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Mineralogy-based quantitative precipitation and temperature reconstructions from annually laminated lake sediments (Swiss Alps) since AD 1580

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[1] We present quantitative autumn, summer and annual precipitation and summer temperature reconstructions from proglacial annually laminated Lake Silvaplana, eastern Swiss Alps back to AD 1580. We used X-ray diffraction peak intensity ratios of minerals in the sediment layers (quartz qz, plagioclase pl, amphibole am, mica mi) that are diagnostic for different source areas and hydro-meteorological transport processes in the catchment. XRD data were calibrated with meteorological data (AD 1800/1864–1950) and revealed significant correlations: mi/pl with SON precipitation ($r = 0.56$, $p < 0.05$) and MJJAS precipitation ($r = 0.66$, $p < 0.01$); qz/mi with MJJAS temperature ($r = -0.72$, $p < 0.01$)and qz/am with annual precipitation ($r = -0.54$, $p < 0.05$). Geological catchment settings and hydro-meteorological processes provide deterministic explanations for the correlations. Our summer temperature reconstruction reproduces the typical features of past climate variability known from independent data sets. The precipitation reconstructions show a LIA climate moister than today. Exceptionally wet periods in our reconstruction coincide with regional glacier advances. **Citation:** Trachsel, M., U. Eggenberger, M. Grosjean, A. Blass, and M. Sturm (2008), Mineralogy-based quantitative precipitation and temperature reconstructions from annually laminated lake sediments (Swiss Alps) since AD 1580, *Geophys. Res. Lett.*, *35*, L13707, doi:10.1029/2008GL034121.

1. Introduction

[2] Temporally high-resolution quantitative regional and global climate reconstructions extending the instrumental period are fundamental to tighten the uncertainty about the sensitivity of the climate system to (anthropogenic) forcings and thus to reduce uncertainty about the magnitude and impact of future global climate change [*Hegerl et al.*, 2006]. While significant advancements have been made in the reconstruction methods and compilation of data [*Luterbacher et al.*, 2004; *Xoplaki et al.*, 2005; *Wahl and Ammann*, 2007, and references therein] the lack of well-calibrated proxy datasets of adequate quality, resolution and spatial distribution is increasingly recognized as the factual bottleneck. This lack of data is particularly critical for paleoclimate archives that (1) preserve signals of low-frequency climate variability (such as, e.g., lakes) and (2) provide information about precipitation which is spatially much more heterogeneous than temperature, especially in complex topography [*Brunetti et al.*, 2006]. However, precipitation variability and related extremes are most relevant for society [*Brazdil et al.*, 2005].

[3] We present a quantitative, high-resolution precipitation and temperature reconstruction derived from mineralogical compositions of annually laminated sediments (glacial varves) from proglacial Lake Silvaplana, eastern Swiss Alps. Based on XRD data from sequential sediment traps [*Bluszcz*, 2003] we hypothesised that the mineral composition of individual varves might record hydro-meteorological processes in the catchment and sediment transport from different source areas: during warm and dry summers, the sediments would predominantly be mobilized by glacial abrasion and mechanical weathering, and be transported by glacial meltwater; these sediments carry the mineralogical fingerprint of the bedrock geology typical for the upper elevations in the glaciated valley. In contrast, during cool and rainy summers, glacial meltwater is reduced and sediments are mobilized from slopes and soil surfaces that were subject to chemical weathering during the Holocene. In pedogenic sediments, relatively instable minerals (amphibole, mica, plagioclase) would be depleted against stable phases (quartz, orthoclase) due to post-glacial soil formation and progressive chemical weathering according to the different soil types that prevail in different areas of the catchment.

[4] To our knowledge, this is the first study dealing with quantitative climate reconstruction from lake sediments based on mineral indices. First, we test this hypothesis with samples from different soil types, river sediments and bedrock material in the catchment. Second, we calibrate XRD peak intensity ratios of diagnostic minerals in individual varves against instrumental monthly temperature and precipitation data. Then we apply the statistical reconstruction models down-core back to AD 1580 and compare our climate reconstructions with independent data sets.

