Climatic variability in the northwestern Alps, France, as evidenced by 600 years of terrigenous sedimentation in Lake Le Bourget

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Received 15 March 2000; revised manuscript accepted 15 January 2001

Abstract: Cores recovered from periglacial Lake Le Bourget deep basin (northwestern Alps) were investigated to examine the influence of the 'Little Ice Age' (LIA) on terrigenous lacustrine sedimentation. Growing glaciers in the regional watershed induced catastrophic Rhône river floods and major underflow deposits in the deep basin during the early fifteenth, the sixteenth and the mid-eighteenth centuries. The LIA is characterized by a decrease in deposition from interflows from AD ~1550 to 1740 and an increase in deposition from underflows from AD ~1550 to 1800. On one hand, spectral analyses of the laminations in interflow deposits reveal 4–5 years cyclicities from AD ~1440 to 1550, as well as 7–8 and 13–14 years cyclicities from AD ~1740 to 1870; on the other hand, spectral analyses of a clay mineral ratio reflecting underflow deposits highlight 45–50 years cyclicities from AD ~1550 to 1800. These pluriannual, decadal and pluridecadal periods are typical of the North Atlantic Oscillation (NAO). A NAO-like period in our data would be a consequence of periodical variations in rainfall and snow accumulation during late autumn and winter over Lake Le Bourget's watershed.

Key words: Alps, 'Little Ice Age', North Atlantic Oscillation, terrigenous lacustrine sedimentation, spectral analysis, watershed palaeohydrology.

Introduction

Among climatic fluctuations on a Holocene millennial timescale recently discussed in several marine, glacial and continental settings (Barber *et al*., 1999; Bianchi and McCave, 1999; Magny, 1993; Von Grafenstein *et al*., 1999), the 'Little Ice Age' (LIA) has been the most studied during the last decades. Global effects for the LIA include glacier fluctuations in Northern and Southern Hemispheres (Villalba *et al*., 1990; Matthews and Karlén, 1992; Leeman and Niessen, 1994; Magny, 1995; Desloges and Gilbert, 1995; Luckman, 1995; Seramur *et al*., 1997; Holzhauser and Zumbühl, 1999; Carlson *et al*., 1999), flow changes in North Atlantic thermohaline circulation (Bianchi and McCave, 1999), and stronger Southern Ocean deep-water formation (Broeker *et al*., 1999). In the northwestern Alps, the LIA has also been related to an increase in hydrologic budgets, producing lake-level transgressions in the Jura mountains (Magny, 1995), and intense flooding in Alpine valleys, which induced a fluvial geomorphological evolution from meandering to braided patterns (Bravard, 1989; Bravard and Peiry, 1993).

The LIA culminated during the years AD 1550–1850, but, depending on altitudes and geographic positions, evidence for earlier cold periods was reported dating back to the end of the thirteenth century (Le Roy Ladurie, 1967; Bravard, 1989; Luckman, 1995; Holzhauser and Zumbühl, 1999). Several studies also emphasized the influence of solar minima (Wolf minimum ~ AD 1300–1350; Spörer minimum ~ AD 1440–1550 and Maunder

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 0959-6836(02)HL520RP

minimum ~ AD 1650–1720) on Northern Hemisphere climatic fluctuations during the Middle Ages (Beer *et al*., 1991; Glenn and Kelts, 1991; Magny, 1993; Stuiver, 1993; Stuiver and Braziunas, 1993; Beer *et al*., 2000).

Based on a multidisciplinary analysis of lacustrine sediments, the present study describes the impact of the LIA on terrigenous sedimentation in a peri-Alpine lake at 45°N, and discusses climate variability over the last 600 years. Lake Le Bourget's sedimentary infill and present-day depositional environments have been studied using high-resolution seismic surveys, side-scan sonar mapping and high-resolution sedimentary analysis based on short coring as well as grab samples (Chapron *et al*., 1996; Chapron, 1999; Van Rensbergen *et al*., 1999).

Settings

Lake Le Bourget (18 km long, 2–3 km wide, 146 m deep) is a 'fjord-lake' of glacial origin located in a tectonically active area (45°N 45′; 5°E 52′), within the Tertiary molasse basin at the periphery of Subalpine massifs and the Jura mountains (Figure 1). Since the Rhône river, which first filled up the northern part of the basin, bypassed the lake during the Preboreal (Bravard, 1989), only large Rhône river floods are currently entering the lake through its outlet (the Savière canal; Figure 1) and/or the Châutagne swamp. This drastic decrease in terrigenous sediment delivered to the basin, together with the climate warming, favoured a mainly authigenic Holocene sedimentation that formed a 15 m thick lacustrine drape clearly visible on seismic profiles. In the vicinity of major inlets (Leysse and Sierroz rivers, and sporadically the Rhône river; Figure 1), under- and interflows feed lacustrine delta fans during autumn and winter floods and delta bottomsets during spring and summer floods respectively (Chapron, 1999). These two different flood-induced sedimentary processes and related deposits are controlled by the density contrast between the inflowing water and the lakewater, density being related to water temperature and suspended load (Stürm and Matter, 1978). When inflowing water is denser than lakewater, an underflow will form, but when inflowing water is less dense than lacustrine deep waters, it will be trapped above the lakewater thermocline and an interflow will form.

