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Sub-decadal- to decadal-scale climate cyclicity during the Holsteinian interglacial (MIS 11) evidenced in annually laminated sediments

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Abstract

To unravel the short-term climate variability during Marine Isotope Stage (MIS) 11, which represents a close analogue to the Holocene with regard to orbital boundary conditions, we performed microfacies and time series analyses on a ~3200-yr-long record of annually laminated Holsteinian lake sediments from Dethlingen, northern Germany. These biogenic varves comprise two sub-layers: A light layer, which is controlled by spring/summer diatom blooms, and a dark layer consisting mainly of amorphous organic matter and fragmented diatom frustules deposited during autumn/winter. Time series analyses were performed on the thickness of the light and dark layers. Signals exceeding the 95 % and 99 % confidence levels occur at periods that are near-identical to those known from modern instrumental data and Holocene palaeoclimatic records. Spectral peaks at periods of 90, 25, and 10.5 yr are likely associated with the 88-, 22- and 11-yr solar cycles, respectively. This variability is mainly expressed in the light layer spectra, suggesting solar influence on the palaeoproductivity of the lake. Significant signals at periods between 3 and 5 yr and at ~6 yr are strongest expressed in the dark layer spectra and may reflect an influence of the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) during autumn/winter. Our results suggest that solar forcing and ENSO/NAO-like variability influenced central European climate during MIS 11 similar to the present interglacial, thus demonstrating the comparability of the two interglacial periods at sub-decadal to decadal timescales.

1 Introduction

An understanding of the mechanisms and effects of natural short-term (i.e., decadal- to sub-decadal-scale) climate variability is essential for providing projections of possible climate change for the near future. Short-term climate changes are linked to shifts in the modes of variability of the climate system (e.g., the southern and northern annular modes; Stenseth et al., 2003); therefore, a better representation of such climate-mode shifts in climate models may improve simulations of abrupt climate changes (Alley et al., 2003). Although the instrumental record is becoming more valuable as it is lengthened, it is still insufficient to cover the full range of climatic behavior. Specifically, instrumental datasets do not reach beyond the past ~300 yr (Jones and Mann, 2004), which precludes deeper insights into the underlying physical processes and the evolution of decadal- to sub-decadal-scale climate variability on longer (e.g. interglacial) timescales. In this context, high-resolution palaeoclimate records, particularly from past interglacials that unlike the Holocene were unaffected by human interference, can make an important contribution towards elucidating natural short-term climate variability and its future evolution during the present interglacial (e.g. Alley et al., 2003; Brauer et al., 2007; Müller and Pross, 2007; Tzedakis et al., 2009).

Marine Isotope Stage (MIS) 11 is considered one of the best analogues for present and future climate based on long-term similarities with regard to orbital climate forcing, i.e., low eccentricity and dampened influence of precession (e.g. Berger and Loutre, 2002; Loutre and Berger, 2003; Ruddiman, 2005). A number of proxy datasets have provided insights into the long-term comparability between MIS 11 and the present interglacial (e.g. McManus et al., 2003; de Abreu et al., 2005; Helmke et al., 2008; Rohling et al., 2010; Tzedakis, 2010), but owing to a lack of data with sufficiently high temporal resolution the short-term comparability between the two interglacials has remained ambiguous.

In contrast to most marine records from MIS 11, which typically exhibit relatively low sedimentation rates, varved sequences from lake sediments yield the potential to test whether MIS 11 and MIS 1 exhibit comparable decadal to sub-decadal climate variability. The terrestrial analogue to MIS 11 in Central Europe has long been a matter of heated debate (e.g. de Beaulieu et al., 2001; Geyh and Müller, 2005; see also Koutsodendris et al., 2010, for a discussion); however, based on evidence from long terrestrial and marine vegetation records from the Massif Central (France; Reille et al., 2000) and off Iberia (Desprat et al., 2005), there is now a substantial body of research that indicates a land-sea correlation of MIS 11c with the Holsteinian interglacial (e.g.

de Beaulieu et al., 2001; Kukla, 2003; Nitychoruk et al., 2005, 2006; Müller and Pross, 2007; Preece et al., 2007).

The variations in the composition and thickness of varves reflect sedimentation processes that are controlled by various climatic and environmental factors at different times of the year (e.g. O'Sullivan, 1983; Lotter, 1989; Anderson, 1992; Lotter and Birks, 1997; Brauer et al., 1999a; Brauer, 2004). Deeper insights into these processes have been gained through the time series analysis of varve thickness datasets; such efforts have successfully linked cyclical patterns in lake sediments with short-term natural periodic climate forcing (e.g. Anderson and Koopmans, 1963; Anderson, 1992; Zolitschka, 1992; Vos et al., 1997; Rittenour et al., 2000; Livingstone and Hajdas, 2001). To date, although several well-preserved Holsteinian varved archives are known (e.g. Turner, 1970; Müller, 1974; Krupiński, 1995; Nitychoruk et al., 2005), the potential of using varves to better understand the decadal- to sub-decadal-scale climate variability during MIS 11 has been poorly explored (Mangili et al., 2005, 2007; Brauer et al., 2008).

In light of the above, we here analyze a ~3200-yr-long Holsteinian varve succession from the Dethlingen palaeolake in northern Germany. In particular, we have performed (i) a detailed microfacies analysis to understand the season-dependent sedimentological processes controlling varve deposition, and (ii) time series analyses on the varve sub-layers thickness in order to investigate the short-term climate cyclicity during MIS 11 and to compare it with instrumental data and palaeoclimatic records of the Holocene.

