PERGAMON

Quaternary Science Reviews 22 (2003) 763–768

QSR VIEWPOINT

Viewpoint

Timing and duration of Last Interglacial conditions in Europe: a chronicle of a changing chronology

Chronis Tzedakis*

School of Geography, University of Leeds, Leeds LS2 9JT, UK

Received 1 August 2002; accepted 29 December 2002

Abstract

Estimates of the length of the Last Interglacial in Europe, conventionally defined by the presence of forest as inferred from pollen diagrams, have varied considerably. Here an account of recent developments, largely instigated by a paper by Kukla et al. (1997), is presented. These include the emergence of new records with improved chronologies and a re-evaluation of previous assumptions of synchroneity between marine and terrestrial stage boundaries and also between northern and southern European changes. The current scheme proposes that the onset of the Last Interglacial in Europe started well into MIS 5e, after deglaciation was complete and was coincident with a rise to peak sea-surface temperatures. However, the timing of the end of the Last Interglacial between northern and southern Europe appears to have diverged considerably: in the north the elimination of forest occurred ca 115 ka, near the time of the MIS 5e/5d transition, while in the south tree populations persisted into the interval of global ice growth, until the onset of significant ice rafting ca 110 ka. This significant N–S diachroneity may be a reflection of the effects of different bioclimatic parameters limiting tree growth in the two areas. These developments highlight the problems of correlating records of different proxies and from different geographical regions.

1. Introduction

The Last Interglacial represents the most recent geological period during which conditions were similar to the present interglacial, but with negligible anthropogenic effects. In Europe, despite an abundance of Last Interglacial pollen records, a persistent handicap has been the lack of sufficiently precise absolute timescales and regionally or globally synchronous stratigraphical markers. This means that long-distance correlation between sites has been problematic and, moreover, inferred terrestrial changes are difficult to place within the global framework of ice volume and sea-level changes. By extension, there has been considerable uncertainty regarding the length of interglacial conditions on land and the timing and nature of vegetation and environmental changes towards the end of the interglacial. Resolving this is critical because ultimately, in order to have confidence in improved predictions of future changes, there is a need to establish the mode and tempo of natural climate variability during situations that resemble the present configuration.

The first important contribution towards an understanding of the duration of the Last Interglacial on land was made by Shackleton (1969) who proposed that the Eemian interglacial of NW Europe was not equivalent to the entire Marine Isotope Stage (MIS) 5 of the deep-sea stratigraphy, but rather to an interval within it (substage 5e). By extension, this meant that the Last Interglacial did not have a duration of half an eccentricity cycle (ca 50 thousand years [kyr]), but rather half a precessional cycle (ca 10 kyr). Astronomical calibration of the marine timescale provided an age of 128 thousand years before present (ka) for the mid-point of the transition from glacial to interglacial values and 116 ka for the interglacial-to-stadial transition (e.g. Imbrie et al., 1984). This appeared to be in agreement with the first direct terrestrial evidence from an Eemian sequence at Bispingen, Germany, which indicated a duration of ca 11 kyr (Müller, 1974). The figure was based on counts of annual laminations covering part of the Eemian and extrapolation based on sedimentation rates for the remainder. Although, the emergent chronology was not anchored by any absolute dates,

*Corresponding author. Tel.: +44-113-343-3300; fax: +44-113-343-3308.

E-mail address: p.tzedakis@geography.leeds.ac.uk (C. Tzedakis).

0277-3791/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0277-3791(03)00004-0

the good correspondence between the marine and terrestrial estimates for the duration of the Last Interglacial led to the assumption that the lower and upper boundaries of the MIS 5e and the Eemian must have been broadly synchronous.

