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Decadal-scale autumn temperature reconstruction back to AD 1580 inferred from the varved sediments of Lake Silvaplana (southeastern Swiss Alps)

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Abstract

A quantitative high-resolution autumn (September–November) temperature reconstruction for the southeastern Swiss Alps back to AD 1580 is presented here. We used the annually resolved biogenic silica (diatoms) flux derived from the accurately dated and annually sampled sediments of Lake Silvaplana (46°27′N, 9°48′E, 1800 m a.s.l.). The biogenic silica flux smoothed by means of a 9-yr running mean was calibrated ($r=0.70$, $p<0.01$) against local instrumental temperature data (AD 1864–1949). The resulting reconstruction (±2 standard errors = ±0.7 °C) indicates that autumns during the late Little Ice Age were generally cooler than they were during the 20th century. During the cold anomaly around AD 1600 and during the Maunder Minimum, however, the reconstructed autumn temperatures did not experience strong negative departures from the 20th-century mean. The warmest autumns prior to 1900 occurred around AD 1770 and 1820 (0.75 °C above the 20th-century mean). Our data agree closely with two other autumn temperature reconstructions for the Alps and for Europe that are based on documentary evidence and are completely unrelated to our data, revealing a very consistent picture over the centuries.

Keywords: Sedimentology; Geochemistry; Limnology; Climate change; Biogenic silica; Little Ice Age; Diatoms

Introduction

High-resolution, quantitative long-term climate reconstructions are essential to put the recent, probably anomalous climate and environmental changes into a broader perspective. In this context, one particular advantage of using lake sediments as climate archives is the length of time they can cover (Sturm and Lotter, 1995; Leonard, 1997; Zolitschka et al., 2000; Wick et al., 2003; Heiri and Lotter, 2005). Up to now, very few sedimentary studies have been employed to obtain quantitative high-resolution climate reconstructions (Hughen et al., 2000; Moore et al., 2001; Weckström et al., 2006), since dating and sampling at (near-) annual resolution can be difficult or even impossible. Furthermore, the response of variables measured in lacustrine sediments to climatic forcing is often complex (Ohlendorf et al., 1997; Anderson, 2000), with the climate signal additionally often being masked to some extent by an anthropogenic signal. While, for instance, diatom assemblages have been widely used for the quantitative reconstruction of environmental variables such as pH (Koinig et al., 1998; Lotter, 2001) and phosphorus (Hall et al., 1997; Wessels et al., 1999), diatom-inferred quantitative high-resolution climate reconstructions are rare (Koinig et al., 1998; Bigler and Hall, 2003; Weckström et al., 2006).

Lake Silvaplana is located in the eastern Swiss Alps near the tree line (1800 m a.s.l.) and thus responds especially sensitively to climatic forcing (Lotter et al., 1999). We used the last 400 yr of well-dated, annually laminated sediments from this lake (Leemann and Niessen, 1994; Ohlendorf et al., 1997; Blass et al., 2007) and analysed the annual flux of biogenic silica (BSi) to the sediments as a proxy for diatom productivity. We show that this proxy contains significant information about air temperatures in autumn (September to November) for the calibration period AD 1864–1949. Here we report on variability

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of autumn air temperature in the eastern Swiss Alps on decadal to (sub)century scales back to AD 1580 as inferred from the biogenic silica data.

Study site

Lake Silvaplana (Lej da Silvaplauna) is located in the Engadine, southeastern Swiss Alps, at an altitude of about 1800 m a.s.l. The lake has a maximum depth of 77 m and a volume of 127×10^6 m^3 (LIMNEX, 1994), and is ice-covered between January and May. It is a dimictic lake with a rather short period of spring mixing after the ice break-up that is followed by a period of summer stratification lasting from June to November. Strong local valley winds develop on sunny days between around 11:00 h and late afternoon if the synoptic-scale upper airflow is weak (Gensler, 1978). This results in a generally well-mixed epilimnion during the summer stagnation period. The second overturn of the year occurs usually in December. The mean water residence time is only 8 months (LIMNEX, 1994) because of the high rate of inflow of glacial meltwater during summer. Lake Silvaplana is oligotrophic with <10 μg l^{-1} orthophosphate in the water column (Bosli-Pavoni, 1971; Bigler et al., 2006). Oxygen concentrations are consistently >5 mg l^{-1} in near-bottom waters (LIMNEX, 1994) and the pH is around 7.8 (Bigler et al., 2006).

The catchment area of the lake extends over 129 km^2. In 1998, about 6 km^2 (5%) of the catchment area was glaciated (Blass et al., 2007). The most important inflow is the Fedacla river, which has a mean discharge rate of 1.5 m^3 s^{-1}, is fed mainly by glacial meltwater and carries a high load of suspended sediment. A second inflow is the Inn River, which connects Lake Silvaplana to Lake Sils. This river has a mean discharge rate of 2 m^3 s^{-1} but carries almost no suspended sediment. The discharge rates of the Valhun and Surlej rivers are 0.7 and 0.3 m^3 s^{-1}, respectively.

The climate of the Upper Engadine is rather continental compared with that of the Swiss Plateau. The amplitudes of the diel and annual air temperature cycles are typically greater, and the climate is relatively dry, with a mean annual precipitation rate (1901–1960) of 1029 mm yr^{-1} (SMA, 2002). Thunderstorms are relatively infrequent (20 days per year, SMA, 2002). The area lies in a meteorological boundary zone and receives precipitation from all wind directions, but most frequently from the south (Brunetti et al., 2006). Monthly mean temperatures range from −7.8 °C in January to 10.8 °C in July. The annual precipitation maximum occurs in August (121 mm mo^{-1}) and the minimum in February (42 mm mo^{-1}).

Methods and data

Two sediment cores of 85 and 150 cm length were recovered during the winter of 2004/05 using a freeze-coring technique (Kulbe and Niederreiter, 2003), which perfectly preserved the sediments. The cores were photographed and sediments were sub-sampled for thin-sections using a freeze-drying technique. Every single varve (identified by digital images and thin sections) was individually sampled in a freeze laboratory (−10 °C). Sub-samples were freeze-dried and analysed for water content. Total carbon concentrations were measured with a gas chromatograph (HEKAtech, Euro AE Elemental Analyser), and a CO_2 coulometer (Coulometric Inc.) was used to quantify the carbonate content (TIC) of the sediment. To determine the BSi content, a leaching method modified after Mortlock and Froelich (1989) was used (Ohlendorf and Sturm, in press). BSi concentrations were corrected for inorganic silica derived from clay minerals (probably chlorite, according to X-ray analysis) using the concentration of Al in the leachate (Demaster, 1981). The Al:Si ratio was analytically determined to be 2:1 (see also Ohlendorf and Sturm, in press). Diatoms were prepared according to standard methods (Battarbee, 1986), dried on coverslips and mounted permanently on microscope slides using Naphrax. By adding a known amount of electronically counted microspheres (Battarbee and Kneen, 1982), diatom valve concentrations (valves per sediment volume) were calculated.

Core chronologies were obtained by measuring the samples from one core for the gamma-decay of ^{137}Cs (at 662 keV) and ^{210}Pb (at 46.5 keV) for 24 h, using Canberra® low-background, well-type GeLi detectors at Eawag, Dübendorf. Varves were counted using high-resolution digital core pictures (2300×1700 pixels) and recounted using thin sections. Turbidite deposits from four major historic floods in AD 1987, 1951, 1834 and 1828 (Schwarz-Zanetti and Schwarz-Zanetti, 1988; Röthlisberger, 1991, 1993) were used as additional time markers (Sturm and Matter, 1978).