2 Material and methods

The Dethlingen palaeolake is located in the Lüneburger Heide region within the lowlands of northern Germany (Fig. 1). After the disintegration of the Elsterian (MIS 12) ice sheet, several deep lakes formed in the vicinity of Dethlingen that were subject to the deposition of diatomaceous, partially annually laminated sediments during the following Holsteinian interglacial (e.g. Benda and Brandes, 1974; Ehlers et al., 1984; Koutsodendris et al., 2010). Based on the spatial extent and thickness of the

Holsteinian diatomite, the size of the Dethlingen palaeolake is estimated to ∼800 m in length and 300–500 m in width (Benda et al., 1984). The deposits cored at Dethlingen (10°08.367′ E, 52°57.780′ N, 65 m a.s.l.) that has yielded the material for this study comprises organic-rich, predominantly regularly and finely laminated lake sediments (Koutsodendris et al., 2010). Here we focus on the interval between 27.93 and 33.68 m below surface (mbs) that comprises annual laminations spanning the mesocratic forest phase of the Holsteinian interglacial in Central Europe (∼411–408 ka BP), including a prominent centennial-scale climate perturbation, the so-called "Older Holsteinian Oscillation" (OHO; Koutsodendris et al., 2010, 2011).

Varve counting and layer-thickness measurements were carried out at 100x magnification on thin sections (size: 120 × 35 mm) using a petrographic microscope. Thin-section preparation followed standard techniques comprising freeze-drying, impregnation with Araldite 2020 epoxy resin under vacuum, sawing, and grinding of the sediment (Brauer et al., 1999b; Lotter and Lemcke, 1999). To warrant continuity of observation successive thin sections with an overlap of 2 cm were analyzed.

Geochemical measurements were undertaken with a micro-X-ray fluorescence (µ-XRF) spectrometer EAGLE III XL at different resolutions (step sizes: 50, 100, 200, 500 µm) for Al, Ca, Cl, Fe, K, Mg, Mn, P, S, Si, Sr, and Ti (60 s count time, 0 kV X-ray voltage and 400 µA X-ray current). Measurements were carried out on sediment blocks that had been impregnated with Araldite 2020 epoxy resin.

Time series analyses were carried out on the thickness measurements of the light and dark layers. Multi-taper spectral analysis (MTM) was used for spectral estimation (bandwidth parameter $p = 5$, and 9 tapers) (e.g. Vautard et al., 1992). The MTM represents an optimal method for producing spectral estimates with high frequency resolution for given degrees of freedom, low bias, and a distribution amenable to the location of confidence levels (Mann and Lees, 1996). In addition, wavelet analysis was applied to identify occurrence intervals and related amplitudes of periodic components of the non-stationary sub-layer thickness time series (Torrence and Compo, 1998).

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3 Results and discussion

3.1 Structure of varves and depositional processes

The finely laminated sediments from Dethlingen comprise biogenic varves consisting of two discrete layers, a light and a dark one. The transition from the light layers to the overlaying dark layers is diffuse, whereas the boundary between the dark and the following light layer is sharp (Fig. 2a–c).

The composition and thickness of the light layers are predominantly controlled by the annual cycle of diatom blooms, which is dominated by taxa of the genera *Stephanodiscus*, *Ulnaria*, and *Aulacoseira*. In most cases, the light layers are dominated by one of these genera, resulting in an almost monospecific diatomaceous layer. However, a successive deposition of two sub-layers of different genera during the growing season can be also observed. The light layers often contain organic matter that increases in abundance towards the boundary with the dark layers. Small-sized (<10 µm) pyrite framboids are often present (Fig. 2d) and occasionally few angular-shaped grains, ranging in size from coarse silt to fine sand, are scattered within the light layers (Fig. 2f).

The dark layers are composed predominantly of amorphous organic matter with fragments of diatom frustules. Reworked periphytic diatoms, plant remains, freshwater sponge spicules from the littoral zone, and chrysophycean cysts are common (Figs. 2e, 3a–b). The dark layers often contain low concentrations of clay particles, in contrast to the light layers where fine-grained minerogenic particles are almost absent.

The succession and characteristics of the individual varve layers as described above suggest that the diatomaceous light layers were deposited during spring and summer, whereas the organic-detrital dark layers were formed during autumn and winter (e.g. O'Sullivan, 1983; Lotter, 1989; Brauer, 2004). In particular, water circulation and high nutrient availability in spring and summer promote diatom blooms that lead to the deposition of diatoms frustules at the lake bottom, forming the light layers. Stratification of the water column in summer leads to anoxic bottom lake conditions facilitating the preservation of varves (e.g. O'Sullivan, 1983; Brauer, 2004). The deposition of diatom frustules, organic matter and other material from the littoral zone of the lake suggests the re-establishment of the lake circulation during the deposition of the dark layers. The mixing of the water column can be attributed predominantly to an enhancement of wind and wave activity during autumn and early winter; in addition, the low content of clay particles in the dark layers points to minor runoff from the catchment area into the lake during that time. The sharp boundary between the dark and succeeding light layer suggests a transient break in sediment accumulation, which may be attributed to an ice-cover of the lake during winter; during that time, single wind-transported coarse silt and sand grains were trapped in the ice, being deposited within the lake sediments after ice melting in spring. These dropstone-like sand grains additionally confirm the seasonal interpretation of the sub-layers. The above-mentioned characteristics suggest that the Dethlingen palaeolake was dimictic, being ice-covered and stratified during parts of the year, and experiencing periods of mixing between these two states (e.g. Lewis, 1983).

3.2 Varve counting and thickness measurements

In total, 2864 varves were counted between 27.93 and 33.68 mbs. For small-scale core intervals where varve preservation was poor or sediment had been disturbed during coring or laboratory processing, interpolations were performed based on the average thickness of 20 varves deposited directly below and above the respective interval. Based on these procedures, the floating chronology for the laminated diatomite at Dethlingen was calculated to comprise 3255 varve yr (Koutsodendris et al., 2011).

