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Deglacial and Holocene vegetation and climatic changes at the southernmost tip of the Central Mediterranean from a direct land-sea correlation

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Abstract

Despite a large number of studies, the long-term and millennial to centennial-scale climatic variability in the Mediterranean region during the last deglaciation and the Holocene is still debated, in particular in the Southern Central Mediterranean. In this paper, we present a new marine pollen sequence (MD04-2797CQ) from the Siculo-Tunisian Strait documenting the regional vegetation and climatic changes in the Southern Central Mediterranean during the last deglaciation and the Holocene.

The MD04-2797CQ marine pollen sequence shows that semi-desert plants dominated the vegetal cover in the Southern Central Mediterranean between 18 and 12.3 kyr BP indicating prevailing dry conditions during the deglaciation, even during the Greenland Interstadial (GI)-1. Such arid conditions likely restricted the expansion of the trees and shrubs despite the GI-1 climatic amelioration. Across the transition Greenland Stadial (GS)-1 – Holocene, Asteraceae-Poaceae steppe became dominant till 10.1 kyr. This record underlines with no chronological ambiguity that even though temperatures increased, deficiency in moisture availability persisted into the Early Holocene.Temperate trees and shrubs with heaths as oak forest understorey or heath maquis expanded between 10.1 and 6.6 kyr, while Mediterranean plants only developed from 6.6 kyr onwards. These changes in vegetal cover show that the regional climate in Southern Central Mediterranean was wetter during Sapropel 1 (S1) and became drier during the Mid- to Late Holocene. Wetter conditions during S1 were likely due to increased winter precipitation while summers remained dry. We suggest, in agreement with published modelling experiments, that the increased melting of the Laurentide Ice Sheet between 10 to 6.8 kyr in conjunction with weak winter insolation played a major role in the development of winter precipitation maxima in the Mediterranean region in controlling the strength and position of the North Atlantic storm track.

Finally, our data provide evidences of centennial-scale vegetation and climatic changes in the Southern Central Mediterranean. During the wet Early Holocene, alkenones-derived cooling episodes are synchronous to herbaceous composition changes that indicate muted changes in precipitation. In contrast, enhanced aridity episodes, as detected by strong reduction in trees and shrubs, are recorded during the Mid- to Late Holocene. We show that the impact of the Holocene cooling events depend on the baseline climate states insolation and ice sheet volume, shaping the response of the mid-latitude atmospheric circulation.

1 Introduction

The Mediterranean region received increasing attention during the past decade when it was identified as a major "climate change hot spot" in future climate modeling projections as a result of the global increase in greenhouse gases (Giorgi, 2006; IPCC, 2007). Sensitivity of the Mediterranean climate and ecosystems to global climate change during glacial and interglacial periods has been demonstrated by a numerous paleoclimatic studies. Holocene Mediterranean records show that the long-term Holocene climatic evolution in response to orbital forcing can be described by three phases: a humid phase from 11.5 to 7 kyr, a transition phase from 7 to 5.5 kyr and an aridification phase from 5.5 kyr to present-day (Jalut et al., 2009; Finné et al., 2011; Pérez-Obiol et al., 2011). However, Holocene environmental conditions in the Mediterranean region remain a matter of debate. Davis and Brewer (2009) even hypothesized that higher Early Holocene moisture availability was not related to increased precipitation but decreased temperature. The respective contribution of climate and human activities to environmental changes, the contrasting and complex information provided by different proxy records and the heterogeneity and complexity of this region contribute to the existing uncertainties on the Holocene climate evolution in the different regions of the Mediterranean (Tzedakis, 2007; Roberts et al., 2011a). This is particularly true for the Southern Central Mediterranean as shown by an increasing number of lake level, pollen and speleothem records depicting contrasting signals. Some paleorecords from Sicily show wetter conditions (Sadori and Narcisi, 2001; Magny et al., 2011b; Peyron et al., 2012b) while others indicate drier conditions during the Early Holocene (Tinner et al., 2009; Calò et al., 2012). Note that “Early Holocene” is defined here as the 11.7 to 6.5 kyr interval and “Mid- to Late Holocene” the interval from 6.5 kyr to present-day. On the southern rim of the Mediterranean Sea, peat sequences from Kroumirie (Ben Tiba and Reille, 1982; Ben Tiba, 1995; Stambouli-Essassi et al., 2007) give a synthetic view of the Holocene vegetation history in the humid mountainous NW Tunisia. More detailed sequences in this area and in the semi-arid plains are needed to get a complete description of the Holocene climatic changes in Northern Tunisia. In addition, delayed forest expansion appears to be recorded by few sites from the southernmost areas of the Mediterranean region suggesting that dry conditions may have persisted into the Holocene (Tzedakis, 2007). A clearer picture of the long-term climatic changes in the Southern Central Mediterranean is a crucial step towards a mechanistic understanding of the regional hydroclimatic changes in response to large-scale orbital climatic changes.

Deglacial vegetation changes in the Central Mediterranean are based on few pollen sequences mainly located in Central Italy and Adriatic Sea (Watts et al., 1996; Combourieu-Nebout et al., 1998; Magri, 1999; Magri and Sadori, 1999). These records clearly show the afforestation associated to the climatic improvement of the last deglaciation as well as the response of the Mediterranean forest to millennial-scale climatic changes. However, the low temporal resolution of available records (Ben Tiba and Reille, 1982; Brun, 1983) does not allow to evaluate the impact of the millennial-scale variability during the last deglaciation. Since the identification of abrupt changes in the North Atlantic during the Holocene (Bond et al., 1997), a number of publications have shown that such changes affected the Mediterranean Sea and borderlands (e.g. synthesis papers and references therein: Magny et al., 2007a; Fletcher and Zielhofer, 2011; Peyron et al., 2011; Roberts et al., 2011b; Sadori et al., 2011). The complexity of the Mediterranean climate as well as the interpretation of proxies and chronological uncertainties remains a major limitation to our understanding of abrupt climatic changes. Records from Central Mediterranean provide evidences of increased dryness during the Holocene cooling episodes which contrasts with the increase in humidity in the European mid-latitudes, above 40° N (Magny et al., 2011b). Recently, a change in nature and tempo of centennial-scale variability during the mid-Holocene has been identified in the SW Mediterranean (Fletcher et al., 2012). However, key questions remain about the impact of Holocene cooling events on the Mediterranean climate and ecosystems and the processes responsible for the propagation and modulation of the North Atlantic variability into the Mediterranean region.

In this paper, we present pollen data from a marine record retrieved from the Siculo-Tunisian strait providing a regional picture of climate and vegetation changes in the southernmost Central Mediterranean during the last deglaciation and the Holocene. Our record based on a direct land-sea correlation will bring new insight into regional long-term trend and millennial to centennial-scale climatic changes. We compare our results with other records from Central and Western Mediterranean to show a coherent pattern between records. Finally, we discuss the potential links between the Mediterranean climate evolution and the low and mid-latitude atmospheric circulation features in relation with insolation and ice sheet volume forcings.

2 Environmental setting and potential pollen source

Core MD04-2797CQ (36°57′ N 11°40′ E, 771 m water-depth) was retrieved from the Siculo-Tunisian Strait at ∼ 50 km east off Cape Bon at the tip of the North-Eastern Tunisian coast and at ∼ 110 km off Sicily (Fig. 1). The strait bottom morphology is characterized by a sill and two troughs separating the Sicilian and Tunisian continental shelf areas. The upper water column is occupied by the Modified Atlantic Water (MAW). This water mass is fed by the Atlantic Tunisian Current (ATC) which is the southern branch of the MAW flowing eastward along the Tunisian coast through the strait while the northern branch flows along the Sicilian coast (Fig. 1) (Béranger et al., 2004). The upper water mass above the core site is influenced by the ATC. At depth, waters originating from the Eastern Mediterranean flowing westward across the Siculo-Tunisian Strait are composed of Levantine Intermediate Water and transitional Eastern Mediterranean water (Astraldi et al., 2002). The surface ocean circulation is driven by the atmospheric circulation dominated by westerly to north-westerly winds (Pinardi et al., 2005).

The present-day climate in Northern Tunisia and Sicily is of Mediterranean-type, characterized by warm and dry summers and cool and wet winters. The orography and maritime influences modulate the climate in both regions. An west to east humidity gradient exists in Northern Tunisia between the humid to sub-humid northwestern mountains and the semi-arid northeastern lowlands while in Southern Tunisia arid conditions prevail (INRF, 1976). The Sicily climate ranges from semi-arid to sub-humid at the highest elevations of the island (Drago, 2005). The autumn-winter-spring seasonal precipitation mainly derives from moisture advection from the Atlantic Ocean. The Western Mediterranean Sea is another source of moisture for the surrounding landmasses through evaporation and atmospheric circulation. Summer dryness results from the subsidence development associated with the northward displacement of the Hadley cell (Lionello et al., 2006).

The vegetation distribution in the Central Mediterranean is controlled by temperature and precipitation gradients and seasonality. The potential vegetation cover of the Medjerda watershed is dominated by *Olea-lentiscus* maquis in the eastern semi-arid areas and by holm oak-aleppo pine forest in the southern upper semi-arid High Tell and Tunisian Dorsal. In the most North-Western Kroumirie region of the Medjerda watershed, cork oak with *Erica arborea* underbrush and high altitude zeen oak forest prevail due to humid and sub-humid conditions in the mountains. Cape Bon considered as the “backbone” of the Tunisian Dorsal is the closest landmass to our core site where moisture from maritime influence leads to semi-arid to sub-humid conditions. Vegetation of Cape Bon is dominated by *Oleo-lentiscus* maquis, kermes oak (*Quercus coccifera*) and Thuya (Gaussen and Vernet, 1958; Posner, 1988; El Euch, 1995; Boussaid et al., 1999).

In addition, numerous permanent or temporary wetlands are located in Tunisia (Posner, 1988) mostly in the humid, sub-humid and upper semi-arid bioclimatic zones (INRF, 1976). Wetlands from Northern Tunisia such as Garaet el Ichkeul are characterized by the dominance of Cyperaceae in the marsh zone although recently replaced by Chenopodiaceae due to decreasing freshwater inflow as a consequence of dams and pipeline constructions (Ramdani et al., 2001). In temporary wetlands such as Sebkhet Ariana located in the semi-arid region, north-east of Tunis, vegetation is dominated by halophyte plants in particular Chenopodiaceae (Posner, 1988).