Varve thicknesses were measured on the digital core pictures 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 transform thickness measurements into flux rates, taking into account both water content and organic carbon. Layers interpreted as turbidite deposits with a thickness exceeding 1 mm were excluded from the record. Because annual layers were not recognisable in the freeze-cores from 12 to 18 cm (AD 1954–1977), this short sequence had to be completed with data from a gravity core taken at the same position. Thus, sediment samples taken from the freeze core are not strictly annual in this 6-cm long section, but are sampled in a regular and highly resolved manner (3 mm, which corresponds approximately to 1 yr). These data were not used for the reconstruction.

High-pass Gaussian filtering was performed using the AnalySeries 1.1 Software (Paillard, 1996) and statistical calculations were performed using the open source R-software (r-project.org). Homogenized meteorological data from a nearby meteorological station at Sils-Maria are available since AD 1864 (Swiss Federal Office of Meteorology and Climatology) and were used to calibrate the sediment proxy data.

Results

Sediment characteristics and chronology

The recovered sediments are characteristic for oligotrophic lakes with high particle loads from inflowing rivers. They are predominantly composed of fine (average median = 11.1 μm; σ = 1.1 μm) silici-clastic material with low organic carbon content (0.5–3 wt.%). They are continuously annually laminated (Leemann and Niessen, 1994; Ohlendorf et al., 1997). The blackish anoxic water-rich top part of the core (0–18 cm, covering the last 50 yr) consists of about 3-mm-thick couplets (varves) with a light clastic bottom part and a black organic-rich top. The varves in the lower part of the core show a slightly blackish top that disappears at a depth of about 35 cm, corresponding to the period 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 organic matter content in the different sections of the core has been attributed to changes in the silici-clastic sedimentation, productivity changes and anthropogenic eutrophication in the second half of the 20th century (Ohlendorf et al., 1997).

The varve chronology is in close agreement with the ^{137}Cs peak years in AD 1986 and 1963 (varve chronology 1987 and 1961); the turbidites interpreted as flood deposits in AD 1987, 1951, 1834, 1828 (varve chronology 1987, 1951, 1831, 1826); and the independent varve chronology after Ohlendorf et al. (1997) (for details see Blass et al., 2007). Our conservative estimation of error amounts to 10% in the uppermost 40 cm and to 5% for the lower part of the composite, where varves are generally very nicely developed. Varve counting was very difficult and inconclusive in the sediment sequence from 90 to 95 cm (AD 1779–1794).

The biogenic silica record back to AD 1580

Concentrations of biogenic silica (BSi) are very low from AD 1580 to 1957 (about 0.5 wt.%) and reveal distinct decadal to centennial-scale variations (Fig. 1b). After AD 1960, BSi concentrations increase abruptly up to 12% and suddenly show very high inter-annual variability. Water contents show the same sharp increase after 1957 (Fig. 1a). In order to convert BSi concentrations into annual BSi mass fluxes, the total annual mass accumulation rates (MAR) derived from varve thickness were used (Fig. 1c). BSi flux displays a different picture than BSi concentrations (Fig. 1d) as the MARs vary considerably over time from 10 to 759 mg cm^{-2} yr^{-1} (Blass et al., 2007). BSi fluxes are on average about three times higher after 1960 than before this date. There is a conspicuous long-term trend (Fig. 1d) with a minimum around AD 1840 and a maximum around AD 1600. The inter-annual variability of the BSi fluxes is relatively high.

Recent eutrophication and implications

The high water content, the exceptionally high BSi fluxes, and the blackish anoxic state of the sediment after around AD 1960 have been attributed to recent anthropogenic eutrophication (Ohlendorf et al., 1997). BSi concentrations in the sediment correspond well with the diatom valve concentrations recorded (Figs. 1a and b). Moreover, SEM images revealed no dissolution traces on diatom frustules. Thus, BSi in the sediment reflects here a well preserved indication of diatom productivity, which is expected in this type of lake (Battarbee et al., 2001).

As shown in Figures 1 and 2, BSi flux, and thus productivity, increased drastically in AD 1957. While tourism developed gradually after the Second World War as illustrated by the number of overnight stays in Sils (Gemeinde Sils, 1994), BSi fluxes show a sudden increase to very high levels in AD 1957 (Fig. 2) following installation of the town's sewer system (Reich, 2002). Prior to 1957, every household and hotel had its own sewage pit, which released its nutrients slowly and diffusely into the environment. In contrast, the installation of a new sewage system (and later the effluent from the newly built sewage plant) led to direct and more concentrated nutrient injections into the lake.

We compared historical information with the BSi flux data and found no indication of a significant anthropogenic influence before AD 1950. Neither the opening of new hotels in Sils (in AD 1865, 1875, in the 1910's and 1920's) nor the economic crisis (in the 1870's, 1880's, 1920's and 1930's) and times of war seem to have affected BSi productivity in the lake (see Fig. 2, Bergier, 1983; Zuan, 1984). However, there is an increase of the hypertrophic taxon *Stephanodiscus parvus* from AD 1865 to 1880 (Bigler et al., in press), which very likely indicates a higher phosphate level for that specific time window.

Biogenic silica as climate proxy—a comparison with local instrumental data 1864–1949

In order to test the potential of BSi as a climate proxy, annual pre-eutrophication BSi fluxes were compared with instrumental meteorological data of Sils from AD 1864–1949. On the annual scale, there is a significant correlation between BSi flux and the mean annual temperature (r = 0.37, p < 0.001; Fig. 3a). On the seasonal scale, significant correlations were found for autumn (r = 0.36, p < 0.001; Fig. 3b) and winter temperatures (r = 0.27, p < 0.05). These correlations were calculated by shifting the original chronology (i.e., fully independently developed, no tuning) of the BSi series by plus 1 yr, which is fully within the dating uncertainties of varve counting. In addition, BSi fluxes and monthly mean temperatures reveal significant correlations in September, October, November and January (Table 1). No correlations between BSi flux and precipitation were found.

In order to eliminate statistical artefacts due to varve counting errors and dating uncertainties, we applied a 9-yr running mean to the series and focus, and therefore on decadal trends only. The highest correlations of the decadal-smoothed series were found between BSi fluxes and autumn (SON) temperatures (r = 0.70, p < 0.01; see Fig. 3d), as well as between the annual mean (r = 0.68, p < 0.01; Fig. 3c) and summer temperatures (r = 0.67, p < 0.01). Table 1 shows additionally the significant correlations between the 9-yr averaged fluxes and monthly mean temperatures of April (r = 0.52, p < 0.05), September (r = 0.53, p < 0.05), November (r = 0.68, p < 0.01) and December (r = −0.52, p < 0.05).