The catchment area of Lake Le Bourget is characterized by a 'local' pluvionival watershed related to the Leysse and Sierroz rivers (629 km^2, culminating at 1845 m, mean altitude being 700

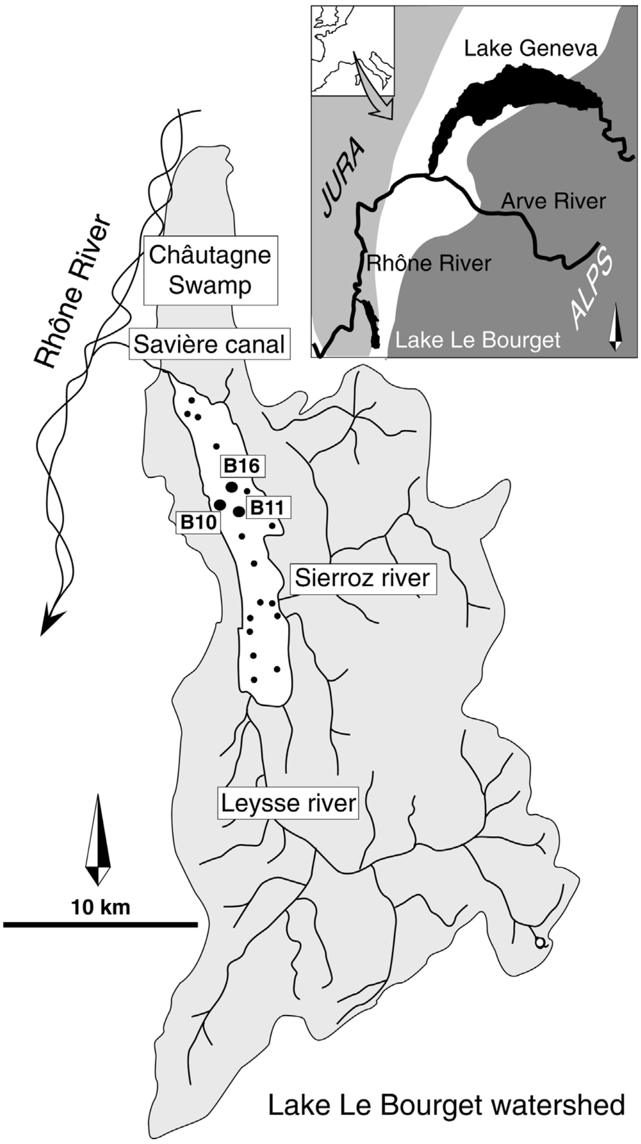

Figure 1 Simplified sketch map of the study area, showing Lake Le Bourget's regional setting and its local drainage basins (Sierroz and Leysse rivers). The Rhône river only discharges into the northern part of the lake during large floods. This regional drainage basin, South of Lake Geneva, is dominated by the Arve river. Among the studied cores in Lake Le Bourget, cores B10, B16 and B11 were analysed in detail to document the evolution through time of Rhône river floods.

m); and a sporadic 'regional', nival to pluvionival watershed associated with the Rhône river system flowing south of Lake Geneva (4000 km^2, culminating at 4808 m and mainly related to the Arve river supply; Figure 1).

Data description

During a benthos coring survey in 1997, the different sedimentary environments identified by side-scan sonar mapping were sampled. Among them, three cores have been acquired in the deepest part of the lake within the lacustrine plain (>130 m water depth), distally fed by both drainage basins (Figures 1 and 2). Generally, these cores consist of faintly laminated grey marls and discontinuous fine black laminations, but the uppermost centimetres are dark and light rythmites characterized by an exponential increase in organic matter (Figure 2). Sediments contain 40 to 60% of bio-induced micrite mixed with siliciclastic silty clay (<2 μm: 25–35%). Sporadic dark clayey flood deposits occur which differ slightly from the host mud in the basin, and present different facies according to their location within the lacustrine plain. In the basin axis and along the highest slope gradient (cores B16 and B11), distal underflow-type flood deposits (Rhône or Sierroz river supply) present a sharp base, sometimes containing organic debris (leaves, branches) and can reach more than 1 cm in thickness (Figure 2). Along the western part of the lacustrine plain (core B10), distal interflow-type flood deposits (Rhône river supply deflected to the west by winds and Coriolis force) are thinner, without organic debris and present no clear contacts. At this site, a fine lamination is formed by interflow deposits, but some lateral underflow deposit can also exist, during major floods of the Rhône river (Figure 2). These sedimentary environments are also visible at a larger scale on seismic data, and in the vicinity of delta regions on side scan sonar mapping (Chapron, 1999).

Methodology

Age-depth model

^{210}Pb and ^{137}Cs dating, using a sampling interval of 1 cm on the upper 20 cm of core B11, allowed us to clearly identify supported and not-supported ^{210}Pb fractions, and to define a sedimentation flux (dry sediment) of 852 g m^{-2} yr^{-1} for this century, corresponding to a sedimentation rate of 0.13 cm yr^{-1} (Figure 2). The resolution of this dating is limited by the sampling interval (eight years), as indicated by the depth of ^{137}Cs peaks associated with Chernobyl accident in 1986 and nuclear tests in 1965. A detailed description of the dating method is given in Pourchet *et al.* (1994). This dating was further confirmed: (1) by the correlation of a thin distal turbidite rich in carbonate (Figure 2) with an earthquake located on the lake shore in AD 1958 (Chapron, 1999); and (2) by the correlation of the base of the rythmite facies (AD 1943 ± 8 yr) with the onset of the lake's anthropogenic eutrophication in AD 1942 (Girel, 1991). The extrapolation of this sedimentation

