Rapid Communication

Modest summer temperature variability during DO cycles in western Europe

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1. Introduction

The nature and origin of the rapid climate shifts associated with Dansgaard-Oeschger (DO) cycles (Dansgaard et al., 1993) has been one of the most intriguing research questions during the past decades. They were first identified in the North Atlantic area, but have now been documented globally (Voelker et al., 2002; Clement and Peterson, 2008). Moreover, the synchronization of Greenland and Antarctic ice core records and evidence from marine sediment cores suggests a bipolar anti-phasing of DO cycles (Blunier and Brook, 2001; Martrat et al., 2007). Despite an increased understanding of the spatial and temporal distribution of DO cycles little is known about their temperature amplitudes both annually and seasonally at different locations in the two hemispheres. Annual temperature changes of 8–16°C have, for example, been reconstructed over Greenland (Landais et al., 2005; Huber et al., 2006) and annual sea surface temperature (SST) changes range between ca 4 and 7°C in the Alboran Sea (Cacho et al., 1999) and at the Iberian Margin (Martrat et al., 2007). Information from continental areas is limited (Voelker et al., 2002). Deciphering the amplitude of temperature change between cold and warm intervals and the distribution of that temperature change over the seasons at different locations are important to better constrain the origin of DO events and their impact on terrestrial ecosystems.

Quantitative temperature estimates for Europe during the Last Glacial are sparse and often lack sufficient temporal resolution to depict DO climate variability (Voelker et al., 2002). Here we present a detailed reconstruction of July air temperatures for the time interval between 36 and 18 thousand years before present. The reconstruction is based on fossil diatom assemblages from the paleolake Les Echets and indicates summer temperature changes of ca 0.5–2°C between stadials and interstadials. This study is the first to reconstruct temperatures with a sufficient time resolution to investigate DO climate variability in continental Europe. It is therefore also the first proxy record that can test and support the hypothesis that temperature changes during DO cycles were modest during the summer season.
2. Les Echets paleobasin and environmental record

Les Echets mire (45° 54′ N, 4° 56′ E) is situated at 267 m above sea level on the Dombes Plateau in eastern France (Fig. 1). The paleo-lake was a closed basin and had a surface of ca 1300 ha. Today this former lake basin contains a sedimentary record covering the early Eemian to the early Holocene (de Beaulieu and Reille, 1984). Detailed investigations of the Les Echets sediments revealed distinct ecosystem changes in concert with DO climate variability during the later part of Marine Isotope Stage (MIS) 3 and more attenuated changes during MIS 2 (Wohlfarth et al., 2008). Synchronous changes in limnic and terrestrial paleoenvironmental proxies showed well-defined lake productivity, catchment run-off and vegetation responses to these climatic events. Transitions between the different ecosystem regimes seem to have taken place in as little as 40–230 years. The rapid shifts at the beginning and end of each interstadial event differ, however, from the sawtooth-shaped Greenland δ18O curve and resemble more the step shape of the Greenland deuterium excess record (d) (Fig. 3e), a proxy for the temperature conditions in the oceanic moisture source regions (Jouzel et al., 2007).