The average varve thickness is 1.74 mm (Fig. 4). The thickness of the light layers varies between 0.05 and 5 mm (average: 0.68 mm), whereas the thickness of the dark layers varies between 0.08 and 5 mm (average: 1.06 mm) (Fig. 4). A qualitative distribution of different types of light layers in the examined core interval was established based on the dominant diatom genera observed in the thin sections; Type-A is dominated by diatoms of the genera *Stephanodiscus* with a size >10 µm (Figs. 3c, d), type-B is dominated by elongated diatoms of the genus *Ulnaria* (Figs. 3e, f), and type-C mainly

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comprises small-sized diatoms (<10 µm) of the genera *Aulacoseira* and *Stephanodiscus* (Figs. 3g, h). In general, representatives of type-A are thicker (average: 0.87 mm) than those of type-C (0.54 mm) and type-B (0.52 mm) (Fig. 4). The distribution of these light layer types within the studied core interval documents a clear succession in diatom assemblages (Fig. 4). The light layers from the lower interval of the laminated diatomite (33.68–31.22 mbs) are dominated by large *Stephanodiscus* species (type-A) succeeded by *Ulnaria* species (type-B) in the middle part (31.22–30.20 mbs), whereas the upper laminated interval (30.20–27.93 mbs) is characterised by a prevalence of small *Stephanodiscus* and *Aulacoseira* species (type-C).

3.3 Time series analyses

The power spectra of the datasets for the light and dark layers exhibit several peaks that exceed the 95 % and 99 % confidence levels (Fig. 5). Significant peaks occur at decadal-scale periods of 90, 25, 15, and 10.5 yr, but also at sub-decadal-scale periods of 5.8–6.1, 3–5, and 2–3 yr. In addition, the wavelet spectra show a prominent cycle at ~512 yr for both the light and dark layers (Fig. 6). In the following, we compare these signals with solar cycles and spatio-temporal modes of global climate variability, such as the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Quasi-Biennial Oscillation (QBO), which are well known from analyses of modern instrumental climate data and the Holocene palaeoclimatic record (e.g. Stuiver and Braziunas, 1993; Mann and Park, 1996; Hoyt and Schatten, 1997; Wanner et al., 2001).

3.3.1 Solar-cyclicity-like variability

Four peaks from the Dethlingen varve time series spectra can be correlated to known solar cycles (Fig. 5; Table 1). The most prominent, at 90 yr, can be attributed to the 88-yr Gleissberg solar cycle (e.g. Gleissberg, 1944; Stuiver and Braziunas, 1993; Hoyt and Schatten, 1997) that has previously been recorded in several glacial (Anderson

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and Koopmans, 1963; Vos et al., 1997; Prasad et al., 2004) and interglacial varve time series (Anderson and Koopmans, 1963; Vos et al., 1997; Dean et al., 2002; Brauer et al., 2008). The 25- and 10.5-yr peaks from Dethlingen may correlate to the 22-yr Hale and 11-yr Schwabe solar cycles, respectively (e.g. Hoyt and Schatten, 1997) that have also been widely found in Quaternary varve time series of glacial (Anderson, 1961; Anderson and Koopmans, 1963; Vos et al., 1997; Rittenour et al., 2000) and interglacial origin (Anderson, 1961, 1992; Anderson and Koopmans, 1963; Zolitschka, 1992; Vos et al., 1997; Livingstone and Hajdas, 2001; Dean et al., 2002; Theissen et al., 2008). The statistically significant expression of all three prominent decadal-scale solar cycles makes the Dethlingen varve record unique because most known varve records only contain evidence for one or two of these cycles, probably because of insufficient sensitivity of each individual lake's sedimentological properties to record the solar magnetic modulation (e.g. Solanki, 2004; Muscheler et al., 2005) over certain time periods (e.g. Anderson, 1992).

In addition to these cycles, our record provides evidence for a centennial-scale cycle at ~512 yr, which has been rarely detected in varve time series (Prasad et al., 2004; Brauer et al., 2008). To date, its origin remains unclear; it is considered to be related to either solar forcing (Stuiver et al., 1995; Sarnthein et al., 2003) or changes in the North Atlantic thermohaline circulation (Stuiver and Braziunas, 1993; Chapman and Shackleton, 2000; Damon and Peristykh, 2000; Risebrobakken et al., 2003).

Because the solar-like cycles are evidenced in both light and dark layer spectra, we argue that solar forcing has influenced the lake sedimentation throughout the year. The light layers at Dethlingen, which represent the primary lake productivity (see Sect. 3.1), are characterized by peaks of all three decadal-scale solar cycles (i.e., Gleissberg, Hale, and Schwabe cycles) at the 99 % confidence level (Fig. 5). This suggests a significant solar influence on the biological productivity of the lake, most likely by affecting water mixing intensity, temperature, and light and UV radiation that exert a strong control on algal productivity (e.g. Bothwell et al., 1994; Beer et al., 2000; Graham and Wilcox, 2000). The occurrence of solar-like cyclicity in the dark layers, particularly the

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Gleissberg cycle (Fig. 5), points to solar influence on lake circulation during autumn and winter, most likely through atmospheric circulation changes that modulated wind and wave activity (see Sect. 3.1). Possible links between solar irradiance and atmospheric circulation have been attributed to the solar influence on stratospheric temperature that may modify zonal winds and storm tracks (e.g. Haigh, 1996; Carslaw et al., 2002).

Summarizing the above, the time series analysis of the Dethlingen varve record suggests a strong impact of solar cyclicity on the processes responsible for the seasonal sedimentation by influencing the lake's primary productivity and the atmospheric circulation over the study area.