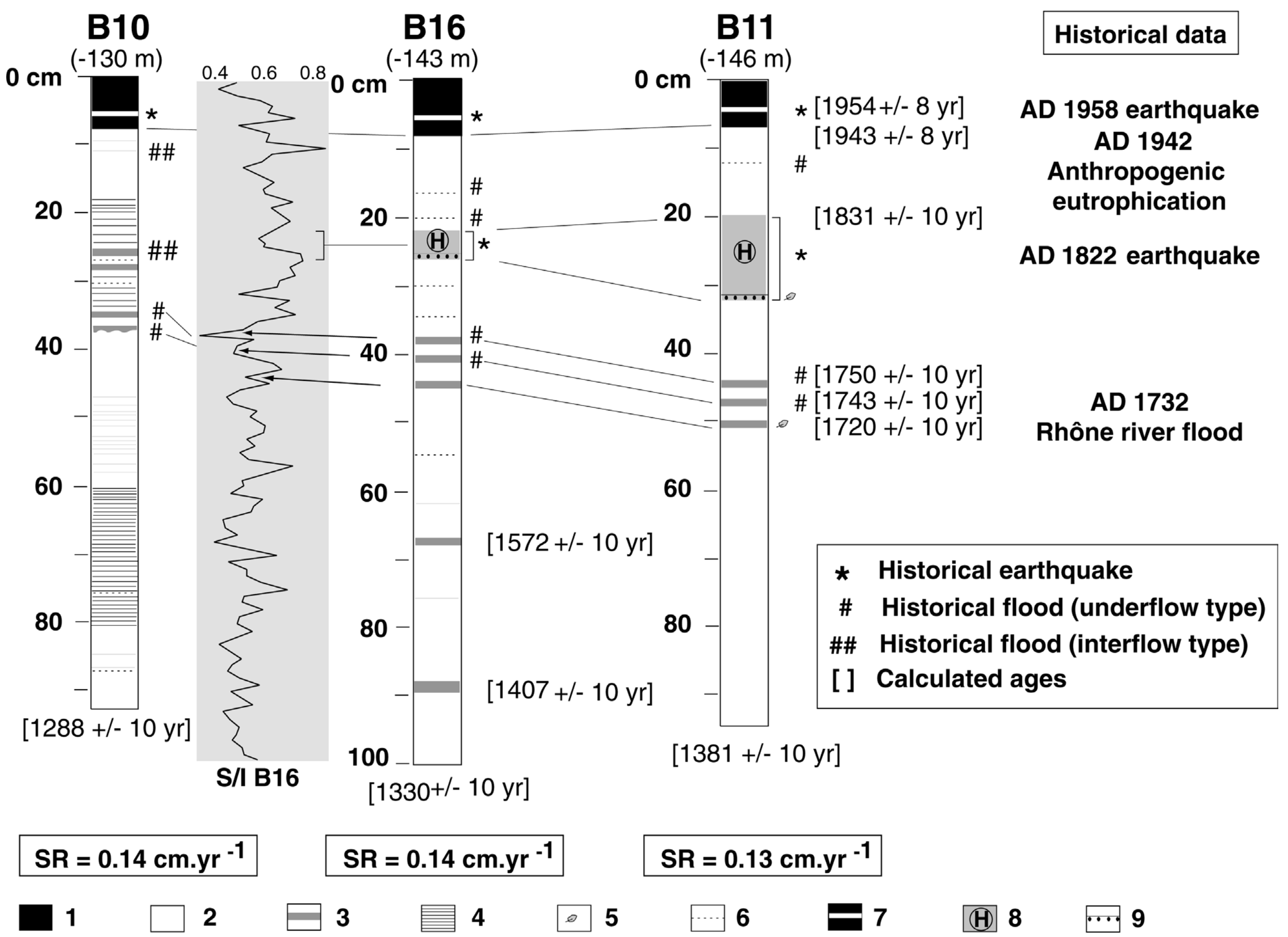

Figure 2 The lithologies of cores B10, B11 and B16 are presented, as well as correlation using ^{210}Pb and ^{137}Cs dating on core B11 and historical data. Because the thickness of the AD 1822 earthquake-induced homogenite is not constant and only present in the deepest part of the basin, the depth of the AD 1732 underflow deposit is different in each core. The smectite/illite ratio (raw data) from core B16 is also presented, and minimum S/I values are associated with Rhône river floods. In these age-depth models, the thicknesses of event layers (homogenite and flood deposits) were substracted. SR = sedimentation rate. (1) Anthropogenic eutrophication producing a rythmite facies. (2) Faintly laminated marls. (3) Major underflow deposits. (4) Lamination produced by interflow deposits. (5) Organic debris. (6) Organic layer. (7) Turbidite. (8) Homogenite. (9) Sandy layer.

rate to older sediments with a 10 years resolution allowed us to correlate a number of event deposits in core B11 with historical data (the thickness of the event layers being subsequently subtracted; Figure 2): the AD 1822 earthquake-induced homogenite and the AD 1732 underflow deposit which is the oldest historical flood of the Rhône river (Chapron *et al.*, 1999). Age-depth models in other studied cores are based on the thickness of the rythmite facies. These sedimentation rates are confirmed in eight cores where the AD 1958 turbidite is present. These sedimentation rates were also extrapolated to older sediments and the resulting age/depth was supported: (1) by the correlation of the AD 1822 homogenite in four cores from the deep basin; (2) by the correlation of a major underflow deposit across the basin (13 cores) with the AD 1732 flood; and (3) by the correlation of most of inter- and underflow deposits next to Sierroz and Leysse deltas (not shown) with main historical floods in the local watershed (Chapron, 1999).

Rhône river flood proxies

In order to define the evolution of Rhône river floods during the last 600 years, it has been necessary to study the evolution of inter- and underflow deposits in two different cores with two different proxies. Clay minerals assemblages were studied with a sampling rate of 1 cm (corresponding to eight years) in core B16, to document the evolution of underflows, whereas evolution in interflow deposits were documented using grey level measurements by video-capture on core B10 with an original sampling interval of 200 μm, resampled every 1 mm (corresponding to less than a year). The general trend of the grey-level signal was then removed from the raw data, by resampling every 10 cm and substracting the resampled time-series from the original signal.

Concerning the clay mineral assemblages, a different mineralogical signature from the 'local' and 'regional' watersheds was first established, based on samples on land (main lithologies and rivers within the 'local' watershed), in Rhône river sediments (sampled during upstream dam emptying) and in surficial sediments of Lake Le Bourget (120 grab samples). These measurements revealed a higher illite content in Rhône river sediments (55% of the clays) and in the northern half of the lake (>40%), but a higher smectite content in the 'local' watershed (ranging from 40 to 60%) and the southern half of the lake (>30%). Thus the smectite/illite ratio (S/I ratio) can be regarded as a proxy for the 'local'/'regional' drainage basin balance through time, reflecting precipitation regimes (or palaeohydrology) over more than 4600 km^2 in the northwestern Alps.