3. Materials and methods

Sediment sequence EC1, obtained from the central part of the basin, has been analyzed for fossil diatom remains between 30.07 and 3.30 m depth (Ampel et al., 2008; Wohlfarth et al., 2008). Here we apply a diatom-July temperature transfer function to this diatom community composition record between 27.47 and 10.05 m corresponding to 36.2–17.6 kyr BP. The age estimates for this part of the record are based on 41 AMS 14C measurements and 16 infrared stimulated luminescence dates. Details on individual dates, laboratory procedures and the age model computation are described by Wohlfarth et al. (2008) and the methodology for diatom analysis is found in Ampel et al. (2008). The diatom-July temperature transfer function from the alpine area was derived by combining two existing regional training-sets from Switzerland (Lotter et al., 1997; Bigler et al., 2006). Overall, eight sites were iteratively identified as outliers and excluded due to high residuals between observed and predicted temperature values. The final transfer function is based on diatom community composition data and July temperature estimates of 90 lakes, including 365 diatom taxa and covering a mean July air temperature gradient from 5.2°C to 21.4°C. As in the original transfer function by Lotter et al. (1997), weighted averaging partial least squares (WA-PLS) (ter Braak and Juggins, 1993) regression and calibration was applied, resulting in better transfer function statistics for the combined training-set than other approaches such as simple weighted averaging or modern analogue technique. The WA-PLS model yielded a jack-knifed coefficient of determination ($r^2$) of 0.76 and a root mean squared error of prediction (RMSEP) of 2.11°C, whereas average and maximum bias were −0.14 and 3.53°C, respectively. The WA-PLS model and temperature reconstruction from Les Echets were developed using the C2 software package (version 1.5.0) (Juggins, 2007).

In general, the fossil assemblages are well represented (>90%) in the training-set, even though the representation is considerably lower during some periods of MIS 3 (Fig. 2). Of 144 fossil taxa, 48 are not represented in the calibration set. However, the missing taxa are not a major component of the diatom assemblages in Les Echets (max. abundance 6%, median abundance 1.5%, max. Hill’s $N_2 = 222$, median Hill’s $N_2 = 12$) (Hill, 1973). In addition, we calculated the proportion of rare taxa for each fossil sample as defined as taxa with Hill’s $N_2 < 5$ in training-set samples.

We calculated the occurrence of “no close”, “no good” and “no” analogues in the fossil samples in relation to training-set samples, applying cut-levels of 2nd, 5th and 10th percentile of all chi-squared distances in the training-set samples. Furthermore, the fit to temperature was estimated by assessing the square residual length (SqRL) calculated between each fossil sample and the axis interpreted as representing the temperature variable in a Canonical Correspondence Analysis (CCA) with July temperature as the only constraining variable, adding the fossil samples passively to the
analysis. Fossil samples with a SqRL higher than the 90th percentile were considered as samples with “poor” fit to temperature, and higher than the 95th percentile as “very poor”, respectively. We used the computer programs C2 and CANOCO (ter Braak and Smilauer, 2002; Juggins, 2007).

4. Diatom-inferred July paleotemperatures at Les Echets between 36 and 18 kyr BP

The reconstructed July temperatures cover the time intervals 36.2–31.7, 30.8–26.3, and 23.6–17.6 kyr BP (Fig. 3a–c). Sections with very few diatoms separate these periods and for these temperature reconstructions were not possible (Fig. 2). The diatom-barren intervals fall within the age ranges reported for Heinrich events 4, 3, and 2 (Thouveny et al., 2000; de Abreu et al., 2003; Roucoux et al., 2005), which suggests that the severe climatic conditions associated with these events (de Abreu et al., 2003; Roucoux et al., 2005) had a signifi
cant impact on the lake and limited diatom production and/or decreased valve preservation (Ampel et al., 2008). Also, samples flanking the diatom-barren intervals show the lowest reconstructed temperature values of the sequence indicating climatic deterioration with significant temperature decreases.

The general trend in our reconstructed July temperature curve is that of higher variability between 36.2 and 31.7 kyr BP (equivalent to MIS 3) and less variable temperatures between 30.8 and 26.3 and 23.6 and 17.6 kyr BP (equivalent to MIS 2) (Fig. 3b and c). The MIS 3 part of the sequence gives evidence for five distinct intervals of increased July temperatures centred at 35.8, 35.0, 34.2, 33.2, and 32.0 kyr BP (A, B, C, D, and E respectively in Fig. 3b). These five intervals differ in their amplitude: A, B and C have higher reconstructed July temperature changes of ca 1.5°C compared to the preceding stadials, while intervals D and E show an increase of ca 1–1.5°C. Overall, intervals A–E depict a descending trend in temperature amplitude, as is often illustrated for a sequence of DO interstadials in ice core δ18O records (Bond et al., 1993).

