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Holocene vegetation and climate changes in central Mediterranean inferred from a high-resolution marine pollen record (Adriatic Sea)

N. Combourieu-Nebout[1], O. Peyron[2,3], V. Bout-Roumazeilles[4], S. Goring[5], I. Dormoy[3], S. Joannin[3,6], L. Sadori[7], G. Siani[8], and M. Magny[3]

[1]CNRS/UVSQ/CEA – UMR8212, LSCE, Gif sur Yvette, France
[2]CNRS – UMR5059 CNRS, CBAE-centre de Bio-Archéologie et d'Ecologie, Montpellier, France
[3]CNRS – UMR6249 CNRS, Laboratoire Chrono-Environnement, Besançon, France
[4]CNRS – UMR8217, Géosystèmes, Université Lille 1, France
[5]Department of Geography, Univ. of Wisconsin-Madison, Wisconsin, 53706, USA
[6]School of Environment and Development, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[7]Dipartimento di Biologia Ambientale, Università "La Sapienza", Roma, Italy
[8]CNRS – UMR8148, IDES, Département des Sciences de la Terre, Université Paris Sud, Orsay, France

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Correspondence to: N. Combourieu-Nebout (nathalie.nebout@lsce.ipsl.fr)

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Abstract

To understand the effects of future climate change on the ecology of the central Mediterranean we can look to the impacts of long-term, millennial to centennial-scale climatic variability on vegetation in the basin. Pollen data from the Adriatic Marine core MD 90-917 allows us to reconstruct vegetation and regional climate changes over the south central Mediterranean during the Holocene. Clay mineral ratios from the same core reflect the relative contributions of riverine (illite and smectite) and eolian (kaolinite) contributions to the site, and thus act as an additional proxy with which to test precipitation changes in the Holocene.

Vegetation reconstruction shows vegetation responses to the late-Glacial Preboreal oscillation, most likely driven by changes in seasonal precipitation. Pollen-inferred temperature declines during the early-mid Holocene, but increases during the mid-late Holocene, similar to southern-western Mediterranean climatic patterns during the Holocene. Several short climatic events appear in the record, indicating the sensitivity of vegetation in the region to millennial-scale variability.

Reconstructed summer precipitation shows a regional maximum between 8000 and 7000 cal yr BP similar to the general pattern across southern Europe. Two important shifts in vegetation occur at 7700 and between 7500 and 7000 yr. These vegetation shifts are linked to changes in seasonal precipitation and are correlated to increased river inputs respectively from the north (7700 event) and from the central Adriatic borderlands (7500–7000 event). These results reinforce the strengths of multi-proxy analysis and provide a deeper understanding of the role of precipitation and particularly the seasonality of precipitation in mediating vegetation change in the central Mediterranean during the Holocene.

1 Introduction

The Mediterranean is highly sensitive to climate change, and Mediterranean ecosystems, already widely affected by anthropogenic pressures, are likely to be strongly impacted by future heat and drought stresses. Precipitation changes are of particular concern for the region. Increasing dryness predicted by GCMs for the Mediterranean will induce large water resource deficits and might threaten the region's habitability (Giorgi, 2006; IPCC, 2007; Giorgi and Lionello, 2008). While modern Mediterranean precipitation is controlled by the influences of both subtropical and mid-latitudinal climatic belts, resulting in dry summers and rainy winters, climate in the Mediterranean has changed during the Holocene, providing an opportunity to study ecosystem response under a range of climate conditions. In particular, past shifts in precipitation may help to envisage the future response of the Mediterranean region to predicted climate change. Reconstructions of past vegetation and climate in the different basins of the Mediterranean will thus produce information that allows us to draw a general framework to understand regional change and the drivers of environmental and climate change across the Mediterranean basin.

The South Adriatic provides an excellent opportunity to record high-resolution vegetation changes in Italy and the Balkans in response to Holocene climate variability. Its central location in the Mediterranean basin should be highly sensitive to the connections and conflicting influences between Northern and Southern atmospheric systems and their relative roles in mediating precipitation and runoff in the central Mediterranean during the Holocene.