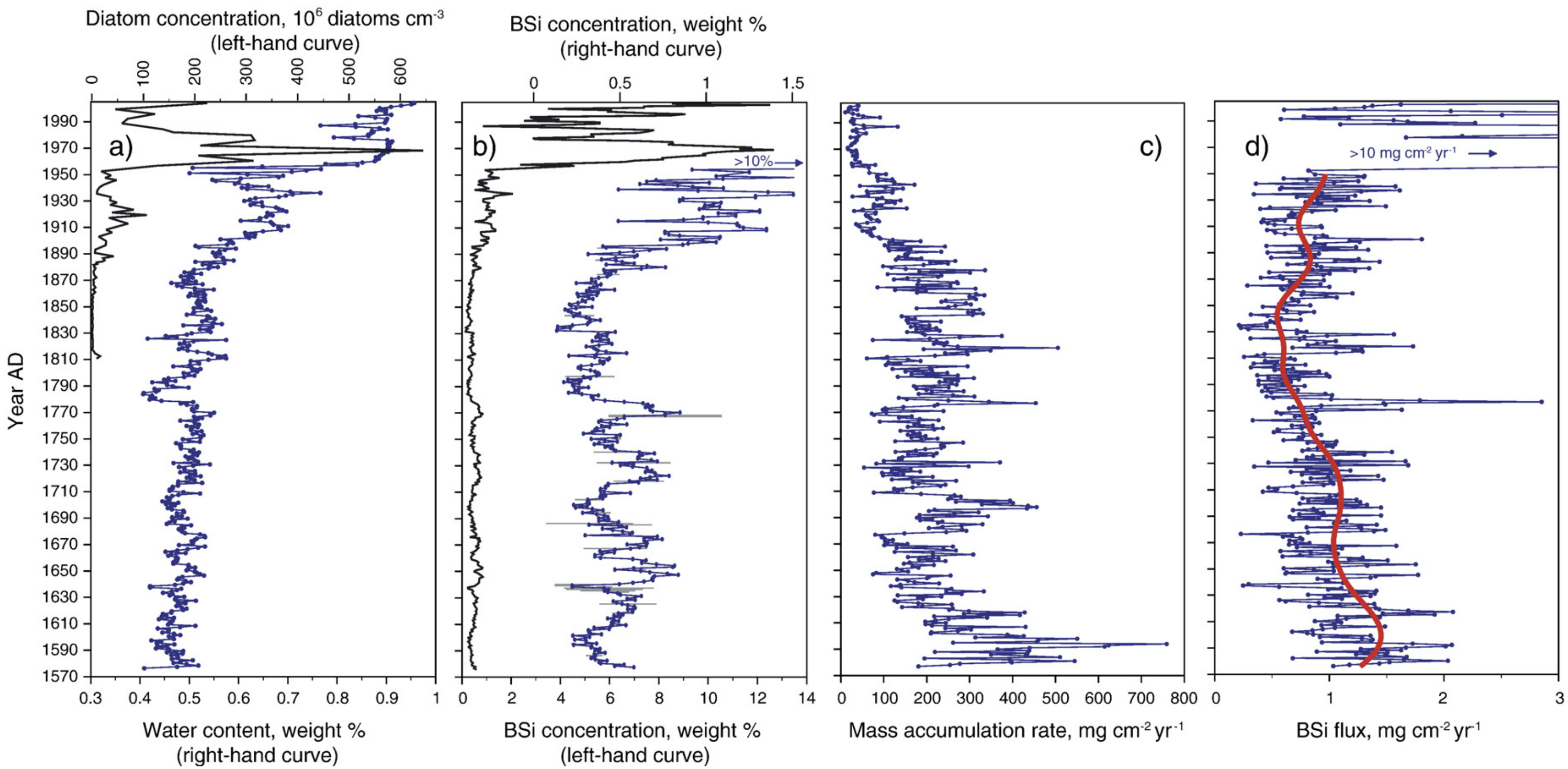


Figure 1. Annually resolved water content and diatom concentration (about 2-yr resolution) (a); annual biogenic silica (BSi) concentrations (wt.%), differently scaled (b); total sediment mass accumulation rate MAR (c); and BSi fluxes (d). Water content, BSi concentrations (wt.%) and fluxes show a very similar overall pattern with abruptly increasing values after AD 1950 due to anthropogenic eutrophication. The full BSi flux graph with no cut-off is shown in Figure 2. Diatom valve and BSi concentrations are well correlated, indicating that BSi is a consistent measure for diatom productivity. Pre-1950 BSi fluxes reveal a distinct long-term trend (150-yr Gaussian low-pass filter) and high inter-annual to decadal-scale variability. The error bars shown for the BSi concentrations represent the 95% confidence interval.

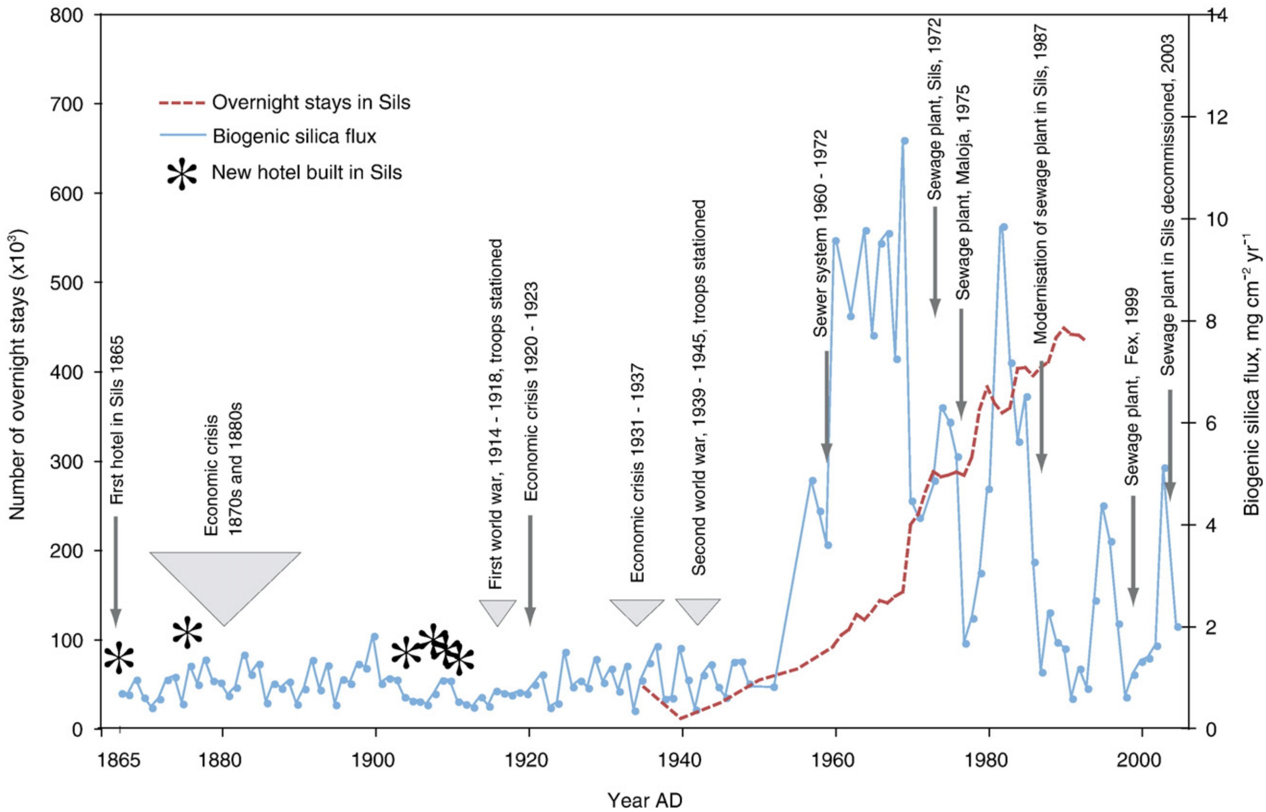


Figure 2. Comparison of biogenic silica (BSi) fluxes in Lake Silvaplana with the number of overnight stays in the nearby village of Sils (Gemeinde Sils, 1994), showing selected historic events (Bergier, 1983; Zuan, 1984; LIMNEX, 1994; Reich, 2002). No apparent anthropogenic influence on BSi productivity is found prior to AD 1950. The rapid increase in BSi fluxes around AD 1960 is attributable to the installation of a sewer system in Sils, which conveyed waste water from the village directly into the lake. After sewage plants were constructed in the catchment area of the lake, diatom productivity in the lake sank immediately.