Reconstructed July temperatures for MIS 2 have lower amplitudes, although some variability occurs. Four modest temperature increases seem to be centred at 29.6, 28.2, 27.3 and 21.3 kyr BP (F–H respectively in Fig. 3b). These events represent a reconstructed July temperature rise of ca 0.5–1°C in relation to their preceding stadials. The overall low temperature variability after 30 kyr BP follows the general climatic trend characteristic for MIS 2. However, intervals F–H appear less distinct than comparable DO events in ice core records (Dansgaard et al., 1993), which suggest that local climatic conditions (i.e. the growth of Alpine glaciers in the near proximity) exerted a stronger influence on the environment at Les Echets (Wohlfarth et al., 2008).

July temperatures for 23.6–17.6 kyr BP show little variability around an average of 9°C (Fig. 3b and c). Although this interval corresponds in time to the Last Glacial Maximum (LGM) (19.000–23.000 cal-yr BP) (Mix et al., 2001) we do not observe any

Fig. 2. The diagram shows the most common taxa and the total percentage of benthic and planktonic species between 36.2 and 17.6 kyr BP. The taxa are arranged in successional order and Navicula spp. has been divided into a stadial and interstadial group because most taxa in this genus have demonstrated a distinct preference for either stadial (e.g. N. jenteszhi, N. jaernefelti, and N. scutellodes) or interstadial (e.g. N. radiosa, N. rhyphocelba, and N. papula) conditions (Ampel et al., 2008). The Detrended Correspondence Analysis (DCA) scores for axis 1 (explaining 28.3% of the total variance) summarize the compositional changes in diatom communities (Ampel et al., 2008). The representation in the calibration dataset shows the relative amount of species at each level which are present in the temperature calibration dataset.

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distinct temperature minimum that could be identified as the “culmination” of the LGM. Instead, we note that eastern France seems to have been characterised by a prolonged interval with rather low July temperatures during the LGM.

These results should be interpreted with caution as the numerical evaluation (Fig. 4) shows that 222 of the 252 fossil samples have an abundance of rare taxa higher than 10%, while 21 samples had more than 5% rare taxa and 9 samples less than 5% rare taxa. 8% of the fossil samples have no close analogue in the training-set, 73% have no good analogue and 19% have no analogue. 2% of the samples show a good fit to temperature, whereas 92% show a poor fit and 6% a very poor fit to temperature. These three evaluation parameters are not independent of each other but illustrate the reliability of the calibration set in different ways using the same initial data.

5. Comparison with other quantitative records

Detailed summer temperature estimates over individual DO cycles are lacking for the European continent. Most records have insufficient temporal resolution to reveal DO stadial to interstadial changes or suffer from inadequate chronological control. It is therefore difficult to compare in detail the high-resolution summer temperature reconstructions and their evolution over a succession of DO cycles at Les Echets with other records. Instead we evaluate how average summer temperatures during MIS 3 and 2 at Les Echets compare with fragmentary summer temperature reconstructions from other sites in Europe (Ponel, 1995; Coope et al., 1997; Huijzer and Vandenberghe, 1998; Bos et al., 2001, 2004; Jost-Stauffer et al., 2001; Whittington and Hall, 2002; Brown et al., 2007) between 36 and 18 kyr BP (Fig. 3).

Our reconstructed average temperature of $\sim 10^\circ C$ during MIS 3 falls well within the temperature estimates of ca $10-12^\circ C$ from Gossau (Jost-Stauffer et al., 2001), La Grande Pile (Ponel, 1995), London (Coope et al., 1997), Niederlausitz (Bos et al., 2001), NW Europe compilation (Huijzer and Vandenberghe, 1998), London (Coope et al., 1997), Sourlie (Bos et al., 2004), Balglass (Brown et al., 2007) and Tolsta (Whittington and Hall, 2002) between 36 and 18 kyr BP (Fig. 3).

