data selection and calibration methods used (Esper and Frank, 2005). In addition, one general assumption is that statistical calibration models

*Author for correspondence (e-mail: alex.blass@eawag.ch)

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developed for the instrumental period are stationary and applicable to past proxy series.

The annually resolved 400-yr long sediment record of Lake Silvaplana (Engadine, Swiss Alps, 1800 m) offers the unique opportunity to test this assumption: two new high-resolution climate reconstructions are available for this region, (i) an Alpine tree-ring series of summer (JJA) temperatures (Büntgen *et al.*, 2005) and (ii) a gridded summer temperature reconstruction for the Alpine area based on long instrumental station data and documentary proxy evidence (Casty *et al.*, 2005). All of these reconstructions are completely independent and do not share any common predictor.

We relate high-resolution (2–4 days in summer, 3 weeks in winter) sediment trap data from 2001 to 2005 to runoff and climate data, which provides an insight into recent particle dynamics and hydro-climatic processes. In the light of this information, we compare 140 years of local instrumental station data with the annually resolved sediment record of Lake Silvaplana. This step-by-step aggregation from the daily to the annual scale provides information about how sedimentary processes change with the hierarchy of the integrated fine steps.

We develop a statistical calibration and reconstruction model for summer temperature by using (a) twentieth-century local instrumental data and (b) eighteenth/nineteenth-century gridded (46°N, 9°E) early instrumental temperature data according to Auer *et al.* (2006). We further compare our data with regional summer temperature reconstructions derived from tree ring widths (Büntgen *et al.*, 2005) and multiproxy data (Casty *et al.*, 2005) back to AD 1580. We illustrate why our twentieth-century reconstruction model is not valid for 'Little Ice Age' conditions and discuss its limits and validity in detail. We also use the early instrumental series from Auer *et al.* (2006) to establish a model for sediment-derived pre-instrumental (ie, 'Little Ice Age') summer temperature reconstructions for the eastern Swiss Alps.

Study site

Lake Silvaplana is located in the Engadine, southeastern Swiss Alps, at an altitude of 1800 m a.s.l. (Figure 1). The lake has a maximum depth of 77 m, a volume of 127×10^6 m^3 (LIMNEX, 1994) and a surface area of 2.7 km^2. The lake is ice-covered between January and May. The catchment area stretches across 129 km^2 with about 6 km^2 (5%) of glaciated area (status 1998). The Fedacla river is mainly fed by glacial meltwaters (average runoff of 1.5 m^3/s), and is the most important tributary regarding sediment supply to the lake. A second tributary is the Inn river that connects Lake Sils with Lake Silvaplana. Mean discharge amounts to 2 m^3/s but with almost no suspended sediment load. The river Valhun and Surlej contribute with 0.7 and 0.3 m^3/s, respectively.

The Engadine has a more continental climate than the Swiss Plateau. Larger diurnal and annual temperature amplitudes and drier conditions are typical. Monthly mean temperatures range from −7.8°C in January to 10.8°C in July. On average, maximum precipitation occurs in August (121 mm) whereas a minimum is observed in February (42 mm). Total precipitation amounts to 1029 mm per year (average 1901–1960; Schweizerische Meteorologische Anstalt, 2002). Moist air comes predominantly from the south.

Methods and data

Two sediment cores of 85 cm and 150 cm were recovered from Lake Silvaplana in winter 2004/2005 using a freeze-corer (Kulbe and Niederreiter, 2003). This coring technique preserves the sediments perfectly. The choice of coring sites (Figure 1) was based on seismic profiles and previous studies (Ohlendorf, 1998). The cores were photographed and sediments were subsampled for thin-sections using a freeze-drying technique. Subsamples of the individual annual layers (identified by digital images and thin-sections) were carefully scratched off the frozen sediment slab. The core temperature was constantly kept below −10°C. Subsamples were freeze-dried and analysed for water content. Grain-size measurements were made with a Malvern Mastersizer Hydro 2000S after removing the organic matter and biogenic silica content (diatoms). Maximum value of the grain-size distribution curve was used as a measure for sorting.

^{137}Cs and ^{210}Pb gamma decay was measured for one core at EAWAG, Duebendorf. Counting of varves was carried out on high-resolution digital core photographs (2300×1700 pixels) and verified on thin-sections throughout the cores. Mass flow deposits of four major historic floods (1987, 1951, 1834, 1828) were used as additional time markers (Schwarz-Zanetti and Schwarz-Zanetti, 1988; Röthlisberger, 1991, 1993).

Varve thickness measurements were taken from the photographs along three scan lines with a digital benchmark and mean values were calculated. The annual mass accumulation rate (MAR) was assessed using the algorithms of Berner (1971) and Niessen *et al.* (1992) that transfer thickness measurements into flux rates considering both water content and organic carbon. One short sequence (12–18 cm core depth, AD 1951–1986) of the freeze-cores had to be complemented with data from a gravity-core taken at the same position. Layers that were interpreted as mass-flow deposits with a thickness exceeding 1 mm were excluded from the record.

Homogenized meteorological data of the nearby MeteoSwiss station Sils-Maria (Figure 1) are available from AD 1864 (Swiss Federal Office of Meteorology and Climatology) and were used to calibrate the sediment proxy data. In addition, run-off, turbidity and water temperature of the Fedacla river, the main tributary of Lake Silvaplana, were measured with an automated hydrometric station at Sils-Maria between 2001 and 2005 (Federal Office for the Environment). Data were carefully checked for possible inhomogeneities resulting from construction work in the river channel or water deviations to an overflow channel during peak flood discharge. Discharge between May and mid-July 2003 was artificially controlled because of the construction work.

Particle flux-rates were recorded with sediment traps (Technicap) attached to a mooring string at the deepest part of the lake (Figure 1). Two sequential traps at water depths of 25 m and 72 m (near bottom) recorded particle fluxes continuously at 2- to 4-day intervals during summer and about 3-week intervals during winter between 2001 and 2005. Six integrating cylindrical traps at depths of 10, 25, 50, 60, 70 and 74 m recorded approximately 3-month intervals of sediment flux. Total flux rates include detrital silici-clastic and biogenic fractions. The silici-clastic fraction clearly dominates the total particle flux with about 80–98 wt% from June to September and 60–90 wt% in the months of May and October, respectively (M. Sturm, unpublished data, 2006; Margreth, 2006).