Given the uncertainties associated with dating terrestrial material beyond the radiocarbon limit, the notion of presumed synchroneity between marine and terrestrial stage boundaries, led to attempts to assign the marine timescale to terrestrial sequences. This approach was used by Tzedakis et al. (1997) who aligned the four longest pollen sequences of the last 500 kyr from southern Europe to the SPECMAP stacked $\delta^{18}O$ record (Imbrie et al., 1984). Glacial-to-interglacial transitions were used as the tie points on the basis that these transitions represent relatively rapid events and the response of vegetation would not have significant delays in southern Europe because of proximity to glacial stations of temperate trees. However, Tzedakis et al. (1997) refrained from fixing the ends of interglacials to the marine timescale, reasoning that the elimination of interglacial vegetation may represent a temporally diffuse event and that in the absence of direct evidence from southern Europe, it may have been inappropriate to tune the records more intensely. The effect of using only the onset of interglacials as the tie points was that terrestrial interglacials appeared to continue well into the time of the ensuing glacial interval in the marine stratigraphy. In the case of the Last Interglacial, the onset of the terrestrial interglacial (defined by the expansion of forest) was fixed at 128 ka, but the end of the forest period in the pollen sequences appeared to extend until around 111 ka, well into MIS 5d. Tzedakis et al. commented that the stadial period following the Last Interglacial appeared to be much shorter than the length of MIS 5d on the marine stratigraphy, but stopped short of making any generalizations on the length of interglacials, other than underlining the need for the development of independent terrestrial chronologies.

In contrast, that same year Kukla et al. (1997) did not shy away from making strong statements on the length of the Eemian on the basis of a similar land-sea alignment exercise. Kukla et al. tuned the Grande Pile pollen record, one of the legendary European sequences (Woillard, 1978), to the marine stratigraphy of North Atlantic record V29-191 (McManus et al., 1994), by fixing the beginning of the Last Interglacial to the MIS 6/5 boundary (at 130 ka) and the onset of the early Pleniglacial to the MIS 5/4 boundary (at 74 ka). Interpolating between these ages led to an inferred duration for the Last Interglacial at Grande Pile (locally defined as the Lure Interglacial) of 23 kyr, from 130 to 107 ka. Kukla et al. concluded that the Lure extended well into MIS 5d and that the end of the terrestrial interglacial was coincident with the onset of significant ice rafting in the North Atlantic (event C24 of McManus et al. (1994). Underlying this conclusion, was the earlier observation that in core V29-191 the change towards heavier benthic oxygen isotope values, indicating the transition from MIS 5e to 5d, pre-dates the re-appearance of ice-rafted detritus and of the polar foraminifera *N. pachyderma* (s) associated with event C-24 (McManus et al., 1994). This implied that warm conditions persisted in the North Atlantic for several thousand years after the initiation of ice cap growth and, by extension, could explain the prolonged duration of the Eemian well into MIS 5d (see also Broecker, 1998). In September 1998, Kukla presented these views to a meeting of the Subcommission on European Quaternary Stratigraphy in Kerkrade, The Netherlands. The issue was revisited a year later at an Eemfest meeting in honour of George Kukla at Lamont Doherty Earth Observatory of Columbia University, New York, USA[1]. The opposing case for a short interglacial duration was presented by Merkt who showed evidence from additional sites in Germany with annual laminations, extending the Bispingen absolute chronology (and thereby reducing the interval of extrapolation) and providing further support for a short duration of ca 10–11 kyr (Caspers et al., 2002). However, by this time evidence for an interglacial duration somewhere between the long and short chronology was beginning to emerge from southern Europe. Tzedakis et al. (2002) presented a Last Interglacial pollen record from Ioannina, Greece, which was astronomically calibrated, using a direct vegetation-orbital link. According to this age model, the Last Interglacial lasted 16 kyr, from ca 127 to 111 ka. The most compelling evidence, however, was by Shackleton et al. (2002, in press) who presented results from a high-resolution pollen record in deep-sea core MD95-2042, located off southwest Portugal. The sequence was supported by detailed benthic and planktonic $\delta^{18}O$ stratigraphies and a chronology based on inferred sea-level still-stands correlated with radiometrically dated marine coral terraces. This meant that pollen-stratigraphical changes could be directly compared with changes in global ice volume and could be also placed within an absolute chronological framework (Fig. 1). The length of the forested interval was 16 kyr, with the onset at 126 ka and the end at 110 ka, while the lower and upper age boundaries for MIS 5e were 132 and 115 ka, respectively. Although the actual date for the MIS 6/5e boundary (the mid-point of the deglaciation) may be a matter of some debate, with certain researchers favouring an even earlier timing (e.g. Henderson and Slowey, 2000; Gallup et al., 2002), the phase relationship between pollen and benthic $\delta^{18}O$

[1] Proceedings of this meeting were published in the July 2002 issue of Quaternary Research, in the form of a long joint summary (Kukla et al., 2002a,b) and additional short papers by individual participants.

