

Cyclic climate fluctuations during the last interglacial in central Europe

Ulrich C. Müller Institute of Geology and Paleontology, Johann Wolfgang Goethe University, 60054 Frankfurt, Germany, and Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964, USA

Stefan Klotz Institut für Geowissenschaften, Universität Tübingen, D-72076 Tübingen, Germany

Mebus A. Geyh Leibniz Institute for Applied Geoscience (GGA), D-30655 Hannover, Germany

Jörg Pross Institute of Geology and Paleontology, Johann Wolfgang Goethe University, 60054 Frankfurt, Germany

Gerard C. Bond Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964, USA

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 $^{230}\text{Th}/\text{U}$ dating of the interglacial fine-detritus mud has been carried out. One absolute $^{230}\text{Th}/\text{U}$ 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 $^{230}\text{Th}/^{234}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity ratios (AR), which were evaluated by the isochron method (Ku and

Liang, 1984). We obtained an actual $^{230}\text{Th}/^{232}\text{Th}$ AR of 0.341 ± 0.013 (2σ), which was used for the detritus correction of the $^{230}\text{Th}/^{234}\text{U}$ AR (Geyh, 2001). The obtained corrected $^{230}\text{Th}/\text{U}$ ages yielded a mean $^{230}\text{Th}/\text{U}$ age of 125.3 ± 2.2 k.y. (2σ) with a χ^2 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 $^{234}\text{U}/^{238}\text{U}$ AR and closed-system conditions for uranium prevailed. Hence, both pollen data and the mean $^{230}\text{Th}/\text{U}$ 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-