In Sicily, vegetation is distributed along humidity and temperature gradients resulting from the orography. *Oleo-ceratonion* maquis dominates the lowlands in the warmest and driest areas of the SE Sicily. At higher elevations, the potential vegetation has been assigned to mesophilous Mediterranean evergreen woods (*Quercetum ilicis*). Increased humidity in the submontane areas allows the development of deciduous woodlands (*Quercetalia pubescenti-petraeae*) while at highest altitudes of Sicily, *Geranio versicoloris-Fagion* association is favoured (Morinello, 1999).

A number of studies have shown that marine pollen signal provides an integrated picture of the vegetation from the nearby continents (Heusser and Balsam, 1977; Naughton et al., 2007). Studies on present-day pollen deposition in marine sediments show that pollen grains are fluvial and wind-transported from the adjacent continent and that agglomeration, flocculation and zooplankton feeding processes enable rapid sinking of pollen through the water column (Heusser and Balsam, 1977; Heusser, 1978; Chmura et al., 1999; Dupont and Wyputta, 2003; Mudie and McCarthy, 2006). Further, cores such as MD04-2797 CQ located near continental regions with well-developed hydrographic basins and prevailing offshore winds, mainly recruit pollen from rivers (Heusser, 1978; Turon, 1984; Dupont and Wyputta, 2003). Pollen grains belonging to the fine-particle fraction have a similar behaviour as fine sediments during the sedimentary processes (Muller, 1959; Chmura and Eisma, 1995). Medjerda and Miliane oueds are the two most important and permanent water streams in Tunisia discharging into the Gulf of Tunis and providing sediments to the shelf area (Fig. 1). The Medjerda oued is the main Tunisian stream flowing SW–NE between the Northern Tell and High Tell mountains, from Eastern Algeria to the Gulf of Tunis. Floods are recurrent in Northern Tunisia which receives most rainfall in winter and spring. Floods enhance material transport and contributed to the recent filling in of the Gulf of Tunis (Zahar et al., 2008). The riverine system of Sicily is not well developed and climate varies from semi-arid in the low land to sub-humid upland. Wind-driven sediment input to the shelf might be important in semi-arid regions. Given the dominant Westerly winds and surface ocean circulation, the bathymetry of the strait and large river systems of Northern Tunisia, the Southern Central Mediterranean and most probably also Northern Tunisia are likely be main source of pollens to our core site. Therefore, even though long-range transport of pollen cannot be ruled out, we interpret the pollen signal of core MD04-2797CQ as reflecting vegetation changes in this region.

3 Material and methods

Sediment core MD04-2797CQ was subsampled for pollen analysis every 2 to 10 cm over the first 590 cm. The sample preparation technique followed the procedure described by de Vernal et al. (1996). Exotic pollen (*Lycopodium*) was added to each sample to determine pollen concentrations. After chemical and physical treatments (cold HCl, cold HF, cold KOH and sieving through 10 µm nylon mesh screens), the residue was mounted unstained in glycerol. Pollen was counted using a light microscope at 400 and 1000 (oil immersion) magnifications. 100 to 160 pollen grains without *Pinus* and a minimum of 20 taxa were counted in each of sample. 10 out of 94 samples analysed were considered as sterile due to extremely low pollen concentration, in particular in the upper 80 cm of the core. Pollen percentages for each taxon are based on the main pollen sum excluding *Pinus* because of its over-representation in marine deposits (Heusser and Balsam, 1977; Turon, 1984). *Pinus* percentages were calculated from the main pollen sum including *Pinus*. Spores and aquatic pollen percentages were obtained from the total sum that includes all pollen grains plus aquatic plant and indeterminable pollen grains and Pteridophyta spores.

Quantitative climatic reconstruction based on the Modern Analogue Technique (MAT) was performed from pollen data. The MAT have been used to reconstruct here, annual, winter and summer temperatures and precipitation by considering the proportion of pollen assemblages (Guiot, 1990). Methods and results are presented and discussed in details in Peyron et al. (2012).

Direct land-sea correlation is obtained in comparing pollen to marine proxies from MD04-2797CQ sediments. Dinocyst and planktic foraminifera assemblages and derived SSTs, planktic foraminifera δ^{18}O and SST obtained from the C_{37} alkenones unsaturation index have been published earlier (Essallami et al., 2007; Rouis-Zargouni et al., 2010). In this paper, we compare our pollen data with the new high resolution alkenone-derived SST record (Sicre et al., 2012).

4 Results and interpretations

4.1 Chronological framework and pollen analysis results

Core MD04-2797CQ chronology was established from 13 radiocarbon dates among which 6 are from the upper 4 m of the core corresponding to the Holocene interval (Table 1). Except for the date at 0 cm, all radiocarbon dates have been replicated, thus increasing the reliability of the age-depth model. Averages of the ^{14}C date duplicates were corrected for a reservoir age of 400 yr for the Holocene, GS-1 and LGM intervals, of 560 yr for GI-1 (level 470 cm) and of 800 yr for Heinrich Stadial 1 (HS1) (level 510 cm), according to Siani et al. (2001). Corrected dates were calibrated using the calibration curve INTCAL 09 (Reimer et al., 2009). The age-depth model was obtained using linear interpolation between dated levels (Fig. 2). The upper 80 cm represents the last 5800 yr and is only chronologically constrained by two radiocarbon dates (5830 and 670 yr cal BP). A strong change in sedimentation rate occurred in between the two dated levels increasing age uncertainties for this interval. Here after, ka and kyr will be used for ages in cal BP.

According to the age-depth model (Fig. 2), the MD04-2797CQ pollen record encompasses the last 18 000 yr. Pollen analyses were performed at high temporal resolution (less than 100 yr) for the Holocene interval between 12 and 5.5 kyr. Unfortunately, the low pollen richness and sedimentation rate did not allow a high resolution study of the upper 80 cm. Most of the samples of the upper 40 cm were even pollen barren making the pollen record only reaches 2.2 kyr. The alkenone-SST record also displays the highest temporal resolution (20 to 75 yr) over the first half of the Holocene (Sicre et al., 2012).

Pollen zones (PZ) were identified visually from the pollen diagram shown in Fig. 3 and confirmed using constrained hierarchical clustering analysis based on Euclidean distance between samples using *chclust* function from the R package *Rioja* (Juggins, 2009). Clusters were determined from pollen data filtered at 1 % taxa presence in at least 5 % of the samples using the R package *PaleoMas* (Correa-Metrio et al., 2011). A summary of the pollen diagram description is presented in Table 2.

4.2 Deglacial vegetation and climatic changes

The core MD04-2797CQ pollen record depicts the deglacial and millennial-scale vegetation changes from Southern Central Mediterranean, a region for which few terrestrial paleodata are available. In particular, pollen records from Tunisia do not resolve the deglacial millennial-scale variability because of low temporal resolution or hiatuses (Ben Tiba and Reille, 1982; Brun, 1985; Stambouli-Essassi et al., 2007).

Our marine pollen record shows that a steppe with semi-desert plants (*Artemisia*, *Ephedra distachya*, *Ephedra fragilis*, Chenopodiaceae) dominates the vegetal cover up to 12.3 kyr, indicating prevailing dry conditions during the last deglaciation (PZ-1-2-3; Figs. 3 and 4). Such arid environments likely characterized most of Tunisia during this period, from at least 34° N (Brun, 1985) to the Northern Tunisian coast (this work). However, the moister mountainous NW part of Tunisia provided a favourable habitat for an open oak forest and a conifer forest of pine-cedar-fir in the highest altitudinal vegetation belts (Ben Tiba and Reille, 1982; Stambouli-Essassi et al., 2007).

Two intervals of maximal semi-desert plant expansion, coeval with cold SSTs occurred between 18.2 and 14.7 kyr (PZ-1) and 13.1 and 12.3 kyr (PZ-3) (Figs. 3 and

4) broadly at the time of HS 1 and GS-1, respectively. These time intervals are major abrupt climatic changes interrupting the last deglaciation that are widely documented as strong cooling in the North Atlantic, Europe and over Greenland (Johnsen et al., 1992; Walker, 1995; Bard et al., 2000; Peterson et al., 2000; Naughton et al., 2007). These events presumably result from the abrupt reduction in Atlantic Meridional Overturning Circulation (AMOC) due to massive iceberg discharges or freshwater releases in the North Atlantic (MacAyeal, 1993; Bond and Lotti, 1995; McManus et al., 2004; Broecker, 2006). Our sequence indicates that in Southern Central Mediterranean, climate shifted toward cold and dry conditions in response to HS 1 and GS-1 (Fig. 4). Prevailing arid conditions in Tunisia during GS-1 are confirmed by large aeolian terrigenous supply as detected by high illite, palygorskite and zirconium contents in our core (Bout-Roumazeilles et al., 2012). Similar climatic variations were reported from Western Mediterranean marine pollen and SST records (Cacho et al., 2001; Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout et al., 2009). Despite extremely arid conditions, our record indicates that deciduous tree populations, mainly deciduous *Quercus*, probably persisted in some remaining humid areas, and that the conifers *Cedrus* and *Pinus* were present in the regional vegetation. Some deciduous taxa pollen grains may originate from Sicily or even from Southern Italy where scattered woodlands have been detected (Magri and Sadori, 1999; Allen et al., 2002). However, most of the tree pollen grains recovered at our site during HS 1 and GS-1 were likely transported from NW Tunisia uplands by wind or river (Medjerda) where open oak and conifer forests were present during the last glacial and deglaciation (Ben Tiba and Reille, 1982; Stambouli-Essassi et al., 2007).Note the increase in *Cedrus* abundances during HS1 and GS-1 while deciduous oak decrease (Fig. 3). A similar pattern has been described in marine pollen records from the Alboran Sea documenting cedar variations in the Moroccan Rif (Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout et al., 2009). As discussed in Fletcher and Sanchez Goñi (2008), increases in cedar pollen abundances could reflect either (1) enhanced wind-driven pollen supply due to wind strengthening and opening of the vegetation or (2) maintenance of some degree of moisture since cedar is

generally considered as a cold tolerant-moisture demanding conifer. Colder conditions and moisture availability at mid to high altitudes during HS 1 and GS-1 could have favoured cedar expansion at the expense of deciduous oak in NW Africa, from the Moroccan Rif to the High Tell. The Mediterranean region presents a wide range of habitats due to highly variable topography and local climate conditions which enables refugia zones during the last glacial period (Médail and Diadema, 2009). This work supports the idea that tree populations maintained in the mountainous region of North Africa even during the most severe episodes of the last deglaciation.