Holocene vegetation change in the central Mediterranean has been investigated using continental and marine records (e.g. Watts et al., 1996; Combourieu-Nebout et al., 1998; Jahns and van den Bogaard, 1998; Magri, 1999, Magri and Sadori, 1999; Allen et al., 2002; Oldfield et al., 2003; Piva et al., 2008; Kotthoff et al., 2008, 2011; Di Donato et al., 2008; Di Rita and Magri, 2009; Di Rita et al., 2013). Although these records vary in temporal and taxonomic resolution, they show a general pattern of forest expansion linked to warming climates in the Holocene, as well as the influence of millennial scale climate variability on continental paleoenvironments. Most records from the central Mediterranean divide the Holocene into three phases, similar to those in other regions of the Mediterranean (e.g. Jalut et al., 2000, 2009; Finne et al., 2011) with boundaries that have been recently refined by Walker et al. (2012): (i) an early Holocene humid period from 11 700 to 8200 yr; (ii) a mid-Holocene transitional period from 8200 to 4200 yr; and, (iii) a late-Holocene period of aridification following 4200 yr.

The new vegetation record from the marine MD-90-917 core indicates a new pattern of change for the central Mediterranean. This study, part of the French multi-proxy project LAMA, provides a new understanding of the links between hydrological variability, climate and vegetation in the central Mediterranean by confronting continental and marine data to draw an integrated interpretation of the paleoenvironmental response to Holocene climate changes. This paper investigates the impacts of long-term and millennial-scale climate variability during the Holocene through temperature and precipitation stresses on Italian and Balkans vegetation. By examining dust inputs through clay fraction ratios from the same core we will be able to discuss patterns of local and regional runoff linked to precipitation and seasonality changes.

2 Lithology and age model

Core MD 90-917 (41° N, 17° 37′ E) was obtained in the Adriatic Sea by the R/V *Marion Dufresne* at a depth of 1010 m (Fig. 1). The core is described more fully in Combourieu-Nebout et al. (1998) and Siani et al. (2004, 2010). Sediments are composed of 21 m of clay, interrupted by two black layers corresponding to the deposition of the S1 sapropel in two levels, S1a and S1b, respectively, at 249–255 and 229–239 cm downcore (Siani et al., 2004). The pollen record presented in this paper focuses on the upper 3.3 m of the core.

The age model of the core uses tephra layers and 21 AMS ^{13}C dates performed on monospecific assemblages of planktonic foraminifera (Siani et al., 2004, 2010, 2013).

For this paper, only 13 ^{13}C dates are used, providing a reliable age model for the last 13 000 cal yr BP (Table 1).

3 Present-day environmental settings

3.1 Climate and atmospheric circulation pattern

Atmospheric circulation in the Adriatic is controlled by two dominant climatic systems. In the winter the Eurasian high extends south-westward, retreating northward in the summer when it is replaced by the north-eastward expansion of the Açores high. This pattern results in a typically Mediterranean climate (Fig. 1): winters are generally stormy and cool/cold while summers are warm/hot and dry. Spring climate in the region is generally long, characterized by fluctuating weather while autumn is very short with an abrupt transition toward winter. The length and intensity of summer dryness increases southwards across the Adriatic; total annual precipitation grades from a maximum in the east to a minimum in the west (Fig. 1). The mountainous regions in the Adriatic basin may show patterns that are dramatically different than their surroundings. In the Apennines or Dinarides temperatures decrease and precipitation increases according to altitudinal elevation.

A number of winds blow over the central Mediterranean (Fig. 1). The Bora is a cold wind that commonly blows from the North and North-east during winter. The Mistral (Italian Maestral) is a northwest wind that blows from spring to autumn, more often in summer with decreasing strength to the south. The Sirocco blows from the south from autumn to spring, bringing dust from North Africa. The Ostro is a southerly wind often identified with the Sirocco. The Jugo is an east to south-east dry wind that blows most often in the winter. The west to south-west wind called Libeccio blows year-round but rarely reaches the Adriatic basin.

