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# Abrupt climate changes of the last deglaciation detected in a western Mediterranean forest record

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## Abstract

Evidence for abrupt changes in western Mediterranean climate between 20 and 6 cal ka BP is examined in marine core MD95-2043 (Alborán Sea), using pollen data for temperate Mediterranean forest development and pollen-based climate reconstructions using the modern analogue technique (MAT) for annual precipitation ($P_{ann}$) and mean temperatures of the coldest and warmest months (MTCO and MTWA). Major climatic shifts with parallel temperature and precipitation changes occurred at the onsets of Heinrich Event 1 (equivalent to the Oldest Dryas), the Bölling-Allerød (BA), and the Younger Dryas (YD). Multi-centennial-scale oscillations in forest development related to regional precipitation ($P_{ann}$) variability occurred throughout the BA, YD, and early Holocene, with drier atmospheric conditions in phase with Lateglacial events of high-latitude cooling including GI-1d (Older Dryas), GI-1b (Intra-Allerød Cold Period) and GS-1 (YD), and during Holocene events associated with high-latitude cooling, meltwater pulses and N. Atlantic ice-rafting (events at 11.4, 10.1, 9.3, 8.2 and 7.4 cal ka BP). The forest record also indicates multi-centennial variability within the YD interval and multiple Preboreal climate oscillations. A possible climatic mechanism for the recurrence of dry intervals and an opposed regional precipitation pattern with respect to western-central Europe relates to the dynamics of the jet stream and the prevalence of atmospheric blocking highs. Comparison of radiocarbon and ice-core ages for well-defined climatic transitions in the forest record suggests possible enhancement of marine reservoir ages in the Alborán Sea by ~200 years (surface water age ~600 years) during the Lateglacial.

## 1 Introduction

Numerous palaeoclimate records from Greenland ice cores, N. Atlantic marine sequences and northern European terrestrial sequences indicate that the last glacial-interglacial transition was punctuated in the N. Atlantic region by abrupt (millennial- and centennial-scale) climate changes (e.g. NGRIP members, 2004; Björck et al., 1996; Dansgaard et al., 1993; Lehman and Keigwin, 1992; Bard et al., 1987). While questions remain about the ultimate role of internal climate variability, solar activity, volcanism and other forcings in the origin of these climatic oscillations, several lines of evidence including geological and modelling studies point to disruption of the oceanic thermohaline circulation (THC) by punctuated meltwater discharge as a mechanism for abrupt cooling of the North Atlantic region (e.g. Flesche Kleiven et al., 2008; Renssen et al., 2007; Donnelly et al., 2005; Nesje et al., 2004; Teller et al., 2002; Clark et al., 2001).

In order to improve our understanding of the wider impacts of perturbation of the North Atlantic climate and the mechanisms underlying the transmission of climatic changes, high-resolution palaeoclimate records are required from beyond the North Atlantic region. In this respect, the Mediterranean is a key region, being characterised by close atmospheric and oceanic linkages to the North Atlantic region but also by a distinct climatic regime and teleconnections to distant climate patterns including the African and Asian monsoons (Lionello et al., 2006). Variability of the western Mediterranean climate on millennial and shorter timescales since the end of the last glacial period remains poorly understood, as few continuous palaeoclimate records are currently available with sufficient resolution and/or chronological control to permit the identification of discrete sub-millennial events. As such, outstanding questions remain regarding the timing, nature and mechanisms of abrupt climate changes in the western Mediterranean region.

In this study we present evidence for multi-centennial-scale fluctuations in temperate forest development and reconstructed climatic parameters (annual precipitation, winter and summer mean temperatures) during the last deglaciation period, i.e. 20 to 6 thousand calendar years before present (cal ka BP), from a marine sediment core from the western Mediterranean basin. High sedimentation rates during the last deglaciation provide an opportunity to study at high temporal resolution climatic changes in the western Mediterranean region associated with events of meltwater discharges and perturbation of the North Atlantic circulation.

## 2 Study region

The Alborán Sea is the westernmost basin of the Mediterranean Sea, located between SE Iberia and N Africa (Fig. 1). The lands bordering the Alborán Sea are dominated by the mountains of the Baetic-Rifan zone, reaching over 2400 m in the Rif (Morocco) and 3400 m in the Sierra Nevada (Spain). The regional climate is Mediterranean with hot, dry summers governed by the strength of the Azores anticyclone and mild, humid winters influenced by mid-latitude atmospheric circulation patterns and the latitudinal position of North Atlantic storm tracks (Lionello et al., 2006). Altitudinal contrasts yield a wide range of regional thermal conditions (thermomediterranean to cryomediterranean), with mean temperature of the warmest month (MTWA) between 20°C (high altitudes) and 25°C (low altitudes), and mean temperature of the coldest month (MTCO) between 2°C and 12°C (Arévalo Barroso, 1992). Regional precipitation patterns are strongly influenced by the westerly origin of Atlantic moisture and the orographic complexity of the neighbouring landmasses, with annual precipitation ($P_{ann}$) values ranging from >1400 mm/yr in the western Baetic-Rifan highlands to <400 mm/yr in the semi-desert lowlands of the eastern basin. Predominant wind directions are northwesterly during winter, with southerly and southwesterly winds occurring during summer associated with weakening of the westerlies.

Although strongly altered by anthropic pressure, the natural forest vegetation of the Alborán borderlands is dominated by oaks (*Quercus* spp.), with sclerophyllous shrublands and evergreen oak formations at low altitudes (up to ~1200 m), and mixed evergreen/deciduous and deciduous oak forest formations at mid-altitudes (~1200–1800 m) (Quezel, 2002; Benabid, 2000; Peinado Lorca and Rivas-Martinez, 1987). At higher altitudes, coniferous vegetation (with *Juniperus*, *Pinus*, *Abies* and *Cedrus*) develops, giving way to xerophytic shrublands and pasturelands at the highest altitudes. Dry areas with $P_{ann}$<250 mm/yr are dominated by semi-desert steppe vegetation.