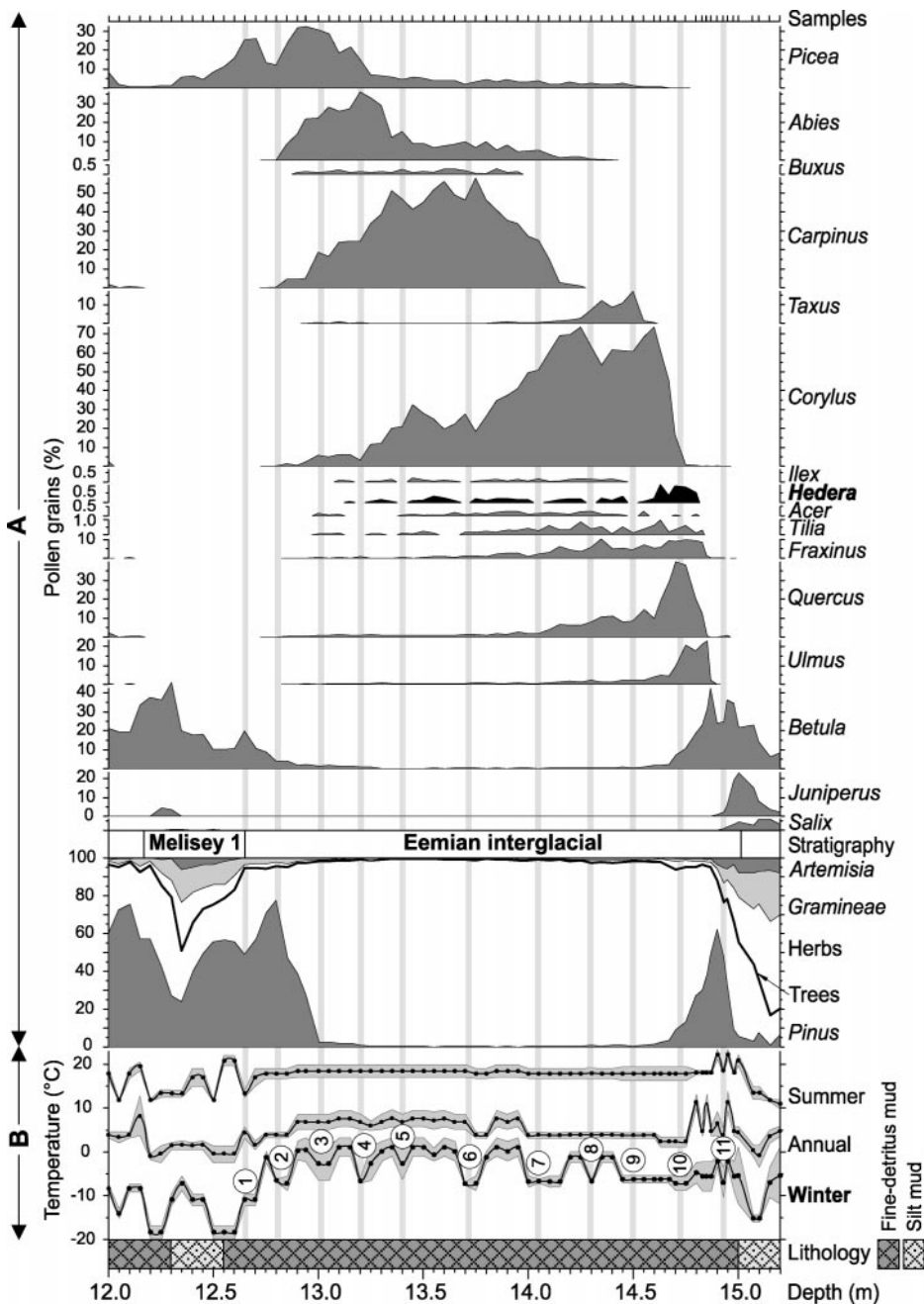


Figure 1. A: Eemian pollen diagram at Jammertal, southwest Germany. As result of extraordinarily high counting sum of more than 2000 pollen grains per sample, it was possible to reveal robust presence-absence pattern in curve of *Hedera*, frost-sensitive species that requires oceanic winter climates, 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).

mer, and annual temperatures. The first step is to determine the present-day climatic existence interval of each taxon found in a fossil sample on the basis of plant distribution maps. Thereafter, the common intersection of these existence intervals is regarded as the climatic interval in which all taxa from this sample can coexist. Finally, we assume that the tempera-

tures at the time of the sample were most likely within the coexistence interval. This reconstruction method is sensitive to the presence and absence of taxa in the sample, and is independent from modern analogs in terms of plant communities since members from fossil assemblages are evaluated as isolated entities.

The results of the PCS reconstruction (Fig.

1B) show that during the Eemian interglacial mean winter temperatures underwent recurring setbacks, whereas mean summer temperatures appeared relatively stable. Considering the co-occurrence of *Abies alba*, requiring mean winter temperatures above -4°C , and *Picea alba*, requiring mean winter temperatures below 0°C to be competitive (Aalbersberg and Litt, 1998), the amplitude of the fluctuation in winter temperatures during most of the Eemian was restricted to $<4^{\circ}\text{C}$. The circumstance that the winter temperature curve in Figure 1B displays fluctuations slightly higher than 4°C during the Eemian is a relict of (1) the anthropogenic influence on the present-day plant distribution maps used for the PCS calculations, which results in plants growing in areas where they are naturally not competitive, and (2) the 0.5×0.5 grid resolution of those maps. Although the amplitude of temperature fluctuations may be somewhat overestimated in Figure 1B, the number of cold events will stay the same.

Both 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 an 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.