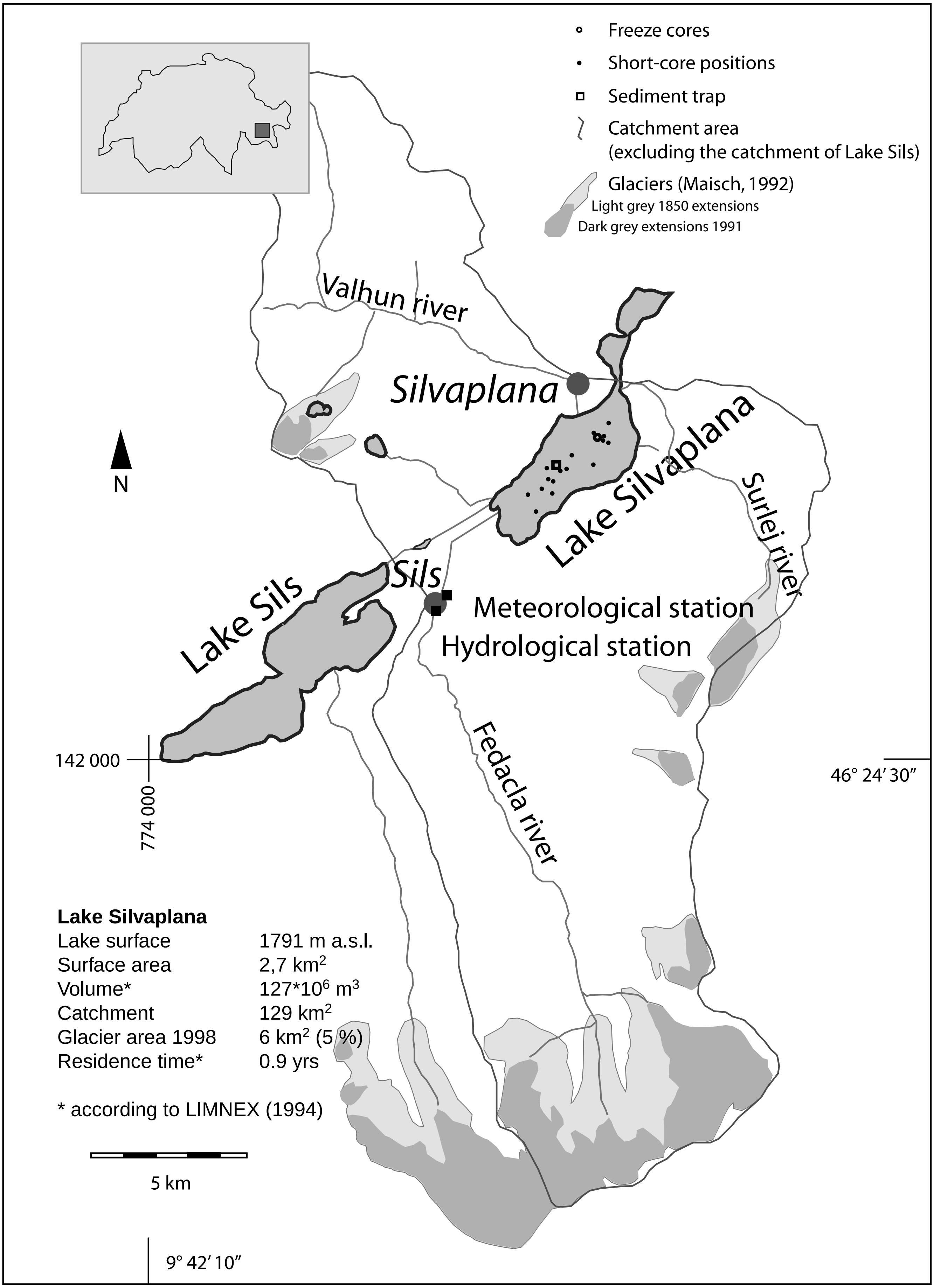


Figure 1 Overview map of the geographical setting around Lake Silvaplana with catchment area, glacier extents (1850 and 1991) and positions of coring sites, sediment traps, hydrological and meteorological stations

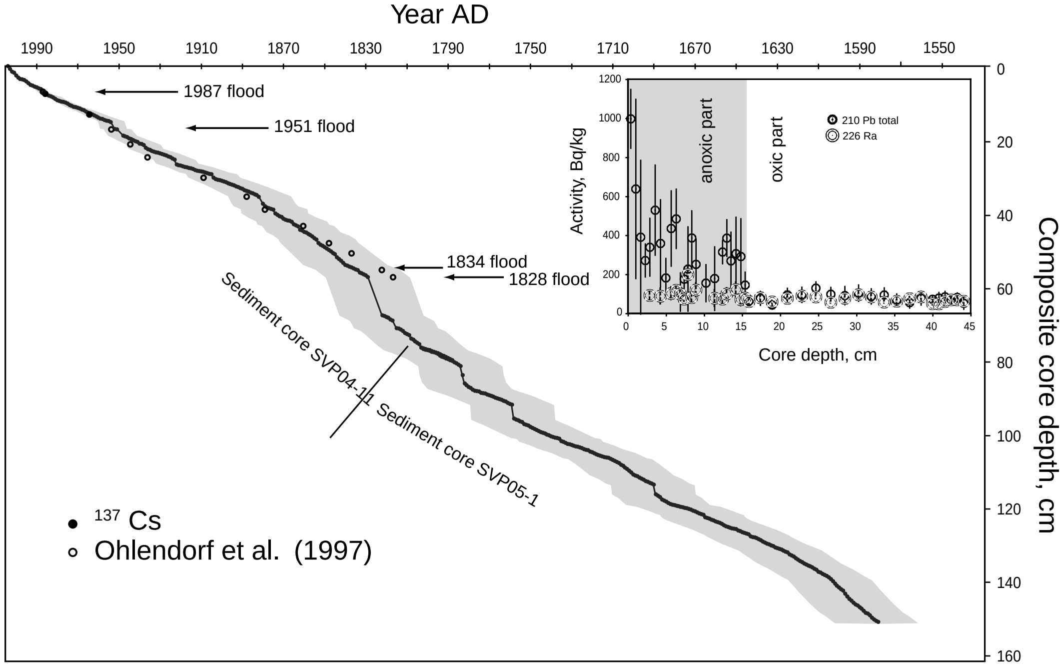


Figure 2 Composite age–depth model compared with ^{137}Cs dates and varve ages according to Ohlendorf *et al.* (1997). Four historical floods are used as additional time markers. Error estimates are fixed at 15% in the uppermost 40 cm and at 5% for the lower part of the composite. Inset: unsupported ^{210}Pb activities indicate a strong relation with productivity in the lake and are therefore not used for dating

Results

Sediments and chronology

The recovered sediments are predominantly composed of fine siliciclastic material with low contents of organic carbon (0.5–3 wt%) and are annually laminated (Leemann and Niessen, 1994a; Ohlendorf *et al.*, 1997). The blackish, anoxic, water-rich top-part of the core (0–18 cm, covering the last 50 years) consists of about 3-mm thick couples (varves) with a light, clastic bottom part and a black, organic-rich top. The varves in the underlying sediment still show a slightly blackish top that disappears in a depth of about 35 cm, ie, around AD 1900. The sediment deposited before AD 1900 is characterized by greenish clastic varves with a generally coarse, silty bottom and a very thin clayey top. The difference in colour and biogenic content is attributed to eutrophication in the twentieth century (Ohlendorf *et al.*, 1997).

The varve chronology is in close agreement with the ^{137}Cs-peak years in 1986 and 1963 (Figure 2). We estimate errors to 15% in the uppermost 40 cm and 5% for the lower part of the cores where varves are very nicely developed. Discrepancies compared with the chronology according to Ohlendorf *et al.* (1997) are small (Figure 2). Unsupported ^{210}Pb activities, however, are biased by the strong increase in primary productivity in the lake after 1950 (Figure 2) with enhanced scavenging of ^{210}Pb from the water column and consequently higher ^{210}Pb-fluxes to the sediment (Moore and Dymond, 1988; Shaw *et al.*, 1998).