## 3 Data and methods

Core MD95-2043 (36°9′ N, 2°37′ W, 1841 m water depth) was recovered in the Alborán Sea (western Mediterranean), and is characterised by continuous deposition of hemipelagic muds, and by high sedimentation rates throughout the deglaciation period (Cacho et al., 1999) (Fig. 2). The age-model for core MD95-2043 for the deglaciation period is based on 13 AMS radiocarbon dates on monospecific foraminiferal samples previously published in Cacho et al. (1999). In this study, radiocarbon dates have been calibrated using the Marine04 calibration curve (Hughen et al., 2004), which incorporates a standard marine reservoir correction of ~400 years (Table 1).

Pollen data for the deglaciation section of the core was obtained employing standard methods of pollen extraction, identification and counts reported in Fletcher and Sanchez Goñi (2008). Due to long-term changes in sedimentation rate (Fig. 2) sampling at 5 cm intervals provides an average temporal resolution of 110 years for the period 6 to 20 cal ka BP, and 70 years for the period 9 to 15 cal ka BP. In this paper, we focus on the pollen percentage record of temperate Mediterranean forest (TMF), a summary category which groups all pollen types typical of the thermomediterranean to supramediterranean altitudinal forests, namely *Acer*, *Alnus*, *Betula*, *Corylus*, *Fraxinus excelsior* type, *Populus*, *Taxus*, *Ulmus*, *Quercus* deciduous type, *Quercus* evergreen type, *Quercus suber* type, *Cistus*, *Coriaria myrtifolia*, *Olea*, *Phillyrea*, and *Pistacia*. Of these constituent taxa, oaks (*Quercus* spp.) are the dominant component, representing ~90% of the TMF pollen. Other components of the pollen spectra include herbaceous taxa of predominantly open ground habitats (e.g. Poaceae, Asteraceae types), shrubby taxa of semi-desert (*Artemisia*, Chenopodiaceae, *Ephedra*) and forest-steppe (Cupressaceae) environments, and montane coniferous taxa (*Abies*, *Cedrus*).The percentages of TMF pollen for the core section 175–835 cm covering the last deglaciation are shown in Fig. 3.

In order to derive quantitative estimates of past precipitation and temperature changes, a climate reconstruction based on the full pollen data-set was performed using the modern analogue technique (MAT) (Guiot, 1990; Peyron et al., 1998). The MAT reconstructions were based on the 10 closest analogues from an expanded database of modern pollen spectra ($n$=3530) from Europe, Asia and northern Africa (Bordon and Peyron, unpublished data). The database includes, importantly, more extensive coverage of the Mediterranean region than an earlier database ($n$=1487) used for previously published reconstructions for Marine Isotope Stage 3 on core MD95-2043 (Sanchez Goñi et al., 2002). Due to the overrepresentation of *Pinus* pollen in marine pollen assemblages, *Pinus* is excluded from both the fossil and database samples, following the practise employed in a number of recent reconstructions performed on marine pollen samples (Kotthoff et al., 2008; Desprat et al., 2005; Sanchez Goñi et al., 2002).

# 4 Results

## 4.1 Variability in temperate Mediterranean forest

The temperate Mediterranean forest (TMF) pollen curve (Figures 3 and 4) reveals a long-term recovery of forest populations across the last glacial-interglacial transition, with minimum values (<10%) during the HE1 interval (as defined on the basis of marine climatic tracers in the same core (Cacho et al., 1999, 2006)), intermediate values (15–50%) during the Lateglacial and Preboreal (prior to 10.6 cal ka BP), and high values (>50%) during the subsequent early Holocene. Following the expansion of forest populations at the end of HE1, discrete intervals of reduced forest development are detected (in all cases by the values of at least two samples) throughout the Lateglacial and early Holocene, centred on 14.0, 13.3, 12.9, 12.4, 11.8, 11.4, 11.1, 10.7, 10.1, 9.2, 8.3, 7.4, and 6.9 cal ka BP (Fig. 4). Decreased abundance of TMF pollen types at the expense of other vegetation components in the MD95-2043 record suggests forest decline in response to dry and/or cold atmospheric conditions.

### 4.2 Comparison with Alborán SSTs

Comparison of the TMF and alkenone SST records from core MD95-2043 (Fig. 3) reveals that variability on long-term to millennial timescales during the deglaciation is in phase between the two records. Both trace a Lateglacial interstadial-stadial oscillation, and show a progression towards maximum values during the early Holocene around 9.5 cal ka BP. On shorter (multi-centennial) timescales, however, variability in the two records is not always in phase. We note, for example, that marked oscillations in TMF within the BA do not have counterparts in the SST record. Similarly, the Alborán cooling (AC) events defined on the basis of SST anomalies (Cacho et al., 2001) do not have clear counterparts in the TMF record (Fig. 3), apart from AC6, a cold reversal near the end of the YD interval that is clearly marked in both records. The differences suggest either (i) a decoupling, or inconsistent coupling, of atmospheric conditions and western Mediterranean SSTs during abrupt climate events, and/or (ii) different proxy sensitivities to specific climatic parameters and/or seasonal influences. We suggest that differences may relate in part to the sensitivity of the Mediterranean vegetation to changes in moisture availability, and in particular (given the adaptation of the Mediterranean flora to summer dryness) sensitivity to perturbation of the autumn to spring (rainy) season climate.

### 4.3 Pollen-based precipitation and temperature estimates

The results of the MAT climate reconstruction are shown in Fig. 4. As marine pollen assemblages reflect a wide, regional pollen source area (Beaudouin et al., 2007; Naughton et al., 2007; Mudie et al., 2002; Heusser and Balsam, 1977), the quantitative estimates based on the MAT are not considered precise values for a particular location, but rather an integrated estimate of a regional signal for the Alborán basin of the western Mediterranean. For this reason, anomalies in the MAT reconstructions (Table 2) may be more informative than the absolute values for any given sample. Three deglacial events (the onsets of Heinrich Event 1, the BA and the YD) are marked by outstanding anomalies in all three parameters, with cooling (summer and winter) in parallel with drying (onsets HE1, YD), or warming (summer and winter) with increased precipitation (onset BA). The remaining multi-centennial-scale forest declines are consistently associated with reduced precipitation estimates (Table 2, Fig. 4). The MAT technique also provides an estimate of the seasonal distribution of precipitation (not shown). $P_{ann}$ anomalies associated with forest decline events reflect decreases in reconstructed autumn to spring precipitation, and do not reflect changes in summer precipitation, supporting the view that forest declines reflect consistent perturbation of the winter (autumn to spring) climate. In contrast with $P_{ann}$, consistent relationships between episodes of forest decline and MTCO and MTWA anomalies are not detected, with different events either varying in seasonal temperature signature or showing no clear anomaly in association with the event. Eight forest decline events are associated with slight winter warming (MTCO increase), and six (in addition to the onset of the YD) are associated with summer cooling (MTWA).