During GI-1, SSTs increased, semi-desert plants and cedar reduced while some deciduous and evergreen oak woodlands and Mediterranean shrubs (*Olea*) developed (PZ-2; Fig. 4). This finding is indicative of relatively warmer and wetter climatic conditions than during HS 1 and GS-1. Despite the temperature rise, the semi-desert plants remained dominant and tree and shrubs expansion limited compared to terrestrial pollen records from Italy (Magri and Sadori, 1999; Allen et al., 2002) or Western Mediterranean Sea pollen records (Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout et al., 2009). This result can be explained by lower water availability in the semi-arid areas of Southern Central Mediterranean. Terrigenous supply to the Siculo-Tunisian Strait remained characterized by a high content of aeolian-driven particles, such as illite and palygorskite, which also indicate prevailing dry conditions during GI-1 (Bout-Roumazeilles et al., 2012). Strikingly, our pollen data do not indicate a tree and shrub expansion maximum at the beginning of the GI-1 but rather slightly higher values at the end of the interstadial at ∼ 13.4 kyr following a long HS1 to GI-1 transition. This feature contrasts with the sharp temperature rise and early GI-1 optimum in Greenland ice cores (NGRIP members, 2004) (Fig. 4) and has already been identified from speleothem records from Northern Tunisia, Southern France and Southern Germany (Genty et al., 2006) as well as from pollen records from the Alboran Sea and Southern Alps (Combourieu-Nebout et al., 2009; Finsinger et al., 2011). This North–South contrast may be linked to the North Atlantic oceanic and atmospheric circulations and sea ice cover (von Grafenstein et al., 1999; Genty et al., 2006). In the Southern Alps, the gradual expansion of *Quercus* have been attributed to increasing summer temperatures and longer growing season probably related to insolation (Finsinger et al., 2011). Stacked temperature records over the latitudinal bands 30–0° S and 0–30° N (Shakun et al., 2012) indicate lower temperature during GI-1 than during the Holocene and display the same peculiar increasing temperatures over the course of the interstadial. Since tropical ocean temperature and associated evaporation regulate the atmospheric moisture content feeding the North Atlantic storm track (Braconnot et al., 2007), stronger inland moisture transport toward the end of GI-1 may be associated with the tropical climate in relation with orbital forcing.

4.3 Holocene long-term vegetationand climate changes

4.3.1 Vegetation and climate in and off Tunisia

In core MD04-2797CQ, the GS-1–Holocene transition is marked by a sharp decrease in semi-desert plants at ∼12.3 kyr while alkenone-SSTs and summer SSTs derived from planktonic foraminifera assemblages increased by 9 °C (Essallami et al., 2007) (PZ-4; Figs. 3 and 4). These vegetation and SST changes seem to precede by 600 yr the sharp rise in temperature recorded in Greenland (Rasmussen et al., 2006). One can attribute this time difference to age uncertainties of the records. However, this difference is quite large and may suggest earlier changes in temperature and precipitation in the Southern Mediterranean region compared to the northern latitudes. Open vegetation with Asteraceae, Poaceae and some semi-desert plants (mainly Chenopodiaceae and *Ephedra fragilis*-type) remained dominant until 10.1 kyr when the open oak forest expands. Although Mediterranean and temperate trees and shrubs slightly increased at 12.3 kyr, they remained restricted at some woodlands/scrubs despite high alkenone-SSTs (Fig. 4). This vegetation change indicates a shift to warmer conditions and increased humidity during the Early Holocene but moisture availability remained too weak before 10.1 kyr to enable a forest development. In the Southern Mediterranean, temperature influences forest composition but moisture availability is overall critical for forest development (Quezel, 2002). During this interval, decreasing semi-desert plants and increasing Cyperaceae and Ericaceae values suggest a gradual increase in moisture availability (Fig. 4). Therefore, the abrupt tree and shrub expansion observed at 10.1 kyr would likely result from crossing ecological thresholds during gradual climatic change. The gradual decrease in aridity before 10 kyr is supported by mineralogical and geochemical data found at core site MD04-2797CQ (Bout-Roumazeilles et al., 2012).

From 10.1 to 6.6 kyr, open deciduous oak forest with heath understorey and maquis developed along with a maximal sedge expansion (PZ-5). Mediterranean plants (mainly *Pistacia*, evergreen *Quercus* and *Olea*) remained limited over this interval and only start expanding after 6.6 kyr at the expense of heath maquis (PZ-6). At present-day, in the Central Mediterranean and in particular in Tunisia, Ericaceae are mainly represented by *Erica arborea*, *E. scoparia* and *E. multiflora* (Posner, 1988; Ojeda et al., 1998). Although *E. arborea* and *E. scoparia* have a wide range of distribution, they are related to humid climate and particularly atmospheric humid conditions (Jalut et al., 2000). This is well illustrated by the Ericaceae distribution in Northern Tunisia. Both species are widely distributed in the sub-humid zones of NW Tunisia and Cape Bon as understorey of *Quercus canariensis* and *Quercus suber* or as maquis of heather, while *E. multiflora* mainly grows in the *Olea-lentiscus* maquis or with aleppo pine and holm oak association in the semi-arid areas of Northern Tunisia (Posner, 1988). Therefore, the development of Ericaceae along with deciduous trees suggests that the most humid conditions of the Holocene occurred during this phase. Another line of evidence supporting this interpretation is the concurrent maximal development of sedges. Cyperaceae is a family comprising numerous species that can grow under a wide range of ecological conditions although most of them develop in humid area (Brun, 1985). Therefore, increased precipitation can potentially favour their contribution in the Asteraceae-Poaceae steppes. Sedge expansion can also reflect enhanced humid habitats, such as inland or coastal wetlands that are common features in Northern Tunisia. For instance, extensive sedge marshland surrounded Garaet el Ichkeul lake until dam constructions dramatically decreased water supply (Ramdani et al., 2001). Part of the strong sedge representation in our record might also result from coastal environment modifications related to post-glacial sea-level rise up to 6.6 kyr. The highest sedge percentages are also seen in MD95-2043 and ODP 976 sites during the same period, although lower than in our sequence. In these Alboran Sea records, sedges are associated with maximum forest development sustained by the most humid conditions of the Holocene (Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout et al., 2009). Our pollen record therefore suggests that the 10–6.6 kyr interval is the wettest Holocene phase. However, in NE Tunisia water availability was never high enough, even during the most humid phase to sustain the regional development of a closed forest. Decreasing Ericaceae and Cyperaceae between 6.6 and 5 kyr (PZ-6) suggest a transition toward drier conditions. After 5 kyr, the expansion of Mediterranean plants such as evergreen *Quercus* and *Olea* suggests lower available summer moisture and warmer winter.

Precipitation estimates derived from our pollen record support the earlier interpretation of highest rainfall between 10 and 6.6 kyr, occurring mainly in winter, with mean annual precipitation of ~ 670 mm (Fig. 5, Peyron et al., 2012a). This period coincides with the highest pollen concentrations (Fig. 4) possibly due to both strong terrigenous inputs and increase biomass. After 5 kyr, while dryness increased on land, the SSTs show moderate warming, although different time-scale variability resulting from different temporal resolution may introduce bias. This warming seems however to be confirmed by increasing abundances of warm water dinocysts (Rouis-Zargouni et al., 2010).

Interpretation of our pollen record may appear contradictory regarding the gradual increase of temperate trees and shrubs all along the Holocene. Changes in post-glacial sea level may have influenced our marine pollen signal by modifying the dominant pollen transport agent from fluvial to aeolian. Mediterranean post-glacial sea-level reconstructions suggest that Cape Bon coastline and Medjerda river mouth were closer to our core site until 6.5 kyr when the Laurentide ice sheets (LIS) melting was completed (Lambeck et al., 2004). This could have led to enhance the representation of lowland relative to upland vegetation up to 6.5 kyr and that of the upland open forest afterwards. However, a shift to drier climate could have promoted aeolian transport. Although pollen transport changes may have modified the pollen signal, they do not alter the main vegetation changes. In particular, changes in the lowland shrub communities such as the replacement of heath maquis by *oleo-lentiscus* scrubs remain reliable to evaluate the main traits of the Holocene vegetation and climate history. Sedimentological analyses of core MD04-2797CQ agree with our interpretation of the pollen record. High sedimentation rates, decrease of aeolian-driven clay particles (palygorskite and illite), enhanced contribution of smectite likely reflecting fluvial supply and higher Zr/Al ratio indicate increased sediment supply to the shelf. Higher riverine discharge are likely sustained by more precipitation between 6 and 9.5 kyr (Bout-Roumazeilles et al., 2012).