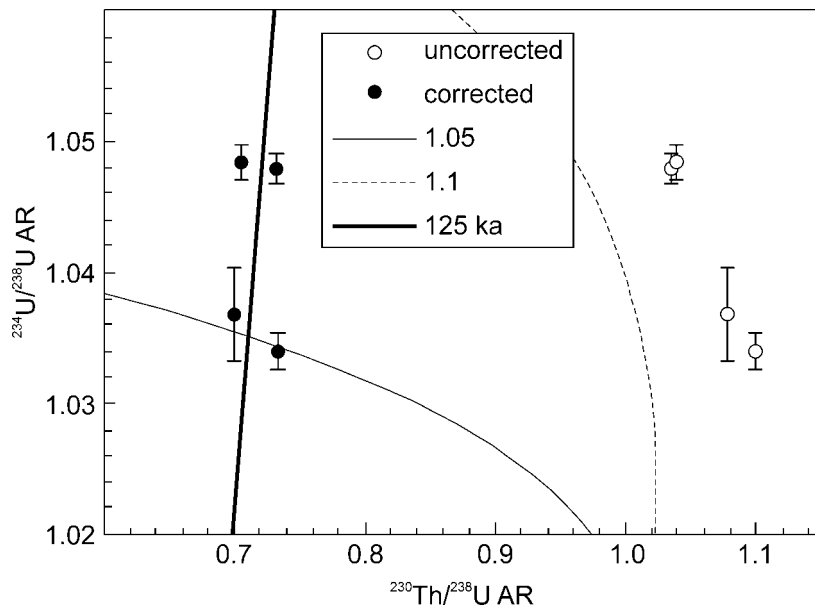


Figure 2. Osmond-Ivanovich plot (Osmond and Ivanovich, 1992) to check open-system conditions for uranium. Two sets of two samples had slightly deviating initial $^{234}\text{U}/^{238}\text{U}$ activity ratios (AR) and formed two clusters that confirm closed-system conditions. After detrital correction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

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 cyclicality (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 cyclicality 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 multicentennial 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

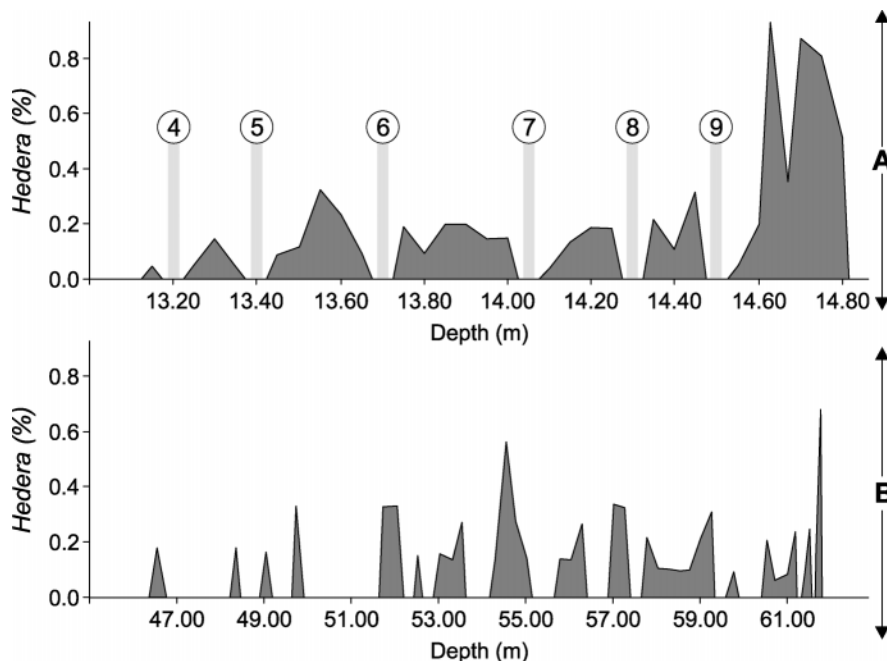


Figure 3. Presence-absence pattern of *Hedera* during last interglacial in high-count and normal-count record. A: High-count approach (average of 2102 grains per sample) performed for Jammertal record reveals robust intermittent pattern in occurrence of this frost-sensitive taxon. Numbers refer to cold 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 relicts 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.

ACKNOWLEDGMENTS

We thank J. Hahne for providing raw count pollen data from Quakenbrück. This work was supported in part by grants from the Max-Kade Foundation (New York), the Deutsche Forschungsgemeinschaft (grant Pr 651/3-1), the National Science Foundation, and the Alexander von Humboldt Foundation (Bonn-Bad Godesberg).