## 5 Discussion

### 5.1 Abrupt climate changes

#### 5.1.1 Heinrich Event 1

Forest populations were extremely reduced during Heinrich Event 1 (HE1), consistent with the pattern of severe forest declines detected for earlier Heinrich Events (HE5-HE2) (Fletcher and Sanchez Goñi, 2008). The MAT estimates indicate that HE 1 provoked the coldest and driest atmospheric event of the deglaciation period in the western Mediterranean, with negative anomalies in reconstructed climate parameters with respect to preceding full glacial conditions ($\Delta P_{ann}=-170$ mm, $\Delta$MTCO$=-10^{\circ}$C, $\Delta$MTWA$=-3^{\circ}$C). The very severe conditions detected during this interval are coeval with the virtual elimination of meridional overturning in the North Atlantic (McManus et al., 2004), suggesting that reduced northward transport of oceanic heat impacted strongly on warmth and evaporative moisture supply to the western Mediterranean region. The findings reinforce the view that HE1 is the equivalent of the Oldest Dryas in southern European terrestrial pollen sequences (Naughton et al., 2007; Combourieu-Nebout et al., 1998), a period of marked aridity at the end of the last glacial period characterised by the expansion of semi-desert environments in the Mediterranean region (e.g. Drescher-Schneider et al., 2007; Magri, 1999; Pérez-Obiol and Julià, 1994; Pons and Reille, 1988).

### 5.1.2 Glacial-interglacial transition

Rapid forest expansion in phase with SST warming marks the last glacial-interglacial transition (Fig. 3). This forest expansion is observed to have occurred in two stages, identified as an initial inter-sample increase in TMF values from 4 to 15% at 722 cm depth, and a second inter-sample increase from 14 to 30% at 707 cm, corresponding to modelled ages of 15.4 and 14.9 cal ka BP, respectively ($2\sigma$ uncertainty ~ ±0.4 ka). The detection of an interval of initial (relatively weak) forest recovery followed by a second (more substantial and sustained) forest increase reproduces the pattern of oak expansion detected at the southern Iberian site of Padul (pollen zones P3i-P3j ) (Pons and Reille, 1988), confirming the regional validity of this pattern. MAT reconstructions indicate $P_{ann}$, MTCO and MTWA within the range of glacial and HE1 values for the interval following the first forest expansion, and large positive anomalies ($\Delta P_{ann}$=+420 mm, ΔMTCO=+17°C, ΔMTWA=+8°C) for the second forest expansion (Fig. 4).

Within uncertainties in the radiocarbon age model, the initial (minor) forest expansion is synchronous with indications of moderate atmospheric changes prior to the abrupt onset of the Bölling (GI-1) in Greenland ice-core records at 14.7±0.01 ka (Rasmussen et al., 2006). These indications include the increase in warmth and hydrological activity as detected in northern hemisphere speleothem records from Villars and Chauvet caves (southern France), La Mine cave (Tunisia), and Hulu and Dongge caves (China) between 15.5 and 16 ka (Genty et al., 2006; Dykoski et al., 2005; Wang et al., 2001), as well as a slight high-latitude warming trend seen in the Greenland ice-cores preceding GI-1 (NGRIP members, 2004; Grootes et al., 1993; Dansgaard et al., 1993). This interpretation is supported by indications in the marine climate proxies from core MD95-2043 (e.g. planktonic and benthic oxygen isotopes, *N. pachyderma* (s) abundances) of glacial marine conditions extending throughout the period of the initial forest expansion (Cacho et al., 1999, 2006). In this case, the second and larger forest expansion and reconstructed shift in precipitation and temperature may correspond with the abrupt onset of the Bölling as detected in Greenland ice-core records at ~14.7 ka (NGRIP members, 2004; Rasmussen et al., 2006).

Nevertheless, as dating uncertainties for this transition may be increased due to large possible changes in surface water ages (marine reservoir effect) (Waelbroeck et al., 2001), it is possible that the first forest expansion corresponds to the onset of the Bölling. This second possibility would imply very strongly increased surface water ages at the glacial-interglacial transition of up to 1200 yrs (see also Sect. 5.3), and lags between high-latitude warming and Mediterranean environmental and marine responses.

### 5.1.3 Bölling/Allerød

The development of forest populations during the BA suggests sustained wetter and warmer atmospheric conditions compared with the preceding HE1 interval. These conditions were probably contingent upon the resumption of strong meridional overturning in the North Atlantic (McManus et al., 2004). During the BA, two discrete multi-centennial-scale declines in temperate forest populations are detected, centred at 14.0 and 13.3 cal ka BP (Fig. 4). Modern analogues suggest that vegetation changes during these declines were associated with $P_{ann}$ declines of around 70–85 mm/yr (Table 2). These dry events are in phase and, within age uncertainties, contemporary with high-latitude cooling events as detected in the Greenland ice-cores during GI-1d (Older Dryas) and GI-1b (Intra-Allerød Cold Period), and in phase with central European cooling during the Aegelsee and Gerzensee Oscillations (Lotter et al., 1992). The

MD95-2043 evidence for forest declines and dry conditions confirms that these events were expressed not only in the Atlantic climate sector of the Iberian Peninsula (Muñoz Sobrino et al., 2007; van der Knaap and van Leeuwen, 1997) but also in the Mediterranean sector. The pattern of forest declines and precipitation reductions match recent palynological and lake-level evidence from Lago dell'Accesa (Drescher-Schneider et al., 2007; Magny et al., 2006a). The findings suggest an opposed palaeohydrological pattern with central-western Europe, as GI-1d and GI-1b are characterised by higher lake-levels in the Swiss Plateau, Jura mountains and French Pre-Alps (Magny, 2001).