2. Study Site

[5] Lake Silvaplana (46°27′N, 9°48′E) is a postglacial, high elevation (1800 m), 2.7 km^2 large (water volume $127*10^6$ m^3), 77 m deep, dimictic lake of glacio-tectonic origin (Figure 1). Typically, the lake is ice-covered between January and May. The catchment stretches over 129 km^2 and ranges up to 3441 m. About 6 km^2 (5% of the catchment) are glaciated (status 1998). The Fedacla river (average runoff 1.5 m^3s^{-1}) in the Fex valley is the only glacial river in the catchment and, therefore, the principle

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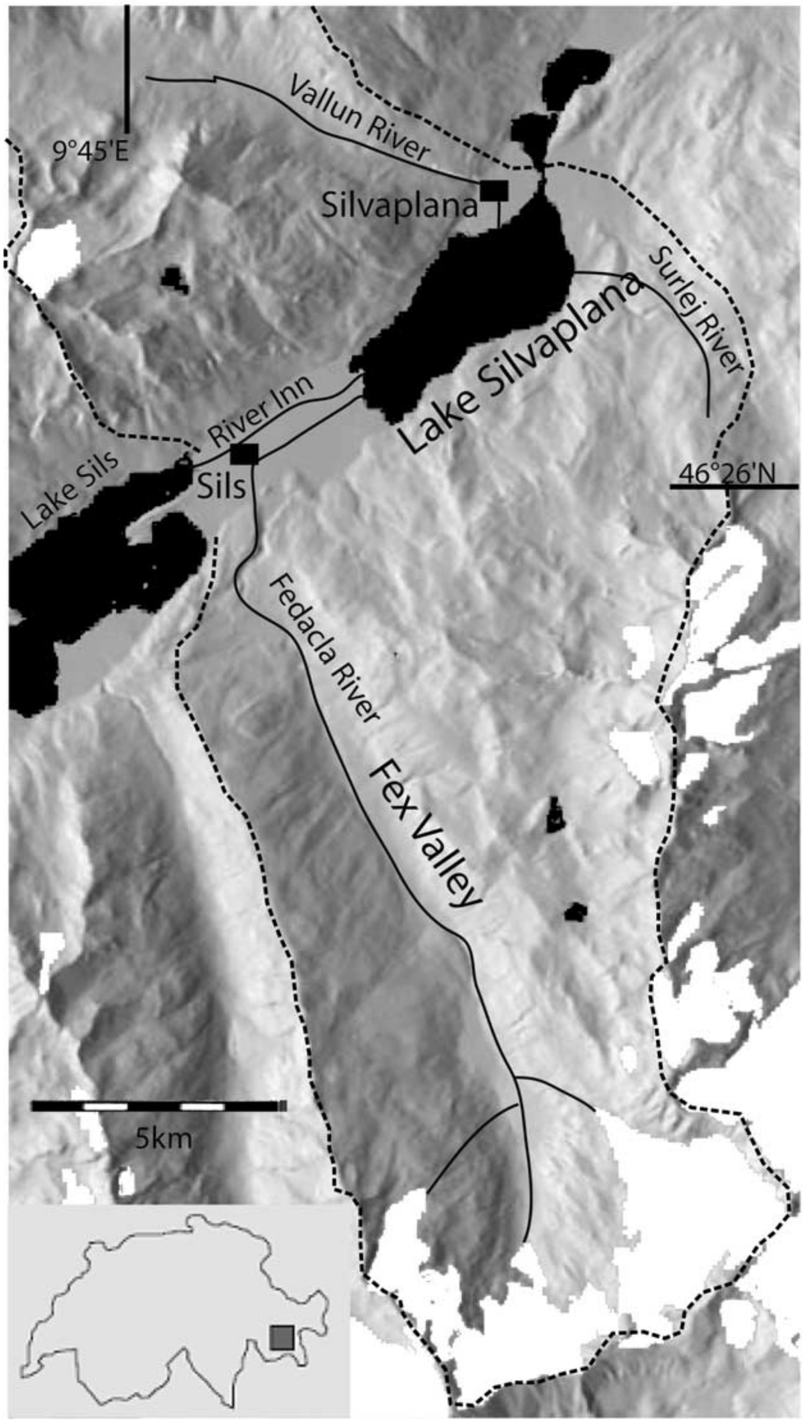

Figure 1. Map showing the Lake Silvaplana catchment (dashed line) including the coring site, the meteorological station, the major rivers and the modern glacier extension (white) [*Swiss Federal Office of Topography*, 2005] (reproduced with permission from Swisstopo (BA081362)).

conveyor of sediments to the lake. The Inn river, connecting Lake Sils with Lake Silvaplana is larger (discharge 2 m^3s^{-1}) but carries almost no suspended sediments. Two small rivers (Vallun; 0.7 m^3s^{-1} and Surlej; 0.3 m^3s^{-1}) are particularly active during spring snowmelt and summer rainstorms.

