Cyclic climate fluctuations during the last interglacial in central Europe

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ABSTRACT
Differentiating natural climate change from anthropogenic forcing is a major challenge in the prediction of future climates. In this context, the investigation of interglacials provides valuable information on natural climate variability during periods that resemble the present. This paper shows that natural cyclic changes in winter climates affected central European environments during the last interglacial, i.e., the Eemian, 126–110 ka. As a result of the extraordinarily high counting sums performed at Eemian pollen samples, it was possible to reveal a robust presence–absence pattern of the insect-pollinated, and therefore in the pollen rain underrepresented, taxon Hedera. This plant is known to require the influence of oceanic winter climates, i.e., moist and mild, in northwest and central Europe. By analogy with recent findings from the North Atlantic’s Holocene interglacial, the trigger of the Eemian climate variability may have been changes in solar activity, possibly amplified by changes in North Atlantic ocean currents and/or in the North Atlantic Oscillation. Our findings suggest natural cyclic changes to be a persistent feature of interglacial climates.

Keywords: climate change, solar activity, environmental change, Eemian, Europe.

A core (48°06′00″N, 9°43′44″E, 578 m above sea level [masl]) has been taken from lake sediments in a subglacial basin called Jammertal located in the southwest German alpine foreland. The interval 12.65–15.00 m, which comprises the interglacial, was analyzed with an average sample spacing of 4.4 cm. This corresponds to an average resolution of either 220 or 300 yr, according to the chronology of Müller (1974) or Shackleton et al. (2003), respectively. To reliably document the occurrence of insect-pollinated taxa (chronically underrepresented in the pollen rain and hence only fragmentarily documented in other records), we analyzed an extraordinarily high number of pollen grains (2000–2500) per sample from the interglacial interval. The resulting pollen diagram (Fig. 1A) shows the successive plant immigration pattern that is typical for the Eemian in central Europe (e.g., de Beaulieu and Reille, 1984; Litt, 1994; Müller et al., 2003). To verify that the Jammertal interglacial represents the Eemian, an absolute 230Th/U dating of the interglacial fine-detritus mud has been carried out. One absolute 230Th/U dating consists of four analyses on two sets of two samples taken at depths of 13.45, 13.53, 13.58, and 13.60 m. The measurements yielded 230Th/234U and 232U/238U activity ratios (AR), which were evaluated by the isochron method (Ku and Liang, 1984). We obtained an actual 230Th/ 232Th AR of 0.341 ± 0.013 (2σ), which was used for the detritus correction of the 230Th/ 234U AR (Geyh, 2001). The obtained corrected 230Th/U ages yielded a mean 230Th/U age of 125.3 ± 2.2 k.y. (2σ) with a χ² value of 5.7. We checked the open-system conditions for uranium using the Osmond-Ivanovich plot (Fig. 2). The detritally corrected AR yielded two clusters. We supposed that the corresponding samples had slightly deviating initial 231U/234U AR and closed-system conditions for uranium prevailed. Hence, both pollen data and the mean 230Th/U age consistently attribute the Jammertal interglacial to the Eemian and allow a correlation with marine isotope substage 5e.

Besides reflecting the well-known Eemian vegetation succession, our high-count approach reveals an intermittent pattern in the occurrence of the insect-pollinated taxon Hedera helix (Figs. 1A and 3A). This plant is known as a frost-sensitive evergreen liane requiring oceanic climate conditions with mild and moist winters in northwest and central Europe (e.g., Iversen, 1944; Frenzel, 1991; Oberdorfer, 1994). Today, Hedera cannot bloom in areas with a mean January temperature below −2 °C (Iversen, 1944; Frenzel, 1991; Aalbersberg and Litt, 1998). In spite of the very high counting sum, the Hedera pollen has not been found in samples 14.50, 14.30, 14.05, 13.70, 13.40, and 13.20 m, although it is present in the intervals below and above (Fig. 3A). A counting sum of 2000 pollen grains yields a probability of 93.75% to detect a given taxon that is represented by only 0.2% in the sample. Hence, the presence–absence pattern of Hedera in the Eemian record can be considered as robust. Moreover, the distribution pattern of Ilex aquifolium, an evergreen tree species with similar requirements of mild winter temperatures (Iversen, 1944; Frenzel, 1991; Oberdorfer, 1994), is mainly in phase with that of Hedera (Fig. 1A). We conclude that the recurring presence–absence of these species points to cyclic (not necessarily periodic) changes in mean winter climates during the Eemian interglacial. The circumstance that the occurrence of Ilex is not totally in phase with Hedera might be explained by differences in the root system and moister supply of these plants in winter rather than temperatures.

