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Quantitative estimates of temperature and precipitation changes over the last millennium from pollen and lake-level data at Lake Joux, Swiss Jura Mountains

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ABSTRACT

This paper presents quantitative climate estimates for the last millennium, using a multi-proxy approach with pollen and lake-level data from Lake Joux (Swiss Jura Mountains). The climate reconstruction, based on the Modern Analogue Technique, indicates warmer and drier conditions during the Medieval Warm Period (MWP). MWP was preceded by a short-lived cold humid event around AD 1060, and followed by a rapid return around AD 1400 to cooler and wetter conditions which generally characterize the Little Ice Age (LIA). Around AD 1450 (solar Spörer minimum), the LIA attained a temperature minimum and a summer precipitation maximum. The solar Maunder minimum around AD 1690 corresponded at Joux to rather mild temperatures but maximal annual precipitation. These results generally agree with other records from neighbouring Alpine regions. However, there are differences in the timing of the LIA temperature minimum depending on the proxy and/or the method used for the reconstruction. As a working hypothesis, the hydrological signal associated with the MWP and LIA oscillations at Lake Joux may have been mainly driven by a shift around AD 1400 from positive to negative NAO modes in response to variations in solar irradiance possibly coupled with changes in the Atlantic meridional overturning circulation.

Introduction

Present-day global warming has provoked an increasing interest in the reconstruction of climate changes over the last millennium (Guiot et al., 2005; Jones et al., 2009). Characterised by a succession of distinct climatic phases, i.e. a Medieval Warm Period (MWP) followed by a long cooler Little Ice Age (LIA) and finally by a post-industrial rapid increase in temperature, the last 1000 years appear to be a sort of laboratory, where climate variability and mechanisms may be investigated and offer a basis to improve predictive models (Solomon et al., 2007, and references therein).

However, even for the best documented areas such as Europe, available data still suffer from insufficiencies, such as (1) the scarcity of instrumental data before AD 1850 (Etien et al., 2008, 2009) and of documentary archives before AD 1500 (Pfister, 1995), (2) possible biases affecting proxies used for palaeoclimatic reconstructions (Mann et al., 1999; von Storch et al., 2004; Goosse et al., 2005), or (3) apparent discrepancies, for instance in the timing and magnitude of temperature minima during the LIA (Mann et al., 2008). In addition, while studies focus on temperature reconstruction (e.g. Jones et al., 2009), one observes a crucial lack of data concerning precipitation (Pauling et al., 2006; Gimmi et al., 2007; Trachsel et al., 2008). This points to the fact that additional proxy records from diverse disciplines and from various locations are still required to improve and complete climate reconstruction of the last millennium (Guiot et al., 2005).

In this general context, the purpose of this paper is to present a new quantitative reconstruction of temperature and precipitation derived from pollen and lake-level data obtained at Lake Joux, in the Swiss Jura Mountains (west-central Europe; Fig. 1). Previous sediment and pollen analyses of a well-radiocarbon dated sediment sequence at Lake Joux recently allowed establishment of a vegetation history for the area and have shown that this lacustrine basin offers highly sensitive archives to document past hydrological changes in relation to the successive climate oscillations that have punctuated the last millennium (Magny et al., 2008). This first dataset made it possible to test forcing factors and mechanisms behind this climate variability.

Study site and results from previous work

Lake Joux (46° 36′ N, 6° 15′ E) is located at an altitude of 1006 m a.s.l. in the Swiss Jura Mountains (Fig. 1). It is a long narrow and overdeepened basin of glacial origin. The water depth reaches 33.5 m and the lake area is 8.67 km^2. The surrounding mountains culminate at ca. 1300–1600 m a.s.l. The catchment area of the lake covers ca.

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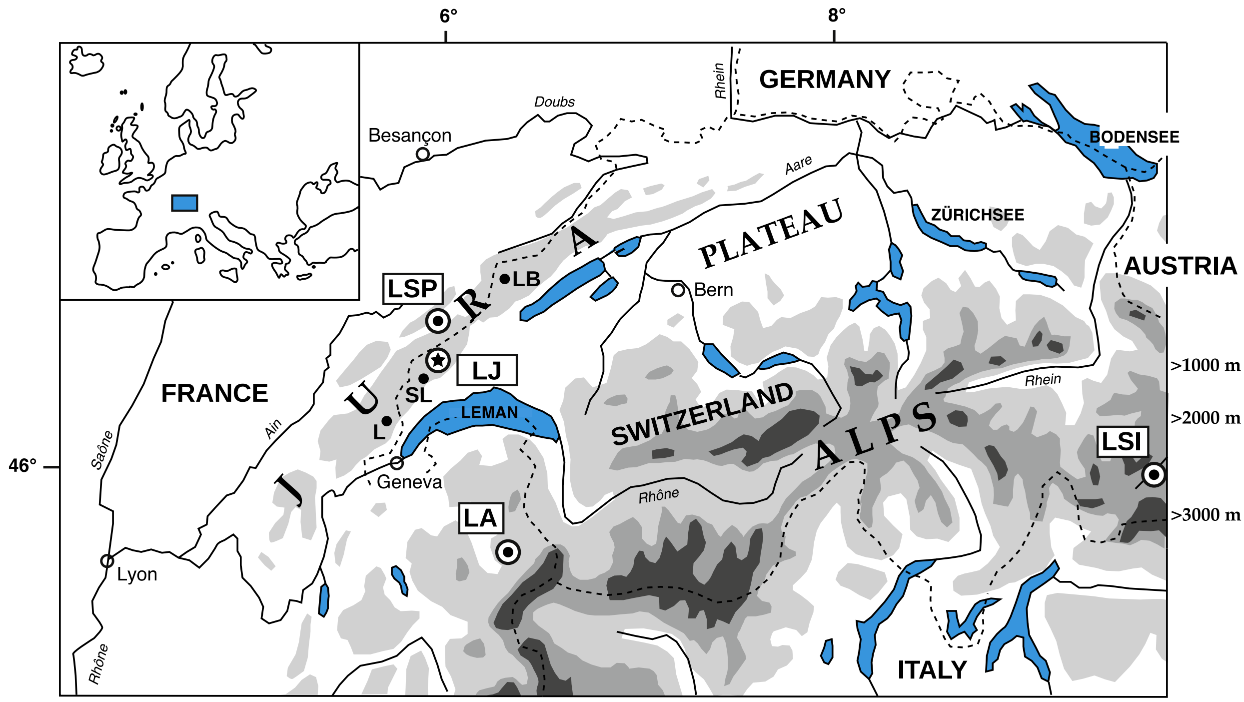

Figure 1. Geographical location of the study site. LJ: Lake Joux; LSP: Lake Saint-Point; L: Lamoura; LA: Lake Anterne; LB: La Brévine; LSI: Lake Silvaplana; SL: Saint-Livres ice cave.