[6] The specific geological setting of the basin is fundamental to our study: Lake Silvaplana is located on the tectonic Engadine Line which separates the Lower Austro-alpine basement (granites with high amounts of feldspar) in the NW from the Penninic basement (dominated by orthogneiss and gabbro, with high amounts of mica) in the SE [*Spillmann*, 1993]. This difference is reflected in the mineral spectra of sediments around the shore of the lake [*Ohlendorf*, 1998].

[7] The climate of the Engadine exhibits the typical features of an inner-Alpine dry valley. Mean monthly

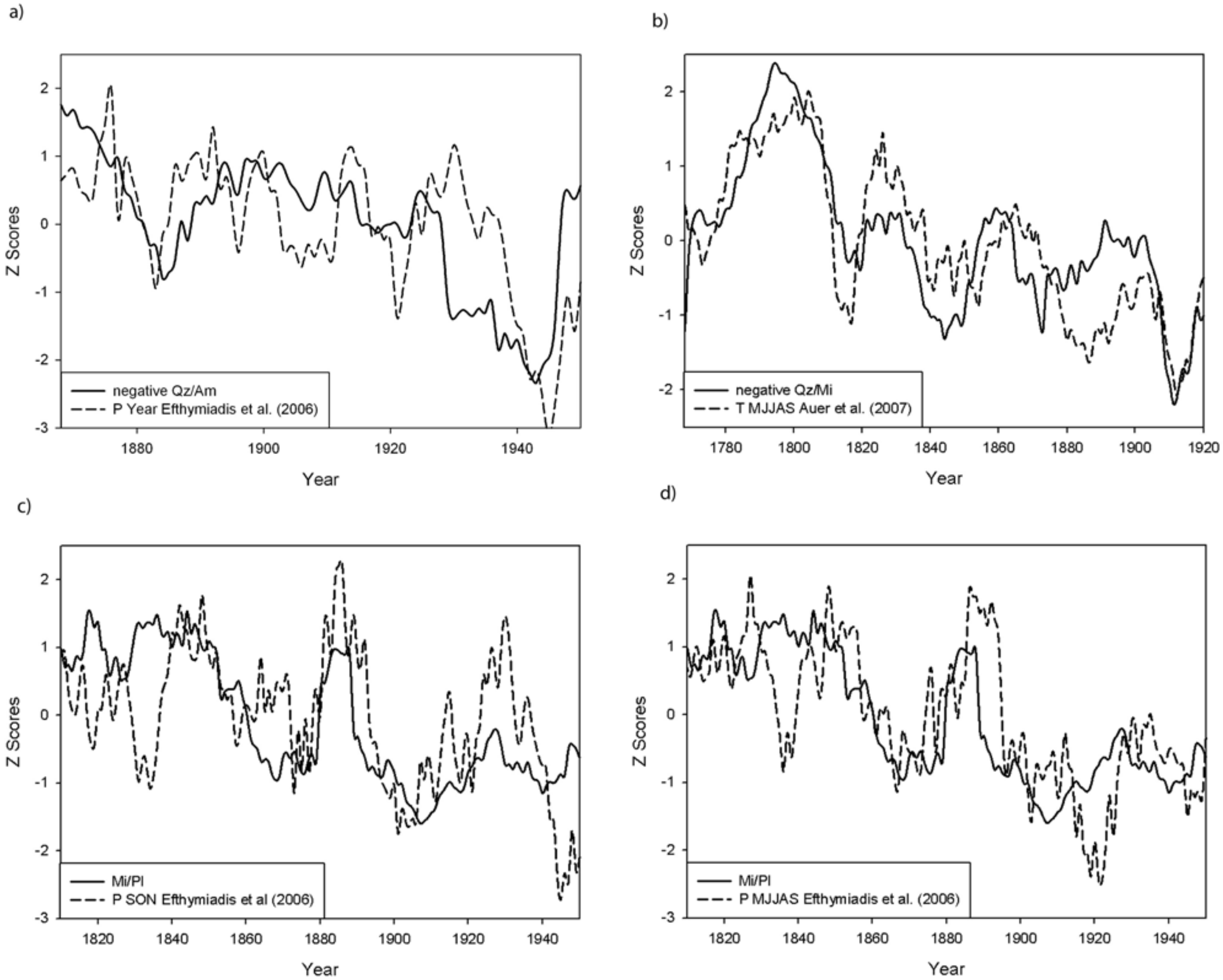

Figure 2. Calibration of the 9-point moving average mineral indices with 9-point moving average meteorological data: (a) negative qz/am ratios and annual precipitation (r = 0.54, p < 0.05); (b) May to September temperature with negative qz/mi ratios (r = 0.72, p < 0.01); (c) mi/pl ratios with autumn precipitation (r = 0.56, p < 0.05), and (d) mi/pl ratios with MJJAS precipitation [*Efthymiadis et al.*, 2006] (r = 0.66, p < 0.01).

temperature ranges from −7.2°C (January) to 10.4°C (July). Maximum monthly precipitation occurs in August (121 mm) whereas a minimum is observed in February (42 mm). Annual precipitation amounts to 978 mm (1961–1990, data from MeteoSwiss). Engadine JJA temperatures explain 50% of the variance of JJA temperatures in Central Europe, while the significance of Engadine JJA precipitation is more regional (southern Alps and northern Italy; see auxiliary material) showing that moisture is predominantly advected from the south [*Gensler*, 1978].[1]