Hydrological and atmospheric influence on sediment supply – observations from sediment trap data 2001–2005

Runoff data from the Fedacla river show a pattern that is typical for a glacio-nival regime with an increase in May resulting from snow melt, peak discharge in midsummer (about 5 m^3/s) and a decline in September (1–2 m^3/s). Summer temperature (May–September) affects glacier ablation and mainly influences the low-frequency trends (> 7 days) of the hydrograph ($r^2 = 0.38$, $p < 0.01$) whereas short-term fluctuations (1–2 days) in discharge (more than 1 m^3/s above the 11-day running mean) are caused by frontal rainfall and thunderstorms. Particle fluxes, recorded by high-resolution (2–4 days intervals) sediment traps in Lake Silvaplana, also follow this distinct seasonal pattern. About 80% of the annual sedimentation occurs from May to October.

To study the different sedimentation processes, relevant on different timescales, data were integrated stepwise (4, 8, 16 days, monthly and seasonally) and classified according to three different weather conditions: (i) dry periods with fair weather (thus related to glacial meltwater and base flow), (ii) days with thunderstorms and (iii) periods of frontal rain with several rainy days in a row and surface runoff in the catchment.

As expected, generally low correlations of particle flux and discharge (Q) were found for four-day intervals (see Table 1, non-linear correlations with particle flux $= a + Q^b$). In the case of frontal rains and thunderstorms, particle flux responses at the near-bottom trap in the lake are observed 1–2 days after the corresponding river discharge peak, while the time lag of

Table 1 R^2 values (non-linear regression: particle flux $= a + Q^b_{max}$) of particle flux to the bottom trap and Q_{max} which is stepwise integrated to 4-, 8-, 16-day and monthly intervals and classified in three different weather types

r^2 (particle flux, Q_{max})	Fair weather	Thunderstorms	Weather front
4-day integral	0.1	0.27	0.22
8-day integral (without 2003)	0.18	0.33	0.68
16-day integral (without 2003)	0.21	0.25	0.91
Monthly integral (all cases, without 2003)		0.59	

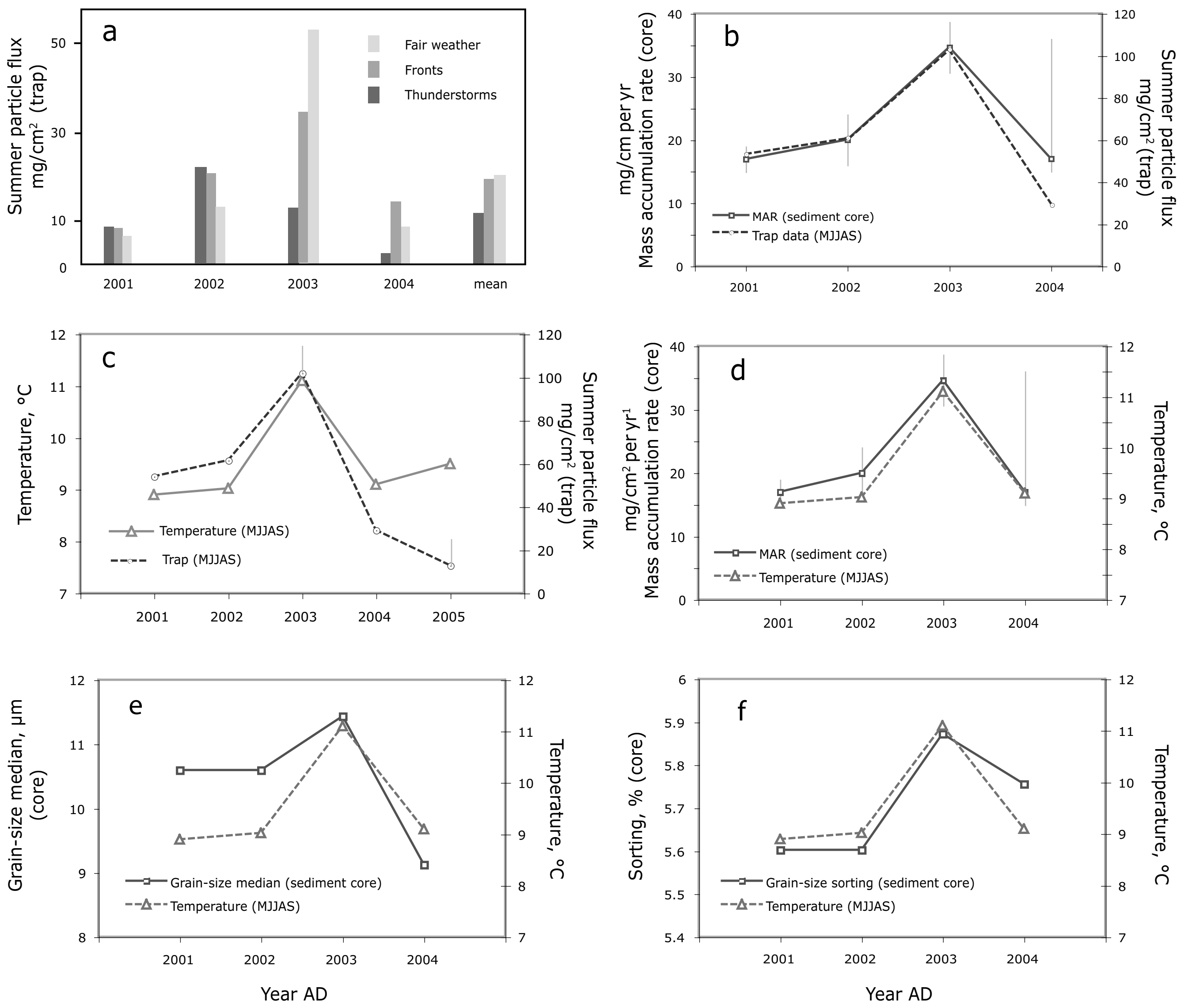


Figure 3 Comparison of sediment mass accumulation rates (MAR) and grain-sizes with particle fluxes, summer temperatures and weather conditions from 2001 to 2004/2005. Particle flux related to periods with fair weather, fronts or thunderstorms show high interannual variations in both magnitude and proportion (a). Particle fluxes in the traps and MARs in the sediments are in good agreement (b). Both grain-size parameters (median, sorting) and MAR correspond to temperature (d–f). Error bars represent one standard deviation

the system response during fair weather conditions is as long as four days or more. Daily maximum discharge (Q_{max}) instead of daily mean values yielded better correlations between river discharge and trapped particles. On average (2001–2004) 35% of the particle flux is related to fair weather conditions. Another 35% is transported during frontal rains. About 20% of the particle flux occurs during thunderstorms with short but heavy rainfalls (Figure 3a). Surprisingly, particle contribution resulting from snow-melt in spring is negligible. The four-year data set is strongly biased by the very hot and dry summer of 2003, when particle flux related to fair weather amounted to 53% of the total mass flux, while contributions during frontal rains and thunderstorms decreased to 34% and 13%, respectively (Figure 3a).

Correlations between particle fluxes and Q_{max} strongly increase with step-by-step aggregation to 8- and 16-day intervals (Table 1). The monthly average of daily Q_{max} explains 59% ($r^2 = 0.59$, $p < 0.001$, linear regression) of the monthly sediment flux.

The four years of detailed particle flux observation in the sediment traps are well reflected in the mass accumulation rates (MAR) of the varves in the sediment core (Figure 3b). The sediment yield in the traps that is three times higher than the MAR is attributed to the fact that sinking particles are generally oversampled by sediment traps (Bloesch and Burns, 1980; Kulbe *et al.*, 2006) and partial removal of surface sediments by weak bottom currents as suggested by small daily temperature fluctuations in the near-sediment bottom waters (P. Bluszcz, C. Ohlendorf, B. Zolitschka and M. Sturm, unpublished data, 2006). According to our detailed survey with short cores, sedimentation rate is 45% higher at the site of the traps in the centre of the lake than at the location near the outlet where the freeze core was taken (Figure 1).