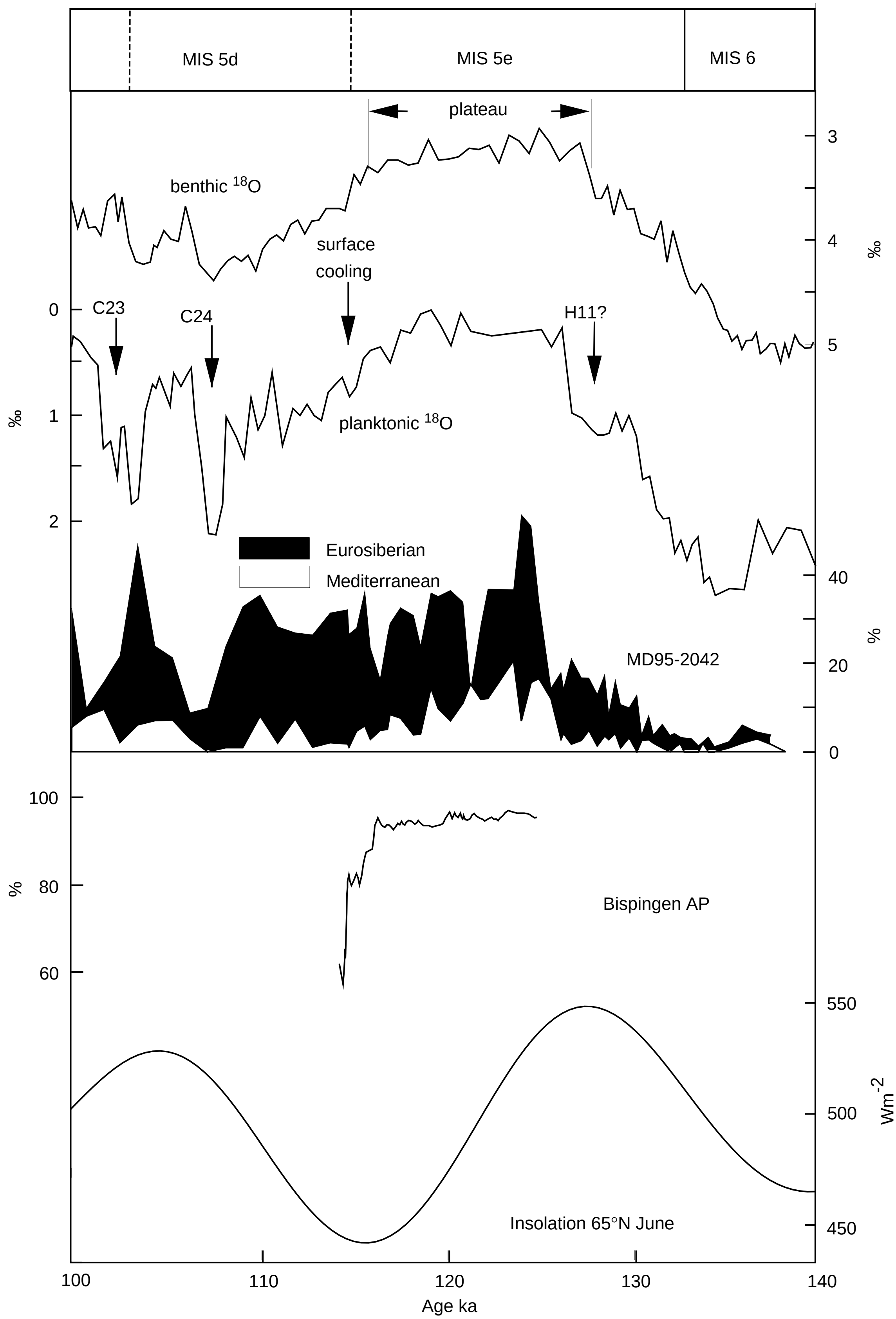

Fig. 1. (i) Benthic and plaktonic δ^{18}O data and summary pollen curves from MD95-2042, off southwest Portugal (from Shackleton et al., 2002); (ii) arboreal pollen (AP) percentages from Bispingen, Germany (Müller, 1974); the onset of the Eemian is here aligned with the terrestrial interglacial in MD95-2042 and then the AP curve is plotted on the timescale of Field et al. (1994); and (iii) June insolation 65°N (Berger, 1978).