4.3.2 Climatic or human-induced vegetation changes

The respective role of climatic change and anthropogenic pressure since the Neolithic has been a long standing debate in our understanding of the Mediterranean vegetation changes recorded by pollen sequences (De Beaulieu et al., 2005; Jalut et al., 2009). In Sicily, human impact appears to be detected in paleorecords since the Bronze Age and not since the Neolithic (Sadori and Giardini, 2007), and intense land use began with the Greek and Roman periods (Tinner et al., 2009). Human impact on the Tunisian environments became noticeable from the Phoenician and Carthaginian epochs (from XIIth to IIth century BC) with a strong agricultural development essentially based on cereal cultivations (Brun, 1983). However, our pollen record does not show this cereal signal. It is known that the dispersal of the large sized cereal pollen grains is poor (Vuorela, 1973), making difficult to get a reliable representation of cultivated Poaceae in marine pollen records. The Late Holocene *Olea* expansion is clearly detected in our record at around 3.2 kyr that may result from human activities during the Bronze Age. Olive tree expansion is also detected at that time in sequences from the Adriatic Sea, Italy and Sicily (Sadori and Narcisi, 2001; Di Rita and Magri, 2009;

Combourieu-Nebout, 2012). Management of olive tree populations for fruit production started as early as the Bronze Age in the Western Mediterranean (Terral et al., 2004). However, as shown by our record, the expansion of *Olea* in Southern Italy is accompanied by a widespread increase of other Mediterranean trees and shrubs that may thus reveal a concomitant vegetation response to climate during the Bronze Age (Di Rita and Magri, 2009). Because of the low chronological constraints in our sequence between 600 and 5800 yr BP, *Olea* increase may also have occurred during Roman times. Expansion of olive trees at around 2000 yr cal BP during Roman occupation is detected in Southern Italy and Sicily (Terral et al., 2004; Di Rita and Magri, 2009). Roman developed an intensive olive tree cultivation for fruits and oil in the Mediterranean region (Terral et al., 2004). Therefore, human influence cannot be discarded since the Bronze Age but beforehand our pollen record primarily reflects climatic conditions.

4.3.3 Major climatic changes in the Southern Central Mediterranean

Land-sea correlation from core MD04-2797CQ indicates without chronological ambiguity that Holocene expansion of tree populations in Southern Central Mediterranean lagged temperature increase by two millennia. Delayed or slow afforestation due to moisture deficiency in the southernmost areas of the Mediterranean has been previously suggested from few terrestrial records (Tzedakis, 2007; Tinner et al., 2009). Dryness in Sicily before 10 kyr is supported by lake level and pollen data (Fig. 6g–i) (Sadori and Narcisi, 2001; Tinner et al., 2009; Magny et al., 2011b). Close examination of the Tunisian pollen records from Kroumirie (Stambouli-Essassi et al., 2007) and from Gulf of Gabes (Brun, 1979, 1985) shows that the deciduous oak forest expansion in NW Tunisia and of *Olea*-*Pistacia* scrubs in central eastern appears delayed by at least one millennium with respect to the beginning of the Holocene (Fig. 6c). Despite loose chronological framework and temporal resolution of the Tunisian pollen records, dry conditions of the Early Holocene derived from our sequence appear to be a robust feature in Northern Tunisia. In addition, the pollen and terrigenous records from core MD04-2797CQ parallel the δ^{13}C signal of the Tunisian speleothem record from

La Mine cave (Fig. 6d) (Genty et al., 2006). Both records suggest a gradual climatic improvement and vegetation development in Southern Central Mediterranean immediately after the GS-1 cooling up to the climate optimum around 10 kyr. This is in contrast with Lake Preola record showing an abrupt rather than gradual change in lake level (Magny et al., 2011b). This contrasting feature could be season-related with a gradual change in winter precipitation from GS-1 to 10 kyr and an abrupt change in summer precipitation at 10 kyr.

Increased moisture availability during the Early Holocene, between 10 kyr and 6.6 kyr, is also consistent with available Tunisian and Sicilian records (Fig. 6). This accounts for example for the expansion of forest upland at Lake Pergusa and Majen M'Hida (Sadori and Narcisi, 2001; Stambouli-Essassi et al., 2007) and of *Pistacia* scrubs at the Western Sicilian coastal sites Lake Preola and Gorgo Basso (Tinner et al., 2009; Calò et al., 2012). After 6.6 kyr, our data and most of the Sicilian and Northern Tunisian records show similar long-term climate changes. Pollen and sedimentary δ^{18}O records and pollen-derived precipitation estimates from Lake Pergusa, lake level record from Lake Preola and stalagmite record from Grotta di Carburangeli suggest a transitional period of decreasing humidity or high amplitude variability in rainfall in Sicily between the wet 10 to 7 kyr interval and the pronounced drier period from 5–4 kyr to present-day (Frisia et al., 2006; Sadori et al., 2008; Magny et al., 2011a; Peyron et al., 2012b). Similarly, increasing dry conditions by 4–5 kyr is reflected by the replacement of the zeen oak forest by a cork oak forest with heath understorey at Dar Fatma in the humid NW Tunisia (Ben Tiba and Reille, 1982). Alluvial records from the Medjerda floodplain (Fig. 6e) showing increased fluvial dynamics with recurrent floods since 5 kyr also suggest prevailing arid conditions over the end of the Holocene (Zielhofer and Faust, 2008).

In contrast, the pollen records from the Sicilian coastal lakes Gorgo Basso, Lake Preola and Biviera di Gela also show a pronounced vegetation change at approx. 7–6.5 kyr. This change has been interpreted as a second step of humidity increase caused by a decrease in summer dryness (Noti et al., 2009; Tinner et al., 2009; Calò et al., 2012). In addition, in Western Sicily, no shift is recorded by 5 kyr, the evergreen forest declines only around 2.8–2.2 kyr likely because of intensified anthropic pressure on Mediterranean ecosystems (Tinner et al., 2009; Calò et al., 2012). However, the long-term climatic variations derived from vegetation changes at Biviera di Gela are not unequivocal and may as well be consistent with our results. Although maximum Mediterranean forest expansion between 7 and 5 kyr is interpreted as a response to moister climate at Biviera di Gela (Noti et al., 2009), the reduction of mesophilous trees over this interval might also be indicative of a rather contrasting drying trend. Furthermore, the partial shift from evergreen forest to *Pistacia*-dominated shrublands at this site became pronounced by 5 to 4 kyr, concurring with a Mid to Late Holocene aridification reinforced by increasing human impact (Noti et al., 2009). A number of hypotheses, although not entirely satisfactory, have been proposed to reconcile these coastal Sicilian pollen records with Lake Preola lake-level record and Lake Pergusa pollen sequence, such as spatial heterogeneity of landscape and climate (Tinner et al., 2009) or changes in seasonal and interannual variability of drought (Magny et al., 2011b). Possible mis-assignment of *Pistacia* pollen taxa to the evergreen species *P. lentiscus*, while pollen grains of the evergreen and deciduous species (*P. terebinthus* and *P. atlantica*) are indistinguishable is another plausible explanation (Sadori et al., 2011). Recently, Calo et al. (2012) also suggested that discrepancies between pollen and lake level records at the Sicilian coastal sites would come from seasonal biases of each proxy.

Rainfall seasonality in response to orbital forcing is an important issue. Lower or higher spring/summer dryness in Southern Central Mediterranean between 10 and 7 kyr than during the Late Holocene has been deduced from continental records (Magny et al., 2011a; Calò et al., 2012) while our marine record shows that summer precipitation (Psum) at regional scale remained low (50 to 100 mm) all over the Holocene, with no significant change (Fig. 5; Peyron et al., 2012a). However, even when Psum are estimated higher, they remained < 100 mm (Magny et al., 2011a). This denotes that dry summers remained a characteristic of the Holocene climate in that region. Subtle variations in Psum from semi-arid regions are particularly difficult to assess from pollen records since summer moisture availability for plants not only depend on summer precipitations but also on groundwater recharge during fall and winter that is critical to sustain vegetation during summer drought (Quezel, 2002; Fletcher et al., 2012), on continental evaporation related to summer temperatures and cloudiness, atmospheric humidity, storminess or soil absorption/retention. In contrast, Tunisian and Sicilian pollen and speleothem records (Frisia et al., 2006; Magny et al., 2011a) agrees with our observations (Fig. 5; Peyron et al., 2012a) underlying that the strongest winter and annual rainfall in the Southern Central Mediterranean occurred during the 10.1–6.6 kyr interval, followed by a decrease toward the Late Holocene.

4.3.4 Relationships with large-scale climatic changes

The Mediterranean climate results from complex interactions between low and mid-latitude atmospheric circulations and local features such as orography or land sea-contrast (Brayshaw et al., 2011). The winter Mediterranean hydroclimate depends on the Mediterranean storm activity (and associated precipitation) which is strongly influenced by the position and strength of the mid-latitude North Atlantic (NA) storm track (Brayshaw et al., 2010), while summer dryness is tightly linked to the summer extension and strength of the Hadley cell and associated subtropical subsidence (Lionello et al., 2006). Holocene changes of both NA storm track and tropical convection in response to insolation forcing are therefore critical factors to explain the long-term climatic evolution in Central Mediterranean and seasonal precipitation changes.

The drier conditions persisting into the Early Holocene up to 10.1 kyr are also detected in the SW and NE Mediterranean with a West to East gradient (Dormoy et al., 2009). The level of annual moisture availability always remained higher in the SW probably due to the stronger Atlantic influence, allowing Mediterranean plants to expand during the first millennia of the Holocene (Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout et al., 2009). Such drier conditions are potentially due to the boreal summer insolation maximum of the Early Holocene (Tzedakis, 2007) resulting in deficiency in effective moisture availability due to strong evaporation (Renssen and

Isarin, 2001). However, limited winter rainfall due to reduced influence of westerly flow-induced cyclones on the Mediterranean region is also probably involved (Kotthoff et al., 2008). The gradual shift from the GS-1 dry-cold situation to the Holocene warm-humid conditions might also be the result of the progressive reorganisation of the global atmospheric circulation associated with the retreat of Northern Hemisphere ice sheets. The LIS which disappeared around 6.8 kyr (Carlson et al., 2008) was large enough to impact on the atmospheric circulation (Montero-Serrano et al., 2010). The Fennoscandian Ice Sheet (FIS) which persisted up to 9 kyr could have influenced the response of the European hydroclimate to insolation forcing in maintaining the NA storm track in a relatively southern position (Magny et al., 2003). However, the NA storm track remained narrow enough not to bring high humidity in the Mediterranean.