211 km^2. The substratum is mainly composed of limestone. Lake Joux does not have a surficial outlet; its outflow is formed by several karstic caves with the lake waters resurging at the Orbe spring near Vallorbe, at ca. 800 m a.s.l., after a 3 km underground course. During heavy rainfall, the karstic caves that usually form the lake outlet may work as inlets to the lake. Thus, before its artificial regulation in the early twentieth century, Lake Joux was very sensitive to changes in climate conditions. It was characterised by large seasonal fluctuations of its water table most often due to autumn rains and spring snowmelt. Minimal levels resulted from summer droughts or winter frost periods.

The Joux Valley is marked by a severe semi-continental climate. At present, mean annual precipitation stands at ca. 1400 mm, with the observed minimum at 851 mm in 1921 and the maximum at 1990 mm in 1930. The mean annual temperature is ca. 5°C, in January −3°C and in July 13.1°C (New et al., 2002). In addition, the semi-continental climate conditions in the Joux Valley are characterised by a wide amplitude of variations in daily extreme temperatures, as illustrated by the year 1888 with −41°C in January and 28.8°C in August (Aubert, 1932). Regarding the present-day vegetation, the lower montane belt (800–1100 m a.s.l.) is dominated by *Abies* and *Picea* accompanied by *Fagus*, and *Fraxinus*, while *Pinus uncinata* and *Betula* develop in humid areas. Above 1100 m a.s.l., *Picea abies* dominates. The highest zones (ca. 1600 m a.s.l.) are occupied by grasslands reflecting anthropogenic deforestation for grazing activities and/or severe climatic conditions.

In order to reconstruct vegetation history and lake-level fluctuations over the last millennium, one core was extracted on the littoral platform, close to the southern extremity of the lake, by means of a Russian peat corer. The results have been extensively published elsewhere (Magny et al., 2008) and are presented in Figure 2. The chronology is based on 10 AMS radiocarbon dates from terrestrial plant macrofossils (Fig. 2). The lake-level fluctuations (Fig. 2, right panel) were reconstructed with a mean temporal resolution of ca. 10 yr (sampling every 1 cm) using a specific sedimentological approach developed by Magny (2006). It is based on multiple lines of evidence, i.e. variations in lithology, sediment texture, and the relative frequency of various carbonate concretion morphotypes, the formation of which depends on aquatic vegetation belts and water depth.

The right panel of Figure 2 compares the Joux lake-level record with the curve of variations in solar irradiance based on cosmogenic nuclides (Bard et al., 2000). Within the age uncertainty given by the radiocarbon dates, the Joux record has been tuned to the solar irradiance record (Magny et al., 2008). Figure 2 (right panel) shows the radiocarbon age and the age uncertainty (maximum probability intervals at 2 sigma range defined by calibration; Stuiver et al., 1998) of lake-level events used to tune the Joux record with the solar irradiance record (Bard et al., 2000).

The lake-level record gives evidence that lowstands of the water table dominated at ca. AD 1100–1400 (i.e. during MWP), and from 1720 onward, with interruption by short-lived rise events at ca. AD 1340 and 1840. Highstands prevailed at ca. AD 1060–1100, and around AD 1450, 1550, and 1700 (i.e. during LIA). Thus, within the age uncertainty given by the radiocarbon dates obtained from the Joux sediment sequence, the comparison of the Joux lake-level record with a solar irradiance record based on the ^{14}C and ^{10}Be cosmogenic nuclides (Fig. 2; Bard et al., 2000) has been shown to support the hypothesis of a major solar forcing of climate variations in west-central Europe over the last millennium (Magny et al., 2008). This does not exclude the possible impact of other forcing factors such as volcanic eruptions. In agreement with previous studies in the Alpine area (e.g. Mangini et al., 2005; Schulte et al., 2009), these results have been recently replicated from lake-level studies at neighbouring Lake Saint-Point (Fig. 1) in the French Jura Mountains (Magny et al., 2010).

Pollen analysis to reconstruct vegetation cover was carried out from the same samples as for the lake-level study. The main features of the vegetation history as illustrated by the pollen diagram (Fig. 2) are consistent with the regional pollen stratigraphy (de Beaulieu et al., 1994; Gauthier, 2004). The entire sediment sequence was deposited during the Subatlantic pollen zone characterised by the development of *Picea* which reaches more than 25% at the base of the sequence. *Abies* remains well represented and the values of *Fagus* appear to be lower. With respect to the human impact history, the pollen diagram shows that before AD 1420 anthropogenic indicators (AI) show a relatively small human impact. After AD 1420, the AI values increased slightly (agriculture and grazing activities) and were maintained at a

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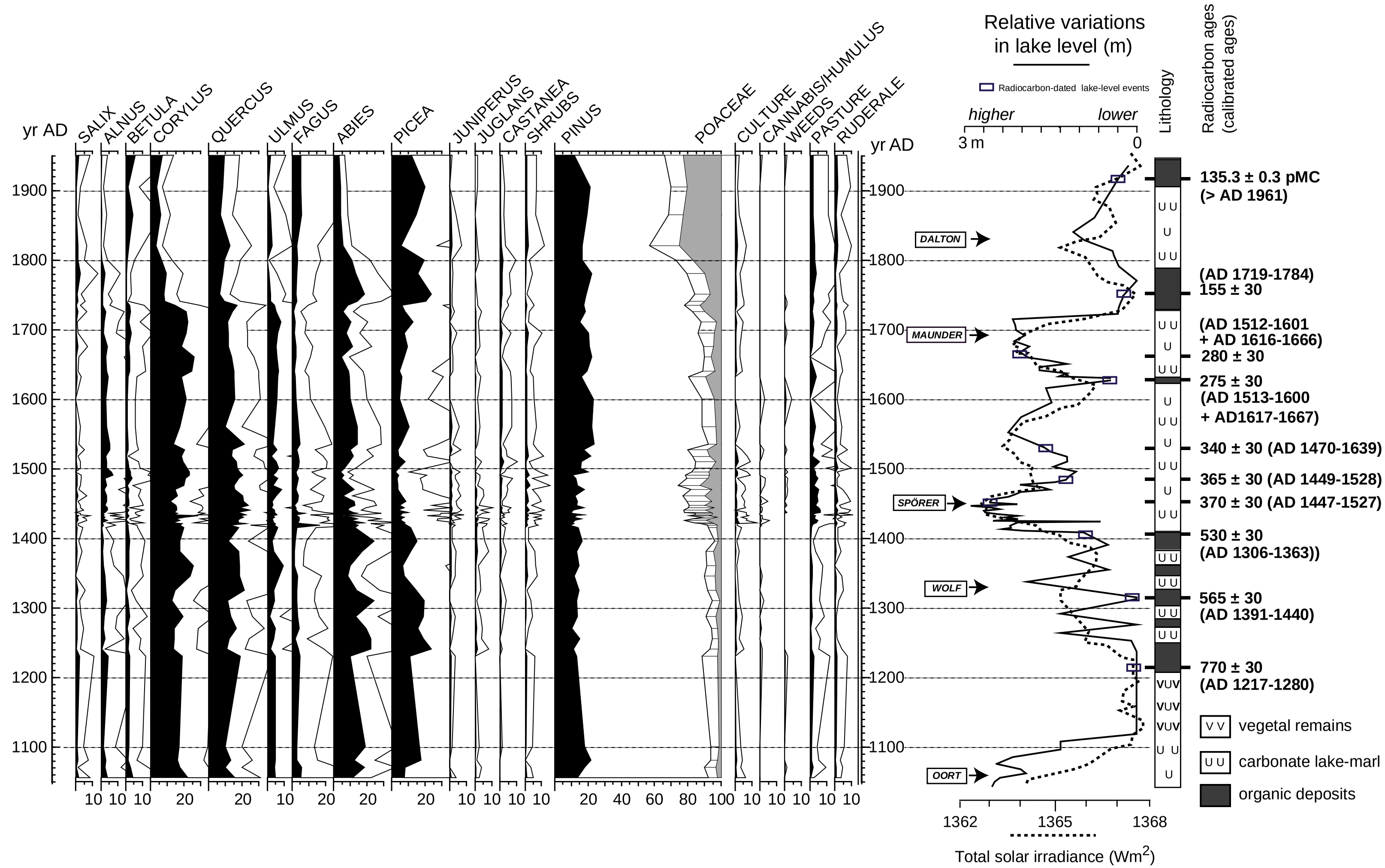