Particle fluxes during the ablation season show high interannual variations with regard to both the timing of the peak flux (June in 2002, August in 2003) and the total mass flux ranging between 40 mg/cm^2 per yr in 2004 and 120 mg/cm^2 per yr in the extremely hot summer of 2003 (Figure 3c; Sturm *et al.*, 2004). Comparison of summer particle fluxes with summer (May to September) temperatures also reveals a good correspondence (Figure 3c and d). In contrast, a negative correspondence with summer precipitation is observed.

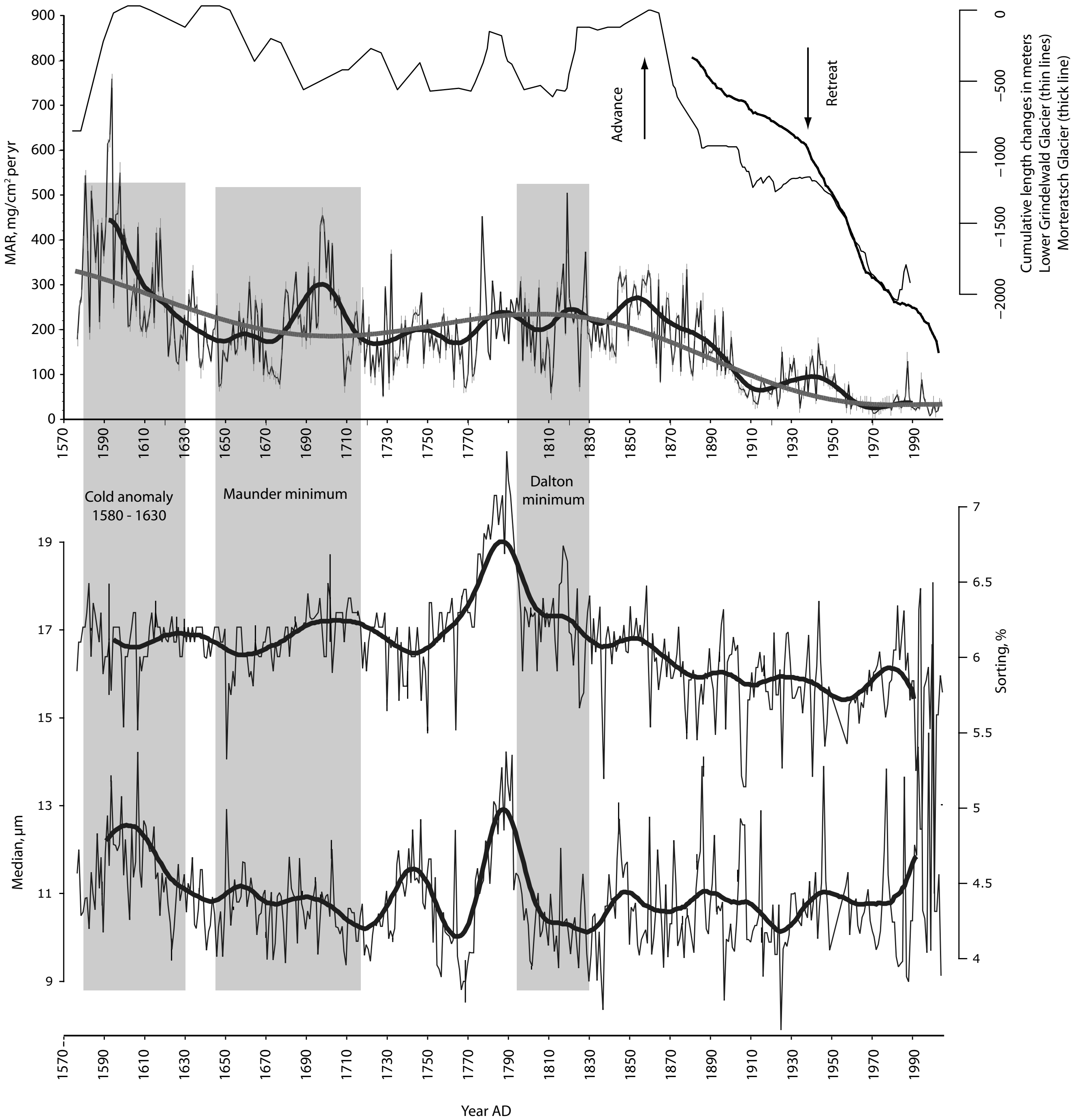


Figure 4 Mass accumulation rate (MAR), grain-size median and sorting from 1581 to 2004 are compared with lengths changes of the Lower Grindelwald Glacier (Holzhauser *et al.*, 2005) and nearby Morteratsch Glacier (data: VAW, Laboratory of Hydraulics, Hydrology and Glaciology, ETHZ). Generally higher MARs and lower grain-sizes but better sorting are observed during glacial high-stands that are especially pronounced in times of major ice advances. All series are smoothed with a 30-yr Gaussian filter. The MAR series is additionally low-pass filtered (200 yr). Error bars represent one standard deviation

Comparable correlations with summer temperature are found for grain-size median (Figure 3e) and sorting (Figure 3f).

In summary, the annual particle fluxes as determined with the sediment traps are in a good agreement with the respective MARs in the cores asserting that the sediment signal is consistent. At monthly, seasonal and annual timescales summer temperature seems to be the dominant climate variable driving the particle flux, whereas at shorter timescales (4–16 days) the importance of precipitation seems to increase and the system response to a meteorological signal becomes increasingly noisy.

Annual sedimentation AD *1580–2004*

Annual mass accumulation rates (MAR) show a broad spectrum (of almost two orders of magnitude) from very low values (10 mg/cm^2 per yr) to extraordinarily high values (759 mg/cm^2 per yr) over the last 400 years (Figure 4). In general, MAR is four times lower during the twentieth century compared with the preceding 300 years of the late 'Little Ice Age' (LIA). In addition, the interannual variability is also three times higher than during the twentieth century. Siliciclastics are better sorted during the LIA than during the twentieth century