The period comprised between 10.1 and 6.6 kyr encompasses to the Sapropel 1 (Mercone et al., 2000). Increased precipitation in Southern Central Mediterranean is coeval with maximum monsoon activity as shown by tropical African paleohydrological records (Lézine et al., 2011). However, a number of evidences clearly show that the African monsoon never reached the Mediterranean region (Tzedakis, 2007). Our data thus confirm these earlier results since the estimated increase in annual precipitation remains limited on average to 700 $\mathrm{mm\,yr^{-1}}$ in our southern region and mainly due to a change in winter/fall precipitation (Fig. 5). In contrast, monsoonal intensification during summer could have played a predominant role on the Mediterranean summer dry season. Limited summer rainfall in Southern Central Mediterranean has been attributed to the development and persistence of subtropical anticyclones as a result of the reinforcement of the Hadley cell related to the African monsoon (Tinner et al., 2009; Gaetani et al., 2011). According to (Harrison et al., 1992), the summer northern position and higher strength of the North Atlantic Subtropical High in response to high summer insolation could have blocked the eastward convection and even generate an offshore flow in Southern Europe. This pattern would explain summer dryness over the whole Central Mediterranean region and the northern progression of summer dryness as observed in pollen and lake level records (Magny et al., 2007a; Finsinger et al., 2010; Peyron et al., 2011).

The winter rainfall maximum from 10.1 to 6.6 kyr, observed in the Southern Central Mediterranean, appears to be a broad feature of the climate in the Western, Central and North-Eastern Mediterranean regions (Fletcher and Sánchez Goñi, 2008; Kotthoff et al., 2008; Combourieu-Nebout et al., 2009; Dormoy et al., 2009; Jalut et al., 2009; Pérez-Obiol et al., 2011; Peyron et al., 2011). The spatial extent and relative simultaneity of maximum winter suggests common mechanisms related to remote controlling factors. Simulations using global and regional models HadSM3 and HadRM3, suggest that increased winter precipitation during the Early Holocene would be linked to shifting NA storm track in response to orbital forcing (Brayshaw et al., 2010, 2011). The Early-Mid Holocene orbital configuration imposes a weaker winter latitudinal insolation gradient that would drive the northern tropical Hadley cell to be narrower and in a more southern position in winter. Consequently, the NA storm-track would weaken and shift to the south, thus enhancing Mediterranean cyclogenesis and winter precipitation (Brayshaw et al., 2010).

A contrasting hypothesis involving the Arctic Oscillation/North Atlantic situation (AO/NAO) has been proposed by Davis and Brewer (2009). According to these authors, increase in moisture availability in the Mediterranean region would be caused by lower evaporation due to cooler conditions (in contrast with our data from the Central Mediterranean). Cool and dry southern conditions would be explained by a more dominant positive AO (Davis and Brewer, 2009) and more northern NA storm track. Bonfils et al. (2004) showed that NAO does not support the winter temperatures and precipitation distribution during the mid-Holocene as shown by European paleodata. They suggest instead an insolation-induced southern entry of the NA storm track in the European mid-latitudes than during the Late Holocene.

The Early Holocene deglaciation of the LIS may have also contributed to increase winter precipitation in the Mediterranean region. The rapid retreat and increased melting of the LIS notably occurred during the wettest phase of the Mediterranean Holocene climate, between 10 and 6.8 kyr (Carlson et al., 2008). The above mentioned modelling experiments performed by Brayshaw et al. (2010) do not show a significant impact of the LIS on the NA storm track. Increased cyclogenesis is simulated only in the Western North Atlantic due to the increased temperature gradient resulting from the LIS cooling effect. Another modelling experiment with the fully coupled AOGCM ModelE-R has been performed to simulate the 9 kyr-climate with a more realistic LIS topography and appropriated freshwater routing (Carlson et al., 2008). ModelE-R outputs showed a stronger impact of the LIS on the ocean and atmospheric circulation over the North Atlantic region. Suppression of the Labrador Sea Water (LSW) formation, substantial reduction of the AMOC (by 15 %), and SST cooling in the NW Atlantic and temperature decrease in NE North America are simulated in agreement with paleodata (Carlson et al., 2008). If effective AMOC reduction is debatable (Renssen et al., 2005; Hoogakker et al., 2011), oceanic circulation reorganisation occurred when LIS retreat had completed. At ~ 6.5 kyr, deep water convection in the Nordic Seas reduced and LSW formation reactivated (Hoogakker et al., 2011). According to the ModelE-R experiment, the impact of the LIS melting on atmospheric and North Atlantic circulation induced a southern and stronger NA storm track providing slightly more winter precipitation to the mid and Southern Europe (Carlson et al., 2008, SI: Fig. 4).

We propose that during the Early Holocene, insolation and ice sheets, in particular the LIS decay, modulated winter precipitation in the Western to Central Mediterranean regions by altering oceanic and atmospheric circulation patterns of the North Atlantic, and strengthening the Mediterranean cyclogenesis. After the final demise of the LIS, increase in winter insolation and latitudinal insolation gradient probably contributed to the long-term decrease in winter precipitation and seasonality in the Western and Central Mediterranean by gradually shifting northward the NA storm track, which thus affected less frequently the Mediterranean region.

4.4 Impact of the Holocene centennial-scale climatic changes on the temperature and hydroclimate in the Southern Central Mediterranean

The pollen record from core MD047-2497CQ displays a series of eight vegetation centennial-scale changes superimposed to the Holocene long-term evolution (11.5–11 kyr, 10.3–9.9 kyr, 9.5–9.1 kyr, 8.5–7.9 kyr, 7.3–6.7 kyr, 6.4–6 kyr, and ∼ 5.5 kyr and 4.5 kyr).

During the Early Holocene dry phase, two centennial-scale dry and cold events at ∼ 11.2 kyr and 10.1 kyr are clearly marked by increases of semi-desert plants with lower tree and shrubs percentages. During the first event, a large amplitude SST cooling is synchronous to vegetation changes, while no SST change is detected during the second one. Further, three cooling events of the SST record at ∼ 9.3 kyr, 8.2 kyr, 7.0 kyr punctuated the wettest Holocene phase (10.1–6.6 kyr) with the last one at ∼ 6.2 kyr, at the onset of the transition toward drier Mid- to Late Holocene. All these events are coeval with a change in herbaceous composition as shown by the strong reductions of Cyperaceae, most of the time replaced by Asteraceae (*Taraxacum*). Strikingly, they do not coincide with trees and shrubs reductions as we would have expected (Fig. 7). For instance, the Mediterranean forest percentages remain stable during the ∼ 9.3 kyr and 6.2 kyr events while they decline at the end of the 7.0 kyr event. Different SST and Mediterranean forest variations have also been reported from the Alboran Sea record MD95-2043 (Fletcher et al., 2012) underlying the possible asynchronism between Mediterranean SST millennial-scale cooling and tree development. A seasonal bias towards summer for SST derived from alkenones and winter for the Mediterranean forest is proposed to explain this divergent pattern (Fletcher et al., 2012). However, alkenone-SSTs from core MD04-2797CQ during the interval 10.1–6.6 kyr do not parallel those found in core MD95-2043, suggesting that they might be controlled by different processes. We will see hereafter that centennial SST coolings from the Siculo-Tunisian Strait are associated to drier conditions, as revealed by the herbaceous layer changes.

Centennial-scale variations in sedge percentages may have different causes. They could result from variations in the extent of coastal humid areas due to minor sea level changes. Such centennial-scale sea level changes during the Early Holocene may be produced by deglacial pulses, sea-water temperature changes through thermal water expansion or AMOC variations (Levermann et al., 2005; Lombard et al., 2005; Tornqvist and Hijma, 2012). Flooding can also favour sedge development in estuary zones and pollen export to the ocean (Bernhardt et al., 2012). However, high sedge percentages do not coincide with increased periods of flooding as recorded in the fluvial floodplains of Northern Tunisia (Zielhofer and Faust, 2008). Regarding the whole pollen assemblage, the most straightforward interpretation is restricted humid areas due to drier conditions. The concomitant *Taraxacum* increase may witness low moisture availability although relatively weak because semi-desert plants did not expand. In modern pollen assemblages, the highest *Taraxacum* percentages are found in dry environments of Greece and Morocco, where mean annual temperatures span from 12 and 17 °C and precipitation from 0 to 250 mm (Leroy, 1997). Therefore, a weak decrease in precipitation and slight cooling as shown by SSTs remaining above 16 °C would explain why oak populations were not affected by abrupt climate changes during that period. In contrast, over the last 6 kyr, our pollen record shows two strong abrupt forest reductions around 5.5 kyr and 4.5 kyr likely resulting from enhanced dryness, even though no SST decreases are recorded.

All the events detected before 6.6 kyr parallel the widely documented abrupt coolings punctuating the Early Holocene: the Preboreal Oscillation (PBO) at ~ 11.2 kyr (Bjorck, 1996), the Boreal Oscillation at ~ 10.1 kyr (Björck et al., 2001; Boch et al., 2009), the 9.3 kyr event (Rasmussen et al., 2007), the "8.2-event" (Alley et al., 1997) and a final event at ~ 7.4 kyr (Bond et al., 2001) which likely corresponds to the drier episode detected at ~ 7.0 kyr bearing in mind the chronological uncertainties (Fig. 7). Our pollen record confirms a decrease in precipitation in the Mediterranean region during the Early Holocene cooling episodes (Combourieu-Nebout et al., 2009; Dormoy et al., 2009; Pross et al., 2009; Fletcher et al., 2010). In addition, the centennial drier events in our record match the higher lake level episodes in the European mid-latitudes (Magny and Bégeot, 2004) (Fig. 7). This finding supports the Early Holocene contrasting pattern of the hydrological changes between the mid-latitudes and Southern Europe (Magny and Bégeot, 2004; Fletcher et al., 2012). These cooling events have been associated with deglacial freshwater outbursts in the North Atlantic from proglacial lakes such as Lake Agassiz (Teller et al., 2002), Lake Labrador-Ungava (Jansson and Kleman, 2004), Lake Superior (Yu et al., 2010) or Baltic ice Lake (Nesje et al., 2004), and with solar activity minima (Bond et al., 2001; Magny and Bégeot, 2004). Early Holocene meltwater pulses and solar forcing have been shown to alter the AMOC and modify the atmospheric circulation in the mid-latitudes but also in the tropics (Bond et al., 2001; Magny and Bégeot, 2004; Marchitto et al., 2010). A southern entry point of the Atlantic jet and associated cyclones in Europe and a stronger zonal flow due to enhanced temperature gradient between low and high latitudes, are suggested from the European hydrological reconstructions (Magny et al., 2003, 2007b; Magny and Bégeot, 2004).