3. Materials and Methods

[8] Continuous sediments from two freeze cores (SVP 04-11 and SVP 05-1) [*Blass et al.*, 2007a] were sampled layer by layer. The chronology is based on varve counting corroborated by ^{210}Pb dating, ^{137}C peaks and flood-event stratigraphy [*Blass et al.*, 2007a]. Organic matter and biogenic silica were removed from the bulk sediment [*Blass et al.*, 2007b], smear slides for XRD analysis were analyzed between 2 and 30° Philips PW 3710, 40 kV, 30 mA $Cu_{k\alpha}$, X'Pert High Score Plus). For this study, chlorite (chl), mica (mi), amphibole (am), serpentine (se), plagioclase (pl), quartz (qz), orthoclase (or) and calcite (cc) were identified, and peak intensity ratios were calculated. As we used peak intensity ratios only, absolute quantification (spiking) was not required. In order to assess sample preparation errors and to optimize the precision of XRD measurements, 30 samples were run with three replicates. Highest reproducibility (1 σ = 5% of the amplitude, subsampling errors, sample preparation, replicate measurements and the instrumental error) was reached at 0.5 s per step 0.02°2θ.

[9] In order to test the hypothesis of diagnostic mineral ratios as a function of the source area, we sampled A-horizons of the two major soil types in the catchment (brown earth-luvisols in lower elevations <2200 m and podzols in higher elevation >2200 m [*Käser*, 2004]; from 10 soil profiles along

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL034121.