### 5.1.4 Younger Dryas

An abrupt and pronounced forest decline (identified as an inter-sample reduction of ~35% in TMF values) marks the onset of the YD. This crash in temperate forest populations occurred within an age-model period of ~70 years and precedes the minimum in SSTs (Fig. 3) suggesting a rapid vegetation response to dry and cold atmospheric conditions in advance of maximum sea surface cooling. In timing and abrupt nature, the onset of the YD in the forest record is similar to that recorded in the speleothem records at Chauvet and La Mine caves (Genty et al., 2006), suggesting a common response to an abrupt change in atmospheric climatic conditions. Reductions of ~240 mm/yr in $P_{ann}$, 5°C in MTCO and 3°C in MTWA are reconstructed for the onset of the YD. This strong signal, second only to the onset of HE1 in severity, matches well the relative decline in meridional overturning at this time (McManus et al., 2004), suggesting a similar, though weaker, impact of reduced oceanic heat transport on western Mediterranean precipitation and temperatures to HE1.

Following the initial forest decline, a general trend of forest recovery during the YD is observed which parallels the gradual reinvigoration of meridional overturning (McManus et al., 2004) and signals of climatic warming in the speleothem records (Genty et al., 2006). However, the TMF record for the YD also displays a complex internal variability at multi-centennial timescales, with a marked intra-YD interval of forest recovery between 12.2–11.9 cal ka BP. This interval, corresponding to a positive $\Delta P_{ann}$ anomaly of ∼70 mm/yr, is in phase with a local peak in SSTs preceding the AC6 cooling reversal (Cacho et al., 2001, Fig. 3). The timing of the event is consistent with a short-lived warming over the European mainland detected in the Chauvet Cave and Ammersee $\delta^{18}$O records at 12.15 and 12.2 ka, respectively (Genty et al., 2006; von Grafenstein et al., 1999), and may be related to warming events detected in a number of terrestrial lake records (Magny et al., 2006b; Hammarlund et al., 1999). This interval may reflect an episode of moderate reinvigoration of thermohaline circulation inside the YD interval related to changes in meltwater routing from the Canadian ice-sheets with probable widespread northern hemisphere impacts (Carlson et al., 2007). The MD95-2043 record indicates that this interval was expressed in the western Mediterranean region in terms of increased moisture availability for forest development. Precipitation patterns within the YD (GS-1) interval again appear opposed to patterns in mid-European lake-levels, where the early and late stages of the YD are marked by high lake-levels, with a middle phase of lake-level lowering (Magny, 2001; Magny et al., 2006b).

### 5.1.5 Preboreal oscillations

While the onset of the Holocene is marked by forest expansion at 11.7 cal ka BP, the development of temperate Mediterranean forest appears limited during the initial Holocene or Preboreal period (11.7 to 10.6 cal ka BP), perhaps reflecting a restricted rainy season during the boreal summer insolation maximum and/or global impacts of residual northern hemisphere ice-sheets (Tzedakis, 2007). During this period, a series of low-amplitude fluctuations in forest populations are detected, with forest minima centred at 11.4, 11.1 and 10.8 cal ka BP. While these fluctuations are of relatively low amplitude in terms of TMF percentages, $P_{\mathrm{ann}}$ estimates (reflecting compositional changes in the full pollen data-set) show quite marked declines (Table 2) in phase with TMF reductions. In common with several central and northern European records which indicate a more complex pattern of Preboreal oscillations (Bohncke and Hoek, 2007; Magny et al., 2006b; Björck and Wastegård, 1999; Whittington et al., 1996;), our findings indicate that multiple Preboreal climatic oscillations can be detected in the western Mediterranean region, as recently suggested for Lake Accesa in central Italy (Magny et al., 2007). The first of this series of Preboreal dry episodes was coeval with a significant cooling anomaly (11.4 ka event) detected in $\delta^{18}$O and accumulation signals in multiple Greenland ice cores (Rasmussen et al., 2007). The evidence for drier conditions at this time in the MD95-2043 record is again consistent with contrasting precipitation patterns across Europe. Magny et al., (2007) propose a tripartite latitudinal division (dry-wet-dry) in hydrological conditions for the Preboreal Oscillation, for which dryness in the southern sector is supported by our findings.

#### 5.1.6 Early Holocene events

An abrupt increase in forest populations is observed at 10.6 cal ka BP, suggesting a sustained climatic shift towards wetter conditions that is reflected in the $P_{ann}$ estimations (Fig. 4). While forest populations were strongly developed overall during the late phases of the last deglaciation, marked oscillations indicate periodic shifts in prevailing atmospheric conditions. A forest decline centred on 10.1 cal ka BP coincides with cooling in the NGRIP record towards 9.95 ka, although this anomaly is not consistent across different Greenland records (Rasmussen et al., 2007). Cooling at this time may be linked to meltwater discharge associated with the draining of the Baltic ice lake at ~10.3 ka and cooling during the Norwegian "Erdalen" glacier advance (Nesje et al., 2004).

Forest minima centred at 9.2 and 8.4 cal ka BP are in phase, and within age-model uncertainties, contemporaneous with high-latitude cooling events at 9.3 and 8.2 ka detected in $\delta^{18}$O and accumulation signals in multiple Greenland ice cores (Rasmussen et al., 2007) and associated with Lake Agassiz meltwater discharges (Teller et al., 2002). The record confirms the regional environmental impact of the 9.3 and 8.2 ka events on the Iberian landscape, as detected in lake drying phases in southern Spain (Carrión, 2002) and charcoal records from the Ebro basin (Davis and Stevenson, 2007). Further forest declines are detected during the final stages of the last deglaciation, with minima centred at 7.4 and 6.9 cal ka BP, for which reduced precipitation and

MTWA are reconstructed. These declines fall within the interval of meltwater outbursts from the Ungava and Labrador Lakes (Jansson and Kleman, 2004).