3.2 Hydrology of Adriatic basin

The hydrology of the Adriatic Sea is seasonally controlled by winds and river inputs. Sea surface circulation follows a general pattern with a south–north inflow from the Ionian Sea through the Otranto basin and then along the east coast, and a north-south outflow along the west coast of the basin. The outflow is strengthened by the discharge from the Po River as well as from small rivers running into the Adriatic along the eastern Italian coast (Fig. 1). The eastern Balkans do not contribute significantly to fresh water inputs into the Adriatic since rivers in the region have short runs with low flow, producing only local effects near the coast. Thus contributions to the fresh water and nutrient inputs in the Adriatic basin are largely derived from Italian river systems. These inputs are dominated by Po River discharges, primarily fed by snow melt in the spring and high run-off in the autumn, particularly in the northern reaches of the watershed (Cattaneo et al., 2003; Frignani et al., 2005; Orange et al., 2005; Palinkas and Nittrouer, 2007).

3.3 Present-day vegetation

Vegetation is organized in altitudinal belts on the Adriatic borderlands according to their ecological significance. Four dominant vegetation types exist in Italy, associated with increasing elevations from the coast to high elevations: the thermo-, meso-, supra- and oromediterranean vegetation types. The thermomediterranean belt is dominated by *Olea* and *Ceratonia* at the lowest elevations; the mesomediterranean belt is composed largely of *Quercus ilex-coccifera* forest; supramediterranean (600–800 m) vegetation is defined by deciduous oak forest with *Quercus* and *Carpinus*; and, at the highest elevations, the oromediterranean belt is characterized by an *Abies-Fagus sylvatica* forest (Ozenda, 1975).

The Dalmatian vegetation has been described by Horvat et al. (1974) and Polunin (1980). Adriatic islands, covered by *Quercus ilex* forest are now largely replaced by pine forest. Inland, forests are dominated by supramediterraean vegetation at higher

altitudes, composed of deciduous trees such as *Carpinus*, *Ostrya*, *Fraxinus* and *Quercus*. At higher elevation where summer precipitation is higher, montane forests are mainly dominated by *Fagus*, *Abies alba* and *Picea*.

Natural vegetation in the region has been affected by human pressure in recent times; forest clearance and intensive farming often result in landscapes of bush-wood or open vegetation.

3.4 Pollen inputs

Palaeoenvironmental interpretation of the changes depicted in the pollen assemblages is based on the assumption that the pollen signal recorded in the marine core reflects the regional vegetation across an area of several hundred square kilometres (Heusser and Balsam, 1977; Dupont and Wyputta, 2003; Hooghiemstra et al., 1992, 2006). Pollen composition in deep basins of the Adriatic Sea must then be strongly affected by the dominant winds and hydrological currents that bring pollen grains from their source to the site in which they are ultimately carried.

Most pollen grains within the MD90-917 core, and especially arboreal pollen from *Quercus*, *Quercus ilex*, *Carpinus*, *Corylus*, *Fraxinus*, and *Abies* are likely to originate on either coast of the Adriatic basin given similarities between coasts in the modern vegetation community structure (Ozenda, 1975; Horvat et al., 1974). However, natural stands of *Olea* are nearly absent on the Dalmatian coast today and are only found in southern Greece on the Balkan peninsula (Ozenda, 1975), thus *Olea* pollen grains are more likely to arrive from the Italian cost. Nevertheless, olive cultivation by human societies during the last millennia (Mercuri et al., 2012) may contribute to broader *Olea* representation. *Picea* today grows only in the Dalmatian mountains, in the northern Apennines and the Alps, therefore its pollen is likely to be derived from these areas, brought to the Adriatic core site by Po river inflow. *Picea* may also be carried by eastern winds, however, *Picea* pollen grains are considered to be transported relatively short distances by wind in Europe (Hicks, 2001), thus *Picea* pollen is probably of northern origin, deposited to the site by discharge from the Po river.

Ultimately, pollen inputs into the Adriatic basin will draw a broad regional picture of Italian and Balkan vegetation from the wide range of habitats extending from the coast to the highlands.

3.5 Clay mineral origin

The Po River and the eastern Apennine rivers are the main sources of clay-sized particles in the western Adriatic. Although the Apennine rivers have relatively small drainage areas, studies have shown that they have very high sediment contributions relative to their drainage area (Frignani et al., 1992; Milliman and Syvitski, 1992; Alvisi et al., 1996; Bartolini et al., 1996; Sorgente, 1999; Tomadin, 2000). Detrital material in the Po River comes largely from the Alps, supplying illite, associated with chlorite, to the Adriatic Sea (Chamley, 1989; Alonso and Maldonado, 1990; Tomadin, 2000). Because illite is resistant to degradation and transport it generally represents the relative contribution of physical weathering to sedimentation. As a result, illite dominates the clay mineral sediment fraction in the deeper parts of the Adriatic (Tomadin, 2000). By contrast, Apennine sediment sources are rich in smectite, which is mainly dispersed southeastward along the coast, with further downslope transport toward the deep basin through seasonal gradient and turbidity currents (Franco et al., 1982; Tomadin, 2000).