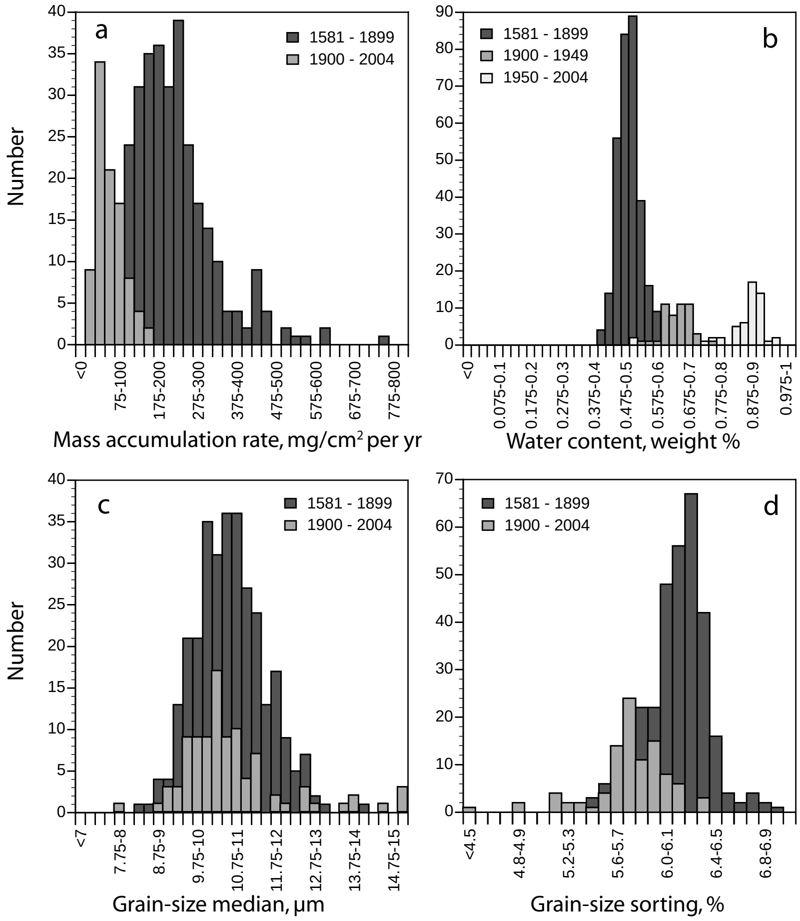


Figure 5 Histograms of mass accumulation rates MAR (a), water content (b), grain-size median (c) and sorting (d). Water contents display three distinct data clusters. The extraordinarily high water contents (ie, organic-rich sediments) from AD 1950 to 2004 reflect anthropogenic eutrophication of the very recent past. Between AD 1900 to 1949 relatively low MARs are observed compared with the pre-1900 data, resulting in comparably organic-rich sediments and high water contents, respectively. Histograms of MAR and sorting show a distinct shift around AD 1900 (at the end of the 'Little Ice Age') whereas grain-size median is constant over time

(Figure 4), whereas the grain-size median does not show such a significant change. Histograms display three distinct data clusters for the time window between 1581–1899 (LIA), 1900–1949 and 1950–2004 (Figure 5a–d) representing three different sedimentary state conditions. Anthropogenic eutrophication started around 1950 (Ohlendorf *et al*., 1997) leading to exceptionally high organic carbon and water contents in the very recent sediments (Figure 5b). During this period, siliciclastic input was very low (Figure 5a). The first half of the twentieth century (1900–1949) is also characterized by low siliciclastic input, relatively high concentrations of organic carbon and water, respectively. The third data cluster represents the time period from AD 1580 to 1900 (ie, LIA conditions) with four times higher siliciclastic sediment yields (Figure 5a).

Relation between climate and MAR in the twentieth century – interannual and decadal variability

In order to remove the strong long-term trend that was attributed to glacier activity (Leemann and Niessen, 1994a; Ohlendorf *et al*., 1997), the MAR series was detrended with a high-pass filter (200-yr; Figure 4). We found a significant positive correlation between summer air temperature (monthly means from May to September) and the annual sedimentation (MAR) from 1900 to 2004 with $r = 0.25$ ($p < 0.02$). No correlation was found with summer precipitation. To reduce inherent problems with the varve counting uncertainty we applied a nine-year running mean to the temperature and MAR series (Figure 6a), which strongly increased the r-value up to 0.69 ($p < 0.001$) from 1900 to 2004. From 1900 to 1950, the r value even increases to 0.84 ($p < 0.001$).

A 30-yr running correlation of the decadal smoothed series reveals a stable positive temperature–MAR correlation between 1900 and 1970 (Figure 6c) with a distinct shift around 1900 when the correlation turns to negative values prior to AD 1900. In addition, we find a very low positive correlation with temperature from 1970 onwards while significant r-values are observed with regard to precipitation. Precipitation is also significantly correlated to MAR between 1900 and 1910, and around 1930. The sensitivity of MAR regarding precipitation seems to vary considerably over time since not every period of increased precipitation actually causes enhanced MARs.

How good is the twentieth-century calibration model?

The running correlation statistics using 9-yr smoothed monthly mean temperatures May–September from Sils demonstrate a stable *positive* correspondence over most of the twentieth century but a *negative* correlation in the early instrumental period from 1864 to 1900 (Figure 6c). It appears that the twentieth century is very different from the previous 300 years (see above sections), which raises the question whether processes and models of statistical relationships between sediment proxies and instrumental data observed today can be extended beyond the calibration period, and whether the actualistic principle is valid.