Abrupt forest reductions around 5.5 kyr and 4.5 kyr may be attributed to major widespread cooling events dating to 5.6–5 kyr and ∼4.2 kyr, respectively (Magny and Haas, 2004; Drysdale et al., 2006; Magny et al., 2009). This coincidence might be fortuitous because the age control and time resolution of our sequence is low over the last 5.8 kyr. Nevertheless, drier conditions in the Southern Mediterranean at ∼5.5 and 4.2 kyr are also suggested by lake-level decreases (Magny et al., 2007a, 2011b). An episode of arboreal biomass reduction at ∼4.2 kyr is recorded in the Central Mediterranean. It has been associated with climate change despite the possible human impact at the beginning of the Bronze Age (Magri and Parra, 2002; Sadori et al., 2011). Both events at ∼5.5 and 4.2 kyr are associated with higher lake levels at mid-latitudes in Europe and in Central Italy in response to North Atlantic cooling and decrease in solar activity (Magny, 2004; Magny et al., 2007a) (Fig. 7). However, hydrological changes at 4.2 and 5.5 kyr are complex (Magny et al., 2006, 2009, 2011b). For instance, the short-lived dry event in Central Italy probably coeval to the “4.2 kyr event” occurred during a cooler and wetter interval between 4.5 and 3.8 kyr (Magny et al., 2009). In contrast, forest reduction episodes in Western Mediterranean at ~5.4–4.5 kyr and 3.7–2.9 kyr do not match those events (Fig. 7). They have been associated to dry conditions in the mid-latitudes and enhanced wind strength in the northern latitudes (Fletcher et al., 2012). However, it is not clear if these forest reduction episodes actually correspond to warm or cold events in the North Atlantic because of a different timing and periodicity of the centennial scale variations recorded in the Alboran Sea pollen record and in the North Atlantic IRD record (Fletcher W. J., personal communication, 2012).

Therefore, given the limitations of the chronology of our core, forest reductions reconstructed from our record may be linked either (1) to higher lake level in the mid-European latitude and lower lake level at Lake Preola, or (2) to the forest reduction in the Western Mediterranean. Answer to this question is crucial to determine the factors controlling the centennial-scale variability during the Mid- to Late Holocene and their impact on the Mediterranean region. From 6 kyr onwards, dry episodes in the Southern Central Mediterranean could involve (1) wetter conditions above 40° N due to a southern and stronger Atlantic jet like during the Early Holocene cooling events (Magny et al., 2004) or (2) drier conditions in the Mediterranean and Mid European latitudes due to an intensification and northward shift of the NA storm track and subsequent limited penetration of storms in the Mediterranean region (Fletcher et al., 2012).

Apart from this, our record shows that changes on land are of weaker amplitude during the Early Holocene, in particular during Sapropel 1. Weaker changes in Mediterranean forest in the SW Mediterranean also characterize the Early Holocene as compared to the Mid- to Late Holocene as shown by the MD95-2043 pollen sequence (Fig. 7). The notable weak expression of the 8.2 event in the Central Mediterranean has already been emphasized from the Accesa or Preola sequences (Magny et al., 2011b; Peyron et al., 2011). This event is even missing in Morroccan and Tunisian alluvial sequences (Zielhofer et al., 2008). This finding emphasizes that impact of cooling events in the Early Holocene was relatively weak on the Western to Central Mediterranean hydroclimate while it appears to have been stronger during the Mid to Late Holocene. Baseline climate states, such as insolation and ice sheet volume, exert a strong control on the atmospheric circulation in the North Atlantic and thus likely modulate the impact of abrupt climate changes on the Mediterranean region.

During the humid Early Holocene, insolation and melting LIS resulted in a mean southern NA storm track, with cyclones becoming stronger and more zonal during cooling events, enhancing precipitation at mid-latitudes and restricting them in Southern Europe. Despite increased dryness, paleodata suggest that precipitations remained relatively sustained in the Western to Central Mediterranean. NA storms were still affecting Southern Europe during the Early Holocene cooling events, though to a lesser extent than during the bracketing warm phases. In contrast, during the Mid to Late Holocene, in the absence of ice sheet forcing, the NA storm tracks were likely more northern, thus less frequently affecting Southern Europe. Therefore, centennial-scale variations may have induced stronger aridity in the Mediterranean region.

5 Conclusions

The deglacial and Holocene climate of the Southern Central Mediterranean are examined at orbital and millennial to centennial time-scale using a marine pollen record (MD04-2797CQ). Our reconstruction provides an integrated picture of the regional vegetation changes and main regional climate features over the last 18 000 yr:

- Prevailing dry conditions during the deglaciation are indicated by the dominance of semi-desert plants. Conditions remained arid even during the GI-1, restricting the expansion of the trees and shrubs despite climatic amelioration.
- Our land-sea correlation shows with no chronological ambiguity that even though temperatures increased at the GS-1 – Holocene transition in the Southern Central Mediterranean, tree and shrub expansion was strongly limited by moisture deficiency persisting into the Early Holocene up to 10.1 kyr.
- Temperate trees and shrubs with heaths as oak forest understorey or heath maquis expanded between 10.1 and 6.6 kyr while Mediterranean plants only

developed from 6.6 kyr to the Late Holocene. Climate in Southern Central Mediterranean was wetter during the Early Holocene interval corresponding to Sapropel 1 and became drier during the Mid- to Late Holocene, mainly because of a change in winter precipitation while summers remained dry.

Our findings suggest, in agreement with modelling experiments, that the Holocene long-term winter precipitation change in the Mediterranean region depends on the mid-latitude atmospheric circulation which is basically controlled by insolation and ice sheet volume. In particular, increased melting of the LIS between 10 and 6.8 kyr combined with weak winter insolation played a major role in the Mediterranean winter precipitation maxima during the Early Holocene. This feature is likely related to more frequent NA storm tracks in a mean southern position, feeding the Mediterranean cyclogenesis, than during the Mid to Late Holocene. Summer dryness along the Holocene suggests a northern progression that may be related to the development of subtropical subsidence in summer in relation with the Early Holocene monsoonal intensification.

Finally, our data provide evidences on the impact of Holocene centennial-scale climate changes on the Central Mediterranean vegetation (11.5–11 kyr, 10.3–9.9 kyr, 9.5–9.1 kyr, 8.5–7.9 kyr, 7.3–6.7 kyr, 6.4–6 kyr, and at around 5.5 kyr and 4.5 kyr). The lack of response of the Mediterranean forest but detection of herbaceous composition changes during the wet Early Holocene indicate muted changes in precipitation contrasting with episodes of enhanced aridity during the Mid- to Late Holocene. We suggest that the impact of the Holocene centennial-scale variability results from baseline climate states, insolation and ice sheet volume, shaping the response of the mid-latitudes atmospheric circulation.

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Table 1. Radiocarbon ages, corrected ages for age reservoir according to Siani et al. (2001) and calibrated ages using INTCAL 09 (Reimer et al., 2009).

Depth (cm)	^{14}C age (year BP)	Depth (cm)	Mean ^{14}C age from paired duplicates (year BP)	1 σ error (year)	Reservoir corrected ^{14}C age (year BP)	Lower cal age (year)	Upper cal age (year)	Calibrated ages (year cal BP)	1 σ error (year)
0	1105± 20			20	705	661	674	668	9
80	5425 ± 30	80	5493	95	5093	5725	5929	5827	144
80	5560 ± 25								
160	6760 ± 30	160	6700	85	6300	7156	7325	7241	120
160.5	6640 ± 30								
199	7580 ± 30	199	7523	81	7123	7917	8017	7967	71
199.5	7465 ± 30								
239.5	8170 ± 40	240	8113	81	7713	8419	8557	8488	98
240	8055 ± 35								
329.5	8810 ± 35	330	8888	110	8488	9398	9556	9477	112
330	8965 ± 30								
410	10 885 ± 40	410	10 863	32	10 463	12 458	12 528	12 493	49
410.5	10 840 ± 40								
469.5	12 850 ± 50	470	12 728	173	12 168	13 786	14 246	14 016	325
470	12 605 ± 40								
510.5	14 000 ± 60	510	13 900	141	13 100	15 495	16 373	15 934	621
511	13 800 ± 100								
610	15 590 ± 50	610	15 590	50	15 190	18 463	18 986	18 725	370
610.5	16 160 ± 60								
700	18 180 ± 60	700	17 660	70	17 260	20 287	20 541	20 414	180
700	17 660 ± 70								
939.5	23 300 ± 100	940	23 415	163	23 015	27 645	28 113	27 879	331
940.5	23 530 ± 120								
1029.5	26 100 ± 130	1030	26 095	7	25 695	30 379	30 600	30 490	156
1030	26 090 ± 150								

Table 2. Description of the MD04-2797CQ pollen record.