Croatian rivers to the east, containing illite and kaolinite with minor smectite (Durn et al., 1999) and Albanian rivers to the south, carrying smectite, supply sediment to the eastern Adriatic. The contribution of these river inputs is reduced because of very low riverine terrigenous loads and particle trapped along the Adriatic margin (e.g. Tomadin, 2000; Cattaneo et al., 2003).

The eolian contribution to deep-sea sediments is of major importance in the Mediterranean. Massive plumes of desert dust export clay-mineral particles toward the Mediterranean (Rea et al., 1985; Guerzoni and Chester, 1996) via regional meridian wind systems (Prospero, 1981; Loye-Pilot et al., 1986; Pye, 1987; Bergametti et al., 1989; Tomadin and Lenaz, 1989; Guerzoni and Chester, 1996; Guerzoni et al., 1999; Moulin et al., 1997; Rodriguez et al., 2001; Torres-Padron et al., 2002; Ginoux et al., 2004). Illite and kaolinite can also be transported through eolian processes. Kaolinite abundance is maximum in the south-eastern Sahara compared to western Sahara while illite displays the reverse pattern (Avila et al., 1997; Caquineau et al., 1998; Guerzoni et al., 1999). The southerly Sirocco wind most likely supplies eolian kaolinite-rich dust from North Africa to the Adriatic Sea during spring and summer (Goudie and Middleton, 2001).

4 Methods

4.1 Pollen record

Pollen extractions from marine sediments followed a previously described standard protocol (e.g. Faegri and Iversen, 1964; Combourieu-Nebout et al., 1998). Samples underwent successive treatments with HCl and HF acids and several sievings to obtain pollen concentrated residues. Pollen grains have been counted on slides with an Olympus light microscope with × 500 magnification. Between 150 and 300 grains were counted in each sample, based on pollen concentration. *Pinus* is over-represented in most marine samples. Because of over-representation of *Pinus* in the MD 90-917 pollen samples, all assemblages had at least 100 non-*Pinus* counts (Heusser and Balsam, 1977; Turon, 1984).

Pollen diagrams use sums excluding *Pinus* pollen. *Pinus* percentages have been calculated using the total sum of identified grains. Pteridophyta is reported using the total sum of all identified pollen grains and Pteridophyta. Pollen zones were visually determined and confirmed using cluster analysis (CONISS software, Grimm, 1987) (Fig. 2a and b).

Fossil pollen assemblages from the MD 90-917 core show similarities to a range of vegetation types from semi-desert to mountain deciduous and coniferous forest. The interpretation of these assemblages follows the modern plant-climate relationships in Eurasia and Northern Africa (Woodward, 1987; Peyron, 1998).

A pollen record spanning from Last Glacial Maximum to Holocene was published by Combourieu-Nebout et al. (1998). This new analysis includes 51 additional counts, improving the temporal resolution of the Holocene section of this core. The new pollen data corresponds to time sampling intervals of from 15 to 500 yr with an average of 140 yr. Samples of the upper 80 cm were pollen poor and did not provide reliable data, possibly as a result of poor pollen preservation. The proposed pollen record, from 3 to 0.8 m depth, highlights vegetation changes at the end of deglaciation and during most of Holocene, from ~ 13 000 to ~ 2500 cal yr BP.

4.2 Pollen-based reconstructions

We use the modern analogue technique "MAT" (Hutson, 1980; Overpeck et al., 1985; Guiot, 1990) to reconstruct past climate for this core. MAT has been successfully tested for the Holocene from Mediterranean terrestrial pollen records (e.g. Davis et al., 2003; Pross et al., 2009; Peyron et al., 2011, 2013; Magny et al., 2012; Joannin et al., 2012) and from marine pollen records (e.g. Kotthoff et al., 2008; Dormoy et al., 2009; Peyron et al., 2013; Desprat et al., 2013) with results that are generally supported by secondary proxies and regional records. Like most pollen-based climate reconstruction techniques, MAT aims to quantitatively reconstruct past climate from fossil assemblages based on the present-day environment.