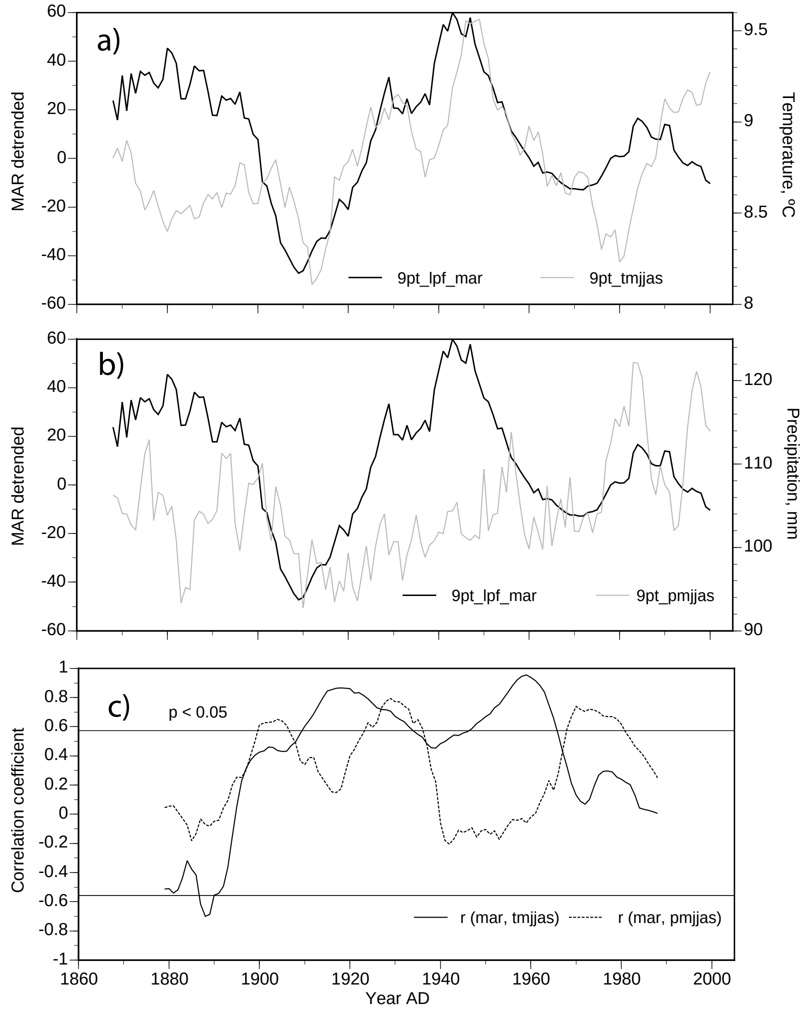
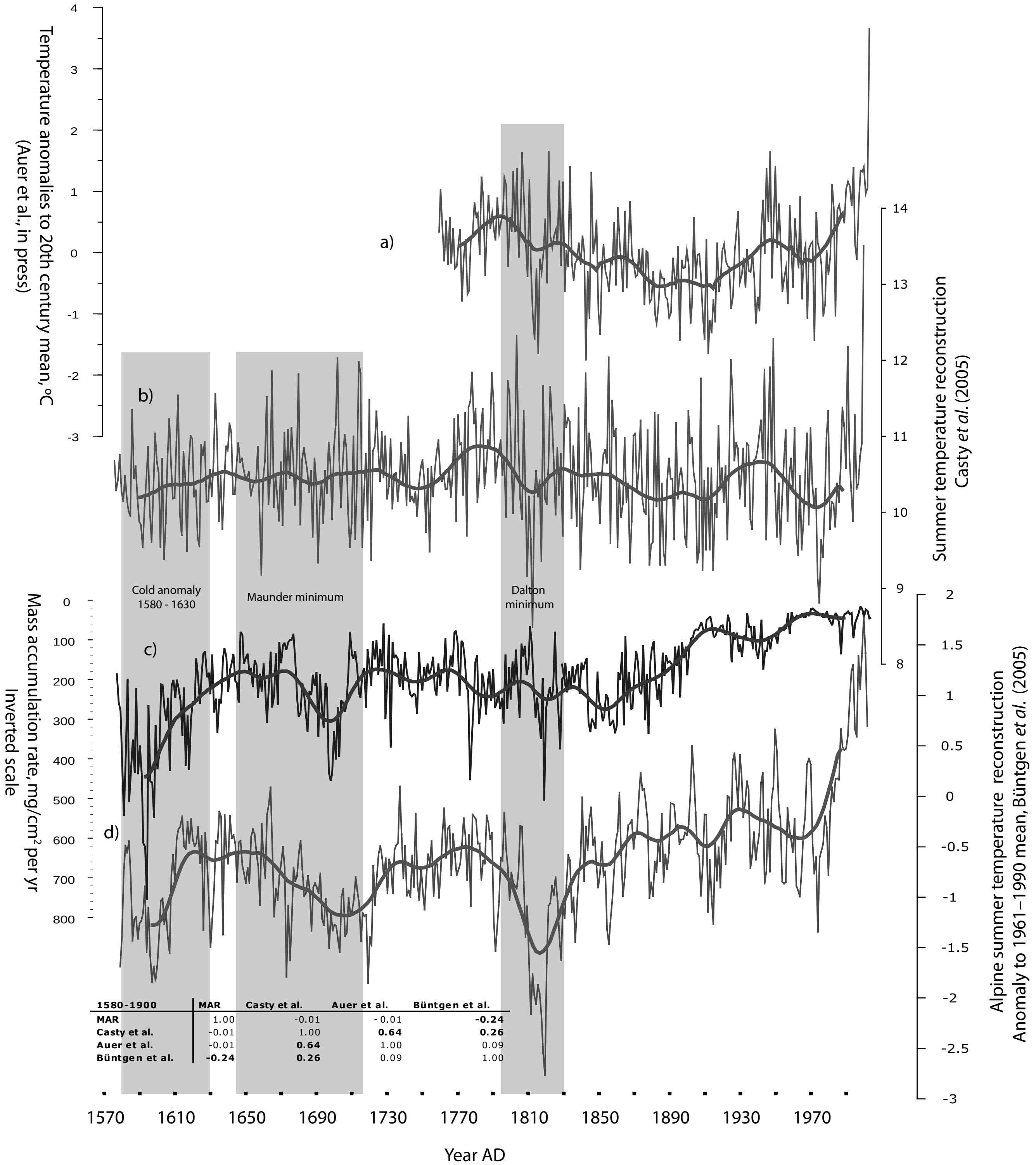


Figure 6 Detrended mass accumulation rate (MAR) compared with local instrumental summer temperature (tmjjas, a) and summer precipitation (pmjjas, b). All series are smoothed with a 9-yr (9 pt) running mean. 30-yr running correlations reveal a positive correspondence of MAR and summer temperature in most of the twentieth century becoming negative before AD 1900 (c). Correlations between MAR and precipitation are significant around AD 1900, 1930 and after 1970. The 95% significance level was determined using Monte Carlo simulations

In order to test this, we compared the MAR data with the fully independent (i) Alpine tree-ring series of summer (JJA) temperatures (Büntgen *et al.*, 2005) and (ii) nineteenth-century gridded (46°N, 9°E) early instrumental temperature data according to Auer *et al.* (2006). Interestingly, there is a significant *negative* correlation of the unfiltered, original MAR to the tree-ring-based summer temperature (JJA) reconstruction after Büntgen *et al.* (2005) between AD 1580 and 1900 (Figure 7c, d) with an $r = -0.24$ ($p < 0.001$). The correspondence is remarkably good during very cold periods, ie, during the cold anomaly between AD 1580 and 1630 (Pfister and Brazdil, 1999), during the Maunder Minimum (AD 1645–1710) and around 1800. After 30-years Gaussian smoothing (to account for the dating uncertainty and to enhance low-frequency trends, Figure 7), the tree-ring-MAR correlation increases to $r = -0.37$ ($p < 0.05$). Accordingly, both annual and low-frequency signals of MAR and tree-ring-based summer temperatures are negatively correlated during the LIA. Additionally, we found a strong negative correlation of filtered MARs and gridded (46°N, 9°E) early instrumental summer temperatures (May–September) according to Auer *et al.* (2006) from 1800 to 1880 ($r = -0.81$, $p < 0.001$, lead = 3 years, 9-yr smoothed). The correlation coefficient for the time period between 1760 and 1880 amounts to $r = -0.48$ ($p < 0.01$).

A summer temperature reconstruction experiment back to AD 1580 was performed by calibrating MAR data against (a) instrumental temperatures of Sils from 1900 to 2004 and (b) gridded (46°N, 9°E) early instrumental temperatures according to Auer *et al.* (2006) from 1760 to 1880 (Figure 8). As expected, both reconstructions show a completely different picture. The twentieth-century reconstruction reveals very poor correspondence with the multiproxy (mainly documentary and early instrumental) summer temperature reconstruction according to Casty *et al.* (2005), which is rather anti-correlated to the MAR reconstruction (Figure 8a). Amplitudes of the twentieth-century reconstruction are very high. On the other hand the eighteenth/nineteenth-century reconstruction corresponds better to the summer temperature reconstruction according to Casty *et al.* (2005), displays lower amplitudes than the twentieth-century reconstruction (Figure 8b), but shows still more variations in the lower frequency domain compared with the Casty-series. However, the relatively low temperatures inferred from the MAR between 1780 and 1800 are missing in the Casty and Auer series, but are evident in the tree-ring record (Figure 7).

In the following we use the summer temperature reconstruction calibrated in the eighteenth/nineteenth century for the LIA period. In accordance with the other independent reconstructions, exceptionally low decadal-scale temperatures



1580-1900	MAR	Casty et al.	Auer et al.	Büntgen et al.
MAR	1.00	-0.01	-0.01	**-0.24**
Casty et al.	-0.01	1.00	**0.64**	**0.26**
Auer et al.	-0.01	**0.64**	1.00	0.09
Büntgen et al.	**-0.24**	**0.26**	0.09	1.00

Figure 7 Mass accumulation rate with inverted scale (c) compared with long instrumental summer temperatures (May–September) after Auer *et al.* (2006) for the grid point Engadine (a), multiproxy summer temperature reconstruction (July–August) after Casty *et al.* (2005) for the grid point Engadine (b) and tree-ring-based Alpine summer temperature reconstruction according to Büntgen *et al.* (2005) (d). All series are smoothed with a 30-yr Gaussian filter. Inset table shows *r* values for all series from AD 1580 to 1900 (bold: significant at 95% level)

were found from AD 1580–1610 (0.75°C below twentieth-century mean) and during the late Maunder Minimum from AD 1680–1710 (0.5°C below the twentieth-century mean). Smaller negative temperature deviations (< 0.5°C) from the twentieth-century mean are recorded around AD 1780 and 1820. Relatively warm conditions are suggested throughout most of the seventeenth century and the first half of the eighteenth century (except for the late Maunder Minimum). In general, summer temperatures did not experience major negative departure from the twentieth-century mean during the late LIA. This finding is consistent with the Casty *et al.* (2005) reconstruction and suggests that the LIA was mainly a phenomenon of the cold season.