Pollen Zones	Interval (cm)	Pollen zone age (cal yr BP)	Description of pollen zones	Vegetation changes	Inferred climatic changes
PZ-7	70–24	5300–2200	Highest values of evergreen *Quercus* and from 40 cm, *Olea* and low percentages of Cyperaceae and Ericaceae. Peaks in deciduous *Quercus* of 20–25 %	Open Mediterranean forest with increased Mediterranean plants contribution	Decreased humidity
PZ-6	120–75	6600–5300	Decreasing values of Cyperaceae and Ericaceae Increasing percentages of Mediterranean taxa (evergreen *Quercus*, *Olea* and *Pistacia*) and deciduous *Quercus*	Expansion of an open Mediterranean forest with Asteraceae-Poaceae steppe	Transition to a period with less rainfalls
PZ-5	344–125	10 100–6600	Increase in AP percentages although AP representation is weak, mainly deciduous *Quercus* and occurrences of Mediterranean taxa (evergreen *Quercus*, *Olea* and *Pistacia*) High *Taraxacum*-type percentages. Highest values of Ericaceae and Cyperaceae. Recurrent oscillations in Cyperaceae percentages.	Open oak forest with heath underbrush or maquis and Asteraceae-Poaceae-Cyperaceae steppe	Increased humidity Centennial oscillations
PZ-4	404–350	12 300–10 100	Fall of semi-desert taxa percentages and rise of *Taraxacum*-type. Decreasing trend in semi-desert percentages (25 to 10 %, mainly *Ephedra fragilis*-type and Chenopodiaceae). Decrease in *Pinus* and virtual absence of *Cedrus* Minor increase in deciduous *Quercus* Gradual increase of Ericaceae and Cyperaceae values	Steppe with Asteraceae, Poaceae and some semi-desert plants and development of oak woodlands with heath underbrush or maquis	Warmer conditions and gradual increase in humidity, although limited precipitations
PZ-3	430–408	13 100–12 300	Rise in *Artemisia*, *Ephedra distachya*-type, *Cedrus* and Cupressaceae values	Steppe with ragweed, chenopods, *Ephedra* and scarce cypress lowland Cedar-pine conifer forest upland	Cold and dry
PZ-2	480–440	14 700–13 100	Decrease in *Artemisia*, *Ephedra distachya*-type although semi-desert plant remains dominant, *Cedrus* and Cupressaceae values Small but significant increase in AP taxa, in particular Mediterreanean tree taxa (evergreen *Quercus* and *Olea*), and Ericaceae Increase in *Taraxacum*	Steppe with semi-desert plants and scarce Mediterranean woodlands Pine conifer forest upland	Warmer and less dry (limitation in water availability, decreasing trend).
PZ-1	590–500	18 200–14 700	Dominance of NAP taxa, in particular semi-desert taxa (*Artemisia*, Chenopodiaceae, *Ephedra distachya*-type, *Ephedra fragilis*-type) Continuous presence of deciduous *Quercus* High *Pinus* percentages and peaks of *Cedrus* and Cupressaceae	Steppe with ragweed, chenopods, Ephedra and scarce cypress lowland Cedar-pine conifer forest upland	Cold and dry

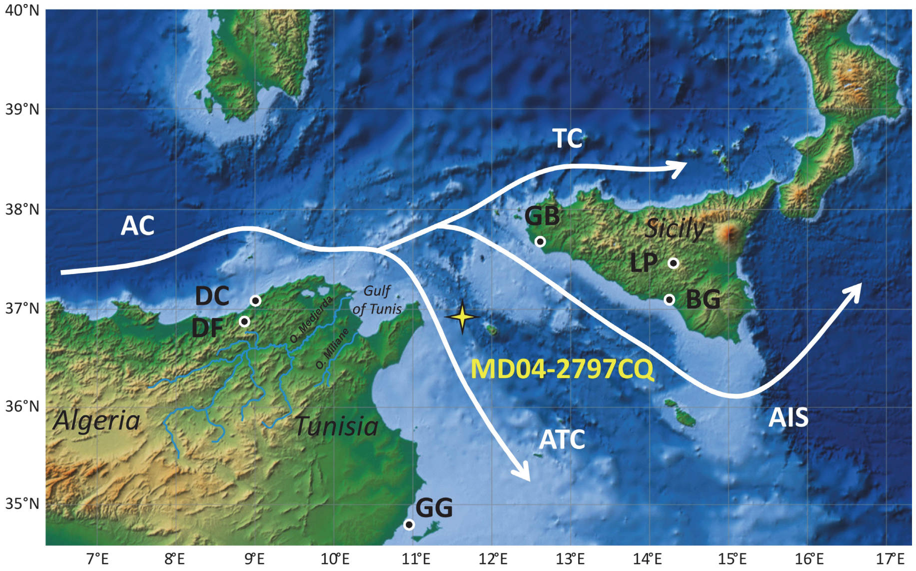

Fig. 1. Map of Central Mediterranean with location of the studied core MD04-2797CQ and the pollen sequences mentioned in the text from the Southern Central Mediterranean. DF: Dar Fatma (Ben Tiba and Reille, 1982), MH: Majen Ben M'Hida (Stambouli-Essassi et al., 2007), GB: Gorgo Basso (Tinner et al., 2009), LP: Lake Pergusa (Sadori and Narcisi, 2001), BG: Biviera di Gela (Noti et al., 2009).

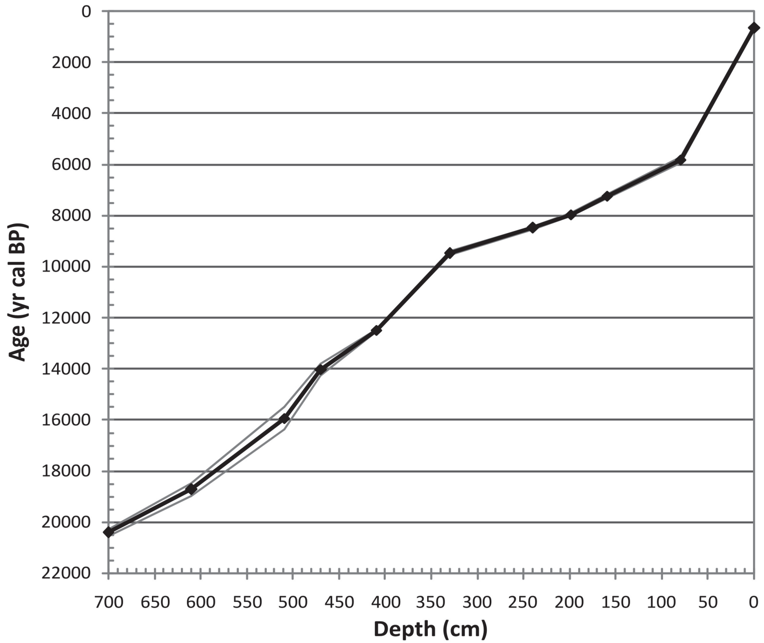

Fig. 2. Age-depth model for core MD04-2797CQ.

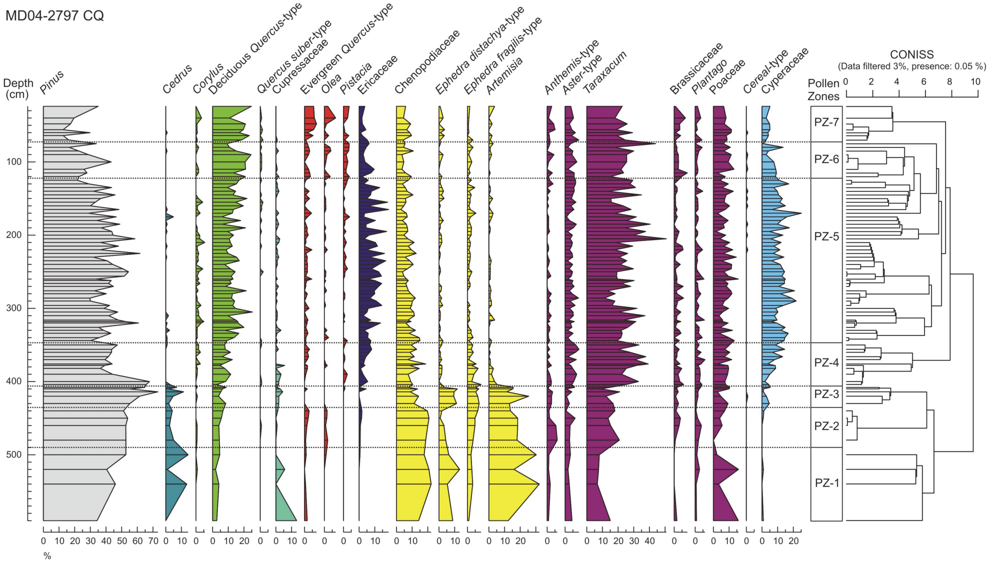

Fig. 3. Percentages of major pollen taxa versus depth, Core MD04-2797CQ, Siculo-Tunisian Strait. Boundaries of pollen zones are based on visual inspection of data and application of clustering analysis (see text for details).

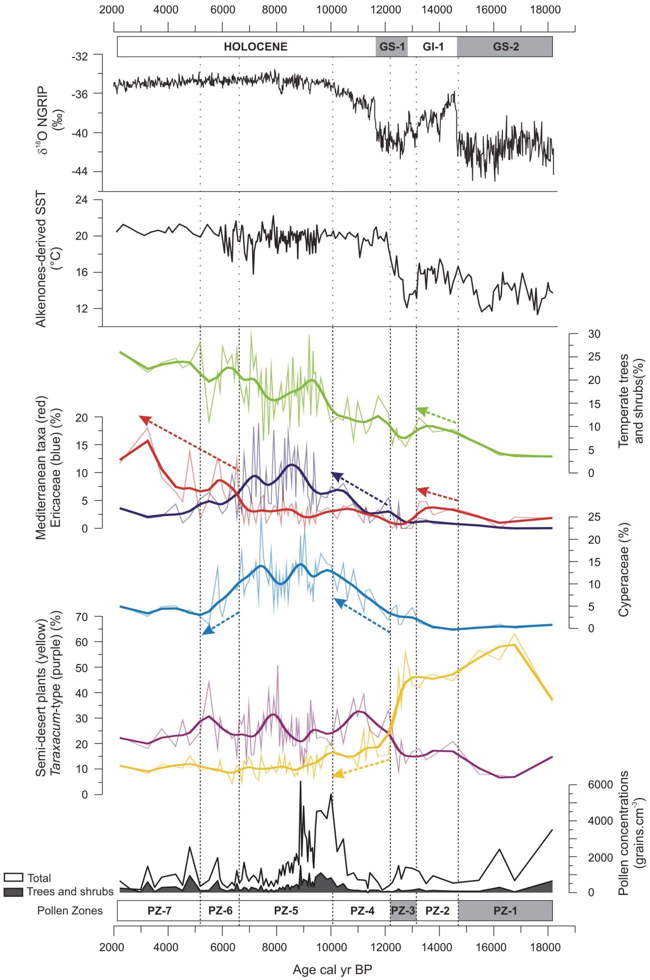

Fig. 4. Caption on next page.