records derived from the same sediment sequence is independent of the precise chronology and clearly reveals that neither the lower nor upper boundaries of terrestrial and marine stages are coincident. The onset of interglacial conditions on land (expressed by the full expansion of tree populations) occurred inside MIS 5e, well after deglaciation was complete and was coincident with a rise to peak sea surface temperatures. This result is in disagreement with the scheme in the Netherlands (where the Eemian type locality is defined), according to which sea level continued to rise during the first 3–4 kyr (into the *Corylus* zone) of the terrestrial interglacial (Zagwijn, 1983; van Leeuwen et al., 2000)[2]. However, it should be remembered that the Scandinavian ice sheet reached the Netherlands during the Saalian and therefore local sea level history is bound to be complicated by glacio-isostatic movements (e.g. Lambeck and Chappell, 2001). At the end of MIS 5e sea surface temperatures began a gradual decline, but essentially interglacial conditions persisted on land with tree populations continuing to survive into MIS 5d, albeit at somewhat reduced densities. The onset of significant ice rafting in the North Atlantic after 110 ka led to the disruption of the thermohaline circulation and an abrupt change in temperature and precipitation regimes, leading to the elimination of tree populations in SW Iberia.

The evidence of Shackleton and co-workers appeared incontrovertible, but its significance to northern Europe was not immediately apparent. If both the German and Portuguese chronologies were correct, this would imply significant diachroneity between northern and southern Europe and the presence of a steep N–S vegetation gradient for 5 kyr during the first half of MIS 5d. What would have led to the demise of northern European forests so much earlier than in the south? More recently an Eemian workshop was convened by Sirocko, Junge and Boettger in Leipzig in March 2002, under the auspices of the German DEKLIM Project. Members of the marine, ice core and terrestrial communities were present, along with climate modellers who added an important dimension to the discussion by shedding light on the conditions leading to glacial inception. In contrast to earlier meetings, a broad consensus appeared to emerge by the end of the workshop. The following represents a possible scenario of the main environmental and vegetation changes in Europe during the Last Interglacial, pieced together from recent developments and discussions over the last 5 years.

Reconstructions from sites distal to ice fields suggests that sea level had reached present values by ca 128 ka (e.g. Lambeck et al., 2002; Muhs, 2002). What is interesting about the penultimate deglaciation is that it preceded the Northern Hemisphere summer insolation peak (ca 127 ka at 65°N), in contrast to the last deglaciation where sea level reached near-present elevation at ca 6 ka, much later than the insolation peak at ca 11 ka (Lambeck and Chappell, 2001). This asymmetry may appear at odds with Milankovitch forcing, but it is worth remembering that during Termination II obliquity peaked earlier (132 ka) than precession (127 ka), while Holocene equivalent peaks were at 10 and 11 ka, and that June insolation at 65°N had already reached Holocene maximum values by 131 ka (Berger, 1978). The combined effect of these factors led to early summer warming in higher latitudes during Termination II, and climate models suggest that Northern Hemisphere land areas were warmer than present by 130 ka (Crowley and Kim, 1994). In addition, the interplay between insolation, ice melting and isostatic rebound may have led to the differences in deglaciation patterns of Termination I and II, and it may be that the last deglaciation is anomalously slow and episodic compared to the penultimate (e.g. Alley et al., 2002).