The downcore evolution of the S/I ratio in core B16 was established on x-ray diffractograms from oriented mounts. Deflocculation of clays was done by successive washing with distilled water after decarbonatation of the crushed sample with 0.2 N HCl. The clay fraction was separated by sedimentation and centrifugation (Brown and Brindley, 1980). Three x-ray diagrams were recorded for each sample, after air-drying, after ethylene-glycol solvation and after heating at 490°C for two hours. The identification of clay minerals was made according to the position of the (00l) series of basal reflections on the three x-ray diagrams (Brown and Brindley, 1980; Reynolds, 1980; Moore and Reynolds, 1989). Clay mineral assemblages are dominantly composed of smectite, illite and kaolinite with minor amounts of chlorite. The S/I ratio has been measured on each sample. It corresponds to the ratio between the intensity of the 17 Å peak of smectite and the intensity of the 10 Å peak of illite measured on x-ray diagrams after glycolation. This ratio in core B16 is characterized by lower values associated with historical Rhône river underflow deposits (Figure 2).

To obtain a continuous clay-mineral signal on core B16 (Figure 3), the thicknesses of the event layers (homogenite and flood events) were extracted. The long-term variation (corresponding to a gradual enrichment in smectite) was also removed by subtracting from the raw data a 15-point moving average reflecting the global trend of the S/I signal.

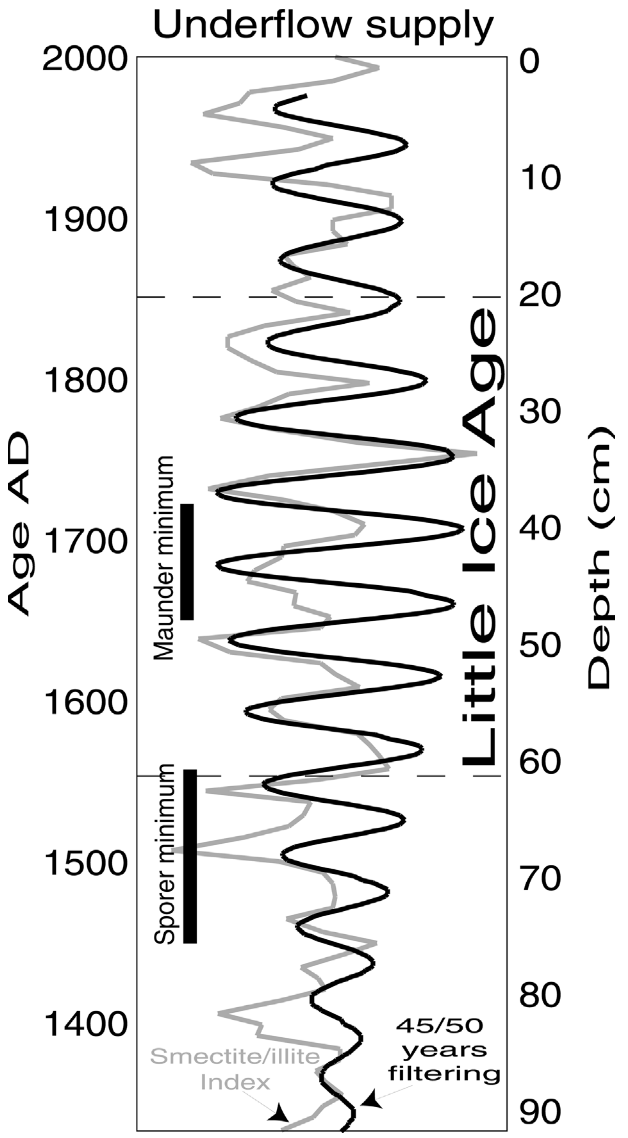

Figure 3 Smectite/illite index from core B16 is shown after extraction of the general trend and the thicknesses of the event layers. This proxy reflects the balance between local (Sierroz, Leysse) and regional (Rhône, Arve) watershed sediment supply to the lake floor by underflows. Superimposed on the smectite/illite ratio is the result of a Gaussian filtering centred at 45–50 years, which is the main period reported by the spectral analysis. The filter amplitude is especially high from AD ~1550 to 1800.

Spectral analysis

The different signal-processing techniques used to analyse our data sets are described in detail elsewhere (De Putter *et al.*, 1998), and involved the Multi Taper Method (MTM), the Blackman-Tuckey method (BT) and the Maximum Entropy Spectral Analysis (MESA). The MTM method provides a statistical test (Fischer-Snedecor test) for the significance of the amplitude spectra. As recommended by Berger *et al.* (1990; 1991) and Yiou *et al.* (1996), the results obtained with MTM were confronted with other methods (BT and MESA) in order to reduce the possibility of spurious results due to a bias of one particular method and to evaluate the variance and the stability of the results.

Results

Spectral analysis (MTM, BT and MESA) of the S/I signal (core B16, 92 data) allowed us to identify only one highly significant (>97%) period at 45–50 years. To evaluate the stability of this period, the spectral analysis was completed by a Gaussian filter applied to the S/I time-series and centred at 45–50 years (Figure 3). The filter amplitude, especially well expressed between AD ~1550 and 1800, is linked with the occurrence of the 45–50 years cycle in the clay-mineral signal.

Spectral analysis (MTM, BT and MESA) of the grey-level signal (core B10, 921 data) identified three highly significant (>98%) periods at 4–5 years, 7–8 years and 13–14 years. In addition to the global analysis of this time-series, a band-pass mapping technique was performed in order to estimate the time stability of the detected frequency periods (Figure 4). It has been done by the use of successive windows corresponding to 20 cm of grey-level record, moving down the time-series with a 90% offset. The process was repeated all the way down the core. The spectra were then stacked to form a grid smoothed with a two-dimensional Gaussian filter and contoured like a map. The result (Figure 4) provides a visual impression of the changes in the frequency composition of the time-series. It exhibits a superimposed multiannual (7–8 years) and decadal (13–14 years) signal occuring during the eighteenth and nineteenth centuries, but a 4–5 years oscillation from the end of the fifteenth to the mid-sixteenth century, corresponding to the Spörer minimum.