Decadal annual mean and autumn temperature reconstruction back to AD 1580

The BSi fluxes seem to have the closest correspondence with autumn temperatures on the monthly as well as on the seasonal scale, and annual mean temperatures on the annual scale. Thus, we developed a decadal (9-yr average) autumn and annual mean temperature reconstruction back to AD 1577. The BSi series was previously FFT high-pass filtered (150 yr) to remove the long-term trend, which may or may not be related to temperature (compare Figs. 4a and b; see also discussion). Additionally, five outliers exceeding the 95% confidence interval of the distribution were removed from the record (total of 422 data points) and replaced with linear interpolations between the adjacent years. Correlations between the detrended BSi series and the instrumental autumn/annual mean temperature between AD 1864 and 1949 are very similar to the unfiltered series with an $r=0.69$ ($p<0.01$)/$r=0.69$ ($p<0.01$).

The autumn temperatures reconstructed for the pre-1900 period remained for the most part (78%) below the 20th century mean (Fig. 4b) and show relatively large decadal scale variations with distinct maximum values around AD 1770 and 1820, and minimum values around AD 1600, 1640, 1670 and 1710. The reconstructed decadal temperatures range from 1.4 °C to 3.5 °C. Decadal autumn temperatures did not experience strong departures from the 20th century mean during the cold anomaly around AD 1600 and during the Maunder Minimum (Figs. 4b, c). Large positive excursions of reconstructed autumn temperatures (+0.75 °C from 20th century mean) are observed around AD 1770 and 1820.

The reconstructed annual mean temperatures show exactly the same pattern over the centuries as the previously described reconstructed autumn temperatures. The same source data, only differently scaled, were used. Pre-1900 annual mean temperatures are mostly (88%) below the 20th century mean, ranging in temperature between 1.1 and 2.0 °C. There are only small departures from the 20th century mean during the cold anomaly around AD 1600 and during the Maunder Minimum.

Discussion

High correspondence with other independent reconstructions

We compared our reconstruction with (i) the gridded multi-proxy- (mainly documentary and early instrumental) based autumn and annual temperature reconstruction done by Casty et al. (2005), (ii) the gridded documentary- and early instrumental-based reconstruction from Xoplaki et al. (2005), and (iii) the gridded multi-proxy annual mean temperature reconstruction from Luterbacher et al. (2004). These already published reconstructions share in part the same input data.

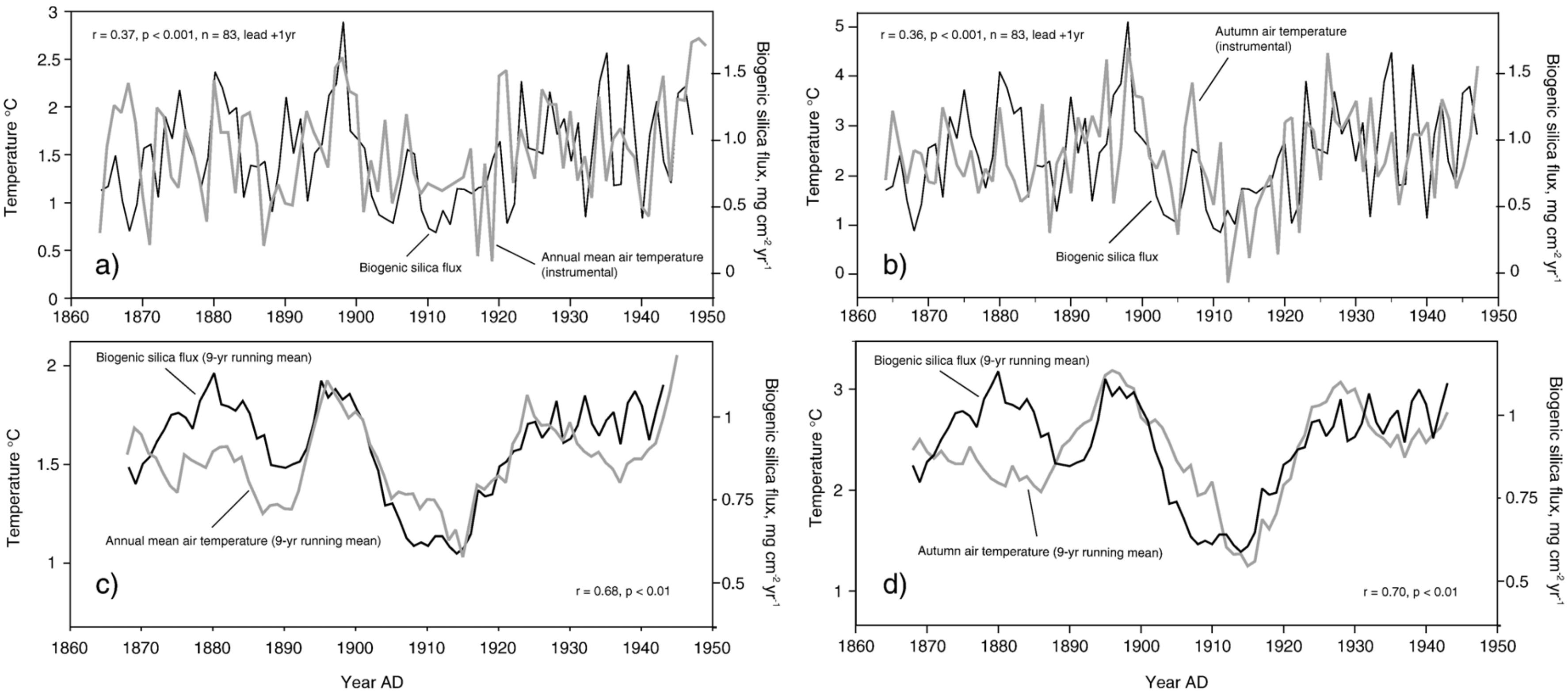


Figure 3. Comparison of annual biogenic silica fluxes in Lake Silvaplana with mean annual air temperatures (a, c) and mean autumn temperatures (b, d) at Sils. All series reveal a strong correspondence on inter-annual scales (upper panels: 1-yr lead, $r=0.36$, $p<0.001$) and decadal scales (lower panels: $r=0.7$, $p<0.01$).

Table 1
Matrix of correlation coefficients between biogenic silica (BSi) flux and monthly to seasonal air temperature measured at Sils from AD 1864 to 1949, for both the original data and the 9-yr averaged data (upper table)

	T mean	T MAM	T JJA	T SON	T DJF							
BSi flux	**0.37**	0.12	0.13	**0.36**	**0.27**							
9pt BSi flux	**0.68**	0.18	**0.67**	**0.70**	−0.20							
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
BSi flux	**0.28**	−0.07	0.09	0.11	0.04	0.06	−0.04	0.15	**0.23**	**0.26**	**0.23**	0.15
9pt BSi flux	−0.02	0.13	0.39	**0.52**	−0.48	0.38	0.49	0.31	**0.53**	0.39	**0.68**	**−0.52**
	T MAM	T JJA	T SON	T DJF								
Annual T mean	**0.66**	**0.29**	**0.62**	**0.32**								

Additionally, correlations between annual mean air temperature and seasonal mean air temperature are shown (lower table). Values of r shown in bold are significant at the $p<0.05$ level.