Figure 2. Schematic pollen and lake-level records established at Lake Joux (Magny et al., 2008). In addition to the ten radiocarbon dates presented on the right hand side of the sediment profile, the chronology has been based on the tuning of the lake-level record to the solar irradiance record (dotted line; Bard et al., 2000). The tuning to the solar record is based on constraints defined by the calibration of the radiocarbon dates (Magny et al., 2008). Rectangles on the lake-level curve mark the radiocarbon-dated events, while on the right hand of the sediment profile, the radiocarbon ages and the age uncertainty of these events (calibration with maximal probability intervals at 2 sigma range; Stuiver et al., 1998) are indicated. Arrows indicate solar minimums. Regarding the pollen diagram, Poaceae, Culture, *Cannabis/Humulus*, Weeds, Pasture, and Ruderale are considered as possible anthropogenic indicators (AI).

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very low level without noticeable variations until AD 1700, when AI give evidence of a relatively more marked expansion reflecting the development of industrial activities with glassworks and iron production (Magny et al., 2008). Overall, the pollen record appears to have been relatively weakly affected by human disturbances. In addition to the late human impact which generally characterises high-elevation Jura zones, this probably reflects a damping effect due to the location of the coring site between a large lake and extensive littoral mires.

Materials and methods

The quantitative reconstruction of various climatic parameters for the last millennium is based on both pollen and lake-level data obtained from the Joux sediment sequence and summarised by Figure 2. The method used for the reconstruction is the Modern Analogue Technique 'MAT' coupled with a multi-proxy approach. The MAT was first developed by Overpeck et al. (1985) and extended by Guiot (1990). It is a commonly used and accepted method for the reconstruction of Lateglacial and Holocene climate oscillations from continental and marine sequences (Guiot et al., 1993; Cheddadi et al., 1997; Davis et al., 2003; Peyron et al., 2005; Kotthoff et al., 2008; Pross et al., 2009). The general principle is to find, for each pollen fossil assemblage, several similar modern spectra (or modern analogues) on the basis of an appropriate distance index. The climate of these analogues is averaged to provide an estimate of the fossil assemblage climate. Only the analogues consistent with the lake-level changes (Guiot et al., 1993; Magny et al., 2001; Guiot et al., 2009) are kept.

In the details, the search for analogues is based on the chord distance (Overpeck et al., 1985):

$$d_{ik}^2 = \sum_{j=1}^{m} \left(\sqrt{f_{ij}} - \sqrt{f_{kj}}\right)^2 \quad (1)$$

where f_{ij} and f_{tj} are the relative frequencies of pollen taxon j (out of m = 104 taxa) in modern pollen spectrum i and fossil pollen spectrum k, respectively. Eq. (1) is used to find a set of s (here $s = 7$) closest modern analogues of the fossil spectra. The quality of the reconstruction is expressed by the climate homogeneity of the s analogues. The reconstructed climate value ^0R_t for each fossil spectrum k is the distance-weighted mean (by the inverse of the distance (1)) of the climate values Ci associated with the s best analogues:

$$^0R_t = \left(\sum_{i=1}^{S} C_i / d_{it}^2\right) \Big/ \left(\sum_{i=1}^{S} d_{it}^{-2}\right). \quad (2)$$

Instead of a unique standard deviation around ^0R_t, the lower and upper limits of this mean estimate were computed (confidence intervals). The lower limit LL_t is given by the distance-weighted mean of the analogues (out of the total $s = 7$) with $C_i < {}^0R_t$ and the upper limit UL_t is given by the distance-weighted mean of the analogues with $C_i > {}^0R_t$. These confidence limits implicitly include errors in the modern climate observations (usually small, a few tenths of a °C or a few mm/month), the natural variability of the assemblages for a given value of the climatic variable, and the influence of non-climatic factors.

As discussed by Peyron et al. (in press), statistical tests based on the updated modern pollen dataset which now contains 3500 pollen samples have shown that the observed climate is well reconstructed from the modern pollen assemblages (RMSEP values for the seasonal parameters). As expected, the correlation between observations and reconstructions is good for the temperature variables and less good for precipitation variables. This is due to the fact that precipitation is not a major limiting factor for vegetation in western European mid-latitudes. As shown by Guiot et al. (2009) and exemplified by Figure 4 (see panel PANN), precipitation cannot be inferred in temperate regions with sufficient confidence from vegetation proxies only. Vegetation uses a part of precipitation failing on the ecosystems, a significant part runs off and consequently, a complementary proxy is needed to better infer the total amount of water available within the ecosystem.

Therefore, lake-level data reconstructed at Lake Joux (Magny et al., 2008) provide a useful constraint to improve the reconstruction of precipitation by using a multi-proxy approach. As explained in detail in previous papers (Cheddadi et al., 1997; Magny et al., 2001; Guiot et al., 2009), the analogues incompatible with the lake-level data (i.e. pollen-derived P–E values inconsistent with lake-derived P–E values) were rejected. The procedure was as follows (Magny et al., 2001; Guiot et al., 2009).

- Within a radius of 5° around the lake, all modern sites documented by pollen and climate information were collected and the variable P–E was interpolated by an average of the P–E of these sites weighted by the inverse of the geographical distance. Thus, the modern value $(P–E)_0$ was obtained for the Joux lake.
- For each of the analogues selected for each fossil spectrum, a value δ(P–E) was calculated which is the difference between P–E of the analogue and $(P–E)_0$. For each fossil sample, only the pollen analogues with a $\delta(P–E)_i$ compatible with the lake-level (Cheddadi et al., 1997; Magny et al., 2001; Guiot et al., 2009) were retained, and their climate parameters were averaged.