In Europe, although small increases in tree populations in the south are recorded in some sites after 129 ka, the onset of full interglacial conditions on land occurred at approximately 126 ka (Fig. 1). There is some evidence of a Lateglacial oscillation around 127 ka, perhaps coincident with Heinrich event 11 (Shackleton et al., 2002). However, the extent of this oscillation appears to have been smaller than the Younger Dryas event during the most recent deglaciation. This means that there was no significant setback to the northward spread of tree populations and this can explain the very fast migration rates that appear to characterize the early Eemian (as determined in annually laminated sediments). Thus, the degree of diachroneity between southern and northern Europe for the onset of Last Interglacial forest expansion appears to have been small (on the order of a few hundred years), although regional species composition differed (e.g. Turner, 2000). Around 125 ka, southern Europe was characterized by a significant expansion of Mediterranean vegetation (including a high proportion of olive trees), a reflection of hot summers associated with the insolation maximum, while the area north of the Alps was dominated by deciduous forest (mainly hazel) (e.g. van Andel and Tzedakis, 1996). As a result of orbital changes, a gradual reduction in Northern Hemisphere summer insolation led to a decrease of temperatures after 120 ka. This would reduce the amount of accumulated growing-season warmth, which is critical for the survival of boreal forest trees and determines the boundary between tundra and taiga (e.g. Prentice et al., 1992). Model simulations (Crucifix and Loutre, 2002) suggest that after 120 ka, sea-ice and tundra vegetation expanded between 60–90°N. The

[2]The relative timing of the marine transgression in the Netherlands is determined in coastal sequences which record a change from lacustrine to lagoonal and finally marine facies that can be compared in situ with the pollen zonation scheme, while its duration is estimated via correlations with the Bispingen chronology (Zagwijn, 1983; van Leeuwen et al., 2000).

effect of this would have been to increase albedo, leading to the settlement of perennial snow. Through time, this continued trend towards reduced summer warmth might have contributed to a retreat of the tundra/taiga boundary further to the south, leading to the disappearance of tree populations in northern Europe by ca 115 ka. However, forest in southern Europe is not limited by the degree of summer warmth, but largely by moisture availability. During the early stages of ice growth most of the subpolar North Atlantic appears to have remained warm, with some cooling being more prominent in the northern and western sectors (Chapman and Shackleton, 1999; McManus et al., 2002). Northward oceanic heat transport continued to operate, providing a moisture source for ice sheet growth (McManus et al., 2002). With oceanic and atmospheric circulation patterns remaining largely unchanged, winter storm tracks would continue to deliver the necessary precipitation for the survival of tree populations in southern Europe. A centennial-scale episode involving a reduction in forest cover ca 118 ka in a number of southern European records (e.g. Tzedakis et al., in press) may have been related to a brief reduction in North Atlantic Deep Water formation (e.g. Cortijo et al., 1994; Lehman et al., 2002), but this had no long lasting impact on vegetation. After 115 ka there was an overall trend towards more reduced forest cover in southern Europe, but tree populations continued to persist for another 5000 years. However, by 110 ka sufficient ice volume had accumulated to initiate ice rafting in the North Atlantic and disruption of the thermohaline circulation. This, in turn, led to a reduction in moisture availability, causing the abrupt demise of southern European tree populations.

Does this represent the final word on the matter? Far from it. First of all, the timing and nature of H11 remains unclear; if deglaciation was complete by ca 128 ka, what could have caused the postulated ice-rafting event at ca 127 ka? In addition, there is also a need to replicate the patterns emerging from the marine sequence off Portugal at other European margins as well as the other side of the Atlantic. More specifically, does the onset of the Last Interglacial show a lagged sea surface temperature and tree population response relative to deglaciation everywhere, or is it geographically dependent? As regards the end of the terrestrial interglacial, if the large diachroneity between southern and northern Europe is indeed correct, where does this leave areas in between, such as France? Did the interglacial there end at ca 115 ka or 110 ka, or somewhere in between? By extension, how steep was the vegetation gradient in Europe during the first half of MIS 5d?

Although most 'Eemianites' would by now consider the value of 23 kyr for the duration of the Last Interglacial at Grande Pile as suggested by Kukla et al. (1997) to be overestimated (to varying degrees[3]), it is important to acknowledge the influence that paper had in stimulating the research that led to recent developments. In a sense, Kukla let the genie out of the bottle and made us reconsider some long-held beliefs. More importantly, he initiated a debate which led to a renewed effort by the palaeoclimate community to generate new data sets designed to test the competing models and advance our understanding of the length of interglacials, an issue of potentially significant implications for future predictions.