MAT reconstructions for the early Holocene declines suggest recurrent reductions in precipitation during the early Holocene forest declines. The sequence of early Holocene forest declines at 10.1, 9.3, 8.2 and 7.4 cal ka BP corresponds closely to peaks in North Atlantic indicators of ice-rafting (hematite stained grains; Bond et al., 1997), indicating a consistent signature of drier conditions in the western Mediterranean during early Holocene N. Atlantic cooling events. The close match between intervals of western Mediterranean forest declines and intervals of mid-European high lake-level intervals (Magny et al., 2007), highlights the continued opposition of precipitation trends between the two geographic sectors.

### 5.2 Regional patterns and a proposed atmospheric mechanism

The MD95-2043 forest records shows that climate of the deglaciation period in the western Mediterranean was characterised by pervasive variability at multi-centennial timescales and evident sensitivity to perturbation of the N. Atlantic climate related to the state of meridional overturning and meltwater impacts. Comparison with the mid-European lake-level records (Magny et al., 2007; Magny, 2001) reveals a consistent opposition of hydrological trends, with dry conditions in the western Mediterranean associated with mid-European high-lake levels during high-latitude and N. Atlantic cooling events (GI-1d, GI-1b, YD (early and late phases), and events at 11.4, 10.1, 9.3, 8.2 and 7.4 ka). This finding extends the pattern proposed for the 8.2 ka and Preboreal Oscillation (11.4 ka event) (Magny et al., 2003, 2007). This climatic opposition also appears more consistent than that detected at Lake Accesa in central Italy (Magny et al., 2006a), suggesting important spatial variability in climatic patterns across different sectors of the Mediterranean basin.

A possible atmospheric mechanism contributing to (a) negative precipitation shifts in the study region during high-latitude cooling events and (b) the opposite precipitation pattern between the study region and central-western Europe relates to the dynamics of the westerly jet stream and the prevalence of "blocking episodes" – an atmospheric situation of predominantly meridional flow with strong slow-moving or stationary anticyclones over the European mid-latitudes (Barry and Chorley, 1998). Blocking episodes are characterised by a branching of the jet stream, promoting significant increases in cyclonic activity and wetter than normal conditions over the western Mediterranean basin and eastern Greenland (Trigo et al., 2004). The contrasting (non-blocking) situation of strong zonal flow is characterised by significant, opposite patterns, i.e. frequent cyclone penetration into northern and central Europe and drier than normal conditions in the western Mediterranean basin and eastern Greenland (Trigo et al., 2004). As individual blocking events can persist for weeks, a small number of blocking episodes can influence the climate characteristics of an entire season (Stein, 2000). Past changes in the prevalence of blocking episodes could explain shifts in western Mediterranean precipitation as well as account for the tripartite latitudinal hydrological zonation illustrated in Magny et al. (2007).

AGCM model simulations of the YD climate have shown that winter cooling and sea-ice formation in the North Atlantic region promotes a stable, strong westerly flow, dramatically reducing the occurrence of blocking highs and promoting the extension of cyclonic activity far into the Eurasian continent (Renssen et al., 1996). In the model, an enhanced westerly jet stream is promoted by the increased surface temperature gradient over the North Atlantic that results from perturbation of the THC and the development of sea-ice cover. Extending these findings to other deglacial cooling events associated with meltwater pulses into the North Atlantic and Arctic Oceans, the following scenario is proposed:

- During deglacial cooling events, thermohaline circulation weakening and sea-ice build-up at high-latitudes of the N. Atlantic (as simulated in Renssen et al., 2007; Wiersma and Renssen, 2006) increased the N. Atlantic surface temperature gradient, leading to jet stream intensification, the extension of cyclonic activity into the European mainland and drier conditions in the western Mediterranean (prevalence of non-blocking situation).

- During warm intervals characterized by weak meltwater perturbation of the THC, reduced sea-ice extent and a reduced temperature gradient contributed to a weaker zonal flow permitting an increased frequency of blocking situations leading to enhanced cyclonic activity and precipitation over the western Mediterranean and dry conditions in western-central Europe (frequent blocking episodes).

The average estimated precipitation anomaly associated with the Lateglacial and early Holocene forest decline events (~65 mm/yr) falls within the range of anomalies related to the difference between blocking and non-blocking episodes in the study region during the period 1958–1997, which is centred around 1 mm/day for the 90-day winter period (Trigo et al., 2004). Moreover, a day-time temperature increase is detected over the Iberian peninsula and Morocco during the non-blocking situation, related to reduced cyclonic activity, clear skies and increased radiative warming (Trigo et al., 2004). This warming effect may account for the (counter-intuitive) weak increases in MTCO detected during several of the forest decline events.

### 5.3 Implications for marine reservoir ages

Abrupt climate changes of the last deglaciation were accompanied by large and geographically variable shifts in the radiocarbon enrichment of surface waters due to changes in oceanic circulation patterns (Waelbroeck et al., 2001; Robinson et al., 2005). These changes have important consequences for radiocarbon chronologies based on the dating of marine organisms. It is known that reservoir ages in the Mediterranean were enhanced during HE1 by up to 400 years (Siani et al., 2001), and decreased towards the onset of the Holocene; however, few data are available to refine this scenario. The detection of abrupt shifts in the Lateglacial MD95-2043 record of temperate Mediterranean forest which can be correlated with high-latitude climate changes provides an opportunity to examine explicitly offsets between the radiocarbon and ice-core chronologies which may relate to changes in marine reservoir effect. Atmospheric climate changes are anticipated to have been virtually synchronous (on the order of 1–3 years) between Greenland and the W Mediterranean due to the abrupt reorganisation of the mid-latitude atmospheric circulation occurring at climate event transitions (Steffensen et al., 2008).

In Fig. 5, MD95-2043 calibrated radiocarbon ages are compared with ages on the GICC05 timescale (Rasmussen et al., 2006) for five major climatic transitions which can be identified by abrupt changes in the TMF record (onsets of the Bölling (GI-1), the Oldest Dryas (GI-1d), the Intra-Allerød Cold Period (GI-1b), the YD (GS-1) and the Holocene). The comparison shows that dates for the five events from the two cores may be identical when uncertainties in both the radiocarbon and ice-core timescales are taken into account. However, if differences between the two sets of dates resulted simply from methodological uncertainties inherent in the construction of the timescales, we would not anticipate a consistent pattern in the offsets between the dates. In fact, a consistent pattern of positive offsets is observed, reflecting the older age estimates on the radiocarbon than GICC05 timescale.