3.3.2 Variability within the ENSO/NAO band

The Dethlingen varve record reveals significant variability at sub-decadal time scales, with signals exceeding the 95 % or 99 % confidence levels grouped into three distinct bands, i.e., 2–2.7 yr, 3–5 yr, and 5.8–6.1 yr (Fig. 5; Table 1). Most of the significant peaks are recorded in the range of 3 to 5 yr within the conventional ENSO bandwidth (Mann and Park, 1994; D' Arrigo et al., 2005). Variability within the ENSO bandwidth has been reported in lateglacial to recent varve sequences from North and South America (Rittenour et al., 2000; Nederbragt and Thurow, 2005; Fagel et al., 2008), but to date has not been clearly witnessed in varves from Europe. The ENSO is a natural mode of oscillation that results from unstable interactions between the tropical Pacific Ocean and the atmosphere, affecting weather and climate worldwide (e.g. Fedorov and Philander, 2000). A teleconnection between the Pacific region and Europe via the stratosphere allows ENSO to influence European climate in late winter and spring (e.g. Brönnimann, 2007; Brönnimann et al., 2007; Ineson and Scaife, 2009). The signal in European climate comprises two modes: during El Niño conditions, when a reduction of coastal upwelling and an increase in sea-surface temperature along the western coast of tropical South America is observed in the equatorial Pacific, the European continent witnesses very low temperatures in NE Europe, increased precipitation in the northern Mediterranean region, and decreased precipitation in Norway. Reversed

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conditions are observed in Europe during La Niña conditions, which comprise the opposite mode of El Niño in the equatorial Pacific (e.g. Brönnimann, 2007). The cyclicity observed at Dethlingen is in agreement with modern weather observations from Europe that suggest an ENSO influence on climate every 3.5 yr (Rodó et al., 1997). The ENSO-like variability is stronger expressed in the spectrum of the dark layers, pointing to a pronounced ENSO impact on winter atmospheric circulation during the Holsteinian interglacial (Fig. 5).

The Dethlingen varve time series further shows significant variability at the margins of the ENSO bandwidth between 5.8 and 6.1 and between 2.4 and 2.6 yr (Fig. 5). Although this variability may again represent an ENSO impact on varve formation, modern observational data suggest that these signals are better attributed to the NAO. The NAO, which represents a hemispheric meridional oscillation in atmospheric masses centered near Iceland and the subtropical Atlantic Ocean, affects European climate particularly in boreal winter from December through March (e.g. Hurrell, 1995; Visbeck et al., 2001; Wanner et al., 2001). The NAO is characterized by a positive mode related to warmer and wetter than average conditions in north Europe and colder and drier conditions in the Mediterranean region, and a negative mode with reversed characteristics. The NAO variability occurs at bandwidths of 2.5–3 and 6–10 yr (e.g. Appenzeller et al., 1998; Hurrell and van Loon, 1997; Pozo-Vásquez et al., 2000). Varve time series from central and western Europe have also reported significant peaks at 6.1–6.2 yr during the Holocene (Livingstone and Hajdas, 2001; O'Sullivan et al., 2002), whereas a similar period at 6.6 yr has been recorded on oxygen isotope variations of calcite varves from the southern Alps during MIS 11 (Mangili et al., 2010). It therefore seems that the ~6 yr signal documented in European varve sequences represents NAO-like variability rather than ENSO-like variability because the latter is generally more pronounced in the 3–5 yr bandwidth (Mann and Park, 1994). Further evidence for a NAO-like variability in the Holsteinian record from Dethlingen is provided by the fact that the ~6 yr signal is only evident in the spectrum from the dark layers. It therefore reflects sedimentation processes during autumn/winter, which is in good agreement with the seasonal impact of the NAO on European climate as known from the Recent (e.g. Hurrell, 1995; Visbeck et al., 2001; Wanner et al., 2001). The variability between 2 and 2.7 yr may be attributed to either the NAO or the QBO (Mann and Park, 1996). The QBO is one of the most commonly recorded circulation patterns in modern data, comprising a variability of the equatorial stratosphere expressed by an alternation in the downward propagation of easterly and westerly wind regimes (e.g. Baldwin et al., 2001). Although such periodicities commonly occur in varved sequences, these signals should be interpreted with caution because of their proximity to the 2-yr Nyquist frequency of annual sampling (e.g. Weedon, 2003).

Finally, the spectrum for the dark layers exhibits a periodicity of 15 yr exceeding the 95 % confidence level (Fig. 5). Such a periodicity has been previously noticed in Central Europe during the Holocene and MIS 11, although its forcing has remained unclear (Livingstone and Hajdas, 2001; Mangili et al., 2010). We suggest that this 15-yr cycle may be related to the interdecadal ENSO variability at 15–18 yr (Mann and Park, 1994). This interpretation is further corroborated by modern observations from Iberia that demonstrate the existence of an amplified ENSO signal at 14.2 yr, i.e., after every four ENSO events (Rodó et al., 1997).

To summarize, the Dethlingen varve time series indicates significant sub-decadal climate variability in European climate during MIS 11, which may be attributed to ENSO- and NAO-like climate modes. The pronounced signals in the spectrum of the dark layers point to a strong influence of the ENSO/NAO-like variability especially on winter climate, possibly through changes in atmospheric circulation that influenced lake mixing and the duration of ice cover.

3.4 Variability of varve thickness through time

The sub-decadal- and decadal-scale cyclicity as described in Sects. 3.3.1 and 3.3.2 is evidenced in most parts of the Dethlingen record (Fig. 6). However, a close inspection of the wavelet spectra for the light and dark layers reveals distinct intervals where this cyclicity appears only in one of the two spectra or is discontinuous in both spectra.

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An example for the first case is a 430-yr-long interval between 1320 and 1750 varve yr (Fig. 6). This interval, hereafter named low-variability interval (LVI), is marked by a strong sub-decadal and decadal cyclicity in the dark layer spectrum and a very weak cyclicity in the light layer spectrum. We therefore hypothesize that although the spectrum for the dark layers points to an external cyclical forcing influencing the Dethlingen palaeolake system, changes in the boundary conditions (e.g., nutrients, water level) during spring and summer precluded the recording of this forcing in the light layer spectrum. To test this hypothesis, we take a closer look at the varve microfacies during the LVI. The onset of the LVI coincides with a major change in the spring-blooming diatom assemblages accompanied by a thinning of the light layers (Fig. 4). In particular, the diatoms dominating the light layers change from *Stephanodiscus* (>10 µm) to *Ulnaria* species, the latter requiring a higher Si:P ratio and higher temperatures (e.g. Kilham et al., 1986; Cox, 1993). Therefore it appears likely that the compositional change in diatom assemblages during this interval is triggered by modifications in atmospheric circulation patterns. Specifically, atmospheric changes may have caused a weakening of the spring circulation, thereby decreasing the phosphorus transport from the hypolimnion to the photic zone to the benefit of diatoms that require high Si:P ratio to grow and increasing surface-water temperature. As a result, the boundary conditions of the Dethlingen palaeolake were seasonally modified, precluding the light layers to record external forcing. The sedimentation processes became susceptible to the recording of external forcing again when the lake system returned to conditions that supported a stronger blooming of *Stephanodiscus* species (Fig. 4).