MAT compares past assemblages to modern pollen assemblages without requiring real statistical calibration, using squared-chord distance to determine the degree of similarity between samples with known climate parameters (modern pollen samples) to a sample for which climate parameters are to be estimated (fossil pollen sample). More details on the MAT are given in Peyron et al. (2013).

This method requires a high-quality, taxonomically consistent modern pollen dataset. The pollen-inferred reconstruction here uses an updated modern pollen dataset compiled by Dormoy et al. (2009), containing more than 2000 samples from the Mediterranean region, to which we added 26 modern surface samples from around Lake Trifoglietti (Calabria, southern Italy) collected by Joannin et al. (2012a), and from around

Mount Altesina and Lake Preola (Sicily). Climate data comes from New et al. (2002). *Pinus* pollen was removed from the modern and fossil samples because of its over-representation in marine pollen assemblages. In this study, the quantitative climate reconstructions for the core MD 90-917 were performed for annual, winter and summer temperature (TANN, MTCO and MTWA), and annual, spring, summer, autumn and winter precipitation (PANN, Pspr, Psum, Paut and Pwin) to emphasize changes in seasonality.

4.3 Sediment clay fraction

Samples were prepared following standard protocols described in Bout-Roumazeilles et al. (2007). All samples were first decalcified with 0.2 N hydrochloric acid. Excess acid was removed by repeated centrifugations. The clay-sized fraction (< 2 µm) was isolated by settling, and oriented on glass slides (oriented mounts). Three XRD (X-ray diffraction) determinations were performed: (a) untreated sample; (b) glycolated sample (after saturation for 12 h in ethylene glycol); (c) sample heated at 490 °C for two hours. The analyses were run on a Philips PW 1710 X-ray diffractometer, between 2.49 and 32.5°. Each clay mineral is characterized by its layer plus interlayer interval as revealed by XRD analysis. Smectite is characterized by a peak at 14 Å on the untreated sample test, which expands to 17 Å after saturation in ethylene glycol and retracts to 10 Å after heating. Illite presents a basal peak at 10 Å on the three tests (natural, glycolated, and heated). Kaolinite is characterized by peaks at 7 and 3.57 Å on the untreated sample and after saturation in ethylene glycol. Both peaks disappear or are strongly reduced after heating. Semi-quantitative estimation of clay mineral abundances, based on the pseudo-voigt deconvolution for the doublet kaolinite–chlorite (3.57–3.53 Å), was performed using the software MacDiff developed by Petschick (2000). Here we use the illite to kaolinite and smectite to kaolinite ratios in order to evaluate the balance between inputs from rivers, respectively Po River (illite) and eastern Apennine rivers (smectite), versus eolian inputs from the south (kaolinite). These ratios are calculated using the semi quantitative estimation of each clay mineral.

5 Vegetation and climate for core MD 90-917

Palynological investigations using marine sediment cores have confirmed close links between pollen data from marine sediments and regional vegetation, and the ability of marine palynology to reconstruct climate changes at a regional scale (e.g. Heusser and Balsam, 1977; Hooghiemstra et al., 1992, 2006; Combourieu-Nebout et al., 2009). The reconstructed vegetation history for MD 90-917 is similar to other Italian and Balkan sequences for the Holocene. This support for the paleoecological accuracy of the MD 90-1917 core suggests its ability to reveal the regional consequences of the climatic events of the last 13 000 cal yr BP on central Mediterranean vegetation (Table 2, Fig. 2a and b).

The Younger Dryas event (GS-1 event) is characterised by the dominance of semi-desert elements such as *Artemisia*, Chenopodiaceae and *Ephedra* (Fig. 2b) which developed extensively around a lowered Adriatic Sea (also described in Combourieu-Nebout et al., 1998). This steppic vegetation is recorded in numerous regional pollen records from the same time (e.g. Watts et al., 1996; Magri and Sadori, 1999; Denefle, 2000; Allen et al., 2002; Bordon et al. 2009; Kotthoff et al., 2008; Combourieu-Nebout et al., 2009; Fletcher et al., 2010; Desprat et al., 2013). They indicate that cold-arid climate conditions prevailing over the whole Mediterranean basin and especially in Adriatic basin (Fig. 3).

