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The MIS 11 – MIS 1 analogy, southern European vegetation, atmospheric methane and the "early anthropogenic hypothesis"

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Abstract. Marine Isotope Stage (MIS) 11 has been considered a potential analogue for the Holocene and its future evolution. However, a dichotomy has emerged over the precise chronological alignment of the two intervals, with one solution favouring a synchronization of the precession signal and another of the obliquity signal. The two schemes lead to different implications over the natural length of the current interglacial and the underlying causes of the evolution of greenhouse gas concentrations. Here, the close coupling observed between changes in southern European tree populations and atmospheric methane concentrations in previous interglacials is used to evaluate the natural vs. anthropogenic contribution to Holocene methane emissions and assess the two alignment schemes. Comparison of the vegetation trends in MIS 1 and MIS 11 favours a precessional alignment, which would suggest that the Holocene is nearing the end of its natural course. This, combined with the divergence between methane concentrations and temperate tree populations after 5 kyr BP, provides some support for the notion that the Holocene methane trend may be anomalous compared to previous interglacials. In contrast, comparison of MIS 1 with MIS 19, which may represent a closer astronomical analogue than MIS 11, leads to substantially different conclusions on the projected natural duration of the current interglacial and the extent of the anthropogenic contribution to the Holocene methane budget. As answers vary with the choice of analogue, resolution of these issues using past interglacials remains elusive.

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1 Introduction

Part of the scientific rationale for pursuing studies of MIS 11 is that it may be important as a potential analogue for present and future natural climate changes. Comparing June insolation variations of the last 3 million years, Loutre and Berger (2000, 2003) found that the interval 405–340 thousand years before present (kyr BP) represented the closest most recent astronomical analogue for the target period 5 kyr BP–60 thousand years after present (kyr AP). This similarity is a function of the modulating effect of the 400 kyr eccentricity cycle on climatic precession: low eccentricity values today and ∼400 kyr BP lead to low-amplitude precessional changes and subdued insolation variations (Loutre and Berger, 2000, 2003). Although the phasing of precession and obliquity changes in MIS 11 and 1 is not identical, the intervals 405–340 kyr BP and 5 kyr BP–60 kyr AP show the highest linear correlation in terms of the insolation signal of recent interglacials with similar values of atmospheric CO_2 concentrations (Loutre and Berger, 2000, 2003).

While the astronomical analogy between MIS 1 and MIS 11 has been incorporated in mainstream literature, there is a distinct difference between the two intervals: the Holocene contains one insolation peak so far, while the MIS 11 interval of full interglacial conditions (Substage 11c of the marine isotopic stratigraphy) extends over two insolation peaks. Thus an interesting situation has arisen with regard to the precise alignment of the two intervals. Loutre and Berger (2000, 2003) synchronized the two intervals by using the precessional variations in summer insolation at 65° N, so that today corresponded to ∼398 kyr BP. The choice of the synchronization parameter was guided by the canonical view that changes in global ice volume are correlated

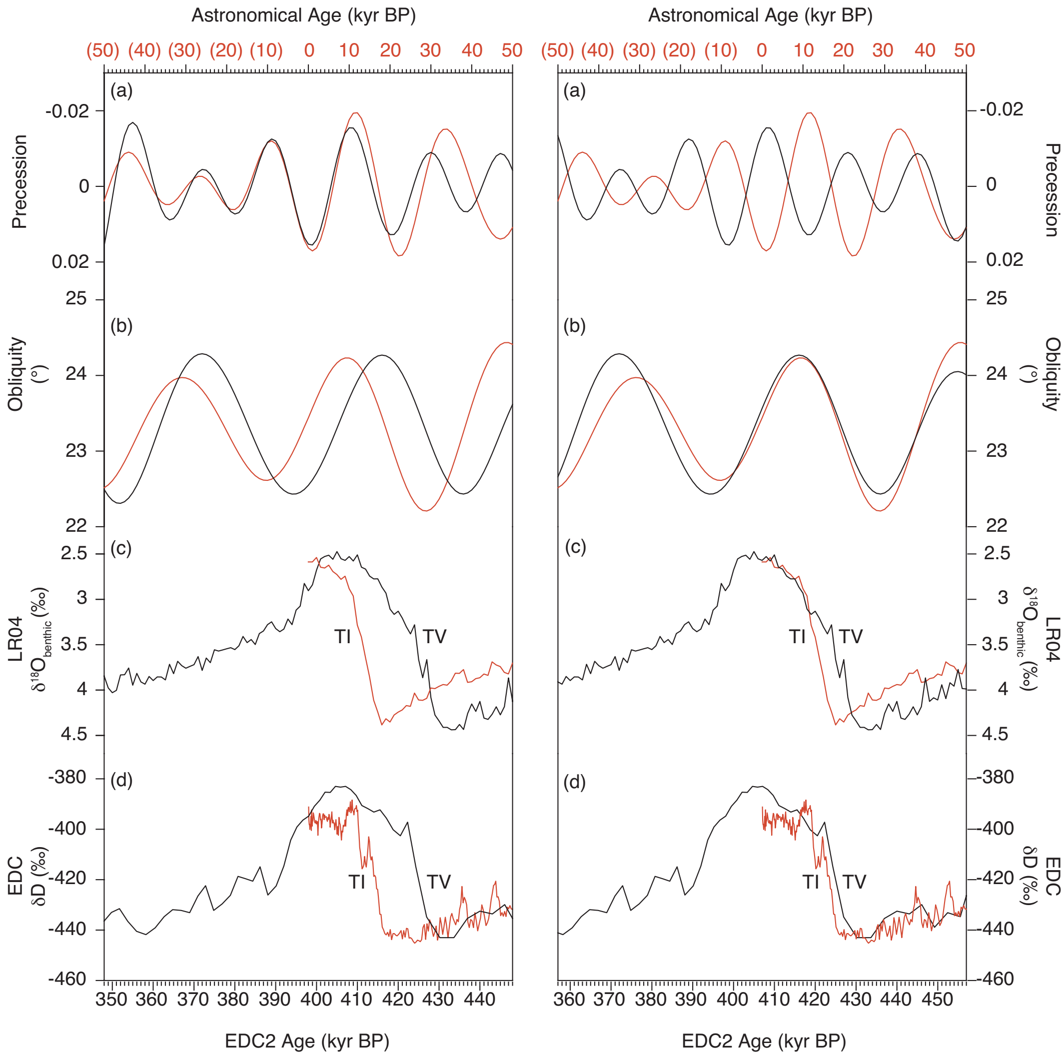

Fig. 1. Comparison of two alignment schemes between the past and future 50 kyr (red) and a 100-kyr interval encompassing MIS 11 (black) (after Masson-Delmotte et al., 2006). Left panel shows synchronization of the precession signal and right panel synchronization of the obliquity signal and also of Terminations I and V in the deuterium record of the EPICA Dome C (EDC) ice core, Antarctica. **(a)** precession index, plotted on an inverse vertical axis (Berger and Loutre, 1991); **(b)** obliquity (Berger and Loutre, 1991); **(c)** $\delta^{18}O_{benthic}$ record from the LR04 stack (Lisiecki and Raymo, 2005), plotted on its own timescale; **(d)** Deuterium (δD) composition of ice in EDC ice core (EPICA Community Members, 2004). Ages in parentheses denote thousand years after present (kyr AP). TI and TV denote Terminations I and V, respectively. The EPICA data in this figure are plotted on the EDC2 timescale used in the EPICA Community Members (2004) paper where the alignment was originally made. In other figures, EPICA data are shown on the more recent EDC3 timescale (Jouzel et al., 2007).

with variations in summer insolation received at high northern latitudes (e.g. Crucifix and Berger, 2006). In contrast, the EPICA Community Members (2004) aligned Terminations I and V in the δD record of the Dome C ice core in Antarctica, which instead suggested that today should correspond to ∼407 kyr BP. In essence, this alignment represents a synchronization of the obliquity signal instead of precession, which according to Masson-Delmotte et al. (2006) may be more appropriate, because of the role of obliquity changes in triggering deglaciation especially during intervals of weak precessional variations, as is the case for MIS 11 and 1. The two schemes (Fig. 1) lead to very different conclusions about the length of the current interglacial, in the absence of anthropogenic forcing. With the end of MIS 11 full interglacial conditions and the start of ice accumulation estimated to have occurred at ∼395 kyr BP (de Abreu et al., 2005; Ruddiman 2005a, 2007), the precessional alignment would suggest that the Holocene is nearing its end, while the obliquity alignment would suggest it has another 12 000 years to run its course. The two schemes also have different implications on the underlying causes on the evolution of CO_2 and CH_4 concentrations during the Holocene.

More specifically, the concentrations of these gases show early Holocene peaks followed by declines, but the downward trend was reversed after 8 kyr BP and 5 kyr BP for CO_2 and CH_4, respectively. In the "early anthropogenic hypothesis", Ruddiman (2003) proposed that humans began modifying greenhouse gas concentrations thousands of years before the industrial era, with forest clearance and intensification of rice agriculture leading to the increases in atmospheric CO_2 and CH_4 levels, respectively. By drawing analogies with natural trends in the previous three interglacials, Ruddiman (2003, 2007) estimated that the magnitude of the late Holocene anomalies (the observed increase plus the value that would have been expected from a naturally decreasing trend) prior to the start of the industrial era was ∼35–40 ppmv for CO_2 and ∼230–250 ppbv for CH_4. The elevated greenhouse gas concentrations countered the natural cooling trend and prevented global climate from slipping into a glacial transition.

The "early anthropogenic hypothesis" has come under substantial criticism, especially regarding the extent to which human activities can account for the Holocene greenhouse gas trends. Using a carbon cycle climate model, Joos et al. (2004) showed that a 40 ppmv increase in CO_2 levels over the past 8 kyr would require a carbon emission of 700 Gt and a decrease in atmospheric δ^{13}C of 0.6‰. They pointed out that this was incompatible with the ice core δ^{13}C record, which shows a 0.25‰ decrease (Indermühle et al., 1999), and exceeded any possible emissions from deforestation. Historical cumulative carbon losses due to deforestation have been estimated to be 180–200 Gt (de Fries et al., 1999), of which 120 Gt have been attributed to post-1850 land-use changes (Houghton, 1999). This leaves 60–80 Gt for pre-industrial carbon losses, which would account for a CO_2 rise of only 4–6 ppmv. Joos et al. (2004) suggested that a range of mechanisms (changes in ocean chemistry, sea surface temperatures, terrestrial carbon uptake and release and coral reef build-up) contributed to the 20 ppmv CO_2 rise in the Holocene (note that that this does not incorporate an additional 15–20 ppmv calculated by Ruddiman (2003, 2007) as the actual anomaly). Although Ruddiman (2007) argued that the extent of pre-industrial carbon losses due to deforestation had been underestimated and proposed a figure of 120–137 GtC, he concluded that this would again account for only a small fraction (∼9 ppmv) of the total anomaly required. Ruddiman (2007) suggested that most likely source for the remaining 26–31 ppmv was an anomalously warm ocean, but conceded that this remained the largest uncertainty of the "early anthropogenic hypothesis".

With regard to methane, Schmidt et al. (2004) suggested that the mid-to-late Holocene increase in CH_4 reflected natural emissions from boreal wetlands and river deltas, thus making any large anthropogenic component unnecessary. In response, Ruddiman (2005b, 2007) pointed out that although boreal wetlands were still expanding during the late Holocene (Smith et al., 2004), net emissions declined because of reduced summer temperatures and a trend towards drier bog types (MacDonald et al., 2006). This is supported by recent ice core analyses, which show that the interpolar gradient declined in the late Holocene, indicating low-latitude methane sources (Brook et al., 2008). As for the possible contribution from river deltas, Ruddiman (2007) suggested that this may also reflect anthropogenic influences, with forest clearance leading to erosion and increased sediment loads in rivers, and contributing to an expansion of river delta systems. In addition, a compilation of archaeological sites in rice-growing areas of China, suggests a ten-fold increase in new sites between 6 and 5 kyr BP (Ruddiman et al., 2008). Further refinement of the anthropogenic hypothesis for the Holocene CH_4 increase, now recognizes that in addition to early rice farming and irrigation, biomass burning, releases from livestock and human waste, and climate feedbacks also contributed to the CH_4 anomaly (Ruddiman, 2007).

One question that has consistently arisen in this debate is if the Holocene increases in greenhouse gases are natural, then why are they not observed in earlier interglacials (e.g. Ruddiman, 2003, 2007)? Broecker and Stocker (2006) proposed that a likely explanation is the dampening of precessional variations by the small orbital eccentricity during the Holocene compared to the previous three interglacials. Thus, while more extreme changes in precession produced "short" interglacials in the last three climatic cycles, these changes are too weak to lead to glacial inception today. Since the last three interglacials are imperfect orbital analogues, MIS 11 has emerged as a more appropriate testbed for the "early anthropogenic hypothesis".

By extension, this meant that the alignment of MIS 11 and MIS 1 became a central issue in this debate. Ruddiman (2005a, 2007) aligned the two intervals by using the precessional variations, so that today corresponded to ∼398 kyr BP, following Loutre and Berger (2000, 2003), and concluded that in the absence of Holocene anthropogenic interference, ice caps and small ice sheets would have started forming in northern polar regions. In contrast, Broecker and Stocker (2006) aligned the two Terminations (and by extension the obliquity signal), as in EPICA Community Members (2004), and suggested that the early part of MIS 11 was similar to the Holocene. Given that the subdued precessional change at ∼419 kyr BP (Fig. 1) did not lead to glacial inception and CO_2 levels remained above 270 ppmv for 28 kyr, they proposed that the Holocene will also be a long interglacial and concluded that the rise in greenhouse gases was natural and not anthropogenic.

With regard to the atmospheric methane record, the precessional alignment (Fig. 2, left panel) suggests that the first MIS 11 peak and subsequent decline in CH_4 (∼425–415 kyr BP), does not have a Holocene equivalent. Instead, it is the second CH_4 peak (∼412–400 kyr BP) that corresponds to the Holocene part, showing an early increase followed by a monotonic decline, which, in turn, implies that

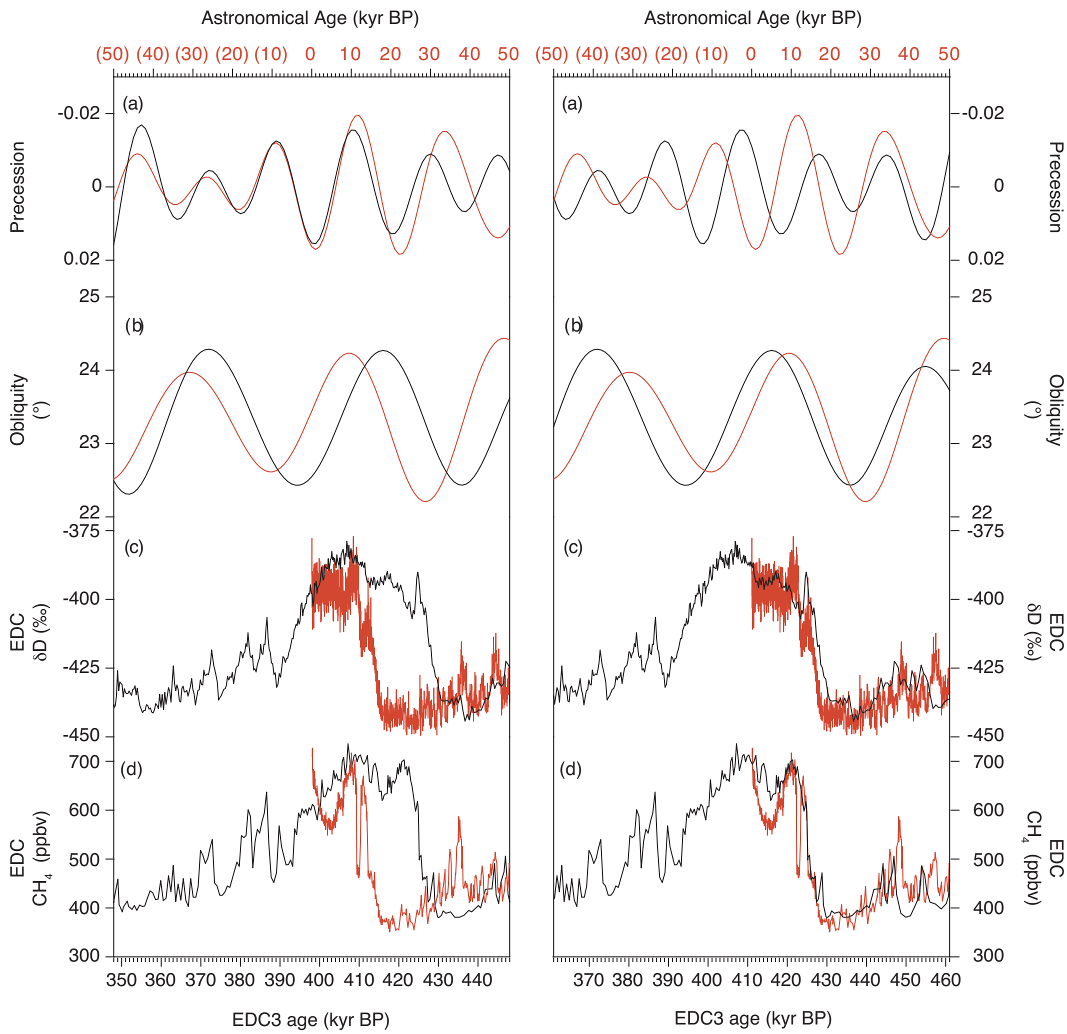

Fig. 2. Comparison of two alignment schemes between the past and future 50 kyr (red) and a 100-kyr interval encompassing MIS 11 (black). Left panel shows synchronization of the precession signal and right panel synchronization of Terminations I and V in the EDC δD record, on the EDC3 timescale. Note that the alignment of the two Terminations no longer leads to a synchronization of the obliquity signal. **(a)** precession index, plotted on an inverse vertical axis (Berger and Loutre, 1991); **(b)** obliquity (Berger and Loutre, 1991); **(c)** δD composition of ice in the EDC ice core, Antarctica (Jouzel et al., 2007); **(d)** atmospheric methane (CH_4) concentration from the EDC ice core (Loulergue et al., 2008). Ages in parentheses denote thousand years after present (kyr AP).

the Holocene CH_4 evolution did not follow a natural trend. In contrast, the alignment of the two Terminations (Fig. 2, right panel) implies that the early MIS 11 peak is equivalent to the early MIS 1 peak (including the Lateglacial Interstadial and Younger Dryas). Both interglacials then show a downward trend and then an upward trend in CH_4 concentrations, the analogy suggesting natural causes and leading to a refutation of the "early anthropogenic hypothesis". The problem, however, with such comparisons of CH_4 (and also CO_2) trends is that it is difficult to evaluate the different alignment schemes and simultaneously assess whether the Holocene evolution of greenhouse gas concentrations is natural or anthropogenic, in other words, to solve two different problems at the same time.

In view of this limitation, independent tests assume a particular significance. The rationale is that if two periods are analogous, the aligned portions of a record should evolve in a similar way. This would then allow an assessment of the performance of different synchronizations. Alternatively, if synchronization is not an issue, the extent to which Holocene trends appear anomalous compared to those of other interglacials can be evaluated. Antarctic temperatures have already been compared (e.g. Masson-Delmotte et al., 2006), but if according to Ruddiman (2007) anthropogenic greenhouse gas emissions countered the natural Holocene cooling trend, then Antarctic temperatures may not be sufficiently independent to address the issue. Here, I argue that southern European vegetation changes may provide an alternative approach to evaluate the alignment schemes and offer some insights into the debate over the natural evolution (or otherwise) of Holocene atmospheric methane concentrations.

Before undertaking such comparisons, the choice of the optimal parameters for the synchronization schemes needs to be discussed. It is worth noting that comparison of Figs. 1 and 2 reveals a discrepancy in the Termination/obliquity alignment. As stated earlier, the alignment of Terminations I and V of the EDC δD record by EPICA Community Members (2004), using the EDC2 ice core chronology, corresponded to a synchronization of the obliquity signal (Masson-Delmotte et al., 2006). However, the higher-resolution EDC δD record (Jouzel et al., 2007) as well as the atmospheric greenhouse gas records (Lüthi et al., 2008; Loulergue et al., 2008) use the revised EDC3 chronology (Parrenin et al., 2007). In EDC3, the mid-point of the MIS 12/11 transition is ∼4 kyr earlier compared to EDC2 (but age uncertainties in that part of the record are in the order of 4–6 kyr). This means that an alignment of the two Terminations on the EDC3 timescale (with today corresponding to 411 kyr BP), no longer leads to synchronization of the obliquity signal, and is therefore more difficult to justify in terms of the physical mechanism leading to deglaciation (Crucifix and Berger, 2006). However, extension of the Dome Fuji Antarctic ice core back to 470 kyr BP, using a chronology based on orbital tuning of the O_2/N_2 ratio of trapped air to local insolation (Kawamura et al., 2007), provides an age for Termination V that is closer to EDC2 than to EDC3 (Kawamura et al., 2008). Thus instead of aligning Termination I to Termination V, the obliquity signal may be more appropriate for the synchronization of the two intervals, not only because ice core timescales may evolve compared to astronomical timescales, but also because the choice of proxy may also influence the synchronization. For example, if the benthic $\delta^{18}O$ record (where Terminations are originally defined) were used to align Terminations I and V, a slightly different solution would emerge (see Fig. 1c and d, right panel). Finally, from a more philosophical point of view it may be argued that since the designation of potential analogues for the Holocene has an astronomical basis, then the alignment of intervals should rely on astronomical parameters associated with specific physical mechanisms leading to ice volume changes. Therefore, here a precessional alignment of MIS 1 and MIS 11 (following Loutre and Berger, 2000, 2003; and Ruddiman, 2005a, 2007) is compared with an obliquity alignment (following Masson-Delmotte et al., 2006).

2 Atmospheric methane and southern European vegetation

A recent comparison of pollen records from marine and terrestrial sequences in southern Europe has revealed a strong coherence between changes in tree populations and atmospheric methane concentrations over the last 800 kyr (Tzedakis et al., 2009). More specifically, analysis of correlation between methane and tree pollen records from the Portuguese margin and Greece showed strong coherency values in the short eccentricity, obliquity and climatic precession bands, but also at shorter, millennial-scale periodicities, at the 95% significance level. Variations in the continental hydrological balance provide a link for the observed patterns, leading to concomitant changes in southern European vegetation and low-latitude wetland methane production (although additional contributions to the methane budget from extratropical sources are not excluded). The close coupling between low- and mid-latitude hydrological changes is thought to reflect shifts in the mean latitudinal position of the Intertropical Convergence Zone (ITCZ) (Tzedakis et al., 2009). This affects (i) the location and magnitude of the rainy season in the tropics and subtropics, including monsoonal systems; and (ii) the extent to which southern Europe is dominated by subtropical or mid/high-latitude influences. While the amplitude of glacial-interglacial variability exceeds that of intra-interglacial variability, hydrological changes occurring during the course of an interglacial, have a prominent influence on both methane concentrations and southern European vegetation (see Tzedakis et al., 2009 and references therein).

More specifically, during boreal summer insolation maxima at the onset of interglacials, the maximum northward displacement of the ITCZ leads to an amplification of the hydrological cycle in northern low latitudes and an increase in wetland extent and CH_4 emissions. During the course of an interglacial, the northernmost position of the ITCZ gradually shifts south in response to decreasing summer insolation and Northern Hemisphere cooling. This leads to weakened Indian, East Asian and African summer monsoons and a reduction in northern low-latitude wetland extent and atmospheric methane concentrations.

With respect to vegetation, it is important to appreciate that the apparent subdued nature of changes in summary tree pollen curves during the course of an interglacial, conceals important shifts in vegetation composition. The term "interglacial vegetation succession" has been used to describe the sequential expansion of different vegetation communities, with certain species tending to appear early and others later during the course of an interglacial (e.g. Tzedakis, 2007). In southern Portugal, pollen diagrams show a pre-temperate (late glacial) phase of open woodland (with juniper, pine, birch, deciduous oak); the onset of the interglacial is characterized by early expansion of mediterranean sclerophylls and deciduous oaks; this is followed by a decrease of mediterranean sclerophylls and an expansion of deciduous trees; the final part of the interglacial is characterized by late successional trees (conifers) and heathland (Ericaceae), and an increase in herbs. These vegetation changes can also be viewed within the context of shifts in the mean latitudinal position of the ITCZ. In the early part of an interglacial, the maximum northward displacement of the ITCZ

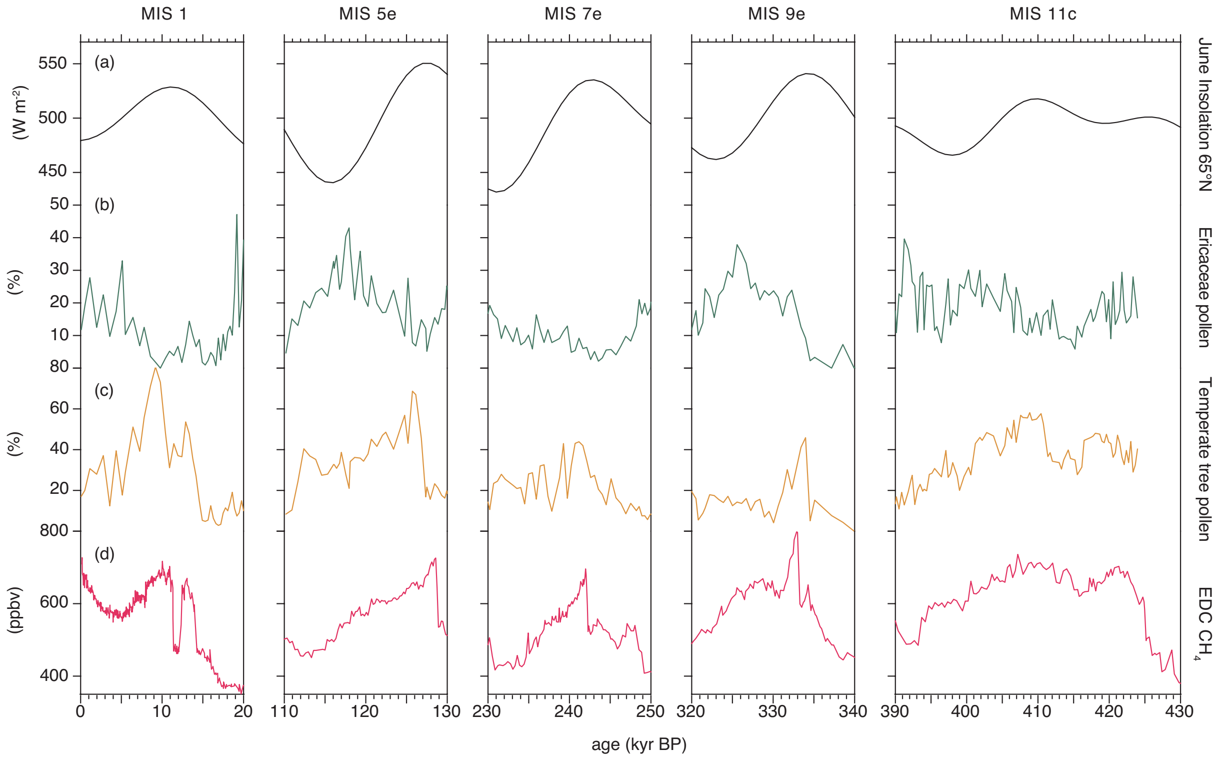

Fig. 3. Comparison of Holocene trends with those of the last four interglacials. **(a)** 21 June insolation 65° N (Berger and Loutre, 1991); **(b)** heathland (Ericaceae) pollen percentages in Portugal; **(c)** temperate tree (Eurosiberian and mediterranean taxa) pollen percentages in Portugal; **(d)** atmospheric CH_4 concentration from the EDC ice core (Loulergue et al., 2008), plotted on the EDC3 timescale. The pollen records used are from deep-sea cores on the Portuguese margin: MD01-2443 for MIS 7e, 9e, 11c (Tzedakis et al., 2004, 2009; Roucoux et al., 2006); MD95-2042 for MIS 5e (Sanchez Goñi et al., 1999; Shackleton et al., 2002); and SU8118 for the last 20 kyr (Turon et al., 2003) (see text for details of age models). Note that the Ericaceae curves are not intended to show any similarity to the methane record, but are used here to denote that the expansion of heathland is a consistent feature of the later part of the interglacial succession when summer insolation is reduced.

in summer brings southern Europe well under the influence of the zone of subtropical descent, leading to more extreme summer aridity and accentuated seasonality of precipitation compared to present, and to the expansion of mediterranean and sub-mediterranean vegetation communities. In the eastern Mediterranean, summer aridity is enhanced by the effects of an intensified summer Indian monsoon on the Rossby wave circulation. As the northernmost position of the ITCZ gradually shifts south during the course of an interglacial, the seasonal impact of subtropical subsidence in southern Europe is reduced and mid-latitude influences become more dominant. This leads to increased annual moisture availability and reduced temperatures and, in turn, to the expansion of late-successional trees and heathlands.

In contrast to CO_2, with its direct effects on photosynthetic rates and water-use efficiency of plants as well as its climatic effects, the direct influence of atmospheric methane on vegetation is limited. Instead, atmospheric methane concentrations and southern European vegetation are linked via shifts in the mean latitudinal position of the ITCZ and their impact on low- and mid-latitude hydrological changes. It is precisely because of the fact that methane is not directly involved in forcing vegetation changes, that a comparison between the two records is sufficiently independent to evaluate the natural vs. anthropogenic origin of the Holocene methane evolution.

3 Pollen records

Figure 3 shows the temperate (Eurosiberian and mediterranean) tree taxa and Ericaceae (heathland) curves from pollen sequences from deep-sea cores on the SW Portuguese margin, along with the 65° N June insolation and CH_4 records for the last four interglacials and the Holocene. The Portuguese margin, where the combined effects of major river systems and a narrow continental shelf lead to the rapid delivery of terrestrial material, including pollen, to the deep-sea environment, has in recent years emerged as a critical area for linking marine and terrestrial records. Aeolian pollen transport is limited by the direction of the prevailing offshore winds and pollen is mainly transported to the abyssal site by the outflow of the Tagus river. Comparison of modern marine and terrestrial samples along western Iberia has shown that the marine pollen assemblages provide an integrated picture of the regional vegetation of the adjacent continent (Naughton et al., 2007). One of the main advantages of this approach is that the combination of pollen and palaeoceanographic proxy analyses from the same sample set allows an in situ assessment of relative leads and lags and the use of the marine timescale for dating land events. The pollen records for MIS 11c, MIS 9e and 7e used here are from deep-sea core MD01-2443 (37°52.85′ N, 10°10.57′ W; water depth 2925 m) west of Lisbon (Tzedakis et al., 2004, 2009; de Abreu et al., 2005; Roucoux et al., 2006). The age model of MD01-2443 has been developed by aligning its $\delta^{18}O_{benthic}$ record to the Antarctic δD ice core record (Tzedakis et al., 2004, 2009), following Shackleton et al. (2000). This provides a detailed chronological control and allows comparisons with records of atmospheric greenhouse gases preserved in ice cores. This is because both the pollen and CH_4 records form independent stratigraphic timeseries with different phase relationships to the $\delta^{18}O_{benthic}$ and δD records that are used in the tuning procedure. The pollen record of MIS 5e is from deep-sea core MD95-2042 (37°48′ N, 10°10′ W; water depth 3146 m) (Sanchez Goñi et al., 1999), near the location of MD01-2443. The sequence is supported by detailed benthic and planktonic $\delta^{18}O$ stratigraphies and a chronology based on inferred sea-level stillstands correlated with radiometrically-dated marine coral terraces (Shackleton et al., 2002). It is worth noting that a new age model based on correlations with an Italian speleothem record suggests an earlier onset of the Last Interglacial (Drysdale et al., 2009), which would bring the pollen and methane peaks closer together. Finally, the MIS 2/1 record is from the SU8118 marine sequence (37°46′ N, 10°11′ N; water depth 3135 m) in the same area, supported by a detailed chronology based on 22 calibrated ^{14}C dates (Bard et al., 2000). The SU8118 pollen record can be compared with the most detailed Lateglacial/Holocene Portuguese pollen sequence from Charco da Candieira (40°20′30″ N, 7°34′35″ W, 1409 m a.s.l.), supported by 26 calibrated ^{14}C dates (van der Knaap and van Leeuwen, 1995, 1997). Charco da Candieira is a small lake of glacial origin located in a valley in the highest central part of the Serra da Estrella mountain range. Annual precipitation at that site is ∼3000 mm and mean temperature of the coldest and warmest months is ∼2.4 °C and 17 °C, respectively (van der Knaap and van Leeuwen, 1995). The comparison (Fig. 4) suggests that the marine SU8118 pollen sequence provides an accurate representation of the major vegetation trends in temperate trees and Ericaceae as recorded at the land site of Charco da Candieira.

Figure 3 draws attention to the overall similarity between trends in temperate tree populations and atmospheric methane concentrations during MIS 5e, 7e, 9e and 11c. This similarity is further supported by consideration of the succession in vegetation communities during the course of an

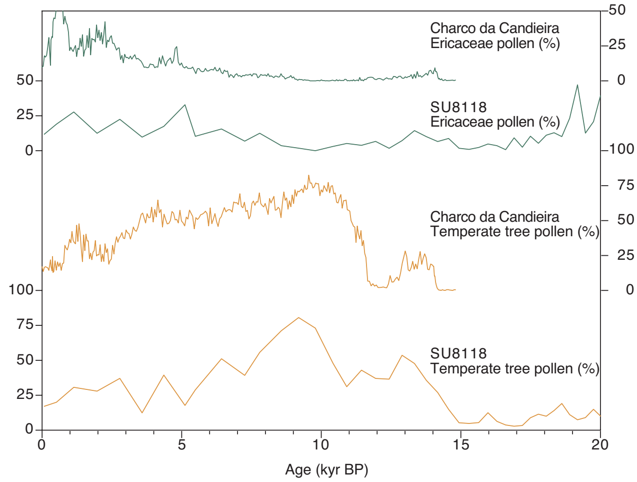

Fig. 4. Comparison of Lateglacial/Holocene changes in temperate tree (Eurosiberian and mediterranean taxa) (orange) and heathland (Ericaceae) (green) pollen percentages in deep-sea core SU8118 on the SW Portuguese margin (Turon et al., 2003) and at Charco da Candieira in the Serra da Estrella mountain range in Portugal (van der Knaap and van Leeuwen, 1995, 1997), plotted on their respective timescales. Note that the record from Charco da Candieira covers only the last ∼15 kyr.

interglacial, as discussed in the previous section: early expansion of mediterranean sclerophylls and deciduous oaks, followed by expansion of heathland. However, before undertaking comparisons with the current interglacial, the extent to which Holocene vegetation changes reflect natural trends needs to be assessed. Van der Knaap and van Leeuwen (1995), infer human impacts on vegetation at Charco da Candieira through most of the Holocene. Using a profound understanding of local ecology and detailed pollen taxonomy, van der Knaap and van Leeuwen (1995) detect evidence of human activity at lower altitudes as early as ∼9.6 kyr BP and in the mountains and the valley sometime around 8.5–8 kyr BP (dates are in calendar years). Small-scale deforestation and grazing increased after ∼6.5 kyr BP and intensified after ∼5 kyr BP, while large-scale deforestation is inferred to have started after ∼3.4 kyr BP. The largest vegetation disturbance took place in the last millennium, which led to complete deforestation and soil erosion. The vegetation today consists of heavily grazed and burnt heathlands, shrublands and grasslands and also pine plantations (van der Knaap and van Leeuwen, 1995). It would appear, therefore, that Holocene pollen record is heavily overprinted with human impacts on vegetation, which would largely invalidate comparisons with natural vegetation changes of earlier interglacials.

However, the attribution of some of the vegetation changes to human activities may be questioned. For example, the earliest evidence of extra-regional human impact ∼9.6 kyr BP is based on the presence of long-distance pollen of olive trees from lower altitudes, but expansion of mediterranean sclerophylls is a consistent feature of the early parts of all pre-Holocene interglacials in southern Europe (e.g. Magri and Tzedakis, 2000; Tzedakis, 2007). The changes around 8.5–8 kyr BP, characterized by small declines in oak and increases in pine values could alternatively reflect the impact of climatic oscillations that are known to have occurred during this interval (e.g. Rohling and Pälike, 2005). The stepwise decreases in tree populations at 6.5, 5 and 3.4 kyr BP are mainly a function of Ericaceae (heathland) expansion. Examination of the record of earlier interglacials (Fig. 3b) shows that expansion of Ericaceae is a consistent feature of the later part of the interglacial succession in this area. Moreover, recent work in the Portuguese margin (Margari et al., 2007) has revealed a clear precessional pattern with Ericaceae expanding during periods when perihelion occurs in NH winter, under lower temperature and reduced aridity regimes. The comparison with earlier interglacials, suggests that the degree to which anthropogenic practices mask natural vegetation trends during the Holocene, prior to 1 kyr BP, may have been overestimated. This is echoed in a recent statistical analysis of the dating of pollen zone boundaries of 492 sites from Europe (Gajewski et al., 2006). This showed that major vegetation transitions were synchronous across the continent and also synchronous with those identified by a similar analysis in North American pollen diagrams. Moreover, these transitions appeared to be coeval with major environmental changes in North Atlantic marine records and Greenland ice cores. The close correspondence suggests that major vegetation changes in the Holocene were forced by large-scale reorganizations of atmospheric circulation (Gajewski et al., 2006). This does not mean that anthropogenic impacts on vegetation can be discounted, but it may suggest that humans took advantage of these climate changes, especially in the more vulnerable ecosystems where tree populations are nearer their tolerance limits.

4 Vegetation trends and interglacial comparisons

If we entertain the premise that Holocene pollen changes until 1 kyr BP primarily reflect natural vegetation trends, though they may have been abetted by anthropogenic practices, then the following observations can be made. Examination of the Holocene methane and temperate tree pollen records reveals opposing trends after 5 kyr BP, to an extent that is not observed in the previous four interglacials (Fig. 3). Even if natural vegetation trends are masked by anthropogenic changes, it is difficult to imagine an increase in temperate tree populations when NH summer insolation is declining (e.g. Tzedakis, 2007). Indeed examination of pre-Holocene interglacial vegetation successions, argues against such possibility. Given the strong coherence between trends in tree populations in southern Europe and atmospheric methane concentrations during previous interglacials, the late Holocene divergence is striking. This decoupling may suggest a predominantly extratropical methane source, such as a contribution from boreal wetlands (e.g. Schmidt et al., 2004), but recent work on the interpolar methane gradient indicates a low-latitude origin (Brook et al., 2008). It is possible that the southward ITCZ displacement during the course of the Holocene transported moisture from one hemisphere to the other, leading to an increase in Southern Hemisphere (SH) low-latitude wetland methane sources (Brook et al., 2008; Burns, 2008). However, the question remains why the same pattern is not observed during earlier interglacials. The more accentuated precessional changes in the last three interglacials should have led to more extreme interhemispheric moisture transfers, but a late-interglacial increase in methane concentrations is not observed. This would imply that barring other methane sources, the late Holocene methane trend may be anomalous compared to previous interglacials.

With respect to the alignment of MIS1 and MIS 11, a comparison of the vegetation trends of the two interglacials may provide an independent assessment of the different synchronization schemes. While neither alignment is excellent, the precessional alignment (Fig. 5, left panel) can be argued to give more parallel changes in vegetation between MIS 11 and the elapsed portion of the Holocene. By comparison, the obliquity alignment (Fig. 5, right panel) leads to a greater divergence between the two curves: after the early MIS 11 peak, the pollen record shows a second expansion of tree populations ($\sim$410 kyr BP), while the Holocene record shows a monotonic decline in tree populations. A similar outcome emerges if the records are plotted on the EDC2 timescale (not shown here). This comparison provides support for the precessional alignment of MIS 11 and MIS 1 of Loutre and Berger (2000, 2003) and Ruddiman (2005a, 2007). By extension, it implies that in the absence of anthropogenic forcing, the Holocene should be nearing the end of its natural course.

The choice of a precessional over an obliquity alignment of the two periods more closely reflects the notion that the search for Holocene analogues is underpinned by the modulating effect of the 400-kyr eccentricity cycle on precession. Thus, synchronization schemes are not completely unconstrained, but are governed by the timing of minima in the amplitude of eccentricity variations, which would suggest that an alignment of the eccentricity signal should not be significantly violated. Although it is impossible to match precisely the phases of precession, obliquity and eccentricity from two different periods (e.g. Crucifix and Berger, 2006), the obliquity synchronization leads to a substantial divergence in the alignment of the eccentricity variations between the two periods (Fig. 5a, right panel), so that instead of the minima in eccentricity values at $\sim$372 kyr BP and 27 kyr AP being matched they are 9 kyr apart. This divergence in the eccentricity signal is further exacerbated by an alignment of the two Terminations (on the EDC3 timescale) (Broecker and Stocker, 2006) or of an alternative synchronization of the intervals preceding the two deglaciations, using the phasing

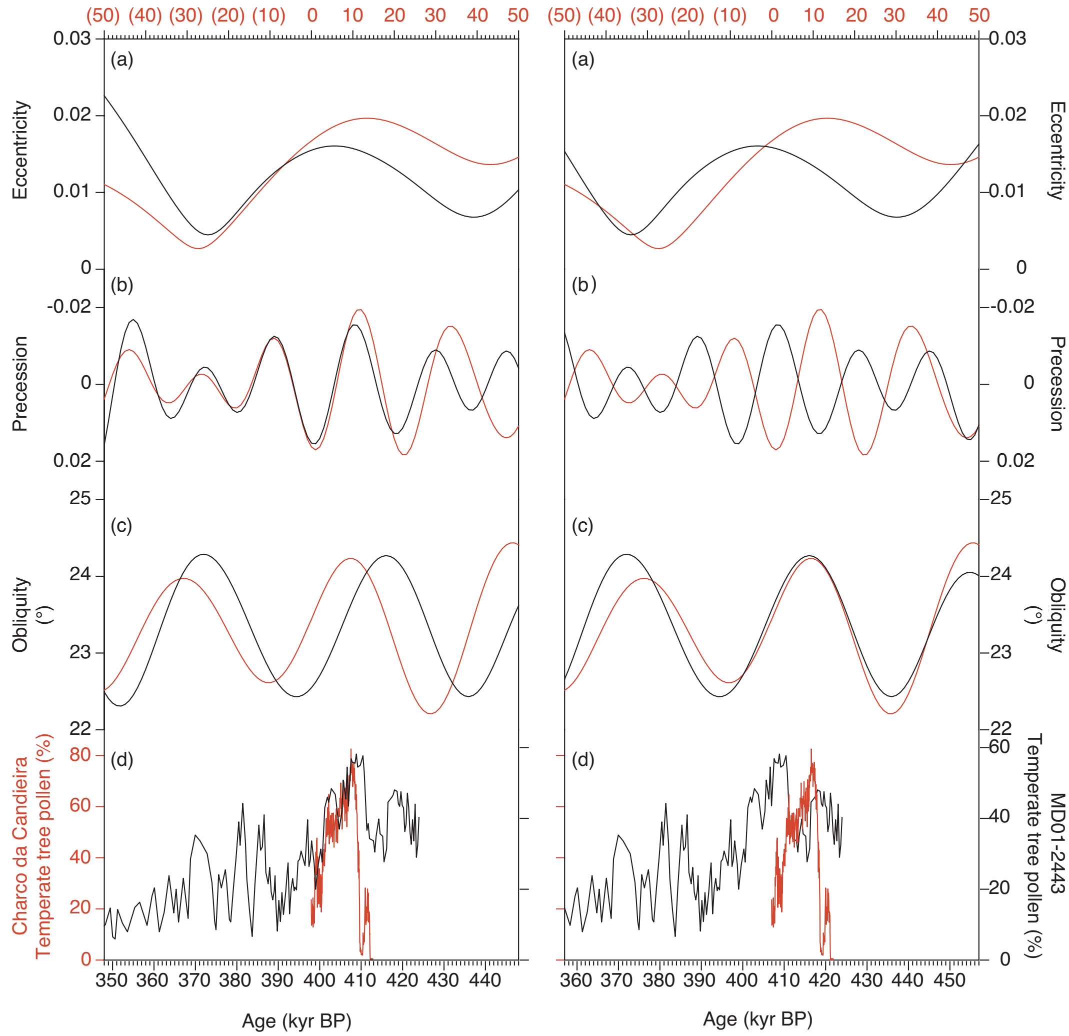

Fig. 5. Comparison of two alignment schemes between the past and future 50 kyr (red) and a 100-kyr interval encompassing MIS 11 (black), using pollen records from Portugal. Left panel shows synchronization of the precession signal and right panel synchronization of the obliquity signal. **(a)** eccentricity (Berger and Loutre, 1991); **(b)** precession index, plotted on an inverse vertical axis (Berger and Loutre, 1991); **(c)** obliquity (Berger and Loutre, 1991); (b) δD composition of ice in the EDC ice core, Antarctica (Jouzel et al., 2007), plotted on the EDC3 timescale; (c) atmospheric CH_4 concentration from Antarctic EDC ice core (Loulergue et al., 2008), plotted on the EDC3 timescale; **(d)** temperate tree (Eurosiberian and mediterranean taxa) pollen percentages in Portugal. The pollen records used are: MIS 11 (black) from MD01-2443 (Tzedakis et al., 2009); and Lateglacial/Holocene (red) from Charco da Candieira (van der Knaap and van Leeuwen, 1995, 1997) (see text for details of age models). The latter is selected over the pollen record from marine sequence SU8118 (see Fig. 4), because of its higher sampling resolution. Note that temperate tree pollen percentages in the marine sequence are generally lower than those at the terrestrial site. This is because marine records incorporate pollen from a variety of environments, including coastal areas, which leads to an overrepresentation of herbaceous taxa. Ages in parentheses denote thousand years after present (kyr AP).

between southeast Atlantic sea surface temperatures and benthic δ^{18}O (Dickson et al., 2009). On the other hand, the precessional solution results in a complete mismatch of Terminations I and V. However, this may reflect the unusually protracted deglaciation in MIS 11 compared to MIS 1 ($\sim$20 kyr vs. $\sim$10 kyr, Rohling et al., 2010), which in turn may be a function of the differences in the relative phasing of obliquity and precession between the two periods. In this view, the two Terminations are incommensurate and MIS 1 is analogous only to the second part of MIS 11c.

5 Alternative analogues and implications

While the above analysis indicates that the precessional alignment of MIS 1 and MIS 11 may be more appropriate than the obliquity alignment, the difference in the phasing of precession and obliquity underlines the limitations of the MIS 1 – MIS 11 analogy and suggests that alternative candidates ought to be explored.

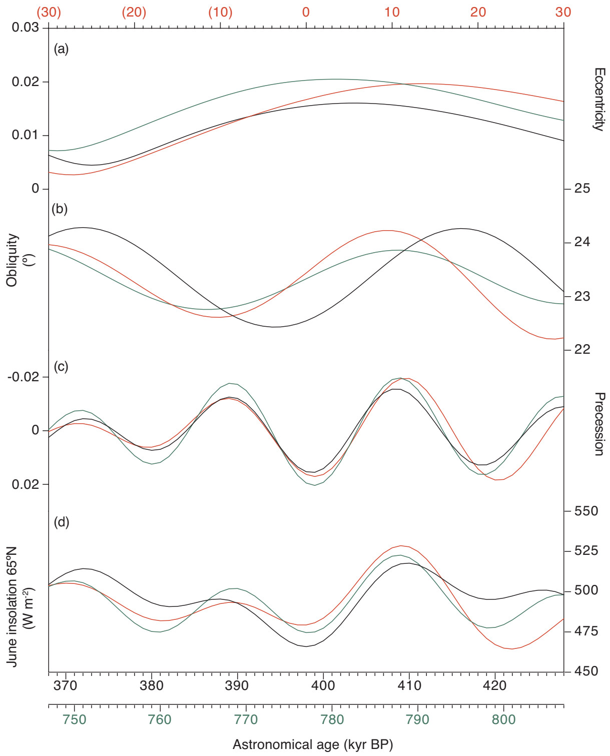

Fig. 6. Comparison of astronomical parameters of the past and future 30 kyr (red), a 60-kyr interval encompassing MIS 11 (black) and a 60-kyr interval encompassing MIS 19 (green). **(a)** eccentricity (Berger and Loutre, 1991); **(b)** obliquity (Berger and Loutre, 1991); **(c)** precession parameter, plotted on an inverse vertical axis (Berger and Loutre, 1991); **(d)** 21 June insolation 65° N (Berger and Loutre, 1991). Ages in parentheses denote thousand years after present (kyr AP).

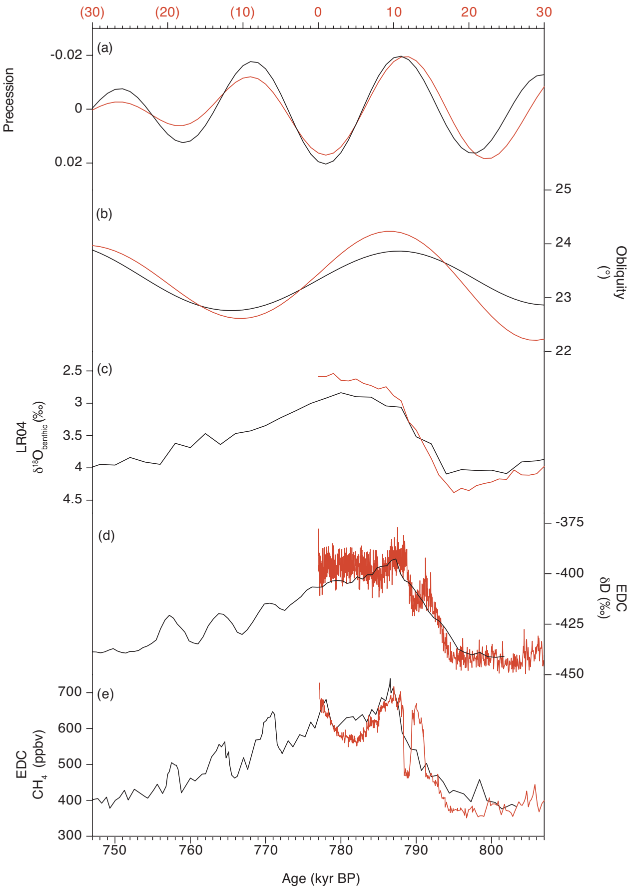

Fig. 7. Precessional (and also obliquity) alignment of the past and future 30 kyr (red) and a 60-kyr interval encompassing MIS 19 (black). **(a)** precession index, plotted on an inverse vertical axis (Berger and Loutre, 1991); **(b)** obliquity (Berger and Loutre, 1991); **(c)** $\delta^{18}O_{benthic}$ record from the LR04 stack (Lisiecki and Raymo, 2005), plotted on its own timescale; **(d)** δD composition of ice in the EDC ice core, Antarctica (Jouzel et al., 2007), plotted on the EDC3 timescale; **(e)** atmospheric CH_4 concentration from the EDC ice core (Loulergue et al., 2008), plotted on the EDC3 timescale. Ages in parentheses denote thousand years after present (kyr AP).

Ruddiman (2007) proposed that of the last four interglacials, MIS 9e might be considered the closest analogue to MIS 1 on the basis of the phasing between obliquity and precession and the caloric half-year insolation trends. However, the amplitude of precessional changes during MIS 9e is larger, leading to substantial differences in mid-June insolation at 65° N. Moreover, the onset of MIS 9e is characterized by overshoots in CO_2 and CH_4 concentrations, which are not observed in MIS 1 (Lüthi et al., 2008; Loulergue et al., 2008).

As dicussed above, a key aspect in the search for orbital analogues for MIS 1 and the future is the subdued amplitude of precessional changes as a result of the effect of the 400-kyr eccentricity cycle. This suggests that closer analogues should occur at times of lowest eccentricity values, representing multiples of 400-kyr intervals. Indeed Loutre and Berger (2000) found a slightly higher correlation of mid-June insolation between MIS 1 and 19 than between MIS 1 and 11. Unlike MIS 11, the phasing between obliquity and precession during MIS 19 is very similar to that observed in MIS 1 (Fig. 6), although the timing of the eccentricity maximum diverges somewhat, and absolute values of obliquity are different because of the amplitude modulation of obliquity with a period of 1.3 million years (Berger et al., 1998). More specifically, the obliquity maximum occurs very near the precession minimum, which means that both obliquity and precession alignments result in essentially the same solutions, so that today corresponds to about 777 kyr BP (Figs. 6 and 7).

Examination of the two interglacials reveals that the respective evolution of Antarctic δD and marine benthic $\delta^{18}O$ records is very similar (Fig. 7c, d). Applying the same criterion used for MIS 11 by Ruddiman (2007), i.e. the point where the $\delta^{18}O$ increase in benthic foraminifera exceeds deepwater temperature effects of up to 0.56‰, thereby signifying new ice growth, the end of the MIS 19 full interglacial conditions is estimated to have occurred ~768 kyr BP. The same solution is reached if the mid-point of the transition in the LR04 $\delta^{18}O$ curve is chosen. If the orbital analogy is correct, this would suggest that the Holocene has another 9 kyr to run its natural course.

Since the alignment of MIS 1 and MIS 19 is not under dispute, a comparison of the evolution of methane concentrations over the two intervals can, in principle, be used to assess the origin of the Holocene methane record. This shows that the aligned sections of the CH_4 record diverge in places (for example there is no MIS 19 equivalent for the Lateglacial oscillation) (Fig. 7e). Of particular interest, however, is that the downward trend in CH_4 concentrations following the early MIS 19 maximum ∼787 kyr BP, is interrupted by a second CH_4 peak ∼778 kyr BP. This reversal in the MIS 19 downward methane trend is shorter and of lower amplitude (∼1.5 kyr and 80 ppbv) compared to the late Holocene increase up to pre-industrial times (5 kyr and 150 ppbv, respectively) and therefore may be a millennial-scale feature, not related to orbital changes (Ruddiman, 2009). However, apart from methane overshoots at the onset of some interglacials (Loulergue et al., 2008), millennial-scale increases in CH_4 concentrations associated with full-interglacial conditions are normally in the order of 30 ppbv. The 80-ppbv increase ∼778 ka appears to be outside that range, which in turn raises the question on the nature of a millennial event that would lead to such a change during an interglacial. It is also worth noting that both the MIS 1 and 19 CH_4 peaks occur during precession maxima, corresponding to minima (maxima) in summer boreal (austral) insolation. As discussed earlier, these changes in the precessional cycle cause a southerly migration in the mean position of the ITCZ and lead to interhemispheric moisture transfer from NH to SH low latitudes. It is possible, therefore, that the second MIS 19 peak reflects an increase in SH low-latitude wetland methane sources as invoked for the Holocene by Brook et al. (2008) and Burns (2008). As stated before, however, the question remains why similar trends are not observed during other interglacials with higher-amplitude precessional changes? The answer may be that the more accentuated changes in boreal insolation led to an earlier glacial inception and therefore the interhemispheric moisture transfer was overtaken by the onset of colder conditions. In contrast, the dampening of precessional variations by the small orbital eccentricity during MIS 1 and MIS 19 means that the decrease in boreal insolation is too small to lead to glacial inception. If that is the case, then we would also expect a peak in CH_4 concentrations near the precession maximum ∼399 kyr BP during MIS 11, which in fact is not observed. It is possible that differences in the phasing of the astronomical parameters may account for this divergence, with the obliquity minimum occurring nearer the precession maximum of 398 ka in MIS 11 (Fig. 6), compared to MIS 1 and 19. In addition, results from Dome Fuji, Antarctica (Kawamura et al., 2008) suggest that the EDC3 timescale for MIS 11 may require substantial revision near this interval, and therefore an accurate evaluation of this issue may be premature.

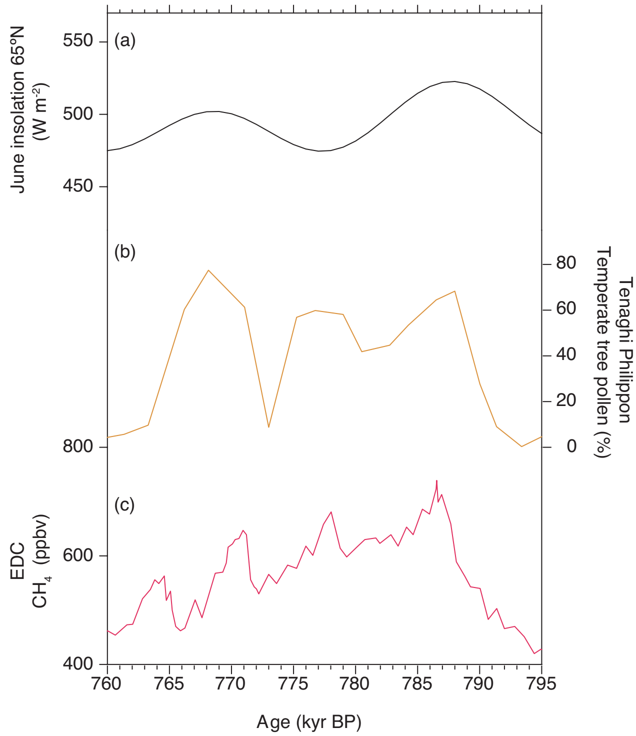

Fig. 8. Comparison of vegetation changes at Tenaghi Philippon, NE Greece with palaeoclimatic records of MIS 19. **(a)** 21 June insolation 65° N (Berger and Loutre, 1991); **(b)** temperate tree (Eurosiberian and mediterranean taxa) pollen percentages at Tenaghi Philippon, plotted on its own timescale (Tzedakis et al., 2006); **(c)** atmospheric CH_4 concentration from the EDC ice core (Loulergue et al., 2008), plotted on the EDC3 timescale.

If the hypothesis of SH low-latitude sources accounting for the second MIS 1 and MIS 19 CH_4 peaks is correct, then we should a priori expect a decoupling between methane concentrations and southern European temperate tree population size. As the mean location of the ITCZ shifts to the Southern Hemisphere, southern Europe would increasingly come under mid-to-high latitude influences, leading to contraction of temperate tree populations and expansion of conifers and herbaceous vegetation. This means that the observed late Holocene divergence between the two records would be consistent with this scenario and therefore cannot be used as support for the "early anthropogenic hypothesis". Extending the argument further, a similar decoupling should also be observed during the second CH_4 peak in MIS 19 around 778 kyr BP. Unfortunately, the Portuguese pollen record does not extend beyond MIS 11. The only southern European record that continuously spans the last 800 kyr (and indeed the last 1.35 million years) is from Tenaghi Philippon, NE Greece (Wijmstra, 1969; Wijmstra and Smit, 1976; van der Wiel and Wijmstra, 1987a, 1987b). While its astronomically-calibrated timescale (Tzedakis et al., 2006) is not as well constrained as that of the Portuguese margin, comparison of the temperate tree pollen record with atmospheric methane concentrations has also revealed a strong coherence over the last 800 kyr (Tzedakis et al., 2009). The chronostratigraphic position of MIS 19 in the Tenaghi Philippon record is supported by the identification of the Matuyama/Brunhes boundary by N. D. Opdyke (in Wijmstra and Groenhart, 1983). Examination of the temperate tree pollen and methane records over this interval (Fig. 8) reveals a good correspondence, with an early peak followed by a decrease and then a second increase centred around 778 kyr BP. The lack of divergence between the two records around 778 kyr BP, would appear to cast doubt on the argument favouring southern low-latitude methane sources and a decoupling of the pollen-CH_4 records in the late Holocene. However, it is important to note that the MIS 19 section of the Tenaghi Philippon record has low sampling resolution and is constrained by only two control points 15-kyr apart. Thus, small variations in sediment accumulation rates could change the observed temporal relation to the methane peak. Resolution of this issue, therefore, will have to await the generation of new detailed pollen records with improved chronological control.

6 Conclusions

Arguably, a comparison of the different synchronization schemes based on southern European vegetation changes is not particularly rigorous, in the sense that what is being assessed is the extent to which the aligned portions of the pollen records show similar trends. However, this can be equally said of comparisons using other proxy records, such as Antarctic δD or benthic $\delta^{18}O$. Moreover, southern European interglacial vegetation changes are sufficiently independent of the CH_4 record to undertake such comparisons, but have the advantage of being closely coupled to low latitude methane emissions via shifts in the mean latitudinal position of the ITCZ.

Based on this, the divergence between atmospheric methane concentrations and temperate tree populations in the late Holocene would appear to favour the view of Ruddiman (2003, 2007) that the CH_4 rise after 5 kyr BP reflects anthropogenic emissions. In addition, an assessment of the vegetation trends in MIS 1 and MIS 11 favours a precessional alignment of the two interglacials, which would support the notion that in the absence of anthropogenic interference, the Holocene should be nearing its natural completion.

However, examination of MIS 19 as an alternative (and indeed closer) astronomical analogue for MIS 1 leads to different conclusions. The alignment of the two interglacials suggests that the Holocene has another quarter of an obliquity cycle to run its natural course. Moreover, this comparison reveals similarities in the evolution of CH_4 concentrations during the late Holocene and equivalent MIS 19 interval, which, provided that the peak at $\sim$778 kyr BP is not a millennial-scale feature, would argue against a primarily anthropogenic explanation for the Holocene trends. The second MIS 1 and MIS 19 methane peaks appear to occur during maxima in austral summer insolation, which may point to SH low-latitude CH_4 sources as suggested for the Holocene by Brook et al. (2008) and Burns (2008). This would also imply that the late Holocene decoupling between methane concentrations and southern European temperate tree population size is not anomalous. By extension, a similar divergence between CH_4 and pollen records should also occur during MIS 19, but the available records lack the chronological precision to answer this satisfactorily.

On balance, what emerges is that projections on the natural duration of the current interglacial depend on the choice of analogue, while corroboration or refutation of the "early anthropogenic hypothesis" on the basis of comparisons with earlier interglacials remains irritatingly inconclusive.

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