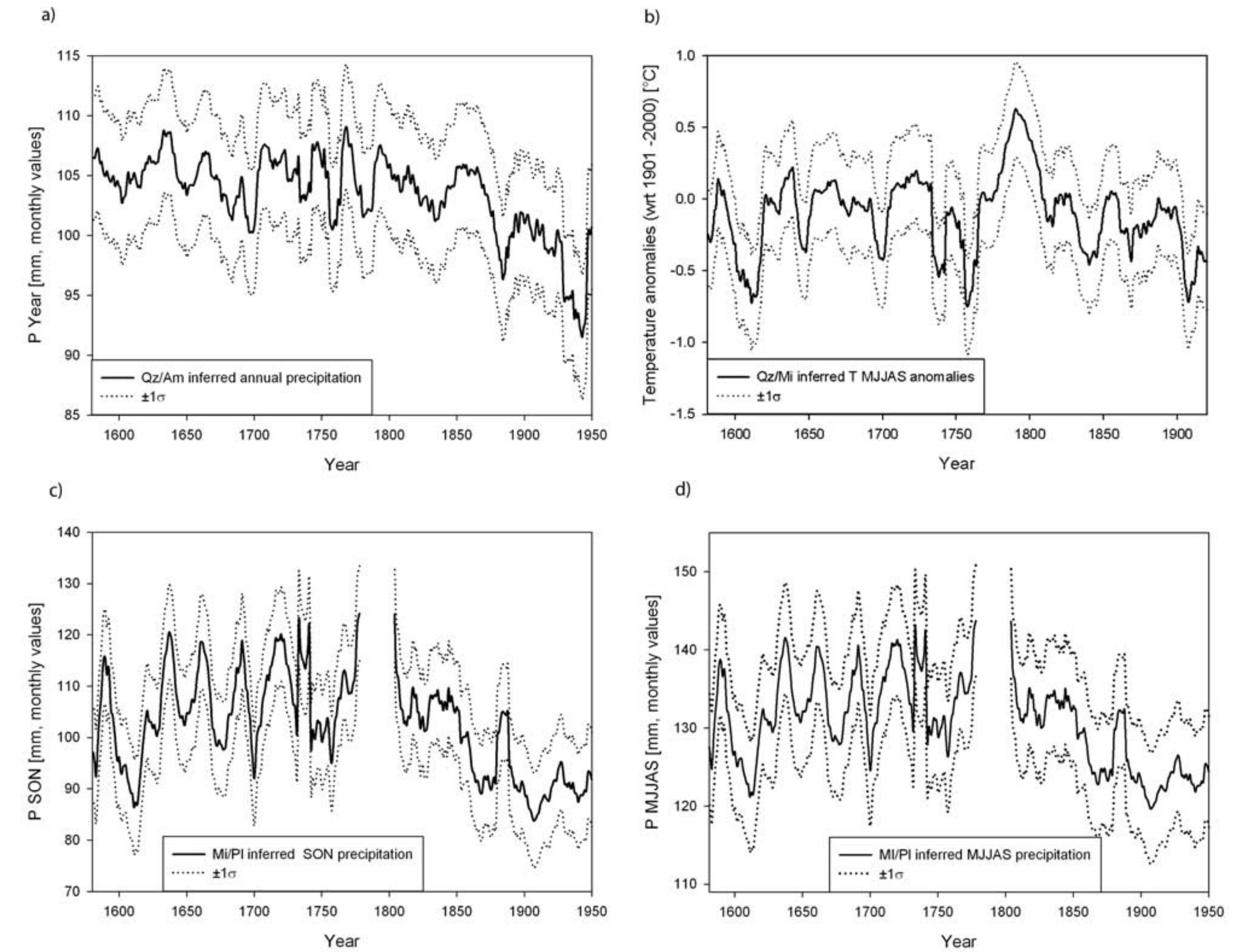

Figure 3. (a) Qz/am-inferred annual precipitation back to AD 1580, (b) summer temperature back to AD 1580 inferred from qz/mi, (c) mi/pl-inferred SON precipitation, and (d) May to September precipitation inferred from mi/pl (calibrated against *Efthymiadis et al.* [2006] dataset). The error bars (±1 σ) include the measurement and the statistical uncertainties.

an altitudinal gradient between 1900 and 2550 m. Sediment samples were taken from the major river beds.

[10] Meteorological data were recorded at nearby Sils from AD 1864 onwards (MeteoSwiss). For the calibration with longer time series (from AD 1800, 1760 respectively) we used the gridded data sets of *Efthymiadis et al.* [2006] (9 gridpoints) and *Auer et al.* [2007] (4 gridpoints) centred around 46°25′N 9°45′E and 46.5°N 9.5°E, respectively.

[11] Although sampled and analyzed at annual resolution, lake sediment data were smoothed (9-years moving average) prior to calibration with meteorological data to account for dating uncertainties in the varve counting [*Blass et al.*, 2007b]. Sediments from AD 1950 onwards were not used for calibration because of the anthropogenic impacts and modifications of the catchment hydrology and the sediment transport regime [*Blass et al.*, 2007b]. The qz/mi calibration period was limited to pre-1920 (AD 1760–1920) because of a strong positive qz/mi trend which is related to rapidly decreasing sediment mass accumulation rates as a result from the retreating glacier in the catchment [*Blass et al.*, 2007a]. XRD-based reconstructions are partly not calculated between AD 1780–1800 because of anomalously low amounts of pl and unusually high grain size medians [*Blass et al.*, 2007b], which is indicative of turbidite admixtures and a non-climatic signal.