While slight lags may be anticipated in the forest record related to resilience in ecosystem changes, it seems unlikely that the offsets observed at these transitions in core MD95-2043 reflect real leads in environmental responses. The consistent positive offset could, however, be explained by an enhancement of the marine reservoir effect in the western Mediterranean Sea during the Lateglacial period, with surface waters approximately 200 years older than the present day global mean age of ∼400 years. The offsets suggest reservoir ages close to the calculated surface water ages given by the dating of marine organisms within tephra-layers in southern Adriatic marine sediments (Siani et al. (2001), Fig. 5c), supporting this evidence for reduction of reservoir ages from HE1 into the BA. However, our findings also suggest a renewed enhancement of reservoir ages during the Allerød, with a larger offset than at either the onset of the Oldest Dryas (GI-1d) or the Holocene. This pattern is fully consistent with trends detected in a recent synthesis of northern North Atlantic surface water reservoir ages (Cao et al., 2007). This finding is reasonable, as no major change in the Mediterranean circulation pattern occurred and the renewal period of the Mediterranean is 100 years (Cacho et al., 2001; Siani et al., 2001). Overall, the offsets derived from comparison of the pollen and ice-core records support similar trends in reservoir ages between the W. Mediterranean and North Atlantic, and provide a tentative scenario against which to compare future data on temporal and spatial variability in reservoir ages in the Mediterranean.

### 5.4 Limitations

Our findings demonstrate the sensitivity of the Mediterranean forest pollen signal to sub-millennial-scale climate variability and abrupt changes of the last deglaciation period. This sensitive register of climate change may relate to the integration of a vegetation signal from a very large regional source area, "averaging out" local patterns related to the heterogeneous landscapes and micro-climates of the surrounding regions. However, while the marine pollen record provides clear indications of rapid climate variability and suggests that precipitation changes were central to this variability, it cannot elucidate how climate impacts may have varied between different environmental settings (e.g. highlands, lowlands, wetlands), nor how vegetation changes were effected in terms of range and/or altitudinal shifts. These tasks need to be elaborated through the future study of terrestrial sequences with strong chronological control at high-resolution.

Also, modern studies indicate a dominance of fluvial transport to the MD95-2043 core location in the Alborán Sea (Fabrés et al. 2001), and the good correlation between the record of vegetation changes in MD95-2043 and at the southern Iberian site of Padul (Fletcher and Sanchez Goñi, 2008) suggests a certain stability of pollen transport from the Iberian Peninsula over time. Nevertheless, given the difficulty of precise definition of the pollen source area for a marine pollen record, it cannot be excluded that changes in pollen source conditioned by concomitant effects of climatic changes (e.g. shifts in prevailing winds) may contribute to variability in the pollen signal. In the case of the Alborán Sea, further investigation of clay mineralogy for the identification of particulate transport from North African sources (Bout-Roumazeilles et al., 2007) could help constrain knowledge of past shifts in wind direction during multi-centennial-scale events.

## 6 Conclusions

The main findings of this study are:

- Major climatic shifts in the Mediterranean region with pollen-based MAT reconstructions suggesting combined changes in $P_{ann}$, MTCO and MTWA occurred at the onset of HE1 (equivalent to the Oldest Dryas), the onset of the BA, and the onset of the YD. Multi-centennial-scale fluctuations in forest development suggest important variability in regional precipitation ($P_{ann}$) throughout the BA, YD, and early Holocene.
- Forest declines related to drier atmospheric conditions occurred consistently during Lateglacial events of high-latitude cooling including GI-1d (Older Dryas), GI-1b (Intra-Allerød Cold Period) and GS-1 (YD, including multiple events), and during Holocene events associated with high-latitude cooling, meltwater pulses and N. Atlantic ice-rafting (events at 11.4, 10.1, 9.3, 8.2 and 7.4 cal ka BP).
- Dry intervals in the western Mediterranean region coincide with high lake-level (wet) intervals in western-central Europe, confirming a previously identified pattern for the Preboreal Oscillation and 8.2 ka event (Magny et al., 2003, 2007). A possible climatic mechanism explaining the opposed regional precipitation pattern relates to the dynamics of the jet stream and changes in the prevalence of atmospheric blocking highs over European mid-latitudes.
- Although calibrated radiocarbon ages for abrupt forest changes correlated with the onsets of GI-1, GI-1d, GI-1b, GS-1 and the Holocene may be synchronous with ages on the GICC05 timescale within methodological uncertainties, a consistent offset suggests that marine reservoir ages in the Alborán Sea may have been enhanced by ~200 years (surface water age ~600 years) during the Lateglacial.

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**Table 1.** AMS radiocarbon dates from core MD95-2043 (Cacho et al., 1999) used in the deglaciation age model.

| Depth (cm) | Sample type | $^{14}$C age (yr BP) | Error | Calibrated age, 2$\sigma$ (cal yr BP)* | Median probability (cal yr BP) |
|---|---|---|---|---|---|
| 14 | *G. bulloides* | 1980 | ±60 | 1384–1690 | 1538 |
| 54 | *G. bulloides* | 3216 | ±37 | 2897–3162 | 3029 |
| 96 | *G. bulloides* | 4275 | ±41 | 4255–4510 | 4391 |
| 178 | *G. bulloides* | 5652 | ±42 | 5936–6172 | 6056 |
| 238 | *G. bulloides* | 6870 | ±50 | 7276–7479 | 7384 |
| 298 | *N. pachyderma* | 8530 | ±47 | 9010-9301 | 9165 |
| 348 | *G. bulloides* | 9200 | ±60 | 9792–10 176 | 10 009 |
| 418 | *N. pachyderma* | 9970 | ±50 | 10 726–11 115 | 10 944 |
| 487 | *N. pachyderma* | 10 560 | ±60 | 11 406–12 043 | 11 797 |
| 512 | *N. pachyderma* | 10 750 | ±60 | 11 936–12 571 | 12 172 |
| 588 | *N. pachyderma* | 11 590 | ±60 | 12 949–13 205 | 13 088 |
| 595 | *N. pachyderma* | 11 880 | ±80 | 13 172–13 496 | 13 327 |
| 682 | *G. bulloides* | 12 790 | ±90 | 14 068–14 873 | 14 412 |
| 708 | *G. bulloides* | 13 100 | ±90 | 14 493–15 318 | 14 970 |
| 758 | *N. pachyderma* | 14 350 | ±110 | 16 174–17 049 | 16 618 |
| 802 | *N. pachyderma* | 15 440 | ±90 | 18 041–18 637 | 18 334 |
| 858 | *N. pachyderma* | 18 260 | ±120 | 20 649–21 517 | 21 094 |