A good example of the second case, i.e., when the spectra of both the light and dark layers do not show variability, is the interval between 2564 and 2782 varve yr (29.15 to 28.73 mbs; Fig. 7) that coincides with the prominent OHO event (e.g. Müller, 1974; Kukla, 2003; Koutsodendris et al., 2010). Across the OHO, the wavelet spectra of both the light and dark layers do not show any statistically significant indication for the 11-yr Schwabe cycle; moreover, there is a strong weakening of the 22- and 88-yr solar cycles (Fig. 7). In addition, the ENSO/NAO-like sub-decadal variability almost ceases with the onset of the OHO and only recovers again after the end of the event (Fig. 7). Following a similar concept as for the LVI, the absence of short-term variability during the OHO may be explained by seasonal changes in the boundary conditions of the Dethlingen palaeolake. In particular, the composition of the light layers shifts from *Ulnaria*-dominated to *Stephanodiscus*-dominated layers with the onset of the OHO, suggesting changes in lake productivity (Fig. 4). However, the observations from thin sections do not support a scenario of seasonal changes in the dark layers. On top of that, μ-XRF data for the onset of the OHO (29.16 to 29.05 mbs) do not yield evidence for modifications in the geochemical signal to support changes in the sedimentation processes during autumn/winter (Fig. 8). In particular, the intensities of minerogenic-detrital indicator elements (such as Al, Ca, K, Ti) and the Si/Al ratio remain rather constant, suggesting no significant change in terrestrial input. In addition, the constant Fe/Mn ratio does not support any oxygenation changes at the bottom of the lake. We therefore suggest that the absence of cyclical signals in the varves during the OHO points to a weakening of the external forcing. If correct, this implies that both the solar activity and ENSO/NAO-like variability were strongly weakened during this period. It has been suggested that the triggering mechanism of the OHO may be similar to the 8.2 ka BP event, with a cooling caused by a transient slowdown in North Atlantic circulation leading to a turnover in central European vegetation (Koutsodendris et al., 2010, 2011). Based on the Dethlingen time series analysis, it also appears possible that this climate oscillation is further related to lower solar irradiation. This may also have modified sub-decadal climate variability, as it has been suggested for prominent climate oscillations of the present interglacial, i.e., the 8.2 ka event (e.g. Muscheler et al., 2004; Rohling and Pälike, 2005) and the Little Ice Age (e.g. Shindell et al., 2001).

The two cases of discontinuous short-term climate variability in certain intervals as evidenced in the Dethlingen varve record highlight the need to apply time series analysis to the seasonal layers thickness measurements. When indications of short-term cyclicities are absent in certain intervals of one of the seasonal layer spectra, but present in the same intervals of the other seasonal spectra, the processes involved

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in varve formation were obviously susceptible to record agents of external forcing only under specific boundary conditions. In contrast, when the cyclic signals are absent from all seasonal spectra, the external climate forcing controlling varve formation was altogether weakened and/or ceased completely.

4 Conclusions

Microfacies and time series analyses from an annually laminated sedimentary archive of the Holsteinian interglacial (MIS 11) yields a strong signal of natural cyclicity at decadal and sub-decadal time scales. The decadal-scale cyclicity is attributed to solar forcing that may have influenced the sedimentation of the light varve layers (spring/summer) by driving changes in the productivity of the palaeolake. The sub-decadal-scale cyclicity is attributed to ENSO and NAO climate modes, predominantly influencing the dark layer formation (autumn/winter) through changes in atmospheric circulation that affected lake mixing. Our analyses clearly demonstrate that in order to interpret the signals of varve time series analysis and to correlate them with temporal modifications of the external climate forcing, it is essential to (a) understand the sedimentological processes controlling varve formation and to (b) compare the results of individually analyzed seasonal layer-thickness datasets.

The solar- and ENSO/NAO-like natural cyclicity during MIS 11 as recorded in the ~3200-yr-long varve time series from Dethlingen is closely comparable with the central European climate variability of the present interglacial. This suggests that the short-term climate cyclicity during the two interglacials is controlled by similar forcing. Taking this observation a step further, we suggest that MIS 11, besides the well-established long-term astronomical analogy, may be regarded as a good analogue for the Holocene with regard to short-term (sub-decadal- to decadal-) timescales. As a result, understanding the short-term climate variability during MIS 11 may potentially contribute to simulate future climate evolution of the present interglacial.

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Table 1. Summary of significant spectral peaks of light and dark layer time series of the Dethlingen varves and their possible forcing mechanisms.