Discussion

Important changes – both in major sedimentary processes and in cyclicities – occurred within the deep lacustrine plain mainly during the coldest part of the LIA. These changes can be discussed in terms of modern human impacts on alluvial systems, and in terms of global climate changes affecting the palaeohydrology of Lake Le Bourget’s watershed over the last 600 years.

Human impacts

Since the thirteenth century, human influences on the watershed of Lake Le Bourget mainly affected vegetation (Girel, 1991), and thus probably enhanced soil erosion and terrigenous supply to the lake during climatic fluctuations. However, from AD ~1870 to the present, human impact has induced strong modifications in the drainage basin, mainly through river training (Bravard, 1981; Girel, 1991; Bravard and Peiry, 1993; Miquet, 1997): efficient embanking developed since the mid-nineteenth century, the first dams on the Rhône river south of Geneva were built in 1950, a floodgate on the lake outlet has existed since 1970 and large dams in the Châutagne swamp (Figure 1) strongly affected the Rhône regime since 1980. Thus, the progressive decrease in the formation of flood deposits (Figure 2) and the disappearance of cyclicities in our proxies from AD ~1870 to the present (Figures 3 and 4) may result from increasing human impacts on alluvial systems, rather than climate change following the end of the LIA.

Impacts of the LIA on the northwestern Alps

The region concerned by the LIA had its southern boundary in the Alps. The cooling occurred abruptly, from AD 1540 onward in northern Italy, and from AD 1570–1580 onward elsewhere (Hughes, 1995; Briffa *et al*., 1999; Koslowski and Gläser, 1999). Daily weather was characterized by cold and wet summers, and by windy and comparatively drier conditions in the winter, with a marked overall deficit in precipitation, although the frequency of snowfall was higher. Consequently, a remarkable advance of Alpine glaciers occurred in the second half of the sixteenth century, and glacial extension culminated in the seventeenth century (Pfister *et al*., 1999; Holzhauser and Zumbühl, 1999). In the upper Arve valley, a similar growth of the main Arve glaciers (Mer de Glace, Glacier d’Argentière, Glacier du Tour) has been reported by Dorthe-Monachon (1988), through mapping of the AD ~1600–1850 moraines.

Advancing glaciers dammed up rivers flowing along their sides, leading to the formation of lakes. Water in these lakes was normally allowed to flow beneath the glaciers, through tunnels cut in ice, but the occasional blockage of such tunnels resulted in lake outbursts, causing disastrous floods at irregular intervals in the seventeenth and eighteenth centuries (Holzhauser and Zumbühl, 1999). In such a glacial setting, similar disastrous floods could also result from surges induced by drainage of subglacial lakes (Shaw, 1985).

According to Bravard (1989), French Alpine rivers and valleys experienced a period of hydrological inactivity prior to the beginning of the fourteenth century, when unstable climate causing frequent and intense flooding started to develop a geomorphologic change to braided pattern along low-order rivers. This progressive evolution reached its maximum during the coldest part of the LIA (seventeenth and eighteenth centuries) and the largest valleys (including the Rhône) were devastated by catastrophic flooding, by an intense deposition of coarse sediments and by the downstream progradation of the braided pattern.

Impacts of the LIA on Lake Le Bourget sedimentation

The effect of the LIA on Lake Le Bourget’s drainage basin, and on the thermal stratification of the lakewaters, appears to be responsible for a significant drop in the formation of distal interflow deposits (core B10) and an increase in the development of underflow supply (core B16) toward the basin axis (Figure 2).

The catastrophic impact of the AD 1732 Rhône river historical flood over the Châutagne swamp (Figure 1) reported by Bravard (1981), and the induced major underflow deposit dated in the lacustrine plain of the lake (Figure 2), most probably illustrate the downstream consequences of a disastrous flood related to the development of the Arve glaciers during the LIA. Other major underflow deposits originating from the Rhône river were recorded in the central part of the lacustrine plain during this period from AD ~1720 to 1750 as well as earlier, around AD 1572 ± 10 years and AD 1407 ± 10 years (Figure 2). Similar major deposits originating from the Rhône were cored in the eastern part of the lacustrine plain (not shown) around AD 1547 ± 10 years; AD 1525 ± 10 years and AD 1389 ± 10 years (Chapron, 1999). Thus, successive catastrophic Rhône river floods were recorded through major underflow deposits in Lake Le Bourget during the early fifteenth, the sixteenth, and the mid-eighteenth centuries. These catastrophic Rhône river floods are attributed to the fluvioglacial regime of the Arve river, related to the progressive development of the Arve glaciers since the early fifteenth century, and to the downstream progradation of the braided pattern along the Rhône valley.

Moreover, during the coldest part of the LIA (from AD ~1550 to 1800), the S/I signal on core B16 shows a well-developed 45–50 years cycle (Figure 3) that is particularly well expressed during a period centred on the Maunder solar minimum (AD 1650–1720). Similar cyclicities have been reported in historical surges of several fluvioglacial streams in the western Alps (Vivian, 1975). The clay signal in core B16 being associated with underflow supplies, it is suggested that: (1) the growth of the Arve glaciers was favoured during the Maunder solar minimum; and (2) the evolution of the Arve river toward a fluvioglacial regime resulted in Rhône river floods characterized by 45–50 years cyclicities from AD ~1550 up to 1800.