[12] The Pearson product-moment correlation coefficient was used for correlation analysis and reconstructions were calculated using OLS (ordinary least square regression), root mean square error (RMSE), reduction of error (RE) and the coefficient of efficiency (CE) according to *Cook et al.* [1994]. Evidently, an extremely precise high-resolution chronology is the foundation of this statistical approach. In order to capture the full range of amplitude, we used the entire meteorological data series for calibration. The results for the split periods (cross validation) are shown in the auxiliary material.

4. Results

[13] The XRD analysis of the soil surface samples in the Fex Valley revealed that the mica/plagioclase mi/pl ratio is significantly ($p < 0.01$) higher in the low-elevation brown

soils (2.25 ± 0.9, n = 6, <2200 m) than in the heavily leached high-elevation podzols (0.7 ± 0.2, n = 4, >2200 m). The fact that both soil types are stacked in different elevation belts of the catchment implies that mi/pl ratios in the sediments reaching the lake might be used to determine differential erosion along a vertical gradient in the basin.

[14] Quartz/amphibole qz/am ratios in soils and streambed samples reveal a north to south (altitudinal and bedrock geology) gradient in the Fex Valley. In the southern (i.e., upper) part of the catchment the samples (n = 5) are devoid of amphibole. In the middle part of the Fex Valley the results are heterogeneous (n = 8, 4 with amphibole and 4 without amphibole), whereas in the northern (lower) part, all samples contain amphibole (n = 4).

[15] River bed sediment samples show the lowest qz/mi ratios (0.05 ± 0.02, n = 5) in sediments from the glaciated Fex Valley (Penninic basement and nappes) compared with the sediments from the rest of the catchment, in particular sediments from the Vallun river (1.35 ± 0.25, n = 3; Lower Austroalpine basement). In consequence low qz/mi ratios in the lake sediments are indicative of high sediment admixtures from glacial meltwater origin and provenience from the Fex Valley.

[16] The correlation analysis of the 9-point moving average mineral ratio series from the varved lake sediments and the meteorological data from Sils show significant and temporally stable correlations between qz/am and annual precipitation ($r = -0.68$; $p < 0.01$, 1864–1950; Figure 2a), and between mi/pl and SON precipitation ($r = 0.59$, $p < 0.05$, 1864–1950; not shown). Particularly good is the correlation in the multi-decadal frequency domain.

[17] The XRD data series were also correlated against the *Efthymiadis et al.* [2006] and the *Auer et al.* [2007] data sets: qz/am also correlates significantly with gridded annual precipitation ($r = -0.54$, $p < 0.05$, 1864–1950; Figure 2a) mi/pl correlates with the gridded SON precipitation ($r = 0.56$; $p < 0.05$, 1800–1950; Figure 2c) and with gridded May to September precipitation ($r = 0.66$, $p < 0.01$, 1800–1950; Figure 2d). Furthermore, qz/mi correlates highly with gridded May to September temperatures ($r = -0.72$, $p < 0.01$; 1760–1920; Figure 2b) For other degrees of smoothing, see auxiliary material.

[18] In the following, the four mineral ratio data series were calibrated with the gridded data series: qz/am versus annual precipitation revealed a RMSE of 5.66 mm, RE = 0.35, CE is negative (for mi/pl versus MJJAS precipitation: 5.24 mm, RE = 0.75, CE = 0.52; for mi/pl versus SON precipitation 11.03 mm, RE = 0.47 and CE = 0.31; for qz/mi versus MJJAS temperature 0.28°C, RE = 0.7 and CE = 0.46; respectively, for additional information, see auxiliary material).