REFERENCES CITED

- Aalbersberg, G., and Litt, T., 1998, Multiproxy climate reconstructions for the Eemian and early Weichselian: *Journal of Quaternary Science*, v. 13, p. 367–390, doi: 10.1002/(SICI)1099-1417(1998090)13:53.3.CO;2-9.
- Beer, J., Mende, W., and Stellmacher, R., 2000, The role of the Sun in climate forcing: *Quaternary Science Reviews*, v. 19, p. 403–415, doi: 10.1016/S0277-3791(99)00072-4.
- Bond, G.C., Showers, W.J., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G., 1997, A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates: *Science*, v. 278, p. 1257–1266, doi: 10.1126/science.278.5341.1257.
- Bond, G.C., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G., 2001, Persistent solar influence on North Atlantic climate during the Holocene: *Science*, v. 294, p. 2130–2136, doi: 10.1126/science.1065680.
- Broecker, W.S., 2003, Does the trigger for abrupt climate change reside in the ocean or in the atmosphere: *Science*, v. 300, p. 1519–1522, doi: 10.1126/science.1083797.
- Cleveringa, P., Meijer, T., van Leeuwen, R.J.W., de Wolf, H., Pouwer, R., Lissenberg, T., and Burger, A.W., 2000, The Eemian stratotype locality at Amersfoort in the central Netherlands: A re-evaluation of old and new data: *Geologie en Mijnbouw*, v. 79, p. 197–216.
- de Beaulieu, J.-L., and Reille, M., 1984, A long upper Pleistocene pollen record from Les Eclats, near Lyon, France: *Boreas*, v. 13, p. 111–132.
- deMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M., 2000, Coherent high- and low-latitude climate variability during the Holocene warm period: *Science*, v. 288, p. 2198–2202, doi: 10.1126/science.288.5474.2198.
- Frenzel, B., 1991, Das Klima des letzten Interglazials in Europa, in Frenzel, B., ed., *Klimageschichtliche Probleme der letzten 130000 Jahre: Paläoklimaforschung Volume 1*: Stuttgart, Akademie der Wissenschaften und Literatur, p. 51–78.
- Geyh, M.A., 2001, Reflections on the $^{230}\text{Th}/\text{U}$ dating of dirty material: *Geochronometria*, v. 20, p. 9–14.
- Gupta, A.K., Anderson, D.M., and Overpeck, J.T., 2003, Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean: *Nature*, v. 421, p. 354–356, doi: 10.1038/nature01340.
- Hahne, J., Kemle, S., Merkt, J., and Meyer, K.-D., 1994, Eem-, weichsel- und saalezeitliche Ablagerungen der Bohrung, Quakenbrück GE 2: *Geologisches Jahrbuch*, v. A34, p. 9–69.
- Hu, F.S., Kaufman, D., Yoneji, S., Nelson, D., Shemesh, A., Huang, Y., Tian, J., Bond, G.C., Clegg, B., and Brown, T., 2003, Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic: *Science*, v. 301, p. 1890–1893, doi: 10.1126/science.1088568.
- Hurrell, J.W., Kushnir, Y., and Visbeck, M., 2001, The North Atlantic Oscillation: *Science*, v. 291, p. 603–605, doi: 10.1126/science.1058761.
- Iversen, J., 1944, *Viscum, Hedera* and *Ilex* as climate indicators: *Geologiska Föreningen Föreläsningar*, v. 66, p. 463–483.
- Klotz, S., Guiot, J., and Mosbrugger, V., 2003, Continental European Eemian and early Würmian climate evolution: Comparing signals using different quantitative reconstruction approaches based on pollen: *Global and Planetary Change*, v. 36, p. 277–294, doi: 10.1016/S0921-8181(02)00222-9.
- Klotz, S., Müller, U.C., Mosbrugger, V., de Beaulieu, J.-L., and Reille, M., 2004, Eemian to early Würmian climate dynamics: History and pattern of changes in central Europe: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 211, p. 107–126, doi: 10.1016/j.palaeo.2004.04.009.
- Ku, T.L., and Liang, Z.C., 1984, The dating of impure carbonates with decay-series isotopes: *Nuclear Instruments and Methods in Physical Research*, v. 223, p. 563–571.