On the one hand, BSi-based annual temperatures display virtually no correspondence before AD 1780 with the regional temperature reconstruction from Casty et al. (2005) (Fig. 4b) and with the European mean annual temperatures from Luterbacher et al. (2004). Between AD 1780 and 1864, the decadal-scale structure of our BSi-based reconstruction is quite similar to the Casty and the Luterbacher series, with rather high temperatures around AD 1820 and comparably low temperatures between AD 1830 and 1860 (Fig. 4b). Nonetheless, correlations for that period are statistically not significant ($p>0.05$).

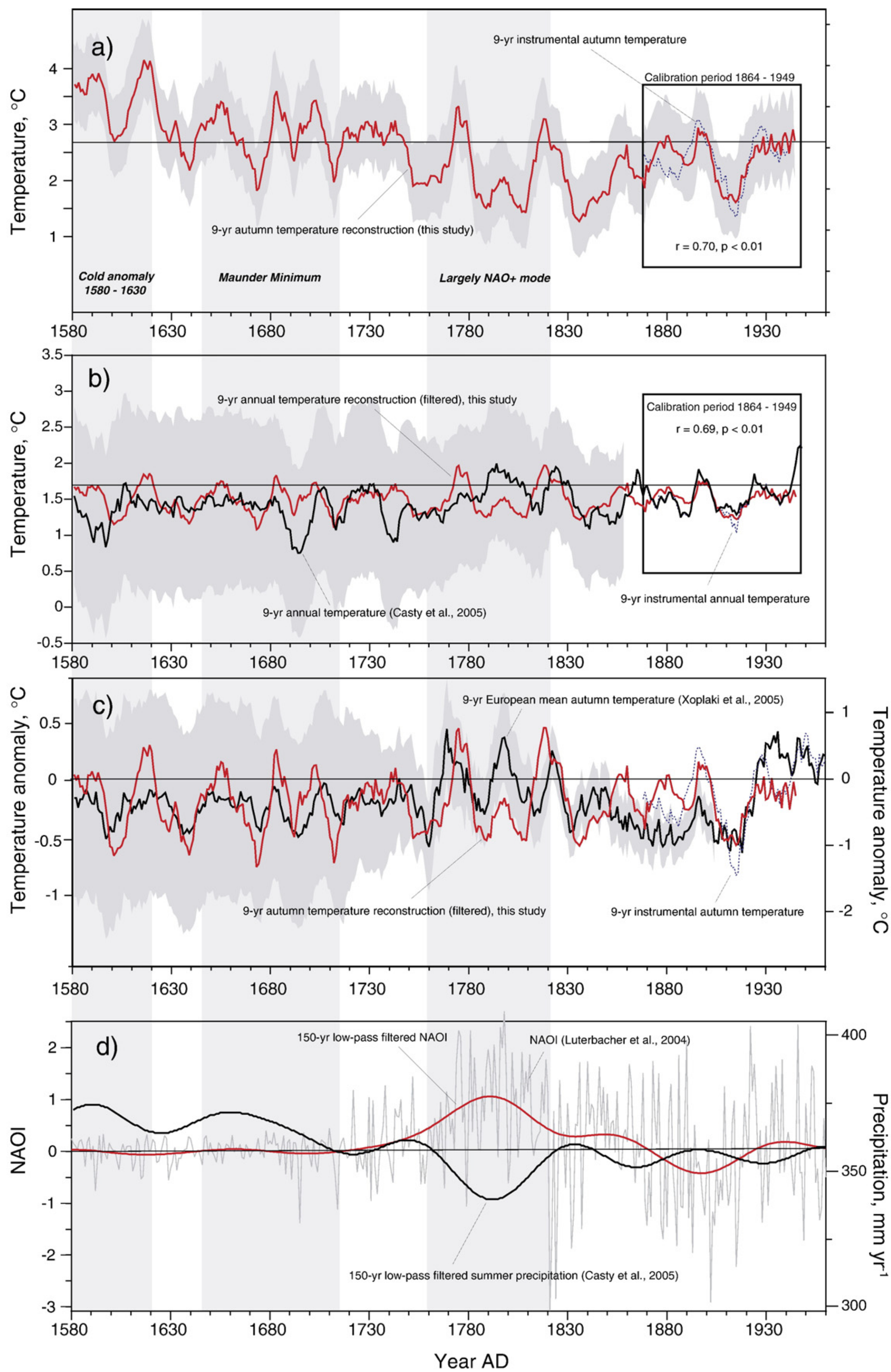
On the other hand, our BSi-based autumn temperature reconstruction displays a remarkably good correspondence with the autumn temperature reconstructions from Casty et al. (2005) and Xoplaki et al. (2005). Generally, autumn temperatures did not experience strong departures from the 20th century mean during the cold anomaly around AD 1600 and during the Maunder Minimum (Fig. 4c), which is in accordance with Casty et al. (2005) and Xoplaki et al. (2005). Our data confirm the large positive excursion of European mean autumn temperatures (+0.75 °C from 20th century mean) around AD 1770 and 1820 reported by Xoplaki et al. (2005). The highest correlations are obtained with the European autumn temperature reconstruction from Xoplaki et al. (2005) between AD 1580–1680 ($r=0.60$, $p<0.01$) and 1681–1780 ($r=0.41$, $p<0.05$). The decadal-scale structure of our reconstruction is strikingly similar compared to both the Casty (Fig. 4c) and Xoplaki series. The slightly different timing of corresponding peaks may be due to varve counting errors (estimated ±5 yr). The amplitudes of the BSi reconstruction are usually larger compared to the regional Casty and Xoplaki series. However, higher amplitudes for local-temperature time series, such as the Engadine, compared with time series representative of larger regions (the Alps or Europe, or even hemispheric or global scales) are expected as the variability of any climate variable is inversely proportional to the space integrated (see scale Fig. 4c). All three time series show the strongest deviations between around AD 1770 and 1840. Surprisingly, this also coincides with a special period associated with the North Atlantic Oscillation (NAO, Fig. 4d), during which the summer NAO is exceptionally high between AD 1780 and 1890 (Luterbacher et al., 2002).