Along the western part of the lacustrine plain (core B10), the well-developed laminations from AD ~1740 to 1870 presenting 7–

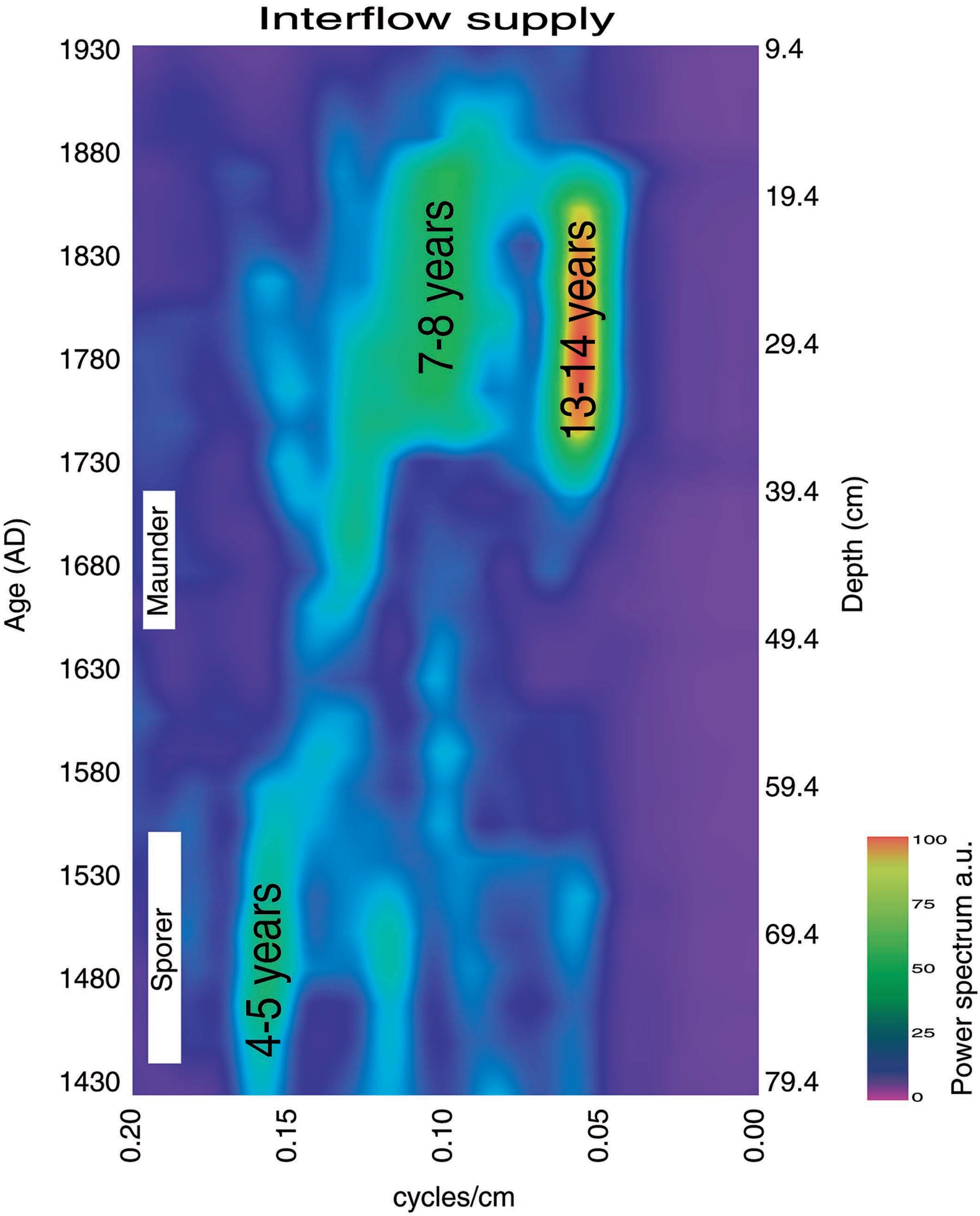

Figure 4 Time stability of the cyclicities detected in grey levels (core B10) through spectral analysis and band-pass mapping. This proxy reflects the laminations in interflow deposits originating from Rhône river floods.

8 and 13–14 years cyclicities (Figure 4), should reflect distal interflow deposits resulting from large floods of the Rhône river during springs and summers. Such floods are interpreted to be caused by snowmelt and/or excessive rainfalls. These interpretations are supported by direct observations of inter- and underflow behaviour in Lake Le Bourget from the years 1995 to 1998, by the side-scan sonar mapping of present-day inter- and underflow sedimentary environments over the lake floor, and by the correlation of the main historical floods of the watershed recovered in 13 sediment cores (Chapron, 1999). From AD ~1550 to 1740, the progressive disappearance of laminations and the lack of any clear cyclicities in core B10 (Figure 4), together with an increase in

carbonate content and the lateral record of two major underflow deposits (Figure 2), are consistent with a significant drop in the formation of distal interflow deposits during this period and an increase in the development of underflow deposits toward the basin axis. Such a change in the record of Rhône river terrigenous supply from core B10 to core B16 during the coldest part of the LIA, is believed to result mainly from: (1) the effect of the geomorphologic evolution of the Rhône valley toward a braided pattern; (2) less developed spring and summer thermal stratification of the lakewaters during the Maunder solar minimum (AD ~1650–1720); and (3) enhanced available suspended load during floods.

Before the abrupt cooling of the LIA, core B10 shows a very fine lamination sequence from AD ~1440 to 1550, presenting 4–5 years cyclicities (Figure 4). Assuming an origin similar to the laminations developed from AD ~1740 to 1870, this older lamination sequence may correspond to distal interflow deposits resulting from large floods of the Rhône river during springs and summers. Snowmelt and/or excessive rainfalls over the regional watershed – not yet fully characterized by a braided pattern – would be responsible for this laminated sequence occurring during the Spörer solar minimum (AD ~1440–1550). In the southern part of the lake, this period is also characterized by the development of major underflow deposits in front of Leysse and Sierroz deltas (Chapron, 1999). These deposits are probably related to the evolution of the Leysse and Sierroz rivers (Lake Le Bourget's local watershed) toward a braided pattern, and are believed to correspond to the geomorphologic change along low-order rivers reported by Bravard (1989) in the French Alps.

Climate variability over the Northern Hemisphere

Many recent papers have unravelled the typical periods of the North Atlantic Oscillation (NAO). This proved to be an intermittent major climate oscillation over the Northern Hemisphere, with pluriannual to decadal periods, as well as low-frequency periods (depending on the studied timespan) at 50–68 years, 80–90 years and >128 years (Hurrell and Van Loon, 1997; Appenzeller *et al.*, 1998; Luterbacher *et al.*, 1999).