In this study, the MAT is based on a new modern pollen–climate dataset, which includes more than 3500 pollen samples from moss polsters, top cores, and soil samples from throughout Eurasia, i.e. from the British isles to the Kamtchatka peninsula, and from Scandinavia to the Mediterranean (Bordon et al., 2009). For this work, the seven nearest analogues compatible with the lake levels have been retained. If fewer than five analogues are found, no climate reconstruction is attempted for that sample. Thus, the number of the best analogues selected varies from five to seven through the whole core. As a result, 57 samples (Figs. 3 and 4) have been retained for quantitative climatic reconstruction, i.e. a mean temporal resolution of 17 yr/sample. Beyond this methodological constraint, variations in the temporal resolution of the climatic reconstruction also originate from variations in the sedimentation rate (Magny et al., 2008).

Results

Figures 3 and 4 present the results obtained for four climatic parameters as reconstructed by MAT: MTWA (mean temperature of the warmest month, i.e. July), PANN (annual precipitation), Psum (summer precipitation: June, July, and August), and Pwin (winter precipitation: December, January, and February). The results are shown as anomalies relative to the reference period 1961–1990.

MTWA (Fig. 3). The beginning of the last millennium is punctuated by a negative anomaly in summer temperatures of ca. 1.5°C peaking at AD 1060. From AD 1100 onwards, this short-lived cooling event is followed by warmer summers with a positive anomaly culminating at 2°C at AD 1320. Around AD 1350, a more than 3°C abrupt cooling marks the beginning of a period characterised by generally cooler summer temperatures until ca. AD 1600. The negative temperature anomaly culminates around AD 1440 (ca. 2.8°C). Since AD 1650, the magnitude of temperature changes has decreased, with a positive anomaly (ca. 1.4°C) around AD 1720–1750, and a negative anomaly (ca. 0.7°C) around AD 1840. Overall, one observes that low (high) lake-level conditions prevailed during positive (negative) summer temperature anomalies, except for the period AD 1660–1710 characterised by both high lake-level and relatively warm summer conditions.

PANN (Fig. 4). Considered as a whole, the PANN and lake-level curves show strong similarities with a maximum around AD 1060, minimal values over the period AD 1100–1250, higher values from AD 1250 to 1710, a minimum from AD 1720 to 1790, and a maximum

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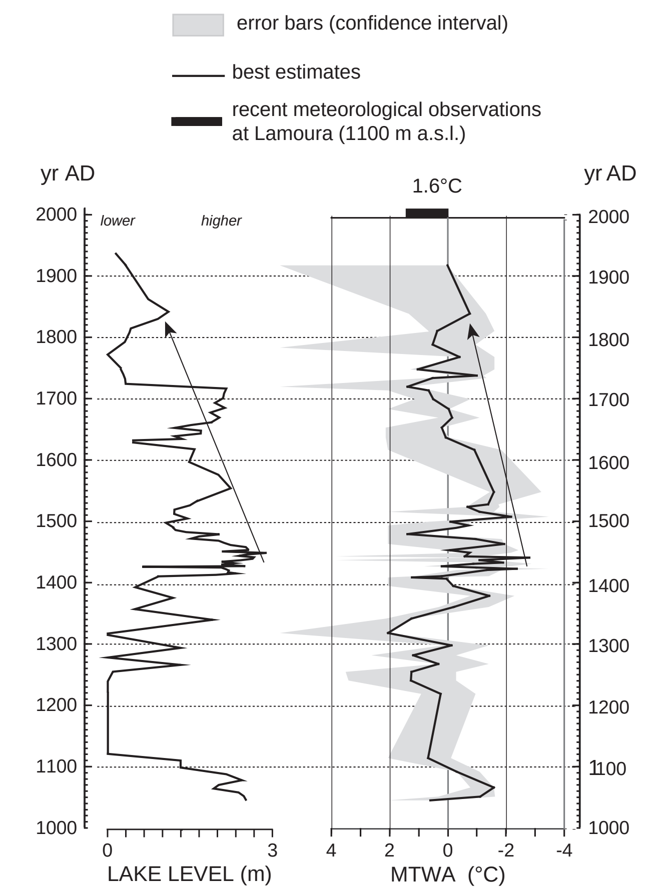

Figure 3. Pollen and lake-level based climate anomalies (MAT) from the Joux sediment sequence for the last millennium: MTWA (mean temperature of the warmest month, i.e. July). Reconstructed positive and negative anomalies are compared to the reference period 1961–1990 (value 0). The black histogram bar represents the mean value of July temperature observed at Lamoura meteorological station (1100 m a.s.l.) for the period 1991–2008 compared to those of the reference period 1961–1990. The black arrows mark long-term trends.

around AD 1840. However, differences also appear between the curves. Thus, from AD 1250 to 1700, PANN gives evidence of a general trend towards increasing precipitation maxima before a last well-marked maximum at AD 1840. Instead, the lake-level record appears to be characterised by a general decrease from a well-marked maximum at ca. AD 1450 to a smaller peak at AD 1840. Taken together, over the last millennium, the magnitude of precipitation changes reaches ca. 400 mm with a maximal positive anomaly of ca. 200 mm and a maximal negative anomaly of around −200 mm.

Psum and Pwin. Figure 4 also allows the seasonality to be observed. Psum and Pwin highlight similar maxima around AD 1060, 1430–1470, and 1840, and minima around AD 1150–1200, and 1750. However, the variations appear to have a larger magnitude for Pwin than for Psum. In addition, with maximal values at ca. AD 1490 and a relatively small peak around AD 1840, Pwin better reflects the general trend marked by the lake-level record than that evidenced by PANN.

Altogether, the temperature and precipitation curves illustrated in Figures 3 and 4 make it possible to distinguish four main successive phases as follows.