Discussion

The MAR time series shows that a major shift in the sediment transport and mass accumulation rate occurred around AD 1900 as indicated by (a) the sediment characteristics (water

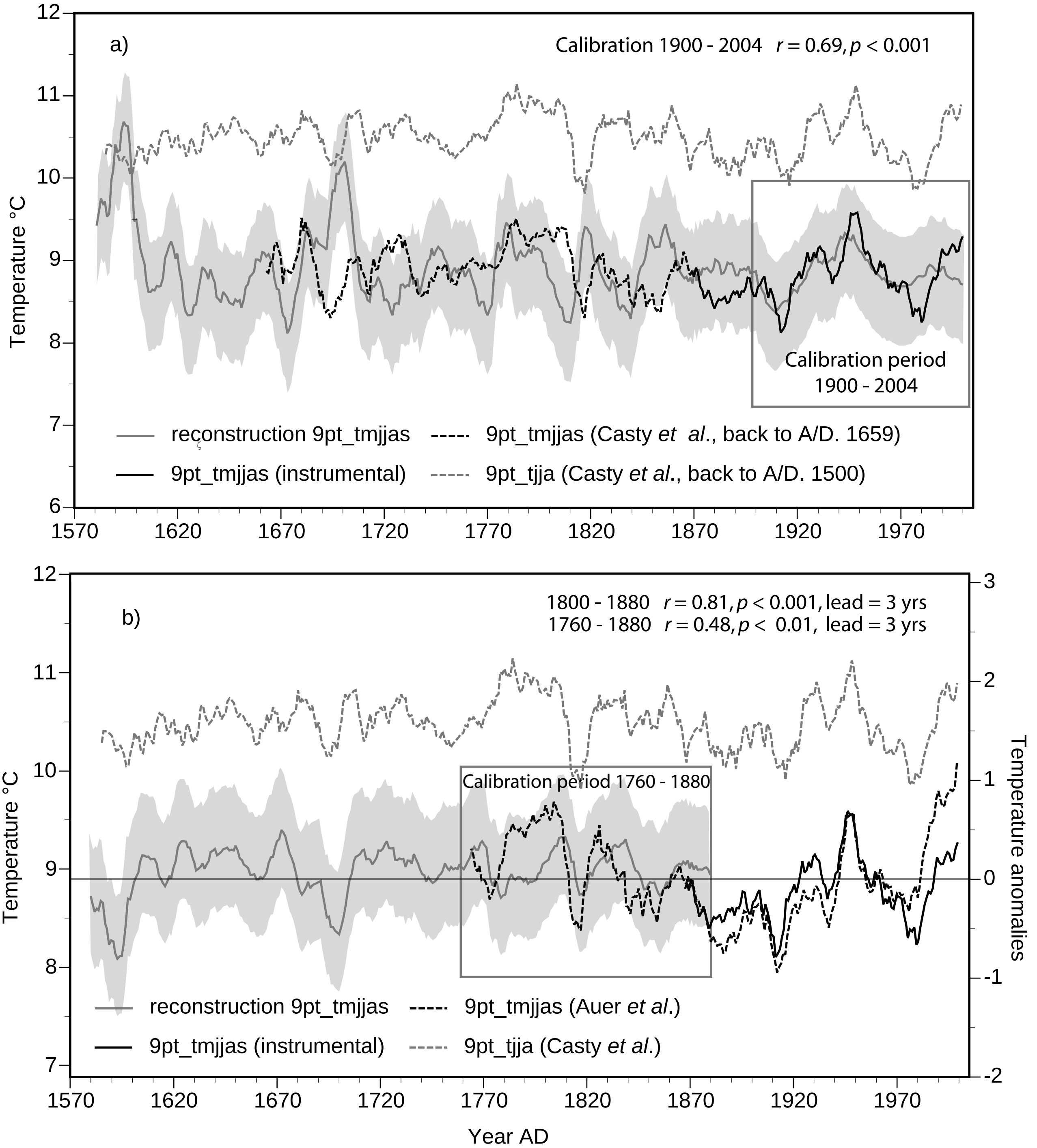


Figure 8 Reconstruction experiment using (a) AD 1900–2004 Sils instrumental data and (b) AD 1760–1880 gridded (46°N, 9°E) early instrumental record according to Auer *et al.* (2006) for calibration. The MAR reconstruction, calibrated in the twentieth century (a), generally displays a very high variability and is anti-correlated to the summer temperature reconstruction according to Casty *et al.* (2005). The MAR reconstruction (right axis) which is calibrated in the eighteenth/nineteenth centuries, ie, 'Little Ice Age' conditions (b) shows a much better correspondence with the summer temperatures according to Casty *et al.* (2005) (left axis). We found exceptionally low temperatures from AD 1580 to 1610 (0.75°C below twentieth-century mean) and during the late Maunder Minimum from AD 1680 to 1710 (0.5°C below twentieth-century mean). In general, summer temperatures did not experience major negative departures from the twentieth-century mean during the late 'Little Ice Age'. The horizontal line indicates the twentieth-century mean. The right axis reflects the temperature deviations in degrees centigrade from the twentieth-century mean. The shaded error range represents ±2 standard deviations

content and colour), (b) the decreasing sedimentation rate by a factor of four with an associated decrease of the interannual variability and (c) the reversal of correlations between MAR and summer temperature from negative values prior to AD 1900 to positive values afterwards.

Besides a pronounced interannual variability, the varve time series also shows a strong variability on the decadal and centennial scale, suggesting that slow and long-term system changes in the lake and the catchment, such as human impact or glacial advances and retreats, may play a role.

Glacial impact and LIA conditions

Glacier high-stands during the late LIA are assumed to be the most likely cause for the enhanced sediment supply and, hence, for the decadal- to centennial-scale fluctuation in the MAR record. Glacial-controlled sediment fluxes have been reported

in previous studies for Lake Sils and Silvaplana (Leemann and Niessen, 1994a; Ohlendorf *et al.*, 1997; Blass *et al.*, 2005) and elsewhere in the world (eg, Desloges, 1994; Leonard, 1997; Matthews *et al.*, 2000; Jansson *et al.*, 2005). Increased sediment supply is especially pronounced in periods of major glacier advances (Figure 4) during the cold anomaly 1580–1630 reported by eg, Pfister and Brazdil (1999), and are often associated with sunspot minima such as the Maunder Minimum around 1645–1715 and the Dalton Minimum 1795–1830 (Pfister, 1999; Brazdil *et al.*, 2005). It does not necessarily mean that low temperatures always coincide with sunspot minima. In accordance with other reconstructions (Büntgen *et al.*, 2005; Casty *et al.*, 2005), low summer temperatures for example occurred only in the second half of the Maunder Minimum (AD 1680–1710; Figures 7 and 8b). The departures between AD 1580 and 1610, and around 1780 do not overlap with a sunspot minimum and might be related to fluctuations that are internal to the climatic system (Hunt, 2006), or be combined with external forcing such as volcanic eruptions (eg, the Laki eruption in AD 1783 and the Tambora eruption in AD 1815; see also Briffa *et al.*, 1998; Robertson *et al.*, 2001).