[*] Converted to calendar ages using the Marine04 calibration curve (Hughen et al., 2004) implemented in CALIB (Stuiver and Reimer, 1993; version 5.02).

**Table 2.** Anomalies in temperate Mediterranean forest (TMF) values and MAT reconstructions associated with MD95-2043 forest decline events, calculated on the basis of changes in the smoothed (3-point moving average) values relative to the preceding interval.

| Forest event (central age estimate ±2$\sigma$, cal ka BP) | $\Delta$TMF (%) | $\Delta P_{ann}$ (mm) | $\Delta$MTCO (°C) | $\Delta$MTWA (°C) |
|---|---:|---:|---:|---:|
| Decline (6.9±0.1) | −3 | −80 | −1 | −2 |
| Decline (7.4±0.1) | −15 | −120 | -1 | -1 |
| Decline (8.3±0.1) | −8 | −20 | −2 | * |
| Decline (9.2±0.1) | −9 | −100 | +2 | −1 |
| Decline (10.1±0.2) | −6 | −45 | +<1 | * |
| Decline (10.7±0.2) | −7 | −70 | +2 | −1 |
| Decline (11.1±0.2) | −1 | −80 | +<1 | * |
| Decline (11.4±0.3) | −4 | −40 | +1 | * |
| Decline (11.8±0.3) | −11 | −10 | +1 | * |
| Decline (12.4±0.3) | −5 | −45 | +1 | * |
| Decline (12.9±0.2) (Onset YD) | −19 | −240 | −5 | −3 |
| Decline (13.3±0.2) | −13 | −85 | +2 | −<1 |
| Decline (14.0±0.3) | −14 | −70 | * | −<1 |
| Decline (Onset HE1) | −4 | −170 | −10 | −3 |

[*] no anomaly clearly associated with this event.

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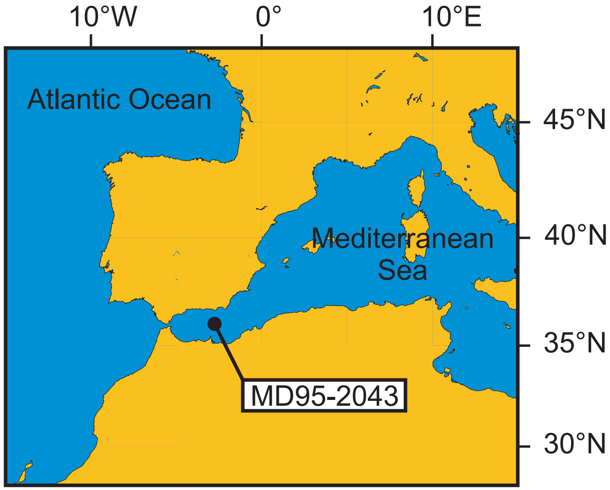

**Fig. 1.** Location of core MD95-2043 in the western Mediterranean Sea.

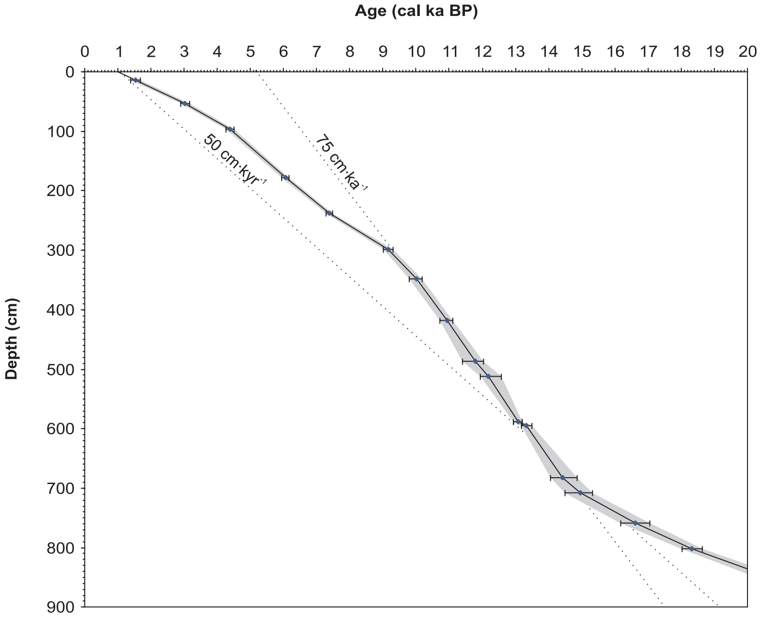

**Fig. 2.** Age-depth profile for core MD95-2043 (last 20 ka) based on calibrated AMS radiocarbon data from Cacho et al. (1999) shown in Table 1, showing the central age estimate and 2$\sigma$ uncertainty intervals. The shaded band highlights the area encompassed by the endpoints of the 2$\sigma$ uncertainty intervals.