Acknowledgements

I am grateful to Nick Shackleton for comments on an earlier version of the manuscript, for making available the curves from MD95-2042 and for being a source of inspiration. I thank R.C. Preece, L. Forsström and an anonymous reviewer for helpful comments on the manuscript and M.R. Frogley for much appreciated help with the figure. I also thank the participants of the Eemian workshops for discussions (especially Jerry McManus), although the views presented here are a personal account of the development of ideas on the Last Interglacial and any failings or omissions are solely my own. Attendance of the meetings in Kerkrade, Lamont and Leipzig was made possible by financial assistance from NERC, Robinson College Cambridge and the University of Leeds, respectively.

References

Alley, R.B., Brook, E.J., Anandakrishnan, S., 2002. A northern lead in the orbital band: north–south phasing of ice age events. Quaternary Science Reviews 21, 431–441.

Berger, A., 1978. Long-term variations of caloric insolation resulting from the earth's orbital elements. Quaternary Research 9, 139–167.

Broecker, W.S., 1998. The end of the present interglacial: how and when? Quaternary Science Reviews 17, 689–694.

Caspers, G., Freund, H., Merkt, J., Müller, H., 2002. The Eemian interglacial in northwestern Germany. Quaternary Research 58, 49–52.

Chapman, M.R., Shackleton, N.J., 1999. Global ice-volume fluctuations, North Atlantic ice-rafting events, and deep-ocean circulation changes between 130 and 70 ka. Geology 27, 795–798.

Cortijo, E., Duplessy, J.-C., Labeyrie, L., Leclaire, H., Duprat, J., van Weering, T.C.E., 1994. Eemian cooling in the Norwegian Sea and North Atlantic Ocean preceding continental ice-sheet growth. Nature 372, 446–449.

Crowley, T.J., Kim, K.-Y., 1994. Milankovitch forcing of the last interglacial sea-level. Science 265, 1566–1568.

[3] Kukla et al. (2002a,b) revised their estimate of the duration of the Lure Interglacial to ca 19 kyr, by setting the lower boundary of the interglacial at ca 126 ka, in agreement with Shackleton et al. (2002), and the upper at 107 ka, coincident with the McManus et al. (1994) estimate for the age of event C24.

Crucifix, M., Loutre, M.-F., 2002. Transient simulations over the last interglacial period (126–115 kyr BP): feedback and forcing analysis. Climate Dynamics 19, 417–433.

Field, M.H., Huntley, B., Muller, H., 1994. Eemian climate fluctuations observed in a European pollen record. Nature 371, 779–783.

Gallup, C.D., Cheng, H., Taylor, F.W., Edwards, R.L., 2002. Direct determination of the timing of sea level change during Termination II. Science 295, 310–313.

Henderson, G.M., Slowey, N.C., 2000. Evidence from U–Th dating against Northern Hemisphere forcing of the penultimate deglaciation. Nature 404, 61–66.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., Shackleton, N.J., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: Berger, A.L., Imbrie, J., Hays, J., Kukla, G., Saltzman, B. (Eds.), Milankovitch and Climate. D. Reidel, Dordrecht.

Kukla, G., McManus, J.F., Rousseau, D.-D., Chuine, I., 1997. How long and how stable was the last interglacial? Quaternary Science Reviews 16, 605–612.

Kukla, G.J., de Beaulieu, J.-L., Svobodova, H., Andrieu-Ponel, V., Thouveny, N., Stockhausen, H., 2002a. Tentative correlation of pollen records of the last interglacial at Grande Pile and Ribains with Marine Isotope Stages. Quaternary Research 58, 32–35.

Kukla, G.J., Bender, M.D., Beaulieu, J.-L., de Bond, G., Broecker, W.S., Cleveringa, P.W., Gavin, J.E., Herbert, T.D., Imbrie, J., Jouzel, J., Keigwin, L.D., Knudsen, K.-L., McManus, J., Merkt, J., Muhs, D.R., Müller, H., Poore, R.Z., Porter, S.C., Seret, G., Shackleton, N.J., Turner, C., Tzedakis, P.C., Winograd, I.J., 2002b. Last interglacial climates. Quaternary Research 58, 2–13.