- Before AD 1100, the first phase coincides with an event characterised by cooler and wetter climatic conditions than today's. MTWA anomalies reach ca. −1.5°C, and PANN positive anomaly ca. +200 mm. This phase is synchronous with high lake-level conditions.
- After AD 1100 and until ca. AD 1320, climatic conditions appear to have been warmer and drier, with positive summer temperature anomalies (ca. +1 to +2°C for MTWA to ca. AD 1320), and precipitation negative anomalies well marked as early as AD 1120 (abrupt transition at approximately AD 1100). This second phase coincides with generally low lake-level conditions.
- Considered as a whole, the period from AD 1320 to AD 1720 shows cooler and wetter conditions. Concerning temperatures, rapid oscillations are observed, associated with a first rapid decrease in values which reach minima (ca. −2°C) at around AD 1450. This decrease was followed by a progressive increase with anomaly values at ca. 0°C around AD 1700. Precipitation highlights distinct patterns. After minimal values around AD 1230, PANN shows a general trend marked by an increase with a maximal positive anomaly by ca. 200 mm around AD 1640–1720. Pwin gives evidence of a slightly different pattern (which better mimics that of MTWA and lake level), with a progressive increase from the AD 1150–1200 minimum to a maximum around AD 1430–1470, followed by a relative decrease until AD 1720. In general, the period AD 1320–1720 coincides with higher lake-level conditions.
- The period after AD 1720 was characterised by generally warmer and drier conditions interrupted by a short cooler and wetter event around AD 1840 (synchronous with a lake-level maximum). Once again, temperature and precipitation curves indicate distinct patterns of evolution, with relatively less pronounced temperature oscillations and well-marked variations in precipitation. PANN shows an abrupt decrease just after AD 1720, similar to that observed at ca. AD 1100, and a last prominent maximum at AD 1840.

The magnitude of reconstructed changes in precipitation and temperature illustrated by the curves in Figures 3 and 4 does not exceed variations observed from instrumental data during the last 150 years. For instance, precipitation values reached a minimum at 851 mm in AD 1921 contrasting with a maximum at 1990 mm in AD 1930 (Aubert, 1932). However, given the mean temporal resolution of 17 yr/sample reached for the present study, such a comparison to modern interannual extremes may be not really representative. Unfortunately, the artificial regulation of the lake level at the beginning of the twentieth century, in addition to the discontinuity of recent meteorological data series for the Joux Valley, prevent a comparison of reconstructed values with those observed in the region after AD 1900 and more particularly since 1990 (recent reinforcement of global climate warming).

Discussion

Climatic conditions and variations in the solar irradiance

With respect to the climate history of the last millennium, the curves in Figures 3 and 4 give evidence of the successive climate periods generally recognised within the last 1000 years: (1) a MWP between ca. AD 1100 and 1320, preceded by a short-lived cooling event around AD 1060, (2) a LIA which, in the Joux Valley, initiated as early as ca. AD 1350 and ended at ca. AD 1870, and (3) a last warmer and drier period (pre-industrial warming) interrupted by a short-lived event centred at ca. AD 1840 with cooler and wetter conditions.

Interestingly, keeping in mind that the Joux record has been tuned to the solar irradiance record (see Fig. 2), the successive phases of solar activity during the last millennium appear to correspond to various patterns of changes in temperature and precipitation in the Joux Valley as follows:

- The solar Oort minimum (around AD 1060) coincided with a short cool wet event in the early part of the millennium, as clearly shown by a synchronous signal of the four reconstructed climatic parameters.
- The MTWA curve suggests that the LIA may have been initiated ca. AD 1350, i.e. around the solar Wolf minimum.

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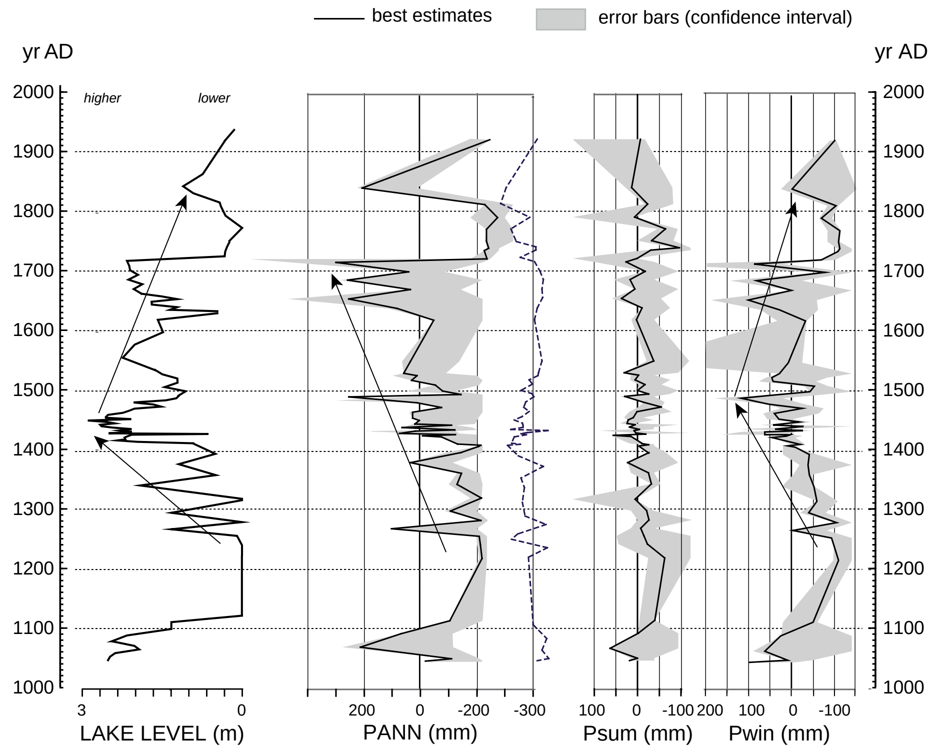

Figure 4. Pollen and lake-level based climate anomalies (MAT) from the Joux sediment sequence for the last millennium: PANN (annual precipitation), Psum (summer precipitation), and Pwin (winter precipitation). The black arrows mark long-term trends. In panel PANN, an additional dotted line shows the curve of annual precipitation reconstructed using pollen data only (without the constraint by lake-level).

- The solar Spörer minimum (around AD 1450) coincided with the lowest values of MTWA and maximal Pwin.
- Before AD 1700, the solar Maunder minimum does not appear to coincide with a marked cooling, but with relatively warm conditions, high values of Pwin, and maximal PANN.
- Around AD 1850, the solar Dalton minimum corresponded to a moderate cooling, but to a pronounced PANN maximum.
- Finally, the two phases of rapid increase in the solar irradiance around AD 1100 after the Oort minimum, and AD 1720 after the Maunder minimum appear to have been synchronous with two periods of rapid and major changes towards drier conditions well illustrated by the curves of PANN and Pwin.

All together, these data may suggest that during the LIA, in the Joux Valley, the Spörer minimum was characterised by a cooling maximum and *relatively* dry winters. By contrast, *relatively* mild temperatures but also maximal humidity prevailed during the Maunder minimum.

Considering the question of present-day global warming on a regional scale, the increase in MTWA by ca. 1.6°C observed at Lamoura (1100 m a.s.l., near the Joux basin, see Fig. 1) for the period 1991–2008, when compared to the reference period 1961–1990, still appears to be in the range of the positive temperature anomaly reconstructed at Lake Joux ca. AD 1300 during the late MWP. Meteorological data observed at La Brévine (1043 m a.s.l.; Fig. 1) suggest a similar pattern with an increase in MTWA by 1°C over the period 1991–2008.