The NAO is described with an index based on the sea-level pressure difference during winters, between Iceland (low) and the subtropics near the Azores (high). This pressure contrast drives the surface winds and wintertime storms from west to east across the North Atlantic (Uppenbrink, 1999).When the NAO index is positive (NAO+), the westerly flow across the North Atlantic and western Europe is enhanced, and brings warmer, maritime air over northwestern Europe, causing a rise in temperature. At the same time, enhanced northerly flow over the northeast Atlantic results in a drop in temperature over the area. When the index is low (NAO–), the opposite occurs. The net result is a 'seesaw' in the temperatures across the North Atlantic-European sector, as well as changes in other climate variables such as precipitation and sea-ice extent (Jones *et al.*, 1997).

The NAO index calculated back to AD 1821, from Gibraltar and Reykjavik by Jones *et al.* (1997), highlights pluriannual oscillations ranging from positive (NAO+) to negative (NAO–) index values, as well as pluridecadal trends of enhanced positive and negative patterns. Whereas the decadal trend in the NAO is thought to be related to the North Atlantic thermohaline circulation component (Hurrell, 1995; Keer, 1997), the interannual trend could result from low latitude-high latitude atmospheric linkages (Black *et al.*, 1999). Ice-core data from Greenland over the last 350 years (Appenzeller *et al.*, 1998), suggest that the NAO is also characterized by temporally active (coherent) and passive (incoherent) phases. According to the authors, atmosphere-ocean interaction on the typical timescales of 5 to 15 years might occur during active phases, but would be absent during passive phases, although spatially coherent patterns still may exist.

It is thus tempting to associate our high-frequency periods (clustering around 4–5 years and 7–8 years), decadal period (13–14 years), and low-frequency period (45–50 years) with the typical periods of the NAO.

Impact of the NAO on the northwestern Alps

The coupling between the NAO and climatic processes in the study area is fairly well understood. The NAO index is a measure of the westerly flow over the Atlantic. When the NAO index is positive and high (NAO+), westerlies over the middle latitudes are stronger than average. The axis of maximum moisture transport thus shifts to a more southwest-to-northeast orientation across the Atlantic Ocean and extends much farther to the north and east onto northern Europe. As a result, a significant reduction of the total atmospheric moisture transport is observed over large parts of southern Europe, the Mediterranean and North Africa. This process results in a gradient in precipitation anomalies, from lower-than-average precipitation over southern Europe to heavier-than-average precipitation over northern Europe and Scandinavia (Hurrell, 1995; Hurrell and Van Loon, 1997; Selten *et al.*, 1999). Dry conditions during high NAO index winters (NAO+) are observed over much of central Europe, including the Alps (Wanner *et al.*, 1997). Moreover, the pressure signal from the NAO index is amplified in the Alpine region, especially under the altitudinal range 1500–2000 m (Beniston, 1997): the high-pressure episodes (late autumn and winter) are accompanied by large positive temperature anomalies and low precipitation, both of which are unfavourable for snow accumulation during the winter.

A NAO-like period in our data can thus be regarded as a consequence of periodical variations in rainfall and snow accumulation during late autumn and winter over Lake Le Bourget's watershed. Pluriannual and decadal cyclicities in interflow deposits on core B10 would then reflect NAO-induced variations in snowmelt under the altitudinal range 1500–2000 m. The origin of the observed 45–50 years 'NAO-like' cyclicity in underflow supply to core B16 is not fully understood; but, in our setting, it would rather reflect fluvioglacial regimes, and only become significant during periods of growing glaciers, such as the coldest part of the LIA. Solar forcing could be involved, as changes in the palaeohydrology of Lake Le Bourget's drainage basins seem to match solar minima. The 45–50 years period could possibly be related to the so-called 'Double-Hale' 45-year solar forcing cycle (Fairbridge and Hillaire-Marcel, 1977). However, coupling between NAO and solar forcing, although most probably effective, is not yet fully investigated (Osborn *et al.*, 1999). Another origin could be the North Atlantic ocean itself, as Delworth *et al.* (1993) noticed thermohaline circulation oscillations of 40–50 years in a coupled ocean-atmosphere model. Such irregular oscillation could be driven by density anomalies in the sinking region of the thermohaline circulation (approximatly 52°N to 72°N) combined with much smaller density anomalies of opposite sign in the broad rising region. The anomalies of sea-surface temperature induce model surface-air temperature anomalies over the northern North Atlantic, Arctic and northwestern Europe.

A working hypothesis concerns the possible occurrence of active and passive NAO phases in our data (Figure 5). As proposed by Appenzeller *et al.* (1998), active and passive NAO phases could be respectively responsible for the development and the disapearance of 5–15 years cyclicities (4–13 years cyclicities in our flood deposits). During a passive NAO phase, pluridecadal periods – related to solar forcing and/or to North Atlantic thermohaline circulation oscillations – could then become significant. From available historical data sets (instrumental NAO index, ice-core data from Greenland and Lake Le Bourget's proxies), it seems that such NAO phases, in between Greenland and Europe, could be out of phase (Figure 5). The occurrence of such a pattern will, however, have to be confirmed over longer timescales.