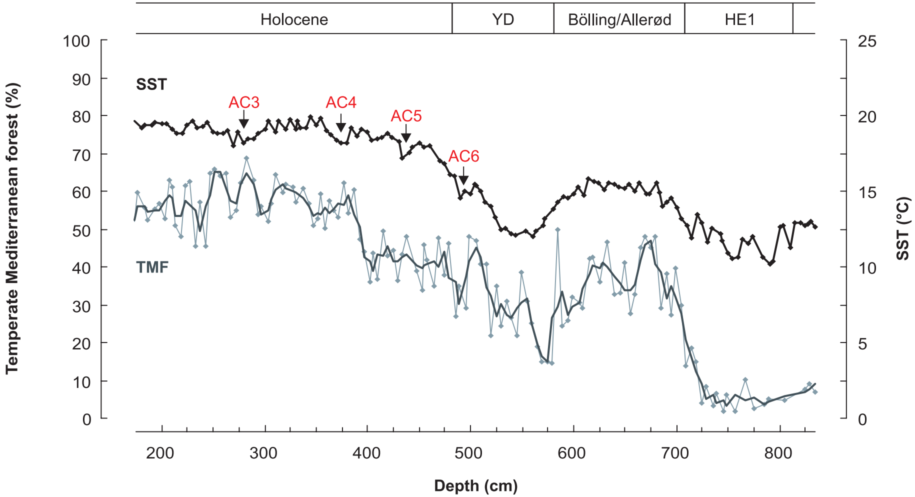

**Fig. 3.** Pollen data and alkenone sea surface temperature (SST) reconstruction from core MD95-2043, plotted against depth; showing pollen percentages for temperate Mediterranean forest (TMF) taxa and 3-point moving average, and the alkenone SST reconstruction of Cacho et al. (1999). Also shown are the positions of Alborán Sea cooling events (AC3-6), defined in Cacho et al. (2001) on the basis of the alkenone SSTs.

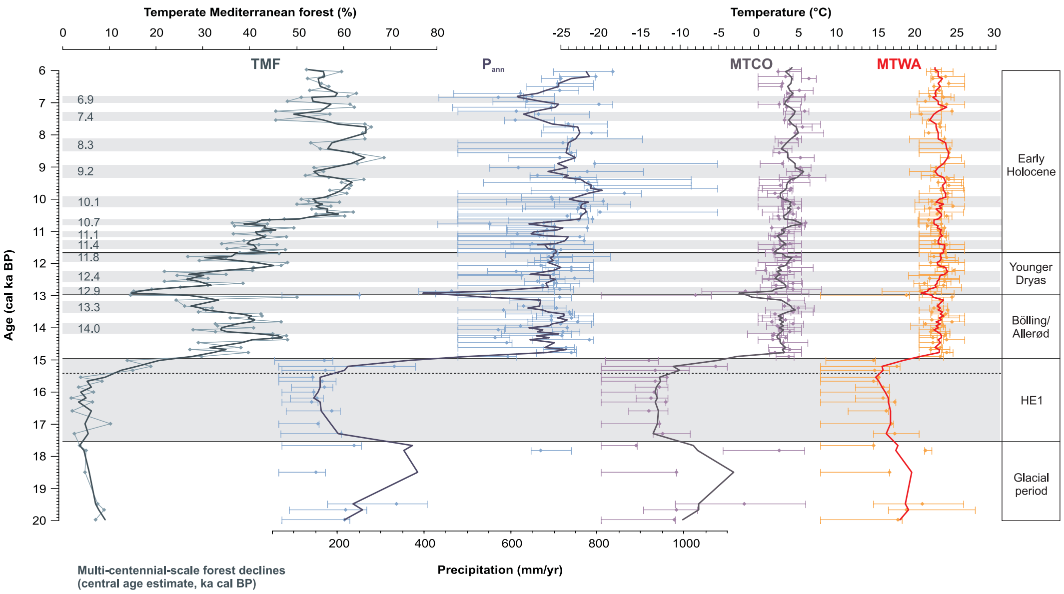

**Fig. 4.** Pollen data and pollen-based modern analogue technique (MAT) climate reconstructions from core MD95-2043; showing pollen percentages for temperate Mediterranean forest (TMF) taxa with 3-point moving average; MAT estimates for annual precipitation ($P_{ann}$), mean temperature of the coldest month (MTCO), and mean temperature of the warmest month (MTWA). MAT reconstructions show the central estimate for each sample with error range, and a 3-point moving average curve. Grey bars indicate multi-centennial-scale forest decline intervals, labelled with the central age estimate of the interval. Dashed line marks the first indication of forest expansion during the glacial-interglacial transition (see Sect. 5.1.2).

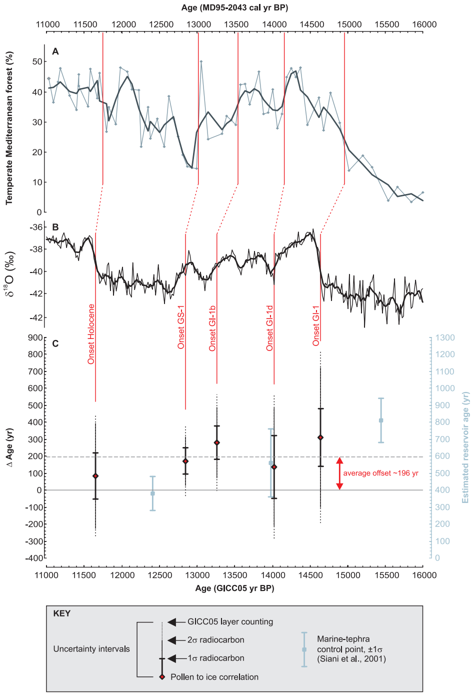

**Fig. 5.** Comparison of MD95-2043 radiocarbon and ice-core (GICC05) age estimates for five Lateglacial climatic transitions, showing: **(a)** Temperate Mediterranean forest (TMF) pollen curve from core MD95-2043 (raw values and 3-point moving average) plotted on the MD95-2043 calibrated radiocarbon timescale; **(b)** NGRIP $\delta^{18}$O values on the GICC05 timescale with 100-yr moving average (NGRIP members, 2004; Rasmussen et al., 2006); **(c)** Difference between calibrated radiocarbon age and GICC05 ages (y-axis) plotted against the GICC05 timescale (x-axis). Positive values indicate older ages on the MD95-2043 radiocarbon timescale. Vertical error bars show uncertainty estimates in the radiocarbon age model, and ice-layer counting in the GICC05 timescale as published in Rasmussen et al. (2006). Surface water age estimates for the Adriatic from Siani et al. (2001).