Fig. 4. Vegetation and climatic changes on land over the last 18 000 yr. From the bottom to the top: tree and shrubs (grey) and total (white) pollen concentrations, pollen percentages of selected pollen taxa and ecological groups, SST derived from alkenones (Sicre et al., 2012) from core MD04-2797CQ, δ^{18}O from NGRIP ice core on GGC05 time-scale (converted to BP) (Rasmussen et al., 2006; Vinther et al., 2006). Long-term Holocene vegetation evolution has been detected by applying a smoothing cubic spline method to selected pollen taxa data. Pollen zones (bottom) and stratigraphical framework (top) are indicated. Note that we will name the Younger Dryas as Greenland Stadial 1 (GS-1) following the INITIMATE recommendations (Lowe et al., 2008) but we will keep using HS 1 in the text (as defined by Sánchez Goñi and Harrison, 2010) because the isotopic changes during GS-2 are difficult to reconcile from one Greenland ice core to another (Rasmussen et al., 2008) and the correlation between GS-2a and HS 1 has to be confirmed.

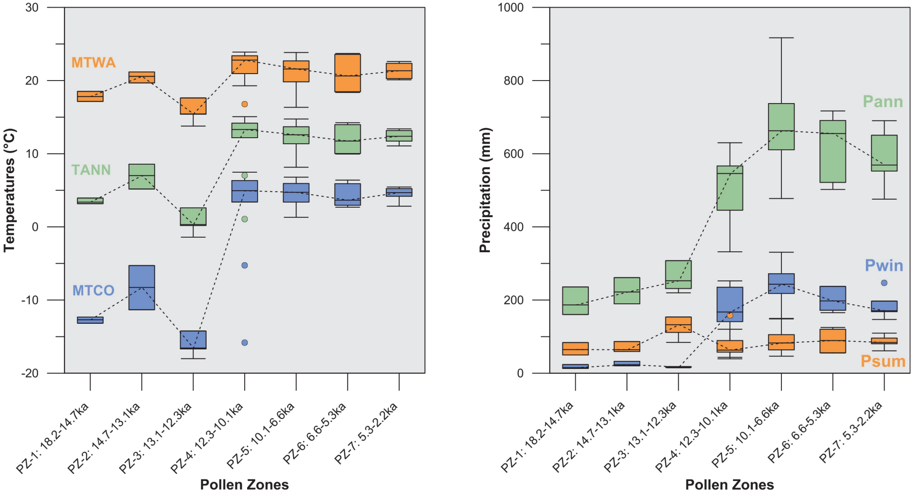

Fig. 5. Box–Whisker plots of estimated annual, summer and winter temperatures (TANN, MTWA, MTCO) and precipitation (Pann, Psum, Pwin) derived from the pollen data of core MD04-2797CQ (Peyron et al., 2012a).

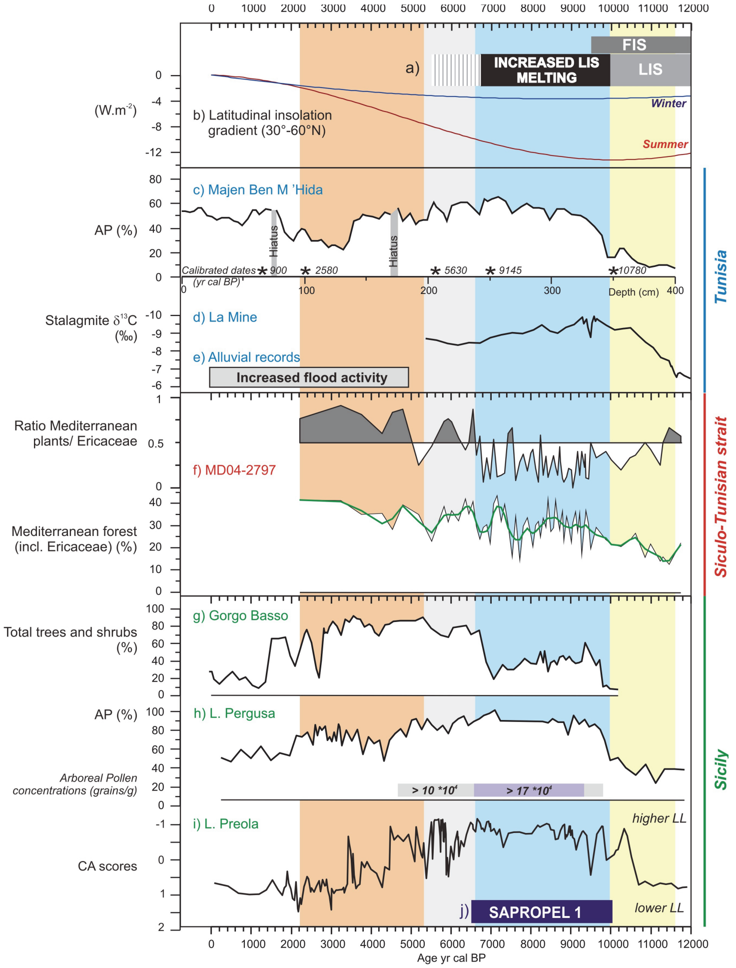

Fig. 6. Caption on next page.

Fig. 6. Comparison of the pollen data from core MD04-2797CQ with other records from Southern Central Mediterranean and with insolation and ice sheet forcing. *Forcings*: **(a)** Early Holocene ice sheet deglaciation: disappearance of the Fennoscandian Ice Sheet (FIS) at 9.5 kyr cal BP (Lundqvist and Saarnisto, 1995) and enhanced Laurentide Ice Sheet (LIS) retreat between 10 and 6.8 kyr cal BP with only small ice caps remaining up to 5.5 kyr (Carlson et al., 2008); **(b)** summer (JJA) and winter (DJF) latitudinal insolation gradient calculated from insolation values at 60° and 30° N (Berger and Loutre, 1991);*Tunisia*: **(c)** peat pollen sequence Majen Ben M'Hida: digitalized data *versus depth* (Stambouli-Essassi et al., 2007), asterisks: original dated levels (65 cm: 985 ± 30 yr BP; 100 cm: 2500 ± 50 yr BP; 205 cm: 4894 ± 40 yr BP; 250 cm: 8190 ± 50 yr BP; 350 cm: 9480 ± 100 yr BP) and calibrated ages using Calib 6.11 (903 (873–959); 2578 (2365–2740); 5629 (5585–5716); 9144 (9014–9287); 10782 (10504–11143) yr cal BP); **(d)** δ^{13}C speleothem record from La Mine cave (Genty et al., 2006); **(e)** Shaded bar representing the increased fluvial dynamics since 5 kyr with recurrent floods associated to drier conditions, based on alluvial sequences from arid to semi-arid Central and North Tunisian floodplains (Zielhofer and Faust, 2008); *Siculo-Tunisia Strait*: **(f)** MD04-2797CQ pollen data: total trees and shrubs percentages including Ericaceae with smoothing cubic spline (bold green line) and ratio of Mediterranean plants to Ericaceae; *Sicily*: **(g)** total trees and shrubs percentages from Gorgo Basso pollen sequence (Tinner et al., 2009); **(h)** Arboreal pollen percentages and arboreal pollen grain concentrations from Lake Pergusa sequence (Sadori and Narcisi, 2001; Sadori et al., 2011); **(i)** relative changes in lake level (LL) from Lake Preola (Magny et al., 2011b); **(j)** Interval corresponding to Sapropel 1 after Mercone et al. (2000). The colored vertical bars represent the successive intervals as described in the text: yellow for the dry interval at the beginning of the Early Holocene, blue for the wet Early Holocene phase, grey for the Mid-Holocene transitional interval and orange for the Mid- to Late Holocene phase of increasing dryness.

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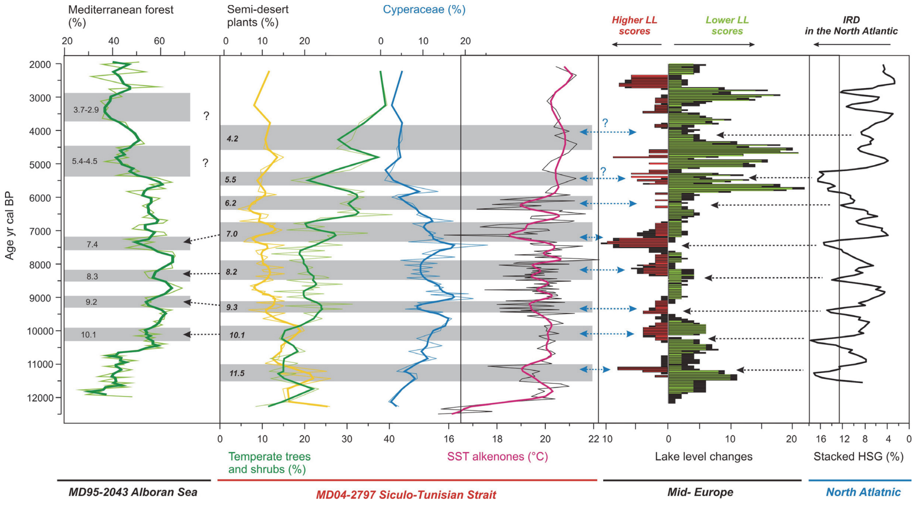

Fig. 7. Comparison of the centennial-scale variability recorded in core MD04-2797CQ with changes detected in the Western Mediterranean, middle latitudes of Europe and North Atlantic. From left to right: Mediterranean forest pollen percentages from core MD95-2043 (Fletcher and Sánchez Goñi, 2008): 3-points moving average (bold green line) with forest reduction episodes indicated by the grey bars as in Fletcher et al. (2012); MD04-2797CQ pollen percentages and alkenone-SSTs (bold lines: cubic smoothing splines with a degree of freedom adjusted to highlight the centennial-scale changes) with abrupt vegetation and SST changes as described in the text; Mid-European lake level (LL) changes (Magny, 2004); Stacked Hematite Stained Grains (HSG) from North Atlantic records (Bond et al., 2001).