During MIS 2 Les Echets summer temperatures have an average of $\sim 9^\circ C$ which is in close agreement with estimates from La Grande Pile (Ponel, 1995) of $\sim 10^\circ C$ and NW Europe (Huijzer and Vandenberghe, 1998) of $\sim 8^\circ C$ (Fig. 3).
6. Seasonality changes during the DO cycle

The role of seasonality in abrupt climate change has been discussed in two recent studies (Denton et al., 2005; Flückiger et al., 2008), which suggest that the large temperature shifts in the Northern Hemisphere were related to winter and spring temperatures, whereas summer temperatures were characterised by much smaller changes. The important actor in this would have been the Atlantic Meridional Overturning Circulation (AMOC), which slowed down during stadials and became stronger during interstadials. The extensive spread of North Atlantic sea ice during stadial winters restricted the ocean-atmosphere heat flux, which caused a significant drop in winter temperatures on adjacent continents. In contrast, less extensive sea ice during interstadial winters would have enabled more oceanic heat release, which would have resulted in less cold temperatures on the continents (Denton et al., 2005; Flückiger et al., 2008).

Model output suggest that the influence from sea ice and ocean heat release was most dominant at northern latitudes above 55°N, whereas areas south of 55°N experienced a larger influence from seasonal changes in snow cover. An earlier onset of the snowmelt in spring led to a strong positive snow-albedo feedback, which amplified the temperature increase and lead to an even larger temperature change in spring than in winter (Flückiger et al., 2008). The fact that Greenland ice core records show major mismatches to European moraine records, but compare well to Asian monsoon records (Denton et al., 2005) together with new model scenarios (Flückiger et al., 2008) suggest that climate was close to a critical winter threshold during the last glacial period. Model results (Flückiger et al., 2008) indicate that this threshold was frequently crossed, which resulted in considerable regional differences during stadials and interstadials: latitudes north of 55°N experienced the largest temperature differences

Fig. 4. Diatom-inferred July air temperatures for Les Echets during three different time intervals a) 36.2–31.7 b) 30.8–26.3 c) 23.6–17.6 kyr BP. The white points indicates samples with a good fit to temperature/rare taxa <5%/no close analogues, while grey points show samples with a poor fit to temperature/rare taxa between 5 and 10%/no good analogues and black points indicate a very poor fit to temperature/rare taxa >10%/no analogues.
between November and February, whereas central European temperature differences were greatest in April and May; in contrast all regions in the Northern Hemisphere show smallest temperature changes from June to September (Flickiger et al., 2008).

Les Echets is the first record in continental Europe, which allows a reconstruction of stadial/interstadial summer temperature changes during several DO cycles between 36 and 18 kyr BP. Despite distinct oscillations in inferred summer temperature (Fig. 3b and c), which correlate with changes in all other paleo-environmental proxies (Wohlfarth et al., 2008), the reconstruction implies that the amplitude of these changes was subtle (~0.5–2 °C). The dataset from Les Echets thus provides independent evidence for the hypothesis that temperature changes over DO cycles were small during the summer season.

The dramatic ecosystem shifts that were identified at Les Echets (Wohlfarth et al., 2008), therefore, most probably reflect a lengthening of the season (i.e. spring warming) during which biological productivity could have taken place rather than a response to the actual temperature change during the summers. These results demonstrate the importance of distinguishing between temperature changes during different seasons when discussing the impact of abrupt climate change on ecosystems. Modest summer temperature changes inferred from the Les Echets dataset support the hypothesis that low summer, but consequently higher winter and spring temperature variability, together with a change in the length of the winter season form a likely scenario to explain the model-data mismatches during MIS 3 (Alfano et al., 2003).

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References