The competing influence of anthropogenic and different climatic factors on biogenic silica productivity

Diatom productivity is influenced by many different factors (Anderson, 2000; Battarbee et al., 2001), but primarily by climate and human activity. We have no indication of significant short-term anthropogenic influence on the diatom productivity in our BSi record before AD 1957 (Fig. 2). Significant eutrophication is immediately observed after the installation of a sewer system, while early tourism, economic activities and the demographic development in the 19th and early 20th century did not leave a detectable impact. Long-term ecosystem changes with diffuse impacts are possible. To at least account for a diffuse, anthropogenic influence between AD 1865 and 1950, a sensitivity analysis was performed (Fig. 5). A hypothetical anthropogenic linear trend was stepwise removed from the original BSi flux data (AD 1865–1950). Firstly, a linear trend of 0–0.2 mg BSi cm^{-2} yr^{-1}, which is about 20% of the average flux from AD 1865 to 1950, was removed. In a second step, 0–0.4 mg BSi cm^{-2} yr^{-1}, about 40% of the average, were removed. The temperature reconstructions with the different calibrations showed that there is almost no effect on the long-term

Figure 4. Decadal-scale autumn temperature reconstruction derived from unfiltered BSi flux data calibrated against air temperatures (SON) measured in Sils from AD 1864 to 1949 (a). The mean annual temperature reconstruction derived from 150-yr high-pass filtered BSi flux data is compared with the regional air temperature as reconstructed by Casty et al. (2005) (b). The autumn temperature reconstruction (derived from filtered data) is plotted together with the European autumn temperature reconstruction of Xoplaki et al. (2005) (c). The BSi-inferred autumn temperatures correspond closely to those reconstructed by Xoplaki et al. (2005), with highest consistency in the 17th and 18th centuries, whereas the annual mean air temperature reconstructed from the BSi data displays very low correspondence with that reconstructed by Casty et al. (2005). As indicated in panel d, the exceedingly high positive NAO mode from AD 1760 to 1830 (Luterbacher et al., 2002) coincides with abnormally dry summer conditions (Casty et al., 2005). Additionally, the highest discrepancies between our autumn temperature reconstruction and that of Xoplaki et al. (2005) are observed at that time. Horizontal lines mark the 20th century annual mean air temperature at Sils (2.7 °C). The shaded error range represents ±2 standard errors of our autumn temperature reconstruction (a), the annual mean air temperature reconstruction of Casty et al. (2005) (b), and the autumn temperature reconstruction of Xoplaki et al. (2005) (c).

temperature trend (Fig. 5), and maximum amplitude change amounts to 0.34 (0.42) °C. The correlation coefficient of the regression decreased from originally $r=0.70$ to $r=0.62$ (0.48). We conclude that a diffuse anthropogenic trend between 1865 and 1950 would be of minor importance in terms of the overall variability of the reconstructed temperature signal. BSi fluxes



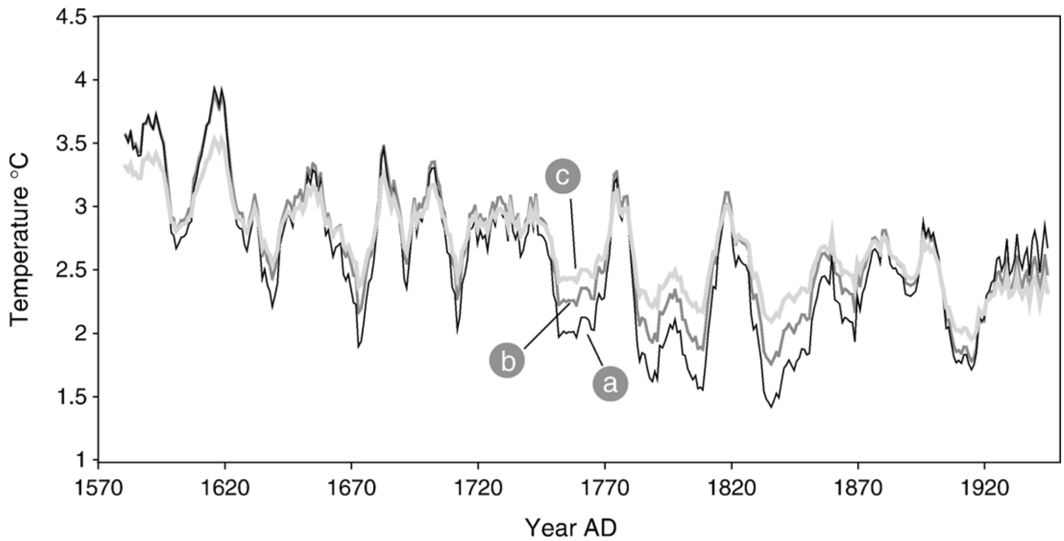


Figure 5. Sensitivity test to account for a diffuse, not easily detectable anthropogenic influence on BSi flux data between AD 1865 and 1950. In a first step 0–20%, and in a second step 0–40%, of the average BSi flux between AD 1865 and 1950 were removed from the original BSi flux data. Using these data, three different calibrations against autumn temperatures were obtained. The resulting temperature reconstructions show that there is almost no effect of the different calibrations on the long-term temperature trend, and maximum amplitude change amounts to 0.34 °C and 0.42 °C, respectively. It is concluded that a diffuse anthropogenic trend between AD 1865 and 1950 would be of minor importance in the overall variability of the reconstructed temperature signal.

are, surprisingly, lower in the 19th and early 20th century (with growing socio-economic impacts on the Engadine valley) compared to higher fluxes (i.e., with higher productivity) in the 17th and 18th century. However, we cannot rule out the possibility that in certain periods nutrient supply to the lake was enhanced due to, for example, intensification of land use and cattle rearing (see also Anderson et al., 1995). This could have been the case around AD 1880, for which time the BSi reconstruction overestimates the temperature signal and hypertrophic diatom taxa appear simultaneously. A high-resolution quantitative total phosphorus reconstruction for Lake Silvaplana has recently been done (Bigler et al., in press) and may in the future be used to remove the anthropogenic signal and, thus, to improve the temperature reconstruction presented here.

Our results indicate a significant influence of temperatures on diatom production in the lake and BSi flux to the sediment. Correlations are about the same for both annual mean and autumn temperatures. However, annual mean temperatures are highly correlated with autumn temperatures (Table 1) and are not independent. The comparison with the other independent temperature reconstructions clearly favours the interpretation of our record as an autumn temperature signal. Additionally, diatom productivity does not relate to the entire year. The major growing season in Lake Silvaplana is restricted to the ice-free season from May to December. Winter and spring temperatures are probably not relevant. As there are generally two peak blooming periods (spring and autumn) and not a continuous growing season (Reynolds, 1973, 1984; Raubitschek et al., 1999; Wessels et al., 1999; Köster and Pienitz, 2006), autumn could indeed be a key period for BSi productivity. We consider as a possible explanation that high autumn temperatures prolong the growing season of the diatoms and therefore increase the overall productivity. Also Weyhenmeyer (2001) found some indication of a temperature influence on primary production in Swedish lakes due to an extended growing season.

Linkage to the NAO

Comparison between the three different data sets for autumn (SON) temperatures (Figs. 4b and c) show substantial differences between AD 1760 and 1830, which is a period with strongly positive summer NAO (see Fig. 4d, Luterbacher et al., 2002). During this period, the BSi reconstruction displays either higher amplitudes (compared with regional Casty et al., 2005) or lower amplitudes (compared with Xoplaki et al., 2005). Both the regional Casty and the regional Xoplaki data sets differ substantially. It appears that autumn temperature reconstructions seem to be difficult to assess in the Engadine during prolonged phases of strongly positive NAO. As our calibration period does not include a comparable situation, we are currently not able to determine whether our temperature amplitudes are real and the calibration model is correct for this period of time, or whether additional climatic variables come into the play. Reconstructed Alpine summer precipitation data (Casty et al., 2005) show, for instance, that positive summer NAO correlates with long-term Alpine summer precipitation minima (Fig. 4d), i.e., dry summer conditions (see also Brunetti et al., 2006). Instrumental data at Sils (1950–2004) also show negative correlations between NAO and precipitation in the months of May ($r = -0.33$, $p < 0.05$), June ($r = -0.45$, $p < 0.001$) and August ($r = -0.45$, $p < 0.001$), which results in larger proportions of glacial meltwater supply and smaller contributions of precipitation to the overall catchment runoff to the lake. The current state of our research does not allow us to provide a sound explanation of why positive summer NAO may impact on BSi production. However, we can say that additional information on large-scale atmospheric circulation patters and dynamics (such as NAO) is likely to further improve our BSi-based temperature reconstruction, or at least to provide the information about the spatial representativeness of our Engadine record back in time.