Between 12 000 and 11 700 cal yr BP, semi-desert elements are replaced by arboreal association composed by *Quercus*, *Carpinus*, *Corylus* and *Abies* showing the afforestation driven by climatic warming at the beginning of the Holocene (Fig. 2a). The spread of thermophilous taxa is observed from several pollen sequences across central Mediterranean corresponds to the Preboreal improvement at the Younger Dryas/Holocene transition (Bjork et al., 1996), however this begins at an older age in the marine core (e.g. Watts et al., 1996; Sadori and Narcisi, 2001; Allen et al., 2002; Sadori et al., 2011; Di Rita et al., 2013). Forest expansion is interrupted by a strong drop in arboreal taxa around 11 700 cal yr BP, marked by an increase in herbaceous taxa (*Asteroideae* and *Cichoriodeae*) and semi-desert taxa, excluding *Artemisia* (Fig. 2a and b).

Climate reconstructions using pollen data show a decrease in temperature and precipitation at this time (Figs. 3 and 4). Although lake records from the central Mediterranean are rare, the same pattern can be seen, an increase in temperate forest followed by a slight return of herbs (lago Trifoglietti – Joannin et al., 2012a; lago di Vico – Di Rita et al., 2013). This climate oscillation recorded in the MD90-917 appears to lead the Greenland ice cores δ^{18}O record (Fig. 4; Rasmussen et al., 2007) and probably corresponds to the ~ 11 300 yr BP Preboreal oscillation (PBO: Bjork et al., 2001; Magny et al., 2012).

Climatic general trend of the pollen data in the early Holocene coincides with the alkenone-inferred SST increase at the same time, obtained from MD 90-917 (Sicre et al., 2013). Both pollen-based temperature and alkenone-inferred SST responses precede the foraminifer-based SST from this same core (Siani et al., 2013; Sicre et al., 2013). To explain such discrepancies, Sicre et al. (2013) suggest a local response in alkenone-inferred SST record. The temporal lead shown by MD 90-917 relative to the Trifoglietti and Lake Vico vegetation records should not be related to local behavior, since MD 90-917 should be representing the regional vegetation of the central Mediterranean. Given this, age discrepancies between continental records and MD 90-917 may be due to ^{13}C date uncertainties. If this is the case, the lead in vegetation response (and alkenone-inferred SST) relative to foraminifer inferred SST from the same core may suggest that the vegetation response to the Preboreal oscillation in the region could be driven by precipitation changes rather than temperature variations.

After 11 000 cal yr BP, a mixed deciduous forest (mainly dominated by *Quercus* with regular occurrence of and accompanied by *Corylus*, *Carpinus*, *Fagus*, *Alnus*, *Betula*) expands (Fig. 2a and b), peaking around 7000 cal yr BP, corresponding to the “Holocene climate optimum”. This expansion occurs in Italy and in the Balkan peninsula at the same time (e.g. Watts et al., 1996; Jahns and van der Bogaard, 1998; Denèfle et al., 2000; Allen et al., 2002). Evidence for a climate optimum at 7000 cal yr BP agrees well with δ^{18}O from planktonic foraminifers (Fig. 5) and the foraminifer inferred SST increase from the same core (Siani et al., 2013). Increases in regional forest biomass also concur with the depletion in ^{13}C, linked to sea-level rise (Siani et al., 2013) in the early-Holocene since depletion in ^{13}C in core sediments may also be interpreted as an intensification of nutrient supply from the continent to Adriatic Sea.