[19] The four reconstructions back to AD 1580 are shown in Figures 3a–3d. Annual precipitation is very stable during Little Ice Age LIA and ranges between 83 and 95 mm precipitation per month. Annual precipitation decreases during the instrumental period. In contrast to annual precipitation, summer precipitation shows pronounced decadal-scale variability with large amplitudes (20%). Most of the summers during the Little Ice Age are wetter than those from the 20th century. Driest summers occur about AD 1610 and again in the 20th century. The Late Maunder Minimum (AD 1690–1710) appears dry whereas maximum humidity was observed around AD 1590, 1640 and 1730. The summer temperature reconstruction shows highest pre-1920 values between AD 1780 and 1805, followed by a decreasing trend until 1910. Coolest summers occurred around AD 1610, 1760 and 1900.

5. Discussion

[20] Our results confirm the initial hypothesis that ratios of diagnostic minerals in the individual varves reflect sediment transport from geologically different source areas with their inherent typical mineralogical composition, which in turn is a function of hydro-climatic processes in the catchment. Uniquely the same archive reveals information about temperature and precipitation for different seasons.

[21] Obvious is the negative correlation between qz/mi and summer temperatures: during warm (cold) summers, glacial runoff is enhanced (reduced). Sediments transported to Lake Silvaplana by glacial runoff carry the original mineralogical fingerprint of the bedrock geology in the glaciated Fex Valley.

[22] The correlation between mi/pl and SON precipitation is explained by the fact that mica is relatively depleted in chemically weathered A-horizons of podzols (upper part of the basin) compared with the brown soils in lower elevations. Autumn precipitation falls in the upper part of the catchment preferably in the form of snow; while rainfall in the lower part of the catchment erodes material from the brown soil A-horizons where mica is not depleted (high mi/pl ratios).

[23] A similar line of argument explains the negative correlation between qz/am and annual precipitation: the crystalline bedrock and, in consequence also the soils of the glaciated southern (upper elevation) part of the Fex Valley are devoid of significant amounts of amphibole. In contrast, soils and river sediments in the northern (low elevation) part of the Fex Valley contain amphibole. Therefore, increased precipitation particularly during spring and autumn and spring snowmelt increase the relative proportion of amphibole-bearing sediments.

[24] We compared the gridded temperature and precipitation data set from *Casty et al.* [2005] for the Sils grid point with our reconstructions (see auxiliary material). Both summer temperature reconstructions compare very well ($r = 0.62$; $p < 0.005$, 1659–1920). The negative anomaly around AD 1760 in the Engadine data set remains enigmatic, while the positive JJA temperature anomaly AD 1790–1805 is well captured and corresponds to the positive sea level pressure anomaly as reported by *Luterbacher et al.* [2002] (see auxiliary material).

[25] As expected, comparison between the Engadine precipitation reconstructions and the *Casty et al.* [2005] reconstructions is poor. In contrast to *Casty et al.* [2005] our results suggest higher precipitation rates during the Little Ice Age compared with the 20th century. Our data set performs very well if compared with early instrumental data from 1800 onwards (Figure 2), and also with the structure of Alpine glacier fluctuations [*Nussbaumer et al.*, 2007]. We point out that we calibrated our data with new long (since AD 1800) and spatially highly resolved

data sets [*Efthymiadis et al.*, 2006] that were not yet available to *Casty et al.* [2005]. According to *Brunetti et al.* [2006], spatial heterogeneity of precipitation in complex topography is fundamental.

6. Conclusions

[26] We present a quantitative, high-resolution precipitation and temperature reconstruction derived from mineralogical compositions of varved sediments from proglacial Lake Silvaplana, eastern Swiss Alps back to AD 1580. XRD peak intensity ratios of diagnostic minerals in individual varves provide high quality proxies for both temperature and precipitation for different seasons. Independent of the varve counting uncertainty the different proxies are internally consistent.

[27] The initial hypotheses of the underlying processes determining the mineralogical composition of varves can be confirmed: for all of the significant correlations between a given mineral ratio proxy and the climate variable for a given season, a sound deterministic explanation for the hydro-meteorological processes is provided.

[28] Our data compare favourably with long gridded or local instrumental data (since AD 1760/1800, 1864), Alpine and European summer temperature reconstructions, and with the structure of Little Ice Age glacier fluctuations in the Swiss Alps. Comparison with Alpine precipitation reconstructions [*Casty et al.*, 2005] is not satisfactory, which may largely be attributed to the spatial heterogeneity of precipitation in complex mountain topography.

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