Our results suggest that during cold periods, the advancing glaciers in the catchment enhanced abrasion and reworked old sediment deposits (see Jansson *et al.*, 2005 and references therein). In contrast to some of the studies cited, we found no noteworthy increase in sediment input during rapid glacier recession phases. Generally, an increase of the glaciated area in the Fedacla catchment during LIA conditions would result in a overall higher discharge (Fountain and Tangborn, 1985) and further increase sediment transport to the lake. It is likely that sediment contributions from smaller glaciers, which are insignificant today, were not negligible during the LIA. In addition, increased glacier cover in the catchment area would result in a higher precipitation sensitivity because subglacial water pressure plays an important role in removing and evacuating basal sediments (Jansson *et al.*, 2005).

According to Steiner *et al.* (D. Steiner, A. Pauling, A. Nesje, J. Luterbacher, H. Wanner and H.J. Zumbühl, unpublished data, 2006), the major advances of the Lower Grindelwald Glacier (Figure 4) from AD 1590 to 1610, and 1810 to 1820 are mainly related to summer temperature. On the other hand, advances around AD 1700 and 1770 are rather linked to winter and spring precipitation and/or spring and autumn temperatures, respectively (D. Steiner, A. Pauling, A. Nesje, J. Luterbacher, H. Wanner and H.J. Zumbühl, unpublished data, 2006). It has been shown that the Morteratsch Glacier (Figure 4), just a few kilometres away from the study area, is generally more sensitive to temperature than to precipitation (Klok and Oerlemans, 2002). Accordingly, high sedimentation rates during the late LIA were likely coupled with cold conditions in the ice-free season of the lake. Since the response time of the glaciers in the catchment to a climate signal is estimated to be approximately 4 years (Ohlendorf *et al.*, 1997), a relatively fast reaction to temperature changes can be expected. This relation between sediment transport and summer temperatures during the late LIA (AD 1580–1900) is strongly supported by the good correspondence with the tree-ring-based summer temperature reconstruction according to Büntgen *et al.* (2005) between 1580 and 1900 (Figure 7). The accordance with the summer temperature reconstruction according to Casty *et al.* (2005), which is based on instrumental and documentary data, is less pronounced. Interestingly, it appears that the two natural proxies, which match very well, record the climatic signal in a similar and possibly more integrative way with additional annual information included, especially in the lower frequency domain (Frank and Esper, 2005).

Temperature-dominated sediment fluxes during the twentieth century

Apart from some small recorded advances in the 1890s and 1920s, glaciers in the Alps have been in a state of continuous retreat since the 1860s (see nearby Morteratsch Glacier, Figure 4). This has caused a drastic decrease in sediment availability and resulted in a substantial decrease of MAR in Lake Silvaplana. Correlations of sediment accumulation and temperature indicate a sedimentation regime that is controlled by ablation and meltwater transport in the twentieth century. Such a temperature influence on varve thickness has been reported by many authors (eg, Leonard, 1985; Desloges, 1994; Leemann and Niessen, 1994b; Hardy *et al.*, 1996; Ohlendorf *et al.*, 1997; Hughen *et al.*, 2000; Moore *et al.*, 2001), whereas evidence for the influence of precipitation on proglacial systems is relatively sparse (Lotter and Birks, 1997; Blass *et al.*, 2003). Sediment release due to glacial advances in the catchment could not be detected in the twentieth-century data.

With continuously decreasing glacier size and the possibility of a complete disappearance of the glaciers in the catchment in the near future, siliciclastic sedimentation will further decrease and, thus, lose its sensitivity to temperature. This may already be the case today, as we observe lower correlations of MAR and temperature since the 1970s (Figure 6c).

Sediment trap data indicate, on a daily scale, that precipitation exerts a stronger influence on sediment transport than does temperature (Figure 3d). In contrast, we found a good agreement between particle flux and temperature on the seasonal and annual scales (Figure 3a). In addition, sediment accumulation is relatively noisy on an interannual scale and influenced by catchment and lake internal processes, many of which are non-linear in nature. Frequent stochastic sediment pulses and sediment exhaustion effects, as for example observed after 2003, may mask or distort the high-frequency climatic signal (see also Ostrem, 1975; Collins, 1990; Forbes and Lamoureux, 2005). A clear temperature signal is only evident on 5-yr to decadal and centennial scales (Figure 6a).

Conclusions

In the proglacial sediment record of Lake Silvaplana we found a distinct shift in the sediment transport system around AD 1900, ie, at the end of the 'Little Ice Age'. This shift is characterized by (a) increased water and organic matter content after 1900, (b) a decreasing sedimentation rate, by a factor of four, with an associated decrease of the interannual variability, (c) a decrease in grain-size sorting and (d) a reversal of the correlations between annual mass accumulation rate (MAR) and summer temperature from negative to positive signs.

Local instrumental summer temperatures and MAR are significantly positively correlated during the twentieth century, thus indicating an ablation- and glacial meltwater-controlled mode of the system. On the seasonal to annual basis, high-resolution sediment trap data (2001–2005) confirm the instantaneous response of the particle flux to summer temperatures (May to September). On shorter timescales (days to months), the trap data indicate that particle transport resulting from precipitation events is important as well as stochastic sediment pulses and non-linear responses of the coupled catchment–lake system to climatic signals.

In contrast to the twentieth century, extraordinarily well-sorted sediments and high MARs, which are observed during the 'cold anomaly' AD 1580–1630, the late Maunder Minimum around AD 1680–1715 and around AD 1780 and 1820, suggest a glacier-dominated sedimentation regime during the late LIA. Advancing glaciers in the catchment (response time approximately 4 years) probably increased the production of fine rock particles by abrasion and reworking of previously deposited material during cold anomalies.

During the late LIA, MARs are negatively correlated with tree-ring and multiproxy based temperature reconstructions (Büntgen *et al*., 2005; Casty *et al*., 2005). Therefore, we used the early instrumental series according to Auer *et al*. (2006) to calibrate our MAR proxy against eighteenth/nineteenth-century temperature data (ie, LIA conditions) and to establish a pre-instrumental, decadal-scale summer temperature reconstruction for the southeastern Swiss Alps. In general, our reconstructed summer temperatures did not experience major negative departures from the twentieth-century mean during the late LIA. Temperatures display relatively warm conditions throughout most of the seventeenth century and the first half of the eighteenth century. Exceptionally low decadal-scale temperature prevailed from AD 1580–1610 (0.75°C below twentieth-century mean) and during the late Maunder Minimum from AD 1680 to 1710 (0.5°C below twentieth-century mean), which is in accordance with the other independent reconstructions. Smaller negative temperature deviations (<0.5°C) from the twentieth-century mean are recorded around AD 1780 and 1820.

Finally, we conclude that the actualistic principle may not be applied for all proglacial lakes as major changes in the coupled lake–catchment system may occur over time that may result in considerably different sediment transport mechanisms.

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