Lambeck, K., Chappell, J., 2001. Sea level change through the last glacial cycle. Science 292, 679–686.

Lambeck, K., Esat, T.M., Potter, E.-K., 2002. Links between climate and sea levels for the past three million years. Nature 419, 199–206.

Lehman, S.J., Sachs, J.P., Crotwell, A.M., Keigwin, L.D., Boyle, E.A., 2002. Relation of subtropical Atlantic temperature, high-latitude ice rafting, deep water formation, and European climate 130,000–60,000 years ago. Quaternary Science Reviews 21, 1917–1924.

McManus, J.F., Bond, G.C., Broecker, W.S., Johnsen, S., Labeyrie, L., Higgins, S., 1994. High-resolution climate records from the North Atlantic during the last interglacial. Nature 371, 326–329.

McManus, J.F., Oppo, D.W., Keigwin, L.D., Cullen, J.L., Bond, G.C., 2002. Thermohaline circulation and prolonged interglacial warmth in the North Atlantic. Quaternary Research 58, 17–21.

Muhs, D.R., 2002. Evidence for the timing and duration of the last interglacial period from high-precision Uranium-series ages of corals on tectonically stable coastlines. Quaternary Research 58, 36–40.

Müller, H., 1974. Pollenanalytische untersuchungen und jahresschichtenzählungen an der eem-zeitlichen kieselgur von bispingen/luhe. Geologisches Jahrbuch A 21, 149–169.

Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A., Solomon, A.M., 1992. A global biome model based on plant physiology and dominance, soil properties and climate. J. Biogeography 19, 117–134.

Shackleton, N.J., 1969. The last interglacial in the marine and terrestrial records. Proceedings of the Royal Society, London Series B 174, 135–154.

Shackleton, N.J., Chapman, M., Sánchez-Goñi, M.F., Pailler, D., Lancelot, Y., 2002. The classic marine isotope substage 5e. Quaternary Research 58, 14–16.

Shackleton, N.J., Sánchez-Goñi, M.F., Pailler, D., Lancelot, Y. Marine Isotope Substage 5e and the Eemian Interglacial. Global and Planetary Change, in press.

Turner, C., 2000. The Eemian interglacial in north European plain and adjacent areas. Geologie en Mijnbouw/Netherlands Journal of Geosciences 79, 217–231.

Tzedakis, P.C., Frogley, M.R., Heaton, T.H.E., 2002. Duration of last interglacial conditions in northwest Greece. Quaternary Research 58, 53–55.

Tzedakis, P.C., Frogley, M.R., Heaton, T.H.E. Last Interglacial conditions in southern Europe: evidence from Ioannina, northwest Greece. Global and Planetary Change, in press.

Tzedakis, P.C., Andrieu, V., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 1997. Comparison of terrestrial and marine records of changing climate of the last 500,000 years. Earth and Planetary Science Letters 150, 171–176.

van Andel, T.H., Tzedakis, P.C., 1996. Palaeolithic landscapes of Europe and environs 150,000–25,000 years ago: an overview. Quaternary Science Reviews 15, 481–500.

Van Leeuwen, R.J.W., Beets, D.J., Aleid Bosch, J.H., Burger, A.W., Cleveringa, P., van Harten, D., Waldemar, G.F., Kruk, R.W., Langereis, C.G., Meijer, T., Pouwer, R., de Wolf, H., 2000. Stratigraphy and integrated facies analysis of the Saalian and Eemian sediments in the Amsterdam-terminal borehole, the Netherlands. Geologie en Mijnbouw/Netherlands Journal of Geosciences 79, 161–196.

Woillard, G.M., 1978. Grande Pile peat bog: a continuous pollen record for the last 140,000 years. Quaternary Research 9, 1–21.

Zagwijn, W.H., 1983. Sea-level changes in the Netherlands during the Eemian. Geologie en Mijnbouw 62, 437–450.