- Kukla, G.J., 2000, The last interglacial: *Science*, v. 287, p. 987–988.
- Kukla, G.J., and 22 others, 2002, Last interglacial climates: *Quaternary Research*, v. 58, p. 2–13, doi: 10.1006/qres.2001.2316.
- Lean, J.L., Wang, Y.-M., and Sheeley, N.R., Jr., 2002, The effect of increasing solar activity on the Sun's total and open magnetic flux during multiple cycles: Implications for solar forcing of climate: *Geophysical Research Letters*, v. 29, 2224, doi: 10.1029/2002GL015880.
- Litt, T., 1994, *Paläoökologie, Paläobotanik und Stratigraphie des Jungquartärs im nordmitteleuropäischen Tiefland unter besonderer Berücksichtigung des Elbe-Saale-Gebietes*: Berlin, Stuttgart, Borntraeger Verlagsbuchhandlung, *Dissertationes Botanicae*, v. 227, 185 p.
- Magny, M., Begeot, C., Guiot, J., Marguet, A., and Billaud, Y., 2003, Reconstruction and palaeoclimatic interpretation of mid-Holocene vegetation and lake level changes at Saint-Jorioz, Lake Annecy, French Pre-Alps: The Holocene, v. 13, p. 265–275.
- McDermott, F., Matthey, D.P., and Hawkesworth, C., 2001, Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland: *Science*, v. 294, p. 1328–1331, doi: 10.1126/science.1063678.
- Müller, H., 1974, Pollenanalytische Untersuchungen und Jahresschichtenzählung an der eemzeitlichen Kieselgur von Bispingen/Luhe: *Geologisches Jahrbuch*, v. A21, p. 149–169.
- Müller, U.C., and Kukla, G.J., 2004, North Atlantic current and European environments during the declining stage of the last interglacial: *Geology*, v. 32, p. 1009–1012, doi: 10.1130/G20901.1.
- Müller, U.C., Pross, J., and Bibus, E., 2003, Vegetation response to rapid climate change in central Europe during the last 140,000 yr based on evidence from the Füramoos pollen record: *Quaternary Research*, v. 59, p. 235–245, doi: 10.1016/S0033-5894(03)00005-X.
- Oberdorfer, E., 1994, *Pflanzensoziologische Exkursionsflora*: Stuttgart, Ulmer-Verlag, 1050 p.
- Osmond, J.K., and Ivanovich, M., 1992, Uranium-series mobilization and surface hydrology, in Ivanovich, M., and Harmon, R.S., eds., *Uranium-series disequilibrium*: Oxford, Clarendon, p. 259–290.
- Pross, J., and Klotz, S., 2002, Palaeotemperature calculations from the Praetiglian/Tiglian (Pliocene-Pleistocene) pollen record of Lieth, northern Germany: Implications for the climatic evolution of NW Europe: *Global and Planetary Change*, v. 34, p. 253–267.
- Pross, J., Klotz, S., and Mosbrugger, V., 2000, Reconstructing palaeotemperatures for the early and middle Pleistocene using the mutual climatic range method based on plant fossils: *Quaternary Science Reviews*, v. 19, p. 1785–1799, doi: 10.1016/S0277-3791(00)00089-5.
- Shackleton, N.J., Sánchez-Goni, M.F., Pailler, D., and Lancelot, Y., 2003, Marine isotope substage 5e and the Eemian Interglacial: *Global and Planetary Change*, v. 36, p. 151–155, doi: 10.1016/S0921-8181(02)00181-9.
- Tzedakis, P.C., 2003, Timing and duration of last interglacial conditions in Europe: A chronicle of a changing chronology: *Quaternary Science Reviews*, v. 22, p. 763–768, doi: 10.1016/S0277-3791(03)00004-0.
- West, G.R., 1957, *Interglacial deposits at Bobbitshole, Ipswich*: Royal Society of London Philosophical Transactions, Ser. B, v. 241, p. 1–31.
- Zagwijn, W.H., 1961, *Vegetation, climate and radiocarbon datings in the late Pleistocene of the Netherlands: Part I: Eemian and early Weichselian*: Mededelingen Geologische Stichting, v. 14, p. 15–45.

Manuscript received 28 October 2004

Revised manuscript received 27 January 2005

Manuscript accepted 4 February 2005

Printed in USA