Long- and short-term signal of the biogenic silica record—significance and implications

The BSi flux record, as indicated in Figure 1d, also shows variability in the low-frequency domain, with a conspicuous minimum around AD 1840 and a maximum around AD 1600. This centennial-scale trend, however, is most likely not related to temperature since the previously published temperature reconstructions do not support such a trend (Casty et al., 2005; Xoplaki et al., 2005), and since temperatures well above (i.e., >1 °C) the 20th century mean (Fig. 4a) are indeed not very likely around AD 1600 during the Little Ice Age. Alternative causes for this long-term trend may include climatic factors other than temperature (precipitation) or long-term natural or anthropogenic ecosystem shifts in the catchment such as LIA glaciation, soil formation, vegetation and land use changes, and variations in the nutrient cycling. There is, for example, a similar centennial trend observed in reconstructed Alpine summer precipitation (June–August) according to Casty et al. (2005), with a minimum around AD 1790 (Fig. 4d).

Consequently, and as our goal is a temperature reconstruction, this non-temperature long-term trend has to be removed for the temperature reconstruction. As possible candidates for underlying atmospheric or catchment processes remain speculative at the current state of research, we cannot assess the appropriate (perhaps even variable) frequency domain and length of the filter that best removes the long-term non-temperature signal in our time series. Our 150-yr filter yields a temperature reconstruction that is highly consistent with the reconstructions by Casty et al. (2005) and Xoplaki et al. (2005). Nevertheless, it is arbitrary and influences significantly the amplitude of the reconstructed temperature range. This implies that the reliability of our reconstruction is limited to the domain of (sub)centennial and decadal variability. In summary, assessing the ‘right’ temperature amplitudes on the multi-centennial or millennial scale (Little Ice Age or the Medieval Warm Period), or assessing whether the 20th century is unusual in light of the last millennium, remains in practice a very difficult problem that we are not able to solve at this moment.

The high-frequency domain (inter-annual variability) is limited by dating uncertainties in our record. Unfortunately, with smoothing we lose the very important information about the inter-annual variability in our data set, although the individual data points measured are indeed annual in resolution. This highlights the fact that the limits for high temporal resolution of reconstructions are determined by chronological uncertainty and not by the sampling resolution of the individual data points. This issue is very important and is often overlooked in high-resolution data sets.

Conclusions

A biogenic silica (BSi) inferred (sub)centennial- to decadal-scale autumn temperature reconstruction for the southeastern Alps is presented back to AD 1580. The reconstruction indicates generally cooler autumn conditions during the late Little Ice Age compared to the 20th century. But reconstructed autumn temperatures did not experience strong negative deviations from the 20th century mean during the cold anomaly around AD 1600 and during the Maunder Minimum. The warmest pre-industrial autumn temperatures are observed around AD 1770 and 1820 (+0.75 °C above 20th century mean). Other documentary-based autumn temperature reconstructions are in close agreement with our reconstruction and display a very consistent picture over the centuries. However, amplitudes are often mismatched, especially around AD 1800, when abnormally dry conditions persisted and the North Atlantic Oscillation was in a significantly positive mode.

It has turned out to be essential to report annual BSi flux rates (instead of BSi concentrations), which requires very accurate dating and annual sampling. This is only possible in annually laminated sediments. The reason is that annual sedimentation rates are highly variable in a proglacial setting, and we believe that this holds true for all lakes in a similar environment.

The last 50 yr (1950–2004) could not be used for calibration (1864–1949) because anthropogenic eutrophication strongly biased the BSi signal. Before 1950, no apparent anthropogenic influence could be detected. It cannot be ruled out, however, that in some periods in the past nutrient supply to the lake was enhanced due to human activity.

In order to make our BSi-based temperature record useful for regional multi-proxy reconstructions, uncertainties have to be carefully assessed and quantified. Of utmost importance is the assessment of the frequency band for the variability that is recorded in the time series. Our record is high-pass filtered (150 yr) to remove possible non-temperature effects, and the limit in the high-frequency domain (9-yr average) is set by chronological uncertainties.

In summary, our reconstruction records sub-centennial to decadal-scale variability. Assessing the ‘right’ amplitudes at the (multi)-centennial to millennial scale is an open challenge for the moment. Nevertheless, given that the last 3000 yr are annually recorded in Lake Silvaplana, there is a great potential to further expand the record and to reconstruct autumn temperatures back to the Bronze Age.

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References

Anderson, N.T., 2000. Diatoms, temperature and climatic change. European Journal of Phycology 35, 307–314.

Anderson, N.J., Renberg, I., Segerström, U., 1995. Diatom production responses to the development of early agriculture in a boreal forest lake-catchment (Kassjon Northern Sweden). Journal of Ecology 83, 809–822.

Battarbee, R.W., 1986. Diatom analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons Ltd, Chichester, pp. 527–570.

Battarbee, R.W., Kneen, M.J., 1982. The use of electronically counted microspheres in absolute diatom analysis. Limnology and Oceanography 27, 184–188.

Battarbee, R.W., Jones, V., Flower, R.J., Cameron, N., Bennion, H., 2001. Diatoms. In: Smol, J., Birks, H.J.B., Last, W. (Eds.), Tracking environmental change using lake sediments. Terrestrial, algal, and siliceous indicators. Kluwer Academic Publishers, Dordrecht, pp. 155–202.

Bergier, J.-F., 1983. Wirtschaftsgeschichte der Schweiz. Benzinger Verlag, Zürich.

Berner, R.A., 1971. Principles of chemical sedimentology. McGraw-Hill Book Company, New York.

Bigler, C., Hall, R.I., 2003. Diatoms as quantitative indicators of July temperature: a validation attempt at century-scale with meteorological data from northern Sweden. Palaeogeography Palaeoclimatology Palaeoecology 189, 147–160.

Bigler, C., Heiri, O., Krskova, R., Lotter, A.F., Sturm, M., 2006. Distribution of diatoms, chironomids and cladocera in surface sediments of thirty mountain lakes in southeastern Switzerland. Aquatic Sciences 68, 154–171.

Bigler, C., von Gunten, L., Lotter, A. F., Hausmann, S., Blass, A., Sturm, M., Ohlendorf, C., in press. Quantifying human-induced eutrophication in Swiss mountain lakes since AD 1800 using diatoms. The Holocene.

Blass, A., Grosjean, M., Troxler, A., Sturm, M., 2007. How stable are 20th century calibration models? A high-resolution summer temperature reconstruction for the eastern Swiss Alps back to A.D. 1580 derived from proglacial varved sediments. The Holocene 17, 51–63.

Bosli-Pavoni, M., 1971. Ergebnisse der limnologischen Untersuchungen der Oberengadiner Seen. Schweizerische Zeitschrift für Hydrologie 33, 386–409.

Brunetti, M., Maugeri, M., Nanni, T., Auer, I., Böhm, R., Schöner, W., 2006. Precipitation variability and changes in the greater Alpine region over the 1800–2003 period. Journal of Geophysical Research 111 (D11): Art. No. D11107 (Jun 7 2006).