Period (yr)	Light layers spectra	Dark layers spectra	Forcing
512	95 %	95 %	Solar or ocean circulation
90	99 %	99 %	Solar (88-yr Gleissberg cycle)
25	99 %	95 %	Solar (22-yr Hale cycle)
15	–	95 %	ENSO
10.5	99 %	–	Solar (11-yr Schwabe cycle)
5.8–6.1	–	99 %	NAO
3–5	mainly 95 %	mainly 99 %	ENSO
2–2.7	99 %	mainly 95 %	NAO/(QBO)

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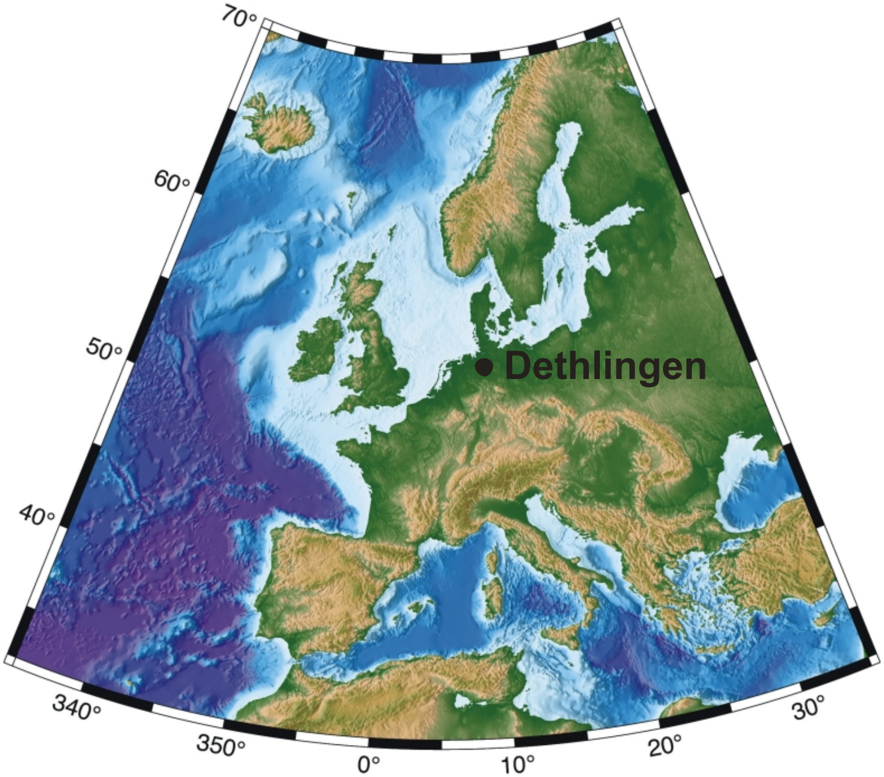

Fig. 1. Map indicating the location of the Dethlingen palaeolake.

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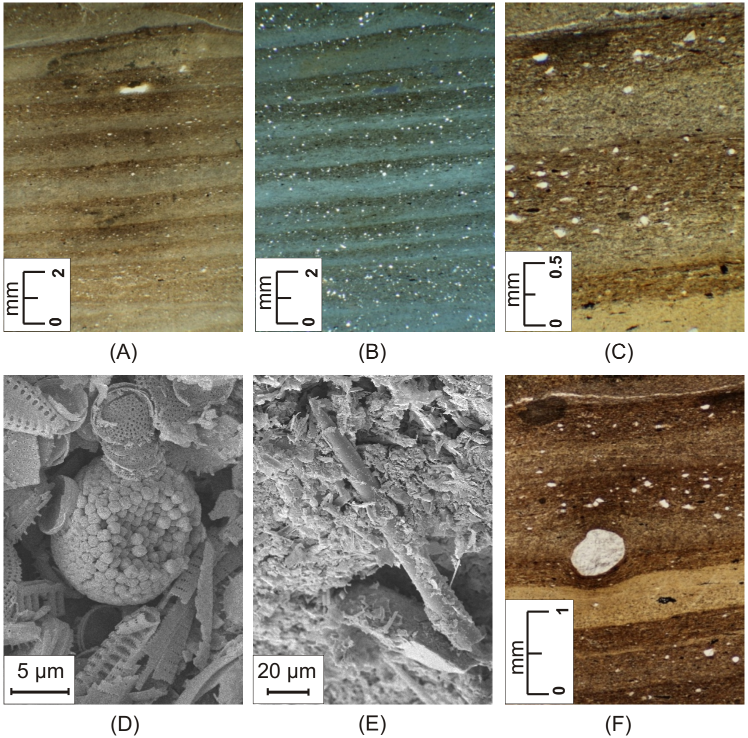

Fig. 2. Thin-section and scanning electron microscope photographs of varves from the Dethlingen core: Light and dark layers **(A)** under parallel-polarized light and **(B)** under cross-polarized light; **(C)** diffuse and sharp boundaries between successive dark and light layers; **(D)** pyrite framboids; **(E)** sponge spicule; **(F)** wind-transported fine sand grain.

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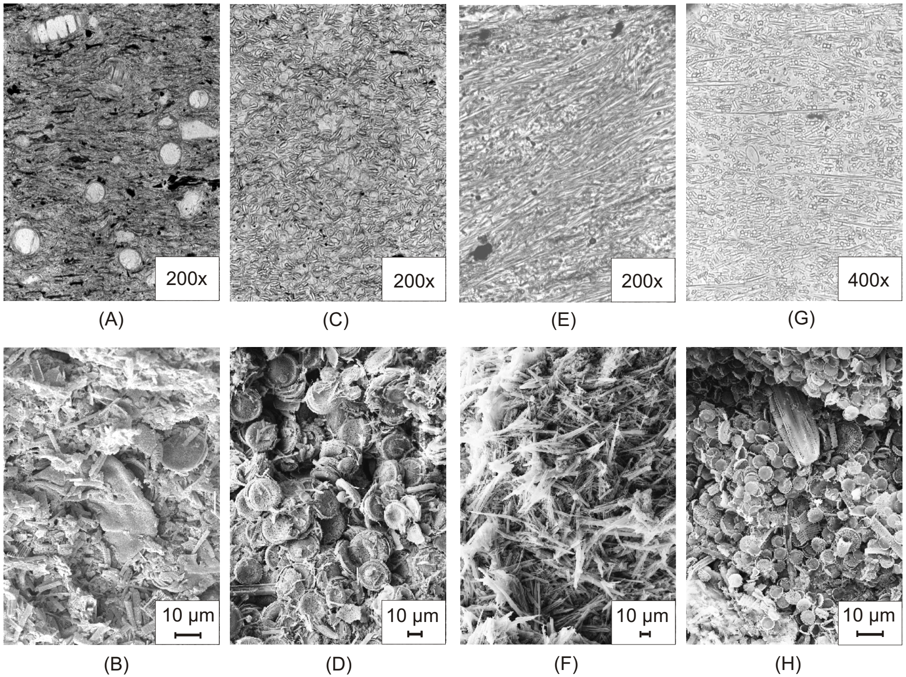

Fig. 3. Thin-section and scanning electron microscope photographs of different varve layers from Dethlingen: **(A, B)** dark layer; **(C, D)** light layer type A; **(E, F)** light layer type B; **(G, H)** light layer type C.