This conclusion is supported by other Eemian pollen records from western Europe, e.g., Bobbitshole in Great Britain (West, 1957), Amersfoort in the Netherlands (Zagwijn, 1961; Cleveringa et al., 2000), Quakenbrück in northern Germany (Hahne et al., 1994), and Les Echets (de Beaulieu and Reille, 1984) in eastern France. They also show an intermittent pattern in the occurrence of Hedera. At these sites, however, the documentation of insect-pollinated taxa shows the relics of counting sums insufficient to reliably document chronically underrepresented grains (Fig. 3B). Therefore, the presence–absence pattern there has not yet received attention.

To verify the fluctuations found at Jammertal, we performed a pollen-based climate reconstruction by means of the probability mutual climatic spheres (PCS) method (Pross et al., 2000; Pross and Klotz, 2002; Klotz et al., 2003, 2004), which is founded on the indicator species concept pioneered by Iversen (1944). The fundamental principle of the PCS method is to determine a climatic interval in which all taxa found in the fossil sample can coexist. This is done with respect to various climate parameters such as mean winter, sum-
Figure 1. A: Eemian pollen diagram at Jammertal, southwest Germany. As a result of extraordinarily high counting sum of more than 2000 pollen grains per sample, it was possible to reveal robust presence–absence pattern in curve of Hedera, frost-sensitive species that requires oceanic winter climates, i.e., mild and moist. This feature points to cyclic (not necessarily periodic) changes in winter climates. B: Pollen-based climate reconstruction calculated with probability mutual climatic spheres method (Pross et al., 2000; Pross and Klotz, 2002; Klotz et al., 2003, 2004) indicates recurring cold events related to mean winter temperatures. Most likely values are shown in full lines with dots; probability intervals are in gray. Shaded horizontal bars with numbers in circles mark position of recurring cold events (cf. Fig. 3A).

The presence–absence pattern of Hedera and the PCS temperature reconstruction allow the identification of 11 cold events during the Eemian interglacial (see shaded bars and numbers in Figs. 1 and 3A). Assuming a 11 k.y. duration of the Eemian interglacial, as has been estimated on the basis of analyses at annually laminated sediments in northern Germany (Müller, 1974), the average recurring time of the cold events would be 1 k.y. Alternatively, assuming a 16 k.y. duration of the Eemian interglacial as resulting from the chronology of marine core MD95-2042 off Portugal (Shackleton et al., 2003), inferred from high-precision radiometric dating of coral terraces, the average recurring time of the 11 cold events would be 1450 yr. The 11 k.y. duration of Eemian forests in northwest Europe and the 16 k.y. longevity of Eemian woodlands in southwest Europe indicate that there may have been a 5 k.y. phase in the declining stage of the last interglacial, when steep climate and vegetation gradients existed (Kukla, 2000; Kukla et al., 2002; Shackleton et al., 2003). During that phase, an open vegetation formation prevailed in northern Europe, whereas Eemian woodlands persisted in southern Europe (Tzedakis, 2003; Müller and Kukla, 2004). A correlation of an array of last interglacial records from sites along a European north-south transect suggests that Eemian woodlands in the southwest German alpine foreland existed for 16 k.y., as in southern Europe, rather than 11 k.y., as in northern Europe (Müller and Kukla, 2004). Therefore, we propose that the average spacing of the recurring cold events during the last interglacial was between 1 k.y. and 1.5 k.y., most likely close to 1.5 k.y.
Recurring cold events with about the same spacing punctuate the Holocene. Available evidence is based on drift-ice proxies from North Atlantic sediments (Bond et al., 1997, 2001), sea-surface temperature data calculated from foraminifer assemblages off West Africa (deMenocal et al., 2000), oxygen isotope measurements from a speleothem in southwest Ireland (McDermott et al., 2001), foraminifer abundance patterns in the Arabian Sea (Gupta et al., 2003), and analyses of lake sediments from southwest Alaska (Hu et al., 2003). These records document a climatic cyclicity (also not necessarily periodic) over a large region of the Northern Hemisphere during the Holocene. A close match of the cyclic changes in drift-ice proxies to variations in production rates of cosmogenic isotopes (Bond et al., 2001) was taken as evidence that the Holocene climate cyclicity may have been influenced by variations in solar activity, manifested as variations in the interplanetary magnetic field (Lean et al., 2002). Magny et al. (2003) showed a correlation between fluctuations of \(^{14}\)C concentrations in the atmosphere and lake-level changes in the French Pre-Alps.