Casty, C., Wanner, H., Luterbacher, J., Esper, J., Boehm, R., 2005. Temperature and precipitation variability in the European Alps since AD 1500. International Journal of Climatology 25, 1855–1880.

Demaster, D.J., 1981. The supply and accumulation of silica in the marine environment. Geochimica et Cosmochimica Acta 45, 1715–1732.

Gemeinde Sils, 1994. Jahresbericht 1993/1994 Kur- und Verkehrsverein Sils, Engadin.

Gensler, G., 1978. Das Klima von Graubünden. Ein Beitrag zur Regionalklimatologie der Schweiz. Habilitation thesis, University of Zurich

Hall, R.I., Leavitt, P.R., Smol, J.P., Zirnhelt, N., 1997. Comparison of diatoms, fossil pigments and historical records as measures of lake eutrophication. Freshwater Biology 38, 401–417.

Heiri, O., Lotter, A.F., 2005. Holocene and Lateglacial summer temperature reconstruction in the Swiss Alps based on fossil assemblages of aquatic organisms: a review. Boreas 34, 506–516.

Hughen, K., Overpeck, J., Anderson, R., 2000. Recent warming in a 500-year paleotemperature record from varved sediments, Upper Soper Lake, Baffin Island, Canada. The Holocene 10, 9–19.

Koinig, K.A., Schmidt, R., Sommaruga-Wögrath, S., Tessadri, R., Psenner, R., 1998. Climate change as the primary cause for pH shifts in a high alpine lake. Water Air And Soil Pollution 104, 167–180.

Kulbe, T., Niederreiter, R., 2003. Freeze coring of soft surface sediments at a water depth of several hundred meters. Journal of Paleolimnology 29, 257–263.

Köster, D., Pienitz, R., 2006. Seasonal diatom variability and paleolimnological inferences—A case study. Journal of Paleolimnology 35, 395–416.

Leemann, A., Niessen, F., 1994. Holocene glacial activity and climatic variations in the Swiss Alps: reconstructing a continuous record from proglacial lake sediments. The Holocene 4, 259–268.

Leonard, E.M., 1997. The relationship between glacial activity and sediment production: evidence from a 4450-year varve record of neoglacial sedimentation in Hector Lake, Alberta, Canada. Journal of Paleolimnology 17, 319–330.

LIMNEX, 1994. Gewässerzustand und Gewässerschutzmassnahmen im Oberengadin. Bericht zuhanden des Amtes für Umweltschutz, Kanton Graubünden. 75 pp.

Lotter, A.F., 2001. The palaeolimnology of Soppensee (Central Switzerland), as evidenced by diatom, pollen, and fossil-pigment analyses. Journal of Paleolimnology 25, 65–79.

Lotter, A.F., Pienitz, R., Schmidt, R., 1999. Diatoms as indicators of environmental change near Arctic alpine treeline. In: Stoermer, E.F., Smol, J.P. (Eds.), The Diatoms: Application for the Environmental and Earth Sciences. Cambridge Univ. Press, Cambridge, p. 482.

Luterbacher, J., Xoplaki, E., Dietrich, D., Jones, P.D., Davies, T.D., Portis, D., Gonzalez-Rouco, F., von Storch, H., Gyalistras, D., Casty, C., Wanner, H., 2002. Extending the North Atlantic Oscillation reconstruction back to 1500. Atmospheric Science Letters 2, 114–124.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., Wanner, H., 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303, 1499–1503.

Moore, J.J., Hughen, K.A., Miller, G.H., Overpeck, J.T., 2001. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. Journal of Paleolimnology 25, 503–517.

Mortlock, R., Froelich, P., 1989. A simple method for the rapid determination of biogenic opal in pelagic marine sediments. Deep-Sea Research 36, 1415–1426.

Niessen, F., Wick, L., Bonani, G., Chondrogianni, C., Siegenthaler, C., 1992. Aquatic system response to climatic and human changes—Productivity, bottom water oxygen status, and sapropel formation in Lake Lugano over the last 10'000 years. Aquatic Sciences 54, 257–276.

Ohlendorf, C., Sturm, M., in press. A modified method for biogenic silica determination. Journal of Paleolimnology.

Ohlendorf, C., Niessen, F., Weissert, H., 1997. Glacial varve thickness and 127 years of instrumental climate data: a comparison. Climatic Change 36, 391–411.

Paillard, D., 1996. Macintosh program performs time-series analysis. EOS 77, 4.

Raubitschek, S., Lücke, A., Schleser, G.H., 1999. Sedimentation patterns of diatoms in Lake Holzmaar, Germany—On the transfer of climate signals to biogenic silica oxygen isotope proxies. Journal of Paleolimnology 21, 437–448.

Reich, A., 2002. Silvaplana-Chronik einer Gemeinde in Graubünden. Reich/Gemeinde Silvaplana Samedan (375 pp.).

Reynolds, C.S., 1973. The seasonal periodicity of planktonic diatoms in a shallow eutrophic lake. Freshwater Biology 3, 89–110.

Reynolds, C.S., 1984. The ecology of freshwater phytoplankton. Cambridge Univ. Press, Cambridge.

Röthlisberger, G., 1991. Chronik der Unwetterschäden in der Schweiz. WSL, Birmensdorf, p. 121.

Röthlisberger, G., 1993. Unwetterschäden in der Schweiz im Jahre 1992. Wasser, Energie, Luf 85, 59–65.

Schwarz-Zanetti, G., Schwarz-Zanetti, W., 1988. Vom Klima in Graubünden. Bündner Jahrbuch 30, 37–42.

SMA, 2002. Jahresbericht der Meteo Schweiz. Annalen der Meteo Schweiz.

Sturm, M., Lotter, A.F., 1995. Lake sediments as environmental archives. EAWAG News 38E, 6–9.

Sturm, M., Matter, A., 1978. Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents. In: Matter, A., Tucker, M. (Eds.), Modern and ancient lake sediments. Blackwell Scientific Publications, Bern, pp. 147–168.

Weckström, J., Korhola, A., Erästö, P., Holmström, L., 2006. Temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. Quaternary Research 66, 78–86.

Wessels, M., Mohaupt, K., Kummerlin, R., Lenhard, A., 1999. Reconstructing past eutrophication trends from diatoms and biogenic silica in the sediment and the pelagic zone of Lake Constance, Germany. Journal of Paleolimnology 21, 171–192.

Weyhenmeyer, G.A., 2001. Warmer winters: are planktonic algal populations in Sweden's largest lakes affected? Ambio 30, 565–571.

Wick, L., Lemcke, G., Sturm, M., 2003. Evidence of Lateglacial and Holocene climatic change and human impact in eastern Anatolia: high-resolution pollen, charcoal, isotopic and geochemical records from the laminated sediments of Lake Van, Turkey. The Holocene 13, 665–675.

Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M., Wanner, H., 2005. European spring and autumn temperature variability and change of extremes over the last half millennium. Geophysical Research 32 (L15713).

Zolitschka, B., Brauer, A., Negendank, J.F.W., Stockhausen, H., Lang, A., 2000. Annually dated late Weichselian continental paleoclimate record from the Eifel, Germany. Geology 28, 783–786.

Zuan, H., 1984. Sils im Engadin. Einst und jetzt. Gemeindeportrait. Buchdruckerei St. Moritz AG, St. Moritz.