Temperature changes in the Jura Mountains and in the neighbouring Alpine areas

Figure 5 presents a comparison of the Joux MTWA curve with other regional summer temperature records reconstructed in the neighbouring Alpine area for the last millennium (except for that from the Austrian Alps which registered annual temperature), i.e. a chironomid-based summer temperature record from Lake Anterne (2060 m a.s.l.) in the French Alps (Millet et al., 2009; Fig. 1), an annual temperature record from $\delta^{18}O$ stalagmite record in the central Alps (Spannagel Cave in Austria; Mangini et al., 2005), and two summer temperature records from tree-ring series in the Swiss Alps (Büntgen et al., 2005, 2006) based on two distinct methods (Maximum latewood Density: MXD, and Ring Width: RW). All these records present clear similarities in the general climate history over the last millennium, but also some discrepancies in the details. Such differences between regions and/or between records from the same region, point to the possible role of internal climatic variability, which makes it unlikely that there were synchronous peak temperatures during the MWP and LIA between different locations (Goosse et al., 2005). However, they probably also point to uncertainties in methodology used for quantitative reconstructions and in our understanding of what climate information is recorded within the proxies (Schmidt and Masson-Delmotte, 2009).

- All the records in Figure 5 allow identification of a MWP culminating between ca. AD 1200 and 1300.
- This MWP was preceded by a short-lived cooling event around AD 1050–1100 well marked in the Lake Joux and Anterne records and in the tree-ring MXD record (Büntgen et al., 2006). Possibly due to uncertainty in the chronology, this event in the Anterne record appears to have occurred a little later than in the Joux and the Swiss Alps records. However, one observes that neither the Austrian $\delta^{18}O$ stalagmite record nor the Swiss tree-ring RW record give a clear evidence of such a cooling event possibly related to the solar Oort minimum (ca. AD 1060, see Fig. 2).
- In general agreement with the AD 1300 to AD 1450 MWP-LIA transition defined by Trouet et al. (2009), all records show the initiation of a cooling trend around AD 1300–1350 marking the end of MWP and the beginning of LIA. In the Joux, Anterne and Spannagel Cave records, the cooling culminated around AD 1450.

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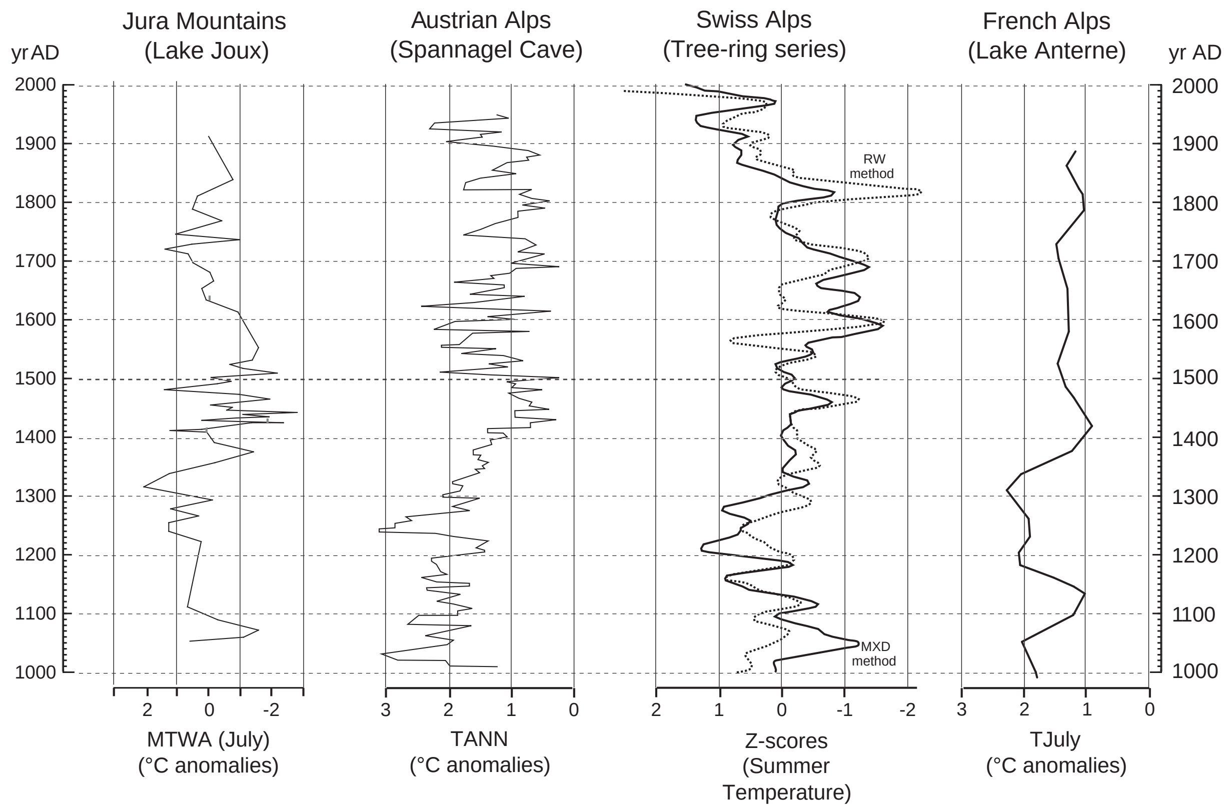

Figure 5. Comparison of the Joux summer temperature record with other regional temperature records from neighbouring Alpine areas: Spannagel Cave in the Austrian Alps (Mangini et al., 2005), tree-ring based records from the Swiss Alps (MXD: maximum latewood density, RW: ring width; Büntgen et al., 2005, 2006), Chironomid-based record of Lake Anterne, northern French Alps (Millet et al., 2009).

However, the Swiss tree-ring records show a maximal cooling around AD 1600 (MXD record) and AD 1820 (RW record).

- Unless the reconstruction uncertainty is taken into account, the Maunder minimum period (around AD 1690) does not correspond to a well-marked MTWA minimum in the Jura Mountains, in contrast to the picture given by other records. However, these warm conditions reconstructed for the Joux Valley correspond well to the reconstruction of relatively warm summer temperatures in Europe during the Maunder minimum by Luterbacher et al. (2004), Etien et al. (2008) and Guiot et al. (2010).