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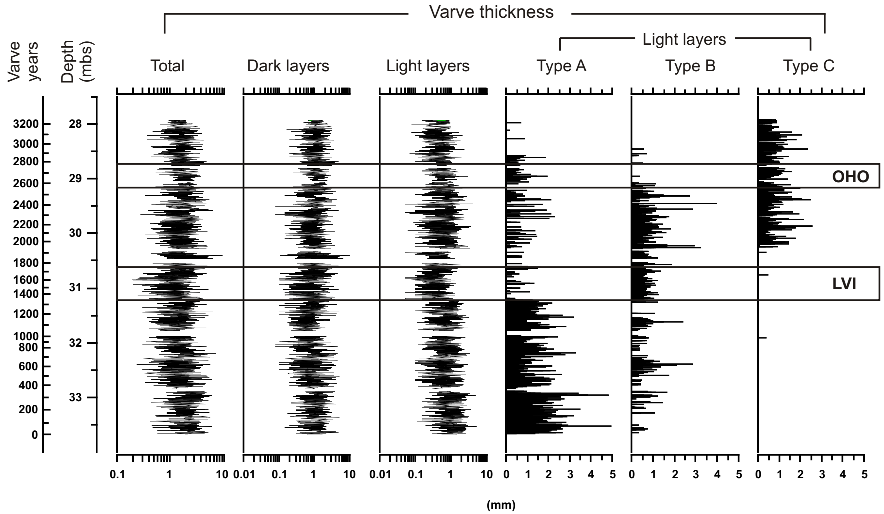

Fig. 4. Varve thickness measurements of dark layers and different types of light layers. Positions of the Older Holsteinian Oscillation (OHO) and the Low Variability Interval (LVI) are indicated.

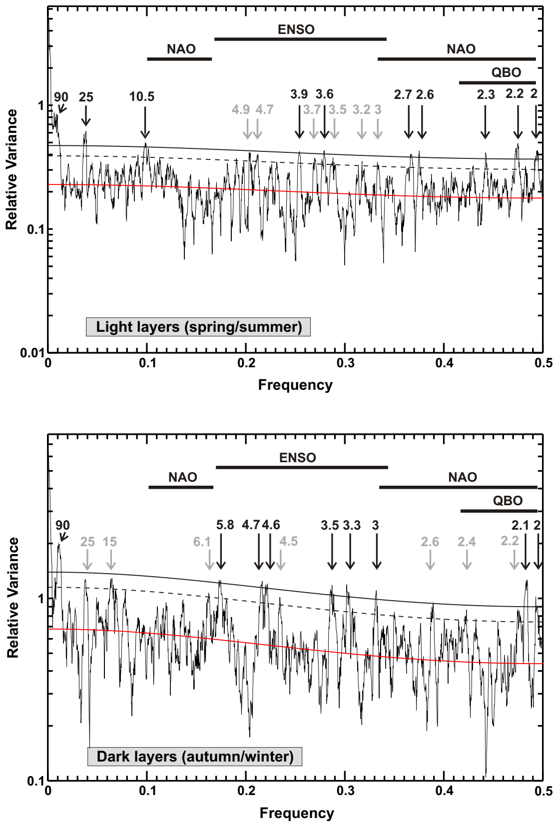

Fig. 5. Power spectra of the light and dark layer thickness measurements. The red line indicates the median red noise; the dashed and solid black lines indicate the 95 % and 99 % confidence levels, respectively. El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Quasi-Biennial Oscillation (QBO) bandwidths are after Mann and Park (1996).

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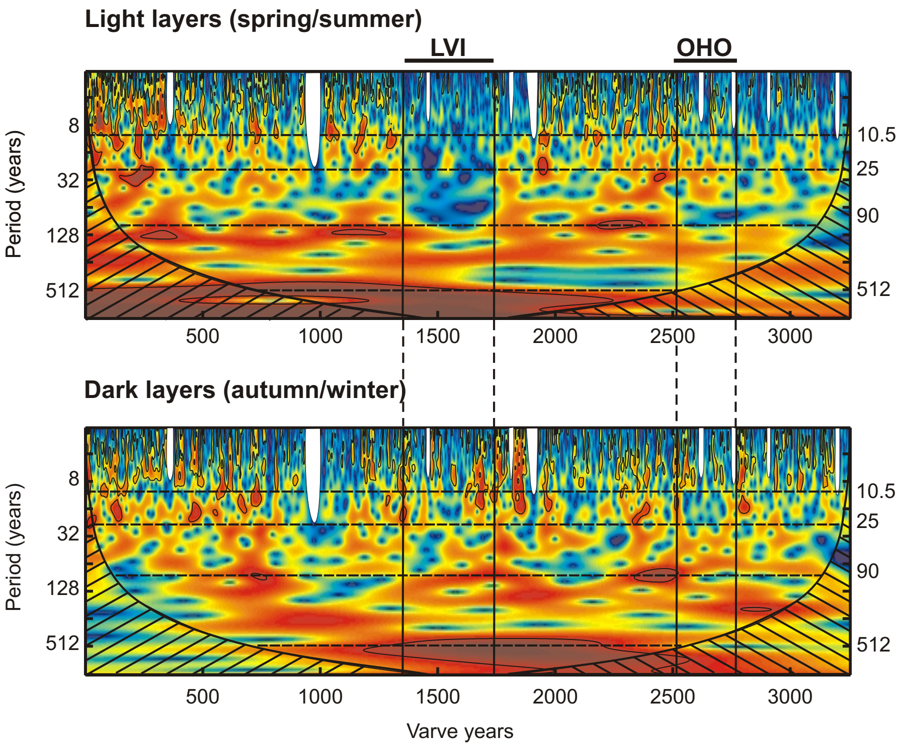