Although temperate forest dominates the vegetation record from 11 000 cal yr BP until ~ 7000 cal yr BP there are several compositional shifts in that time (Figs. 2a and 3). Inferred vegetation is dominated by *Quercus* which declines repeatedly. *Quercus* is sometimes replaced by a mixed deciduous forest with *Corylus*, *Carpinus*, and *Fagus*, occasionally associated with *Fraxinus* and *Alnus*, or is replaced by a mixed coniferous forest with *Abies* and *Picea*. In the first case, *Quercus* dominated forest are replaced with mixed deciduous forests at around 8300 and 7500 cal yr BP, possibly the expression of a forest opening, resulting in the expansion of heliophilous taxa, sporadically developing in the *Quercus* forest and/or on the forest edges. Such changes might be due to slight changes in summer temperature and precipitation or changes in the spring and autumn (Fig. 3). In the second case, *Quercus* forest is replaced by mixed coniferous forest at 7700 cal yr BP, with *Abies* and *Picea*. This change might reflect a slight cooling and/or change in the seasonal partitioning of precipitation, particularly in the Balkan massifs and/or on the northern part of Adriatic basin given that delivery of *Picea* pollen to the core occurs (i) from the rivers of the north Adriatic slopes and/or (ii) from northern Italy and Alps by Po River discharges and then by marine flows. In fact, *Picea* has not been observed in central and southern Italy during the Holocene, only occurring in the Po valley, Northern Italy and over the northern Balkans (Ravazzi et al., 2002; Van der Knaap et al., 2005). As *Abies* and *Picea* pollen grains are not well-transported by wind (only at 5 m away from the trees) and rarely dominate airborne pollen assemblages (Hicks, 2001; Sjoren et al., 2008), in MD 90-917 sediments, the *Abies Picea* increase at ~ 7700 cal yr BP could therefore express their development in the north and north-east mountains around the Adriatic basin and their carrying towards the studied site through rivers contribution.

Temperate forest dominated by *Quercus* fluctuates between 7000 and 5000 cal yr BP, decreasing after 4500 cal yr BP. *Quercus* becomes less abundant while *Carpinus*, *Corylus* and *Alnus* increase. This marks progressive opening of the forest, corresponding to decreases in summer precipitation, reflected in the pollen-based climate reconstruction. A cold, moist event is inferred from the rise in *Abies*, *Fagus*, and to a lesser extent *Picea* around 4000 cal yr BP (Fig. 3). Increased precipitation would have increased river flows, bringing the poorly dispersed *Abies* pollen to the core location. The upper samples of the core sequence, to 3000 cal yr BP, show an increase in herbaceous taxa (Asteraceae and Poaceae), continuing the trend of declining tree cover, probably influenced by increasing of human impacts in coastal Italy and Balkans. The increase in steppic elements such as *Artemisia* during this period may also indicate regional drying, particularly in the summer, and may represent the establishment of the summer conditions associated with the modern Mediterranean climate.

Mediterranean taxa, primarily *Q. ilex*, are continuously present in the pollen record beginning at 8000 cal yr BP. The Mediterranean forest begins to diversify after 6000 cal yr BP with the continuous presence of *Olea* and *Phillyrea* pollen, and, after 3500 cal yr BP with the presence of *Pistacia*. This coincides with the decreasing abundance of deciduous trees, especially deciduous *Quercus*, and the increase in herbs such as *Asteraceae* and steppic taxa (*Artemisia* excluded) at 3500 cal yr BP. This pattern has been observed elsewhere in the central Mediterranean (Sadori et al., 2011) and marks a shift in the precipitation regime, with decreasing summer precipitation and a progressive establishment of the modern Mediterranean climate (Fig. 3). *Olea*, the emblematic plant of the Mediterranean area, occurs weakly at the beginning of the Holocene and remains sporadic up to 6000 cal yr BP, generally associated only with warming climate. After 6000 cal yr BP *Olea* is continuously present but is most abundant in the upper part of the record, around 3000 cal yr BP, in agreement with the central Mediterranean vegetation history proposed by Sadori et al. (2011) using continental records. *Olea* is present in marine records across the Mediterranean at this time (e.g. Combourieu-Nebout et al., 2009; Desprat et al., 2013) and may also reflect the development of olive cultivation at Italian sites (e.g. Lago di Pergusa, Sadori et al., 2013; Mercuri et al., 2012) and possibly in the Balkans.