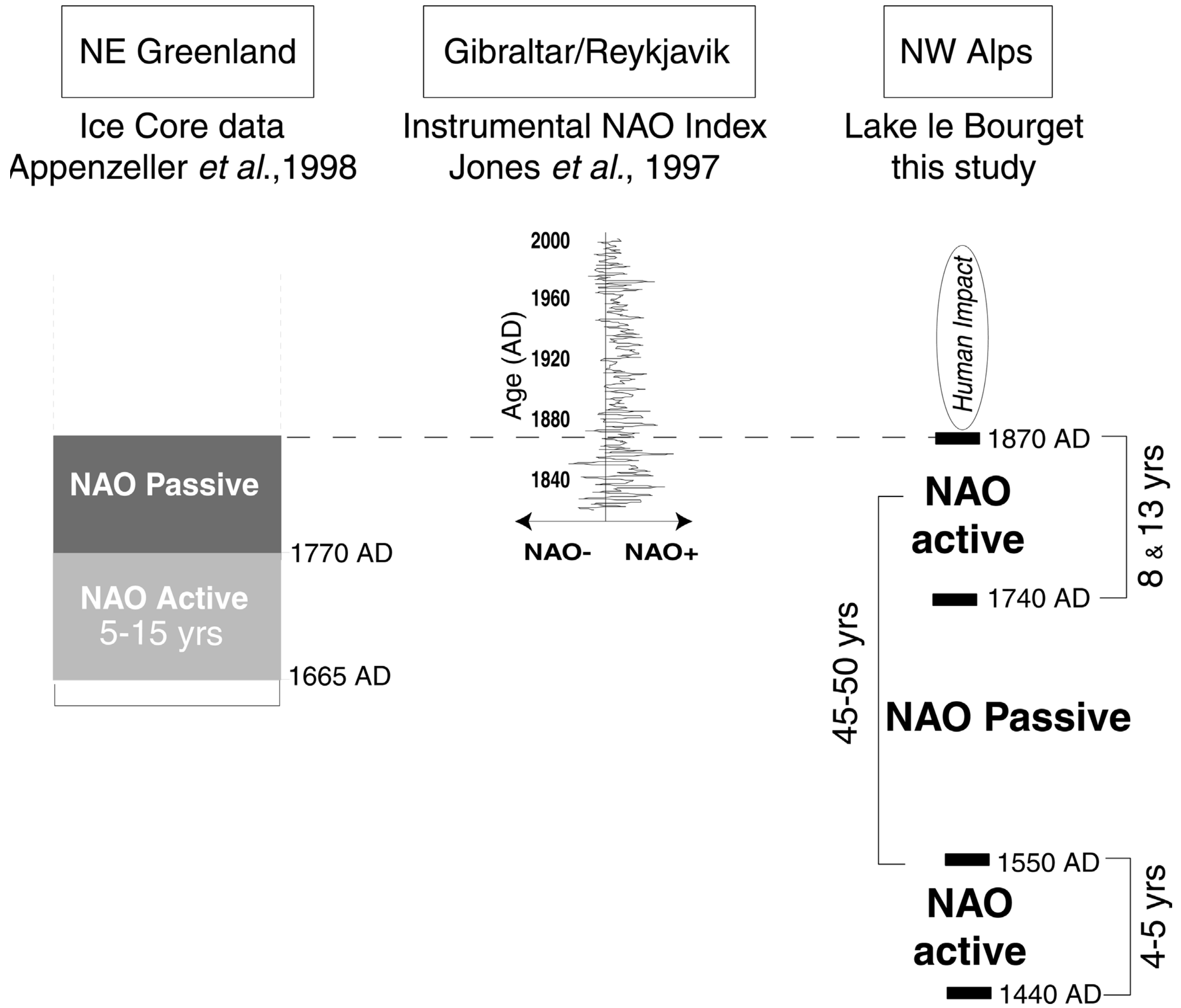

Figure 5 Tentative correlation between NAO index and NAO proxies from Greenland and the northwestern Alps. From AD 1870 to 1821 when the NAO index is mainly positive, the Lake Le Bourget data highlight 7–8 and 13–14 years cyclicities (possible NAO active phase), whereas ice-core data from Greenland present no cyclicities (possible NAO passive phase). On longer timescales, NAO phases from Greenland and the northwestern Alps seem to be out of phase.

Conclusion

Detrital sedimentation in a lacustrine system can be considered as an excellent sediment parameter for high-resolution climate monitoring, when the spatial variability of the different deltaic sedimentary environments has been established. Sediment cores from under- and interflow deposits can then provide a continuous high-resolution record of the changes in the palaeohydrology (and the geomorphology) of the lake's watershed.

This multidisciplinary study of Lake Le Bourget sedimentary infill over the last 600 years shows that the impact of the LIA on the drainage basin and on the thermal stratification of the lake-waters produced from AD ~1550 to 1740 a significant decrease in the formation of interflow deposits during springs and summers, as well as an increase in the development of underflow supply from AD ~1550 to 1800. Growing glaciers in the regional watershed induced catastrophic Rhône river floods and major underflow deposits in the lacustrine plain during the early fifteenth, the sixteenth and the mid-eighteenth centuries.

Spectral analyses of the laminations (grey levels) produced by interflow deposits reveal 4–5 years cyclicities from AD ~1440 to 1550, as well as 7–8 and 13–14 years cyclicities from AD ~1740 to 1870.

Spectral analyses of the smectite/illite index, reflecting underflow supply from Lake Le Bourget local/regional watersheds, highlight 45–50 years cyclicities from AD ~1550 to 1800, that are particularly remarkable during a period centred on the Maunder solar minimum. These pluriannual, decadal and pluridecadal periods are typical of the NAO. A NAO-like period in our data would be a consequence of periodical variations in rainfall and snow accumulation during late autumn and winter over Lake Le Bourget's watershed. Pluriannual and decadal cyclicities in interflow deposits would reflect NAO-induced variations in snowmelt under the altitudinal range 1500–2000 m. The pluridecadal cyclicity in underflow supply may reflect fluvioglacial regime during periods of growing glaciers, and eventually be related to solar forcing and/or North Atlantic thermohaline circulation oscillations. These multidecadal sources of variance need to be better understood if the effects of greenhouse gases on climate are to be properly understood.

Acknowledgements

We acknowledge W. Wildi and Institut F.A. Forel (University of Geneva, Switzerland) for benthos coring survey technical assistance. We also thank M. Pourchet for radiogenic dating, P. Recourt for x-ray diffraction measurements, S. Thiebaut for grey level processing and M. De Batist, P. Van Rensbergen and V. Huvenne for the improvement of the manuscript. We are grategul to K. Briffa and A. Korhola for their constructive review.

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