Fig. 6. Wavelet power spectra of the light and dark layer thickness measurements. Wavelet amplitudes are colour coded from red (high power) to blue (low power). Contoured areas exceed the 95 % confidence levels for a red noise background spectrum. Hatched areas indicate the cone of influence where wavelet analysis is affected by edge effects. Dashed lines mark the solar-like periodicities. White cones indicate intervals with no varve-thickness data. Positions of the Older Holsteinian Oscillation (OHO) and the Low Variability Interval (LVI) are indicated (see Sect. 3.4).

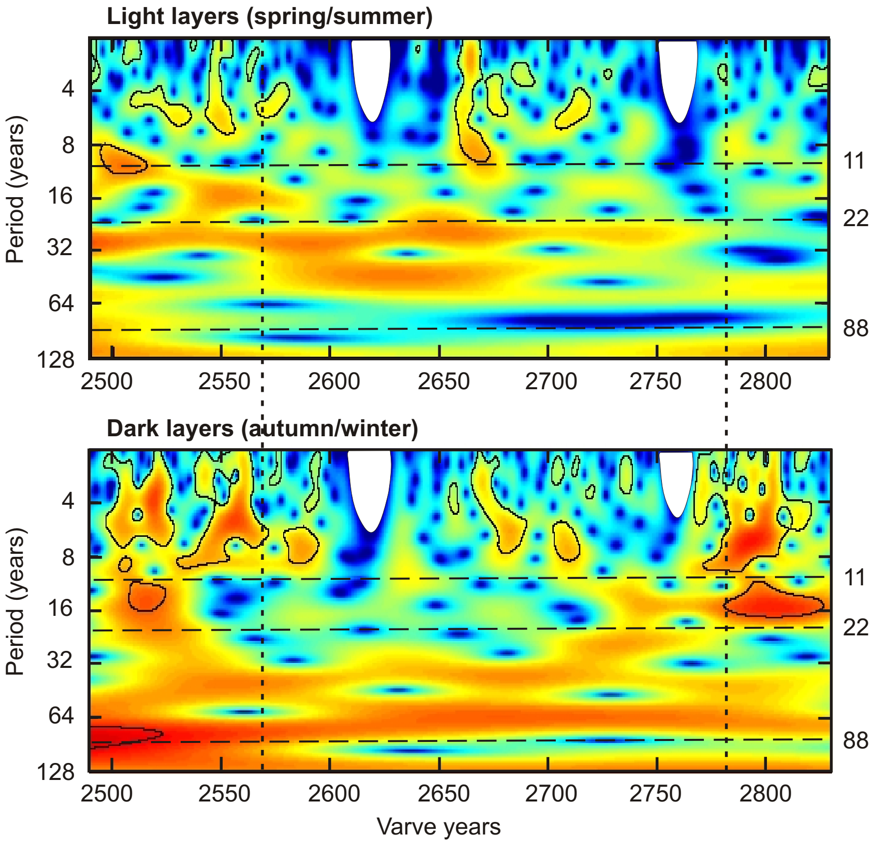

Fig. 7. Wavelet power spectra of the light and dark layer thickness measurements spanning the OHO interval. Wavelet amplitudes are colour coded from red (high power) to blue (low power). Contoured areas exceed the 95 % confidence levels for a red noise background spectrum. Vertical dashed lines mark the boundaries of the OHO at 2565 and 2782 varve yr. Horizontal dashed lines indicate the solar-like periodicities. White cones indicate intervals with no varve-thickness data.

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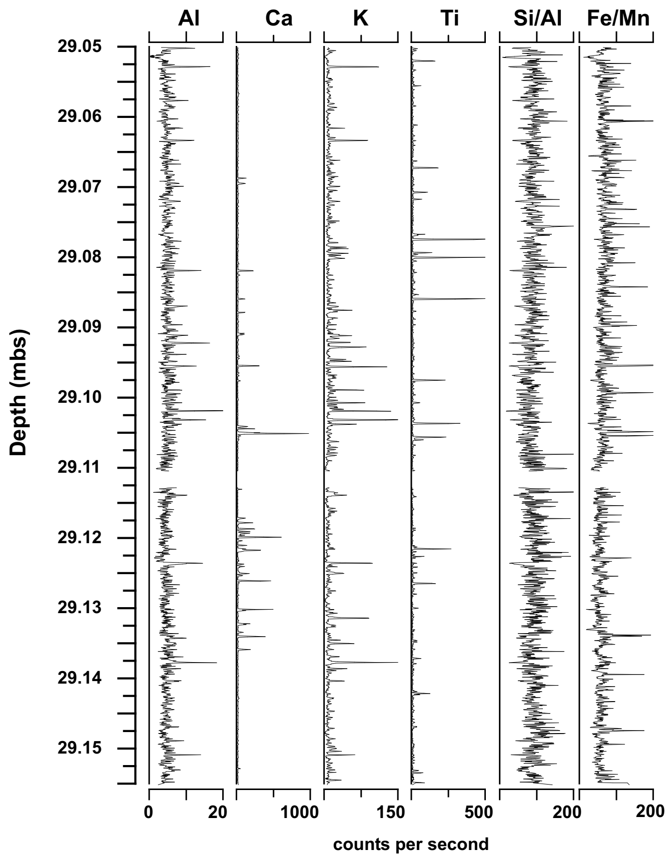

Fig. 8. Geochemical results of µ-XRF (step size: 50 µm) spanning the onset of the OHO in the Dethlingen core.