Precipitation changes in the Jura Mountains and in the neighbouring Alpine areas

Figure 6 compares the Joux record with other precipitation records available for the last five centuries in the Alpine area, i.e. mineralogy-

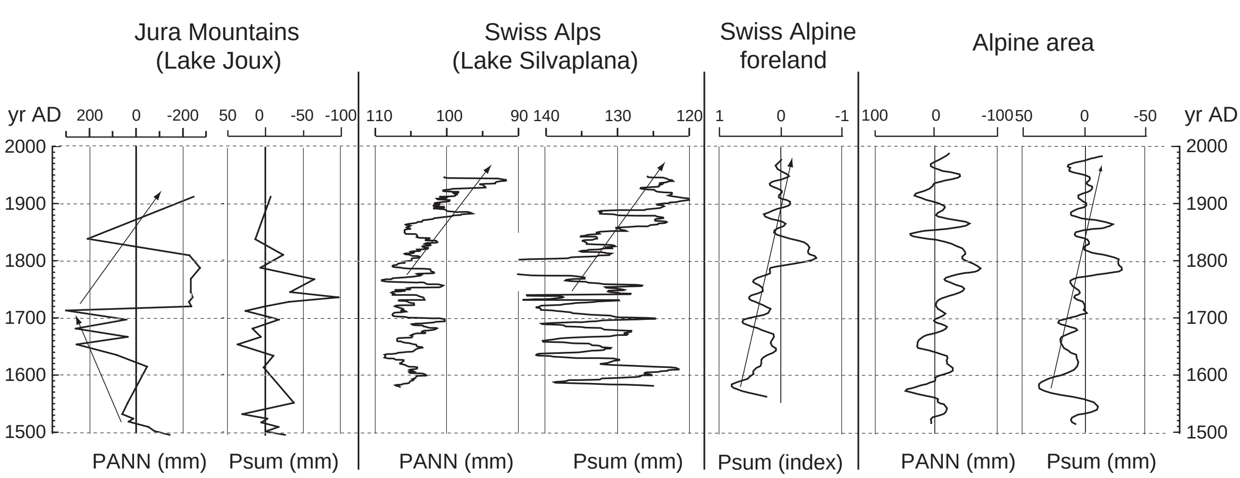

Figure 6. Comparison of the Joux precipitation records with other precipitation records from neighbouring Alpine areas: mineralogy-based record of Lake Silvaplana in the Swiss Alps (Trachsel et al., 2008), documentary archives-based record from the Swiss foreland (Pfister, 1995; Wanner et al., 2000), records for all the European Alps based on instrumental data and documentary proxy evidence (reference period: 1901–2000; Casty et al., 2005).

based records (PANN and Psum) from Lake Silvaplana, Swiss Alps (Trachsel et al., 2008; Fig. 1), a summer precipitation record established for the Swiss Alpine foreland from documentary archives (Pfister, 1995; Wanner et al., 2000), and PANN and Psum records reconstructed for the whole Alpine area by Casty et al. (2005) from a combination of instrumental data and documentary proxy evidence.

Bearing in mind the difficulties due to differences (1) in the methods used for reconstruction, (2) in the temporal resolution and the chronological precision, and (3) in the extent of the documented areas, and also considering only the general trends highlighted by these records, most of the curves in Figure 6 suggest wetter conditions during LIA than afterward, in agreement with the general picture given by the Joux PANN record (see also Fig. 4), or with the summer precipitation record established for Europe by Pauling et al. (2006). This general evolution appears to be less clear in the records established by Casty et al. (2005) for the European Alps, particularly in the PANN curve. This may reflect (1) heterogeneity of the data and the large extent of the area under consideration in Casty et al.'s study, or (2) effects of the seasonality as illustrated by the Joux PANN and Psum reconstructions (Figs. 4 and 6). Such increasing humidity during LIA in west-central Europe is also supported by the general advance of glaciers in the Alpine area (Holzhauser et al., 2005; Magny et al., 2010), by marked river floods in the Swiss Alps dated to AD 1100, 1550 and 1830 (Schulte et al., 2009), and, on a general scale, by model experiments (Raible et al., 2007).

Possible influence of the NAO

As possible forcing factors and atmospheric mechanisms behind the climate change observed over the last millennium in Europe, variations in solar irradiance, volcanic eruptions (e.g. Crowley, 2000), and NAO influence (e.g. Wanner et al., 2001; Cook et al., 2002) are among the most discussed causes and phenomena. As discussed by Trouet et al. (2009) and supported by marine proxy data (Lund et al., 2006; Sicre et al., 2008), atmospheric changes in the NAO modes may have been coupled with changes in the Atlantic meridional overturning circulation. Moreover, GCM experiments have shown how an increase (decrease) in solar irradiance may force a shift towards a high (low) index state of the NAO (Shindell et al., 2001, 2003).

Panel A in Figure 7 presents a comparison between the total solar irradiance (TSI) record (Bard et al., 2000) and the NAO_{ms} record established by Trouet et al. (2009) for the last 1000 years. Interestingly, this NAO_{ms} index is expressed in terms of a hydrological signal from a combination of a speleothem-based winter precipitation record for Scotland and of a tree-ring-based drought record for Morocco, i.e. two strategic places and indicators sensitive to atmospheric variations in the northern and southern modes of the NAO dipole. Considered as a whole, the NAO_{ms} curve actually shows generally strong correspondences with the TSI record from AD 1050 to AD 1700: higher TSI before AD 1400 coincided with higher NAO_{ms} index, i.e. with persistent positive NAO mode as established by Trouet et al. (2009). Conversely, the development of solar irradiance minima between AD 1400 and 1700 (LIA) corresponded to more negative NAO_{ms} index. As additional tests, panels B and C in Figure 7 show a comparison of the NAO_{ms} record with (1) the Pwin curve reconstructed at Lake Joux, and (2) the Joux lake-level record. Both the Joux Pwin and lake-level records have been tuned to the TSI record (see Figure 2; Magny et al., 2008). Thus, panels B and C offer other illustrations of possible links between variations in the solar activity,

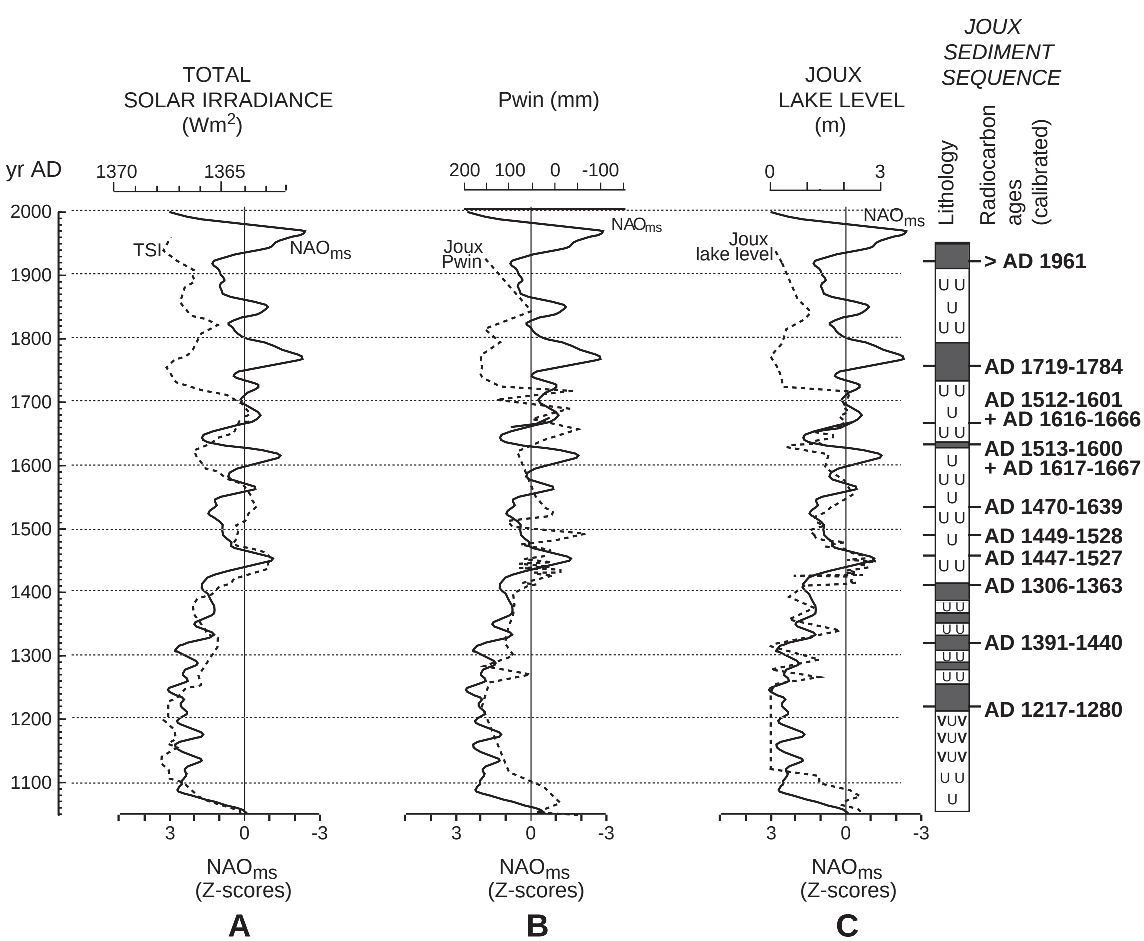

Figure 7. Comparison of the NAO_{ms} index (Trouet et al., 2009) with the Total Solar Irradiance (TSI) record (Bard et al., 2000) (panel A), the Joux Pwin record (this study) (panel B), and the Joux lake-level record (tuned to the TSI record, see Fig. 2; Magny et al., 2008) (panel C).

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the NAO index, and the climate in the Swiss Jura Mountains. The close correspondences between the Joux Pwin and lake-level records and the (winter) NAO_{ms} index may reflect a crucial influence of spring snowmelt (i.e. winter precipitation) on the water table of Lake Joux (see above, section 2). Figure 7 shows that the lake-level record appears to better match the NAO record than the Pwin record does. This probably results from the fact that the Pwin record is restricted to three months (December, January, and February), whereas the lake-level record reflects the entire rainy and snowy season. Such a NAO control on climate history during the last millennium in the Jura Mountains has also been suggested by Stoffel et al. (2009) from an ice accumulation record in an ice cave at Saint-Livres (Fig. 1).

As developed by Wanner et al. (2001) and Trouet et al. (2009), during negative NAO-phases, the Azores High is weakened, resulting in a southward move of westerlies and an increase in moisture transported over the European mid-latitudes. Moreover, in western Europe, a temperature decrease reflects a decrease in the Atlantic meridional overturning circulation (Trouet et al., 2009) and an extension of the Siberian High (Wanner et al., 2001). As a result, increasing winter snow precipitation (and associated spring snowmelt), combined with summer cooling (and associated evaporation decrease), may explain higher lake-level conditions such as those observed at Lake Joux during LIA (Figs. 3 and 4). Inverse processes have prevailed during the MWP marked by dominant positive NAO (Trouet et al., 2009). As predicted by the NAO general pattern, it is noteworthy that the Joux region in west-central Europe presents an opposite evolution to that reconstructed by Luoto and Helama (2010) in eastern Finland, where they observed high (low) winter precipitation during positive (negative) NAO-phases. Instead, at Lake Joux, positive (negative) NAO-phases corresponded to low (high) winter precipitation.

After ca. AD 1700, the NAO_{ms} and the Joux (or TSI) records appear to be disconnected. This may reflect various causes. Goosse et al. (2005) have pointed to the fact that many uncertainties still exist on the impact of external forcing on the NAO. Nevertheless, they also observe that their model does not include stratospheric dynamics as does that used by Shindell et al. (2001). In addition, during the Holocene, a possible solar modulation of the NAO has been suggested by various studies (see for instance Mangini et al., 2007, for the mid-Holocene in the Caribbean, or Proctor et al., 2002, for the late Holocene in NW Scotland). Finally, while the NAO_{ms} record established by Trouet et al. (2009) shows strong correlations with the Lisbon–Iceland instrumental NAO index series over the 20th century, recent studies have also given evidence of a possible modulation of NAO by solar forcing during the last century (e.g. Boberg and Lundstedt, 2002; Kodera, 2002; Gimeno et al., 2003). Moreover, these studies have pointed to the fact that the solar modulation of NAO may be more effective with a higher level of solar activity (Kodera, 2002; Gimeno et al., 2003). This could explain (at least in part) the observation by Casty et al. (2005) that correlations between the NAO index and Alpine climate (temperature and precipitation) have been temporally unstable during past centuries. These authors also point the particular situation of the Alps and the Jura Mountains in an intermediate band of varying influence of the NAO.

In conclusion, the apparent disconnection between NAO and TSI records after AD 1700 illustrated by Figure 7 remains an intriguing feature. A clear indication is given that more studies based on long-term proxy-based reconstructions and model experiments are needed in the future to establish further high-resolution NAO index time series and to examine underlying mechanisms of the NAO variability on different time scales.

Conclusions

Using a multi-proxy approach with pollen and lake-level data from Lake Joux, and on the basis of the Modern Analogue Technique, this paper focuses on quantitative climate estimates for the last millennium in the Swiss Jura Mountains.

Results show warmer and drier conditions during the MWP. The MWP was preceded by a short-lived cold humid event at ca. AD 1060, and followed by a rapid return around AD 1400 to cooler and wetter conditions which generally characterize the LIA. During the solar Spörer minimum (around AD 1450), LIA attained a temperature minimum and a summer precipitation maximum. In the Joux valley, the solar Maunder minimum around AD 1690 corresponded to rather mild temperature but maximal annual precipitation.

These results show a general agreement with other records from neighbouring Alpine regions. Differences also appear in the details, particularly for the timing of the LIA temperature minimum depending on the method and/or the proxy used for the reconstruction.

As a working hypothesis, the hydrological signal associated with the MWP and LIA oscillations at Lake Joux may have been mainly driven by a shift around AD 1400 from positive to negative NAO modes in response to variations in solar irradiance. This external forcing may have been coupled with changes in the Atlantic meridional overturning circulation. Further investigations are needed to test an apparent disconnection between (1) NAO and (2) Lake Joux and solar irradiance records after AD 1700.

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