6 Climate interpretation

6.1 Temperature pattern

The temperature estimates from the MD 90-917 pollen sequence (Fig. 3) are the first to be reconstructed from Adriatic marine sediments. These results can be compared to temperature signals reconstructed from terrestrial pollen sequences at lakes Ledro, Trifoglietti, Accesa and Pergusa (Fig. 1) for a direct land-sea comparison (Peyron et al., 2013). We present annual (TANN), coldest month (MTCO) and warmest month (MTWA) temperature reconstructions from MD 90-917 (Fig. 3). The lowest MTCO in the record occurs during the Preboreal anomaly, before 12 000 cal yr BP, when temperatures decline about 5–7 °C relative to preceding and subsequent periods. Temperatures decline during the early Holocene, to around 7700 cal yr BP, at which point they increase gradually through the upper part of the record (Fig. 3). Temperature anomalies reconstructed between 6000 cal yr BP and present-day are similar to those proposed for southern Italy by Wu et al. (2007), reinforcing the reliability of our climate reconstruction trends. The reconstructed temperature anomalies also mirror the south-west European temperate curve reconstructed using continental pollen records by Davis et al. (2003) (Fig. 6). This confirms that pollen in the Adriatic Sea reflects southern-western Mediterranean climate influences, more so than southern-eastern influences. This feature changes probably reflect an emphasis of the north–south Mediterranean gradient (Magny et al., 2012) and an increase of westerlies influence in north-central Mediterranean during the upper part of Holocene.

Temperature reconstructions indicate several cold and/or dry events during the last 13 000 cal yr BP: The Younger Dryas event, the Preboreal oscillation, the 8200 cal yr BP event, and others events at 7700, 7000, 6400, 5000 and 3000 cal yr BP (Fig. 3). These

cold events are associated with declines in *Quercus* pollen, and have been detected in other marine cores from Mediterranean (Fig. 7; e.g. Combourieu Nebout et al., 2009; Schmield et al., 2010; Fletcher et al., 2010, 2013; Desprat et al., 2013) and may be linked to to the millennial-scale cold events recorded in North Atlantic (Bond et al., 1997, 2001; Combourieu-Nebout et al., 2009; Schmield et al., 2010; Fletcher et al., 2010, 2013; Fletcher and Zielhofer, 2011; Desprat et al., 2013; Magny et al., 2013). The rapid response of the central Mediterranean to millennial scale variability confirms the influence of mid-latitude atmospheric circulation in propagating changes, depending on insolation and ice sheet volume (Desprat et al., 2013). Our reconstruction suggests that the first two events (Younger Dryas and Preboreal Oscillation) were characterized by sharp seasonal contrast with very cold winters; this pattern differs strongly from the modern climate, which established itself progressively after 7700 cal yr BP with warmer winters more favorable to Mediterranean forest communities (Fig. 3).

6.2 Precipitation pattern

Pollen-inferred annual precipitation for MD 90-917 increases from 12 000 to 3000 cal yr BP with a maximum between 8000 and 7500 cal yr BP (Fig. 3). This trend is mirrored by springs and autumn precipitation, but, while summer and annual precipitation show similar trends of increasing precipitation from the early Holocene to 7500 cal yr BP, summer precipitation declines more strongly than annual precipitation to 3000 cal yr BP. The Holocene summer precipitation trend inferred from our pollen data is similar to speleothem records in central Italy (Zhorniak et al., 2011) and east-Mediterranean (Bar-Matthews et al., 1998, 2011), although speleothems record features that should be linked to changes in winter precipitation (Fig. 8).

The summer precipitation record fits well with the pattern described by Magny et al. (2012), which suggests that lakes located southward of 40° N experienced high lake-levels, reflecting precipitation maxima along the Early to Mid-Holocene in Italy, while northern Italian lakes were characterized by low lake-levels. The summer precipitation inferred from four Italian pollen records appears to confirm the opposing precipitation regimes for northern and southern sites in the Mediterranean during the Holocene (Peyron et al., 2013). There is strong agreement between the high lake-levels reconstructed in Sicily, the wet summer conditions reconstructed for southern Italy by Peyron et al. (2013) and the summer precipitation inferred from the MD 90-917 pollen record. It is of note that the MD 90-917 summer precipitation curve shows similarities with the increasing trend at the northern lake Ledro during the early Holocene while the Mid-to-Late Holocene precipitation curve fits with the southern Mediterranean summer precipitation trend (Fig. 8, Peyron et al., 2013; Joannin et al., 2012b). Such a signal may illustrate the possible conflict of mid-latitudinal and subtropical monsoonal climatic systems in the Mediterranean area and emphasizes the fact that our record is located at the confluence between northern and southern influences. Climate changes recorded here are clearly driