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Synchroneity between marine and terrestrial responses to millennial scale climatic variability during the last glacial period in the Mediterranean region

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Abstract Land–sea climatic proxies have been obtained from the Last Glacial section of IMAGES core MD95-2043 (western Mediterranean Sea). Vegetation and alkenone derived SST curves indicate rapid (~150 years) and synchronous terrestrial and marine climatic changes, paralleling the Dansgaard–Oeschger (D–O) climatic variability over Greenland. This frequency of climate change can be related to shifts between the two modes of operation of the North Atlantic Oscillation (NAO). Transfer functions applied to the pollen data indicate that there was an amplification of the climatic signal during Heinrich events (HEs) in comparison with other D–O stadials. The development and persistence of both Scandinavian and Atlantic Mobile Polar Highs over southwestern Europe may explain the extreme cooling (~10 °C) and dryness (400 mm) during Heinrich events 5 and 4 in the Mediterranean region. Comparison of the results of core MD95-2043 with similar climatic data from IMAGES core MD95-2042, located off Portugal, indicates that thermal and precipitation gradients occurred between the Mediterranean and the Atlantic sides of Iberia within HEs. HEs 4 and 5 are associated with more humid conditions in the Atlantic (by 200 mm) than in the Mediterranean site, as is the case at the present time. This comparison also illustrates the different behaviour of these areas during the D–O stadials. In contrast with the Mediterranean site, the Atlantic site shows similar precipitation and temperature drops for all the D–O stadials, including those related to the HEs. Here we propose the operation of different Mobile Polar Highs (MPH) as the driving mechanism for this difference in behaviour between the Atlantic and Mediterranean sides of Iberia. HEs are related to a stronger influence of the Scandinavian MPH, forcing a severe aridification and cooling of the full Iberian Peninsula. The Atlantic MPH may have been dominant during the other stadials, which would preferentially affect Southwestern Iberia.

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1 Introduction

The last glacial period shows evidence of substantial climatic instability at millennial scales (Dansgaard 1985). This instability involved rapid changes in oceanographic conditions over the Atlantic Ocean (van Kreveld et al. 2000) and other oceanographic regions (Schulte et al. 1999) and also changes in atmospheric temperature and humidity balance over different continental regions of the Northern Hemisphere (Fang et al.

1999; Grimm et al. 1993). Although this variability has been intensively studied over the last decade, forces responsible and the mechanisms involved in the interlatitudinal transmission of this rapid variability remain unclear (Alley et al. 2000). Instability of the ice sheets (MacAyeal 1993; McCabe and Clark 1998), changes in the thermohaline circulation (Vidal et al. 1999; Peterson et al. 2000), changes in atmospheric dust concentration (Fuhrer et al. 2000), variations in the strength of the northwesterlies and in high pressure cell intensity over the Asian continent (Wang and Sarnthein 1999) are some of the mechanisms quoted to explain this variability. Two major problems increase the difficulty of understanding relationships between the different mechanisms; first, it is not often possible to access sedimentary records with sufficient time-resolution to analyse this rapid variability and secondly, a major problem exists in the chronological framework of relevant data. Errors in absolute dating methods and uncertainties in correlations between different proxy profiles are larger than several centuries, which limits the possibility of establishing time relationships between different processes (Crowley 1999).

Recent studies on millennial-scale changes carried out on marine sediment cores from the western Mediterranean Sea have demonstrated that this region was very sensitive to the rapid climatic and oceanographic glacial variability described in the North Atlantic region (Rohling et al. 1998; Cacho et al. 1999; Paterne et al. 1999). HEs and D–O cycles have been associated in the Mediterranean marine record with rapid sea surface temperature (SST) oscillations, but also with different modes of the deep water convection of the basin (Cacho et al. 2000). This suggests a strong link between oceanographic changes and the atmospheric conditions over the western Mediterranean region. Pollen records from the Lago di Monticchio (south Italy) also show rapid vegetation shifts during the last glacial period, which have been correlated through radiometric dating, layer counting and tephra-chronology to the HEs and D–O stadials (Allen et al. 1999; Watts et al. 1996). However, this continental sequence cannot be used to document the true leads and lags between marine and terrestrial environmental shifts. The pollen records currently available from Mediterranean marine cores are too coarse for studies at millennial scales (Rossignol-Strick and Planchais 1989). Development of a mixed forest on the Mediterranean borderlands during the HEs has been inferred from the marine sequence KET 80-03 (Paterne et al. 1999) a scenario that is in contradiction with the terrestrial pollen records (Allen et al. 1999; Watts et al. 1996).

A high resolution marine-terrestrial correlation in the Atlantic/Mediterranean transitional zone has been recently carried out in a multidisciplinary study of core MD95-2042, collected off Portugal (Sánchez Goñi et al. 2000). The results have demonstrated that the nucleus of each Heinrich event, i.e. when the input of the Canadian ice rafted detritus (IRD) was at a maximum, and also the maxima of the other D–O stadials, correspond to dry and cold periods in the central Iberian Peninsula. This study provided a first insight into the marine-terrestrial correlation at millennial time scales; however it has not supplied any information directly from the Mediterranean biogeographical region.

The present study is focused on a pollen analysis of the glacial section of the IMAGES core MD95-2043 (Fig.1) collected in the central Alboran sea (western Mediterranean, 36°8′N, 2°37′W; 1841 m water depth), which presents a high resolution record of this period (Cacho et al. 1999). The goal of this work is to establish the vegetation succession and thus, the climatic evolution of the western Mediterranean region in relation to the rapid variability of the last glacial period. A novel aspect of this study involves a direct comparison of a pollen record with alkenone SST estimates, which allows us to determine the relative timing of the marine and terrestrial responses to D–O type climatic variability. In addition, we present here for the first time an application of pollen transfer functions to the marine sediment data set in order to reconstruct paleoprecipitation and paleotemperature conditions on the continent. Finally, we present a close comparison between pollen records from both Alboran (MD95-2043) and Portuguese (MD95-2042) marine cores which permits a discussion of the different climatic behaviour of the two sides of Iberia during the last glacial period.

2 Environmental setting

2.1 Present-day oceanographic conditions

The Alboran Sea is the westernmost basin of the Mediterranean Sea, connected with the North Atlantic Ocean through the Strait of Gibraltar. In this area, the less dense Atlantic Water inflow fills the upper layer and describes two anticyclonic gyres before flowing eastwards to the eastern Mediterranean Sea (La-Violette 1986). The deeper water layers are filled by the Levantine Intermediate Waters and the Western Mediterranean Deep Water, which form the Mediterranean outflowing water. This complete thermohaline circulation system is the result of climatic conditions over the entire Mediterranean that produce an excess of evaporation over precipitation plus river runoff, which in turn generates dense water masses (Béthoux 1979, 1980; Lacombe et al. 1981). Climate over the western Mediterranean basin is dominated in summer by the strong Azores anticyclone, and in winter by the incursions of north westerlies.

2.2 Present-day climate and vegetation

Core MD95-2043 was retrieved precisely between the two surficial anticyclonic gyres, in the mid-point between southeastern Iberia and northwestern Africa. No major rivers enter in this area (Atlas Nacional de España 1993) (Fig. 1). However, the present torrential rain regime produces an important supply of riverine material from the southeastern Iberia region to the Alboran Sea. A recent sediment trap analysis close to the studied area has estimated that only the 12% of the flux of lithogenic particles correspond to aeolian transport (Fabrés et al. 2001). Therefore, fluvial fluxes from the Iberian margin should represent the main pollen supply to our

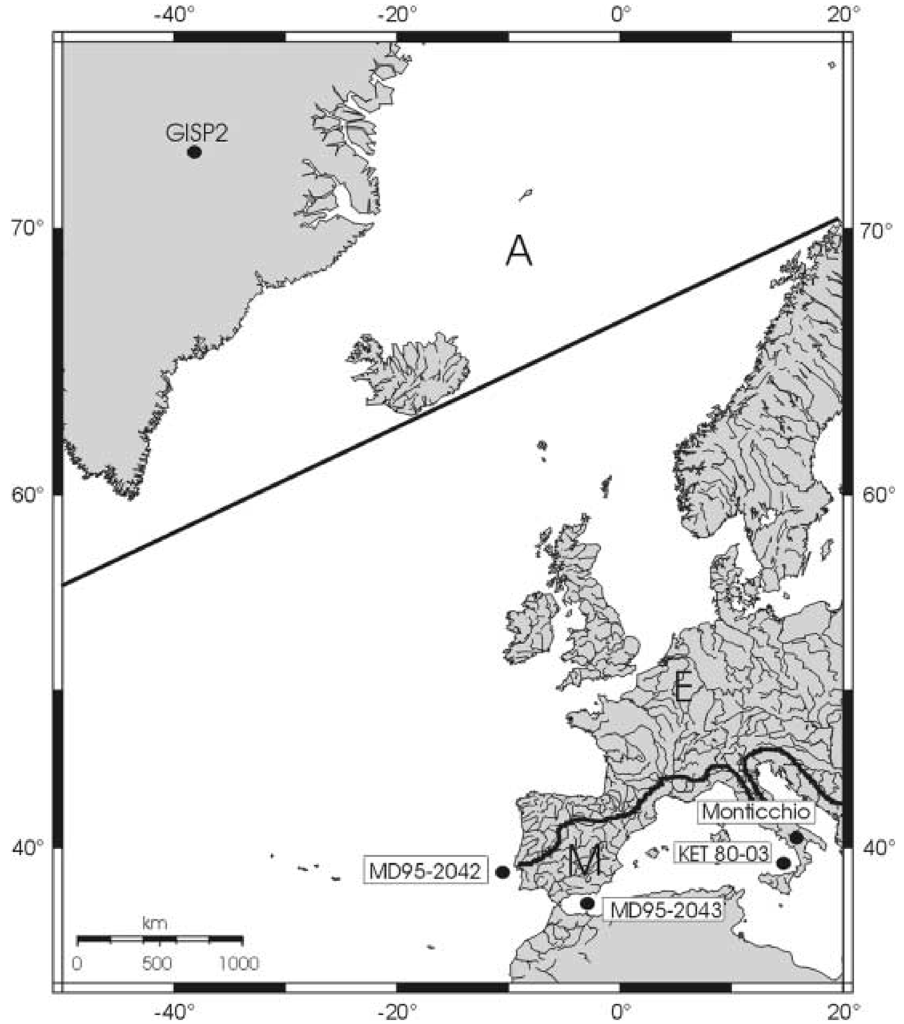

Fig. 1 Location of the cores mentioned in the text. *A*: Arctic flora region, *E*: Eurosiberian flora region, *M*: Mediterranean flora region

Alboran core. The dominant winds come from the north and the west (Atlas Nacional de España 1992) and southern Saharan winds sporadically occur under particular climatic conditions (Rodríguez et al. 2001). Therefore, the sediments from this core mainly preserve pollen from the vegetation colonising the southern part of Iberia. This region is characterised at present by a Mediterranean climate (Rivas-Martinez 1987) with mild winters. The mean temperature of the coldest month (MTCO) is around 5 °C (from –1 to 10 °C), and the area has warm and dry summers, with mean annual precipitation (Pann) of less than 600 mm (Atlas Nacional de España 1992).

Sub-Mediterranean and Mediterranean vegetations, dominated by the evergreen oak forest (*Quercus rotundifolia*) (Blanco Castro et al. 1997), colonise this area. In the littoral zones up to 1000 m a.s.l. ($200 < P < 400$ mm), *Q. rotundifolia* is accompanied by the thermo-Mediterranean species *Olea europea* ssp. *sylvestris*, *Chamaerops humilis* and *Pistacia lentiscus*, among others (Martinez Parras and Peinado Lorca 1987). Higher levels of rainfall in the Betic mountain chain (1000–2000 m a.s.l., $P > 600$), allow the development of deciduous trees such as the deciduous oak *Quercus pyrenaica*, *Q. faginea*, *Acer monspessulanum*, *Sorbus aria*, *S. aucuparia* and *Taxus baccata* along with the evergreen *Q. rotundifolia*. *Pinus sylvestris* and several species of the genus *Juniperus* occupy the altitudes between 2000 and 2900 m a.s.l.. The coldest high summits of the Sierra Nevada, above 2900 m a.s.l., are occupied by pasturelands of *Festuca clementei* and *Artemisia granatensis*, among others (Martinez Parras and Peinado Lorca 1987).

3 Methodology

3.1 Pollen analysis

Most of the samples for pollen analysis were recovered at the same intervals, between 4 and 6 cm, as the samples for alkenone estimates. The temporal resolution is between 40 and 500 years. The preparation technique followed the procedure described by de Vernal et al. (1996). After chemical treatment (cold 10%, 25% and 50% HCl, cold 48% and 70% HF), the samples were sieved through 10 μm nylon mesh screens. The final residue for pollen analysis was mounted unstained in double distilled glycerine. Pollen grains were counted using a Zeiss Axioscope light microscope at ×400 and ×1000 (oil immersion) magnifications.

It is widely accepted (McAndrew and King 1976) that continental pollen spectra including more than 20 taxa and at least 100 pollen grains more than those corresponding to the dominant taxa give an accurate image of the surrounding vegetation. For this reason, a minimum of 100 pollen grains, excluding *Pinus* and spores, were counted at each of the 85 levels analysed. In two thirds of the samples the number of taxa is higher than 20, while in the remaining samples the number oscillates between 16 and 19 taxa. Only one sample has only 15 pollen types. The few spectra with less than 20 taxa are surrounded by richer samples. The poor spectra do not introduce, however, any apparent bias in the percentage fluctuations. Seventy three taxa were identified in a total pollen sum ranging between 292 and 1436 per sample. Twenty pollen zones have been established, based on the definition by Gordon and Birks (1972), independently of other proxy data (Fig. 2). These zones are numbered from bottom to top and prefixed by the abbreviated site name MD43.

Data on the distribution patterns of pollen in recent surface sediments from the Alboran Sea and off Portugal are not available. However, several studies suggest the minimal influence of ocean currents during the process of sinking and, therefore, a high settling velocity of pollen in the Atlantic water column (Hooghiemstra et al. 1992). Furthermore, other studies of modern pollen rain from different regions such as the Bay of Biscay (Turon 1984), the Mediterranean Sea (Koreneva 1971), the Atlantic off northwestern Africa (Hooghiemstra et al. 1986), the northwest Atlantic Ocean, the northeast Pacific Ocean and the Gulf of Mexico (Heusser 1985) confirm that pollen in ocean sediments, carried to the sea by wind and rivers, reflects the regional vegetation of the close continent and, therefore, the environmental parameters of the vegetation from which it is derived.

Interpretation of the pollen zones follows the present ecological preferences of the different plant communities (Prentice et al. 1996; Peyron et al. 1998). Higher percentages of Eurosiberian taxa such as deciduous *Quercus*, *Betula*, *Fraxinus* and *Corylus* indicate temperate and humid conditions. The maximum percentages of Mediterranean plants (evergreen *Quercus*, *Olea*, *Pistacia* and *Phillyrea*) suggest the warmest episodes along with dry summers. Steppe-dominant pollen zones reflect dry and probably cold conditions.

3.2 Pollen estimates of annual precipitation and winter temperature

The floristic diversity and the richness of our pollen spectra as well as the occurrence of pollen from the main plant-climatic indicators permit us to tentatively apply the transfer function technique developed for continental sequences (Guiot 1990; Cheddadi et al. 1998) to the marine core MD95-2043. This technique allows the reconstruction of paleotemperatures and paleoprecipitation from fossil pollen assemblages although the distinction between warm and cold steppes remains problematic (Tarasov et al. 1998). The transfer function is based on 1328 modern pollen spectra (moss polsters, soil surface samples and lacustrine sediments) from Eurasia and northern Africa (Peyron et al. 1998). A large number of these pollen spectra come from the top of lacustrine sequences which, in many cases, represent a large catchment area where pollen was certainly deposited over several years, a situation which is similar to that of samples from marine sequences. This continental pollen database has, however, been slightly modified for this aproach. Since *Pinus* pollen is over-represented in marine sediments (Heusser and Balsam 1977; Turon 1984), this pollen type has been removed from the marine

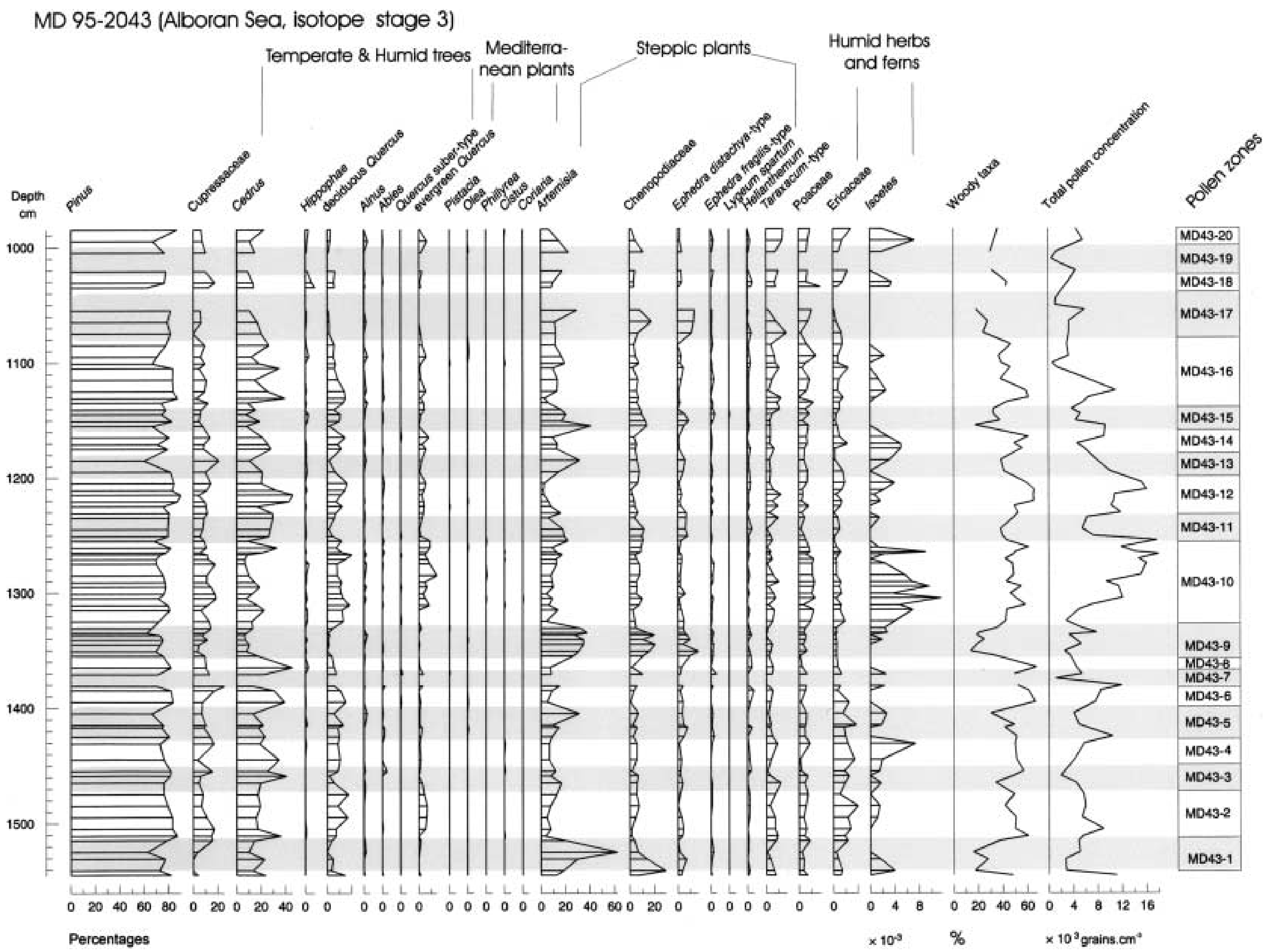

Fig. 2 Pollen percentage diagram with selected taxa, woody taxa percentage curve and total pollen concentration curve from the last glacial section of marine core MD95-2043 plotted against depth

pollen counting as well as from the continental pollen database. The application of transfer functions to marine pollen records in the future needs to be improved by preferentially using modern pollen spectra representative of several years of pollen rain and regional vegetation.

Two climatic parameters, the annual precipitation (Pann) and the mean temperature of the coldest month (MTCO), have been estimated on the basis of the five closest modern terrestrial analogs to our fossil marine pollen samples from core MD95-2043 (Fig. 3). This transfer function has also been applied to the pollen spectra from core MD95-2042. Since potential errors would be similar for the two marine sections being compared, we consider that this approach is still valid for the analysis of past climatic gradients between the two studied areas and also for comparing their relationships with present day environmental conditions.

3.3 Paleoceanographic proxies and chronological framework

Isotopic measurements, alkenone analysis and planktonic foraminifer counting, as well as the chronological framework, have already been presented and discussed by Cacho and collaborators (Cacho et al. 1999, 2000). Using two different age models it was previously demonstrated that a strong link ($r = 0.92$) exists between the D–O climatic variability over Greenland and the SST variability in the Alboran Sea (Cacho et al. 1999). The age model used in the present work is the second one presented by Cacho et al. (1999) which, for the time interval addressed here, is based on graphic correlation between the SST sequence from core MD95-2043 and the ice $\delta^{18}O$ record from the GISP2 core. According to this age model the section presented in this study, from 1545 to 985 cm depth, covers an interval of 20,000 years, between 47,000

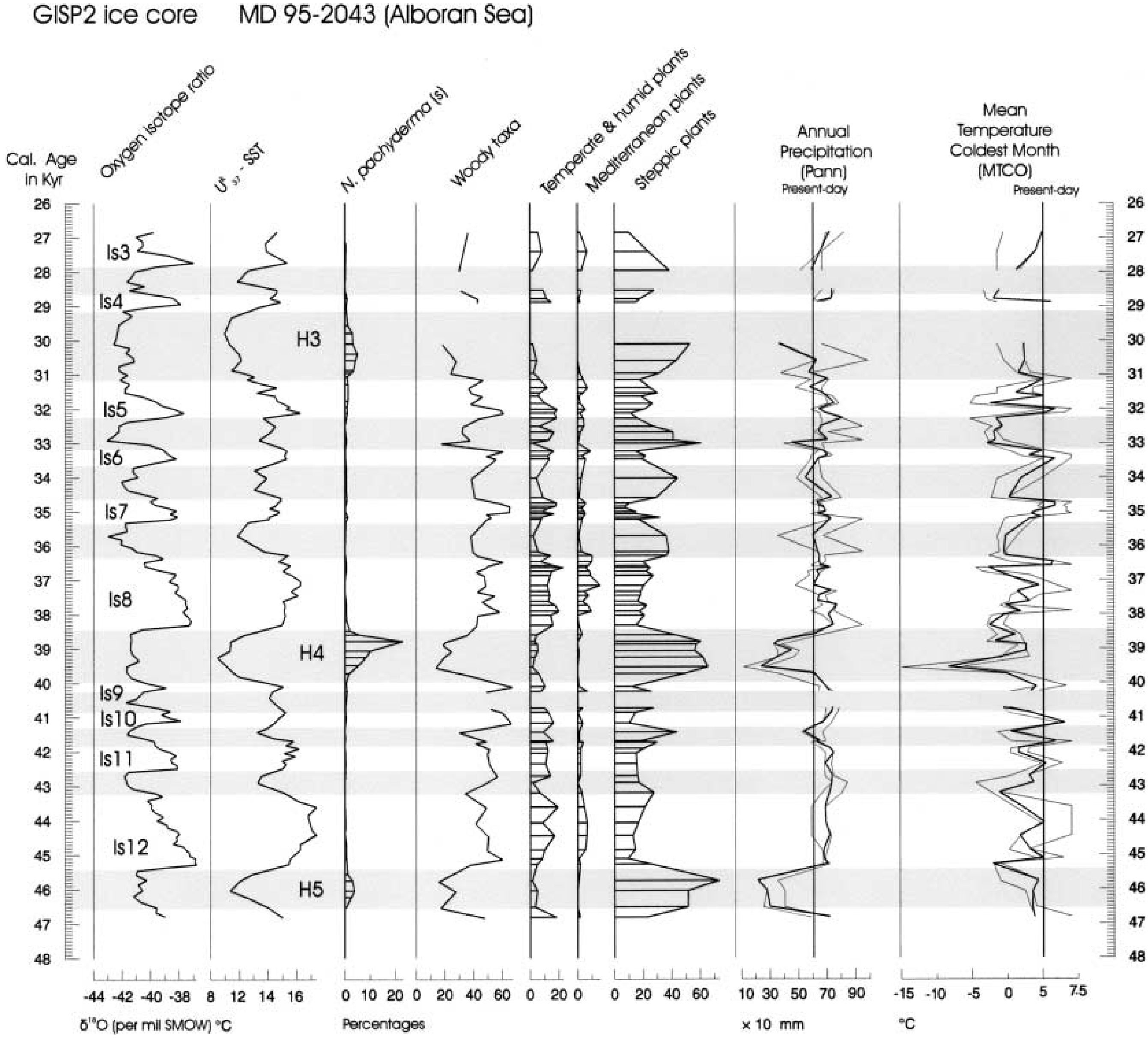

Fig. 3 Comparison between oxygen isotope ratio sequences in the GISP2 ice core, Alboran alkenone-SST and *N. pachyderma* percentage curves with the synthetic pollen diagram from the last glacial section (47,000–27,000 cal years BP) of core MD95-2043. On the *right*, estimated values for the mean temperature of the coldest month (MTCO) and for annual precipitation (Pann) in southeastern Iberia. *Thin solid lines* indicate the lower and upper errors for each MTCO and Pann estimate. *Grey intervals* indicate Heinrich events and the other Dansgaard–Oeschger stadials

and 27,000 cal years BP. We consider this chronological framework sufficient to compare our data with other paleoclimatological-paleoceanographical series; however, any interpretation is done in terms of relative timing rather than absolute correlation with those sequences. All discussion about synchroneity of different proxies is based on measurements carried out in the same sediment core, and with the same sampling interval and is therefore, effectively independent of the age model.

4 Results and discussion

4.1 Rapid vegetation shifts in southeastern Iberia during the Last Glacial period

The pollen diagram (Fig. 2) shows a succession of two types of pollen zones. Pollen zones with odd numbers, MD43-1 to MD43-19, are characterised by the dominance of steppic plants such as *Artemisia*, Chenopodiaceae and *Ephedra*. Relatively high values of deciduous and evergreen *Quercus*, associated with a reduction of steppes, characterises even-numered pollen zones, MD43-2 to MD43-20. Samples taken at 1375, 1051, 1045, 1015 and 1011 cm exhibit very low pollen concentrations and the diagram record, therefore, includes three pollen hiatuses. According to the present climatological system of the area (see Sect. 2.2) the main source for the pollen grains are fluvial discharges from the southern Iberian margin. Nevertheless, changes in the means of pollen transport may be expected to have occurred in accordance with past climatic variability. Sedimentological and geochemical analyses carried out in the same core section suggest that fluvial transport was the main source of detrital particles during the most studied interval (Moreno et al. submitted). Eolian transport increased during some short intervals but the non-parallelism between the different proxies of eolian transport and the pollen profiles supports our assumption that this Alboran pollen record mainly reflects changes in the vegetation cover from the south of the Iberian peninsula.

The alternation between the two types of vegetation, steppe and Mediterranean forest biomes, corresponds to the occurrence of twenty different climatic phases (Fig. 3). The time involved in these vegetation changes was relatively short, as already shown by the Lago di Monticchio pollen record (Allen et al. 1999). The absolute changes of 20% in total pollen of woody taxa, excluding *Pinus*, between forest and steppe intervals lasted for around 150 years (Figs. 2, 3). Comparison of these results with the few other pollen sequences from the Mediterranean region is problematic. Some sequences have lower resolution than our cores (e.g. Padul, Ioannina and the Tyrrhenian sequence KET 8003). Other sequences are fragmentary for the period studied here (e.g. Valle di Castiglione). Still others have a pollen signal with a probably more local character, masking regional vegetation changes following climatic shifts (e.g. Vico and Lagaccione). As a consequence, only a few climatic oscillations are recorded in these sequences between 50,000 and 30,000 years BP (Sánchez Goñi et al. 2000).

The vegetation intervals recorded in the Alboran core perfectly parallel the D–O warm and cold phases previously identified in the SST curve from the same core (Fig. 3). Therefore, our pollen record indicates the occurrence of a mild and wet climate during the D–O interstadials while dry and cold conditions were dominant during the D–O stadials. The onset and termination of each vegetation phase in southeastern Iberia is synchronous with the coeval SST oscillation in the Alboran Sea as recorded by pollen and alkenones in the same core. This observation indicates that, in this geographical domain, there existed a perfect coupling between the terrestrial and marine conditions, at least to the time resolution of our sampling (~200 years).

Three major events stand out from the steppic plants pollen record (Fig. 3). They correspond to the cold Mediterranean events which are the equivalent of HEs 3, 4 and 5, indicating that these were the driest and coldest intervals that occurred during the period studied. Pollen-based estimates of paleoprecipitation confirm that HEs were the driest intervals in the section studied, with annual rainfall values under 400 mm, dropping sometimes to only 200 mm per year. In contrast, the D–O stadials events do not show such decreases in annual precipitation and the results indicate that annual rainfall values (~600 mm) were relatively constant through these D–O oscillations, and close to those of the present-day.

The MTCO curve records low temperatures during the HEs, indicating values of –2 °C for H5 and reaching minimum values during HE 4 (–8 °C). Such severe HE 4-cooling contrasts with those recorded during the other D–O stadials, when the MTCO curve only drops to values around 0 °C. These results indicate that the MTCOs in southern Iberia during D–O stadials were about 5–13 °C colder than at the present day, which are close to the MTCO estimates for southern Italy, ~12 °C less than today (Allen et al. 1999). During the interstadials, the MTCOs were generally over 0 °C and similar to those at the present-day (~5 °C). Our pollen reconstructions suggest that the precipitation regime in southeastern Iberia was less responsive than winter temperatures to the D–O variability of the Last Glacial Period.

4.2 Mechanisms responsible for the D–O climatic variability in marine and terrestrial environments

In the previous study of the SST record from this core, it was concluded that the entrance of a cold polar water mass through the Strait of Gibraltar was the main factor responsible for the amplification of the HEs, while a rapid intensification of the Northern Hemisphere winds could account for the coolings of the other D–O stadials (Cacho et al. 1999). The present pollen results suggest the parallel operation of an additional atmospheric mechanism, which would control the temperature and precipitation conditions over southeastern Iberia during HEs and D–O stadials.

The North Atlantic Oscillation (NAO) dominates the present-day wintertime temperature and precipitation patterns across the North Atlantic Ocean and surrounding continents. The NAO index is calculated as the pressure difference between the Icelandic low and the Azores high (Hurrel 1995; Barlow et al. 1997), and it has been recently demonstrated that North Atlantic sea surface temperatures tend to re-inforce the thermal and geopotential structure of this index (Rodwell et al. 1999). Instrumental records of the NAO can only report interannual to decadal climatic variability through the last century. Recent studies of Greenland ice records suggest that the NAO controlled past decadal-scale variability, at least during the last 2000 years (Barlow 1993). If the NAO was also operating in glacial periods as the Atlantic climatic controller, the millennial scale precipitation and temperature changes inferred from the pollen record could be related to this pressure anomaly. At the present-day, low NAO indices are related to higher atmospheric moisture in western Iberia, coeval with warm temperatures over Greenland (Hurrel 1995; Rodó et al. 1997). High NAO values are in turn associated with Iberian dryness and cold temperatures over Greenland. During the HEs, the northward heat transport through the North Atlantic Ocean may have been drastically reduced by a slow down of the thermohaline circulation. Such conditions would increase the meridional gradient, reinforcing high values of the NAO index. Therefore, the extremely arid and cold conditions recorded in the western Mediterranean region contemporaneous with low temperatures over Greenland during the HEs, especially HE 4, may be the consequence of a rapid and prolonged rise in the NAO index. In this situation the intensity of the northwesterlies would have increased (Hurrel 1995) and this scenario would also explain the enhanced flow of cold and dry winds over the northwestern Mediterranean Sea (Gulf of Lions) during the HEs. This, in turn, would enhance deep water ventilation of the western Mediterranean basin (Turon and Londeix 1988; Cacho et al. 2000). If this NAO index operates during HEs, we would expect a climatic asymmetry between the Mediterranean and the eastern United States and, therefore, an increase of precipitation in the western Atlantic region during HEs (Hurrel 1995). The pollen record from Tulane lake in Florida confirms this, indicating that HEs were characterised by a moisture-adapted vegetation (Grimm et al. 1993). Changes in the NAO intensity could therefore explain the difference in meteorological and oceanographic scenarios between interstadials and HEs as recorded in the Alboran Sea. However, the differences between stadials related to HEs and those not related to HEs remain unexplained.

4.3 Contrast between HEs and the other D–O stadials

Both SST and pollen records from the Alboran Sea show an amplified cold and arid signal for the HEs, in contrast with most of the other D–O stadials. This feature is in disagreement with the corresponding atmospheric coolings recorded over Greenland, where all the D–O stadials show comparable low temperatures to each other. It is also interesting to note that a recent study showing a high resolution alkenone-derived SST profile from a western Atlantic core, located at almost the same latitude as MD95-2043, does not show such amplified coolings for the HEs (Sachs and Lehman 1999). The propagation mechanism therefore appears not to have had an homogeneous latitudinal effect.

Differences between these two types of cold interval are better analysed by the comparison of our Mediterranean pollen record with another record of similar resolution from the Atlantic side of Iberia, core MD95-2042 (Sánchez Goñi et al. 2000) (Fig. 4). Such comparisons allow us to analyse the climatic contrasts between the Atlantic and Mediterranean sides of south Iberia in relation to D–O type climatic variability. Occurrences of the HEs are well documented in this Atlantic core by the high abundances of the polar planktic foraminifer *N. pachyderma* (s) and in addition, by the presence of both IRD peaks and peaks in the magnetic susceptibility curve (Sánchez Goñi et al. 2000). Shackleton et al. (2000) recently developed a high-resolution GRIP (GISP)-based time scale for stage 3 in this core by assuming that the rapid warming events recorded in core MD95-2042 are synchronous with those observed in Greenland.

All the cold intervals in the Atlantic record are well represented by the presence of steppe vegetation pollen in agreement with the Alboran core record (Fig. 4). The transfer function applied to this Atlantic pollen dataset also shows a strong decrease in annual precipitation and in MTCO during HEs. Annual rainfall was around 400 mm and MTCOs were colder than –1 °C, reaching their lowest values (–6 °C) during HE 5. Thus, the reduction of precipitation and winter temperatures during HEs on the Atlantic side of Iberia were of similar amplitude to those recorded on the Mediterranean side of Iberia. In contrast, during the other stadials the MTCO and the annual rainfall reductions were larger on the Atlantic than on the Mediterranean site, with similar amplitudes (5–12 °C and 300 mm) to those of the HEs. This feature strongly supports the hypothesis that climatic conditions during the stadials related to HEs were different to those during the other stadials.

Recent research on present climatic variability has highlighted the role of Mobile Polar Highs (MPHs) as control mechanisms of climatic conditions at high and medium latitudes, and it is also proposed that they controlled past climatic changes (Leroux 1993). The MPHs are defined as large lenses of cold air in the lower levels of the troposphere, which work as the intrahemispheric transfer mechanism between polar and temperate latitudes (Leroux 1993, 1996). These lenses are the result of a downward air motion over polar regions caused by a negative energy balance at the surface. Two different MPHs can affect the climate over our area studied: the Atlantic MPH and the Scandinavian MPH. During severe cold intervals, a substantial development of the Scandinavian MPH would have occurred and could have blocked the southeastward displacement of the Atlantic MPH (Leroux 1996). This situation permits Scandinavian cold and dry winds to reach Iberia, while blocking the influence of the moister Atlantic MPH. A switch between the influence of these two different MPHs would explain the differences observed between the HEs and the other stadials. The Scandinavian MPH could be dominant during HEs, driving the extreme arid and cold conditions in both areas, while during the other stadials the Atlantic MPH may be dominant. Dominance of the Atlantic MPH would preferentially affect the Atlantic side rather than the Mediterranean one, producing more intense cooling and dryness in Southwestern Iberia.

4.4 Gradients between the Atlantic and Mediterranean sides of Iberia

Precipitation and MTCO gradients between the Atlantic and Mediterranean sides of Iberia were not constant

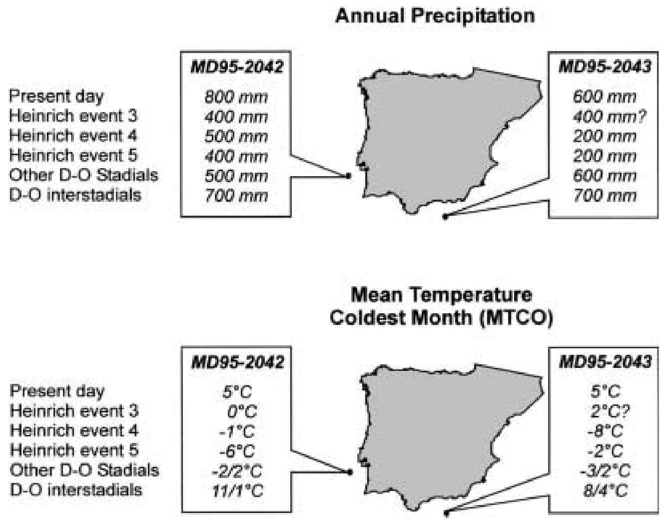

Fig. 5 Annual precipitation and winter temperature gradients between the western and eastern part of Iberia. *Question mark* next to Pann and MTCO estimates for HE 3 in southeastern Iberia indicates the lack of a continuous pollen record for this interval in core MD95-2043

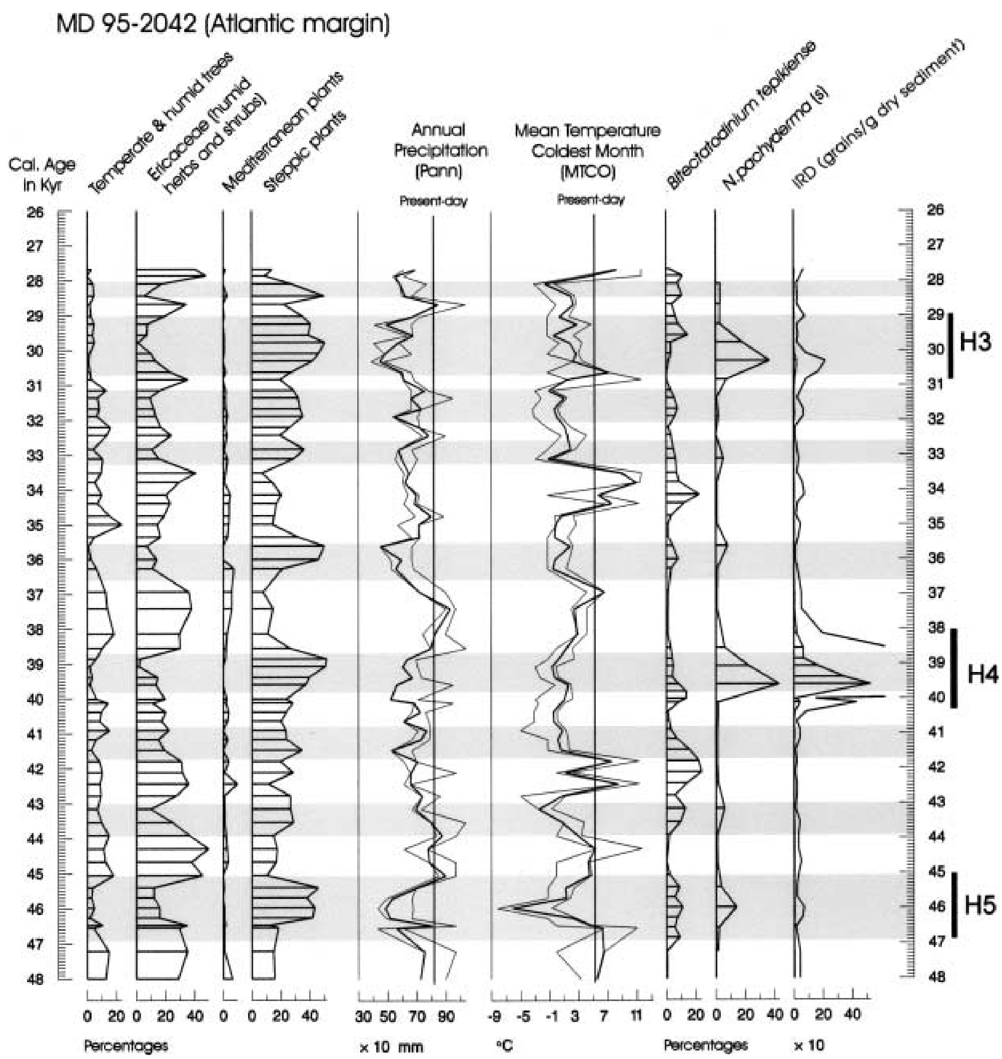

Fig. 4 Comparison between the synthetic pollen diagram from the last glacial section of the Atlantic core MD95-2042, *N. pachyderma* abundance, and the cold dinocyst *B. tepikiense* percentage curves along with the IRD concentration curve in the same core. In the *centre*, estimated values for the mean temperature of the coldest month (MTCO) and for the annual precipitation (Pann) in southwestern Iberia. *Thin solid lines* indicate the mean of the lower and upper errors for each MTCO and Pann estimate. *Grey intervals* indicate Heinrich events and the other Dansgaard–Oeschger stadials

during the different studied climatic intervals (Fig. 5). MTCO gradients changed even between the different HEs. While MTCOs during HE 3 were quite similar at the two sites studied (although this interval is not fully represented in the Mediterranean pollen record), during H4 the Mediterranean was considerably colder and, in contrast, during HE 5 the Atlantic was the coldest site (Fig. 5). These changes in thermal gradients between the different HEs may suggest a different mode of operation and/or intensity of the Scandinavian MPH. However, it cannot be completely ruled out that these different gradients are artefacts derived from a failure of the transfer function to estimate absolute temperatures from fossil steppe assemblages (Sect. 3.2). The precipitation gradients were in contrast more constant, with HEs 4 and 5 showing more humid conditions in the Atlantic (by 200 mm) than in the Mediterranean site.

Rainfall gradients recorded during the HEs were similar to those of the present interglacial (Pagney 1976). Iberian rainfall records for the last few decades divide the peninsula into two different regions according to contrasting precipitation patterns (Rodó et al. 1997). Precipitation in the southwestern part of Iberia is controlled by the NAO index, while the northeastern region shows a stronger relationship with the El Niño-Southern Oscillation (ENSO) (Rodó et al. 1997). This feature produces a precipitation gradient between the east and west of Iberia. The precipitation gradient recorded during the HEs suggests that these two climatic systems may also have operated during these intervals.

D–O interstadials in both Atlantic and Alboran records are marked by an increase in the percentages of temperate and Mediterranean plants but, in addition, the Atlantic core is associated with an increase in Ericaceae percentages, attributable to the acid soils of the western part of Iberia. MTCO estimates for the D–O interstadials (1–11 °C) on the Atlantic side were similar to those for the Alboran side (4–8 °C) and were close to the MTCO present values (~5 °C). The Pann gradient between the two sides was strongly reduced in interstadials compared with the HE intervals, reaching values of around 700 mm on both sides. One possible explanation is that the estimates of precipitation by the transfer function used in this work cannot detect small differences in levels of annual rainfall during intermediate situations such as D–O interstadials.

Finally, a focus on the Mediterranean and Atlantic proxy climatic records (Fig. 6) shows that the maximum development of steppic plants occurs at the onset of HE 4 in parallel with low percentages of *N. pachyderma* (s) and increases in the abundance of the cold dinocyst *B. tepikiense* (work in progress). In contrast, in the Atlantic core the maximum in steppic plant percentages is reached in the second part of HE 4, coexisting with low *N. pachyderma* (s) and *B. tepikiense* percentages. These data would suggest a difference in timing of the responses to the HE 4 event of terrestrial and marine organisms between the Atlantic and Mediterranean regions of southern Iberia.

5 Conclusions

The combined analyses of pollen and SST records from the IMAGES core MD95-2043 have shown the

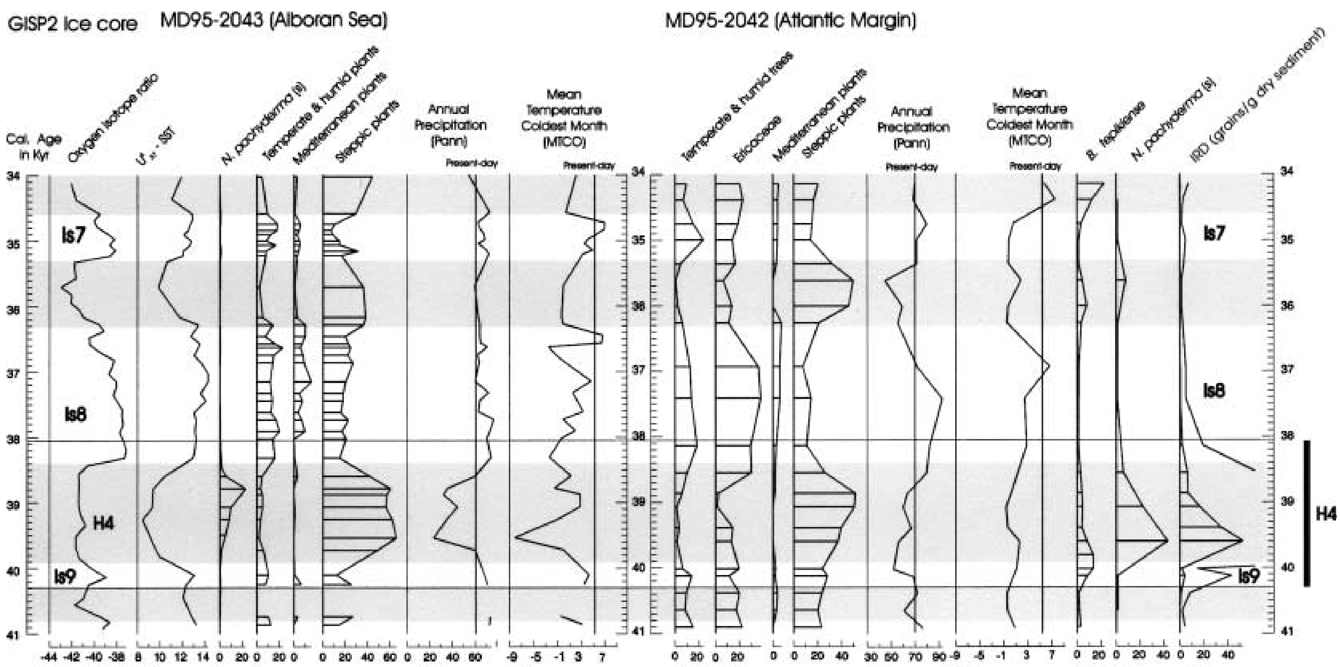

Fig. 6 Detail of HE 4 from core MD95-2043 and its comparison with the same section of core MD95-2042. *Grey bars* indicate cold intervals, the HE 4 and the previous and following Dansgaard–Oeschger stadials

synchroneity in the response of Mediterranean terrestrial and marine domains to the D–O type climatic changes. These shifts were rapid, confirming that significant changes in vegetation and sea surface conditions occurred within about 150 years.

Pollen records show an alternation between dry and cold conditions during the D–O stadials and humid and mild conditions during the D–O interstadials. HEs were associated with the dryest (annual rainfall decreases of around 400 mm) and coldest (between 6–13 °C winter temperature drops) intervals while most of the other D–O stadials were not associated with significant drops in the humidity and temperature of south Iberia. This amplification of the climatic signal on land during the HEs is in agreement with the Alboran SST record, indicating a parallel operation of both oceanographic and atmospheric processes. An interstadial-HE switch from relatively low to high NAO indexes is tentatively proposed here as the driving force for the HE precipitation and temperature anomalies.

A close comparison of the pollen record from the Alboran Sea with one from off Portugal (MD95-2042) shows that, as is the case at the present-day, the precipitation gradient is recorded between the Atlantic and Mediterranean sites during the HEs. Furthermore, this comparison clearly illustrates the different behaviour of these areas during the D–O stadials. In contrast with the Mediterranean site, the Atlantic site shows similar precipitation and temperature drops for all the D–O stadials, including those related to the HEs. This may be linked to a different dynamic of the MPH associated with these different types of cold interval. HEs are related to a stronger influence of the Scandinavian MPH, driving a severe aridification and cooling of Iberia. On another hand, the Atlantic MPH may have been dominant during the other stadials, preferentially affecting southwestern Iberia.

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