Bond et al. (2001) documented similar cyclic changes in drift-ice proxies with an average recurrence time of 1480 yr in North Atlantic sediments of the last interglacial or marine isotope substage 5e. Although it is difficult to assess whether the recurring events found in our European pollen record and the North Atlantic last interglacial drift-ice proxies record are in phase, it is suggested that the observed changes in both regions are influenced by the same mechanisms. *Hedera* requires mild and moist air masses from the North Atlantic during winter: therefore, the recurrent absence of *Hedera* in northwest and central Europe could be taken as consistent with either (1) a persistent negative phase of the winter-dominated North Atlantic Oscillation, which would have reduced advection of warm and moist air to northwest and central Europe, or (2) pulse-like changes in extension, direction, and/or intensity of the North Atlantic current. Both mechanisms have been proposed to explain climate variability (Hurrell et al., 2001; Broecker, 2003); however, both mechanisms act as an amplifier rather than as the ultimate forcing of climate change.

If the analogy drawn between the variations of the Holocene and those of the Eemian is correct, the ultimate climate forcing may have been variations in solar activity (Beer et al., 2000), most likely amplified by changes in the intensity or direction of the North Atlantic current and/or changes of the index of the North Atlantic Oscillation. If that is true, the response to solar forcing may have had at least a regional footprint within parts of the North Atlantic marine realm and in central European ecosystems, at least on multcentennial to millennial time scales. This adds to the growing evidence of a sun-climate connection on long time scales, but it brings us no closer to understanding the mechanisms underlying that connection. To ascertain which mechanisms are involved in the recurring cold events during the last interglacial, more data sets (such as pollen records with extraordinarily high

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**Figure 2.** Osmond-Ivanovich plot (Osmond and Ivanovich, 1992) to check open-system conditions for uranium. Two sets of two samples had slightly deviating initial \(^{234}\)U/\(^{238}\)U activity ratios (AR) and formed two clusters that confirm closed-system conditions. After detrital correction of \(^{230}\)Th/\(^{234}\)U AR, dots reasonably fit isochron of 125 ka.

**Figure 3.** Presence–absence pattern of *Hedera* during last interglacial in high-count and normal-count record. **A:** High-count approach (average of 2102 grains per sample) performed for Jammertal record reveals robust intermittent pattern in occurrence of this frost-sensitive taxon. Numbers refer to cold events (cf. Fig. 1). **B:** Eemian pollen record of Quakenbrück (Hahne et al., 1994) (53°N, 8°E) shows presence–absence pattern as well. Some gaps in *Hedera* curve of Quakenbrück are considered relics of counting sum (average of 794 grains per sample) insufficient to reliably document chronically underrepresented taxa.
counting sums) from sites in the North Atlantic realm are required.

Although the Eemian interglacial is not a perfect analog of the Holocene because of a different influence of orbital forcing then and now, the finding of natural cyclic climate changes during the Holocene interglacial (e.g., Bond et al., 1997; deMenocal et al., 2000; Hu et al., 2003) and during the last interglacial (this study) suggests natural cyclic climate changes to be a persistent feature of interglacial climates, and thus increases the likelihood that the forcing of this cyclicity will act in the future.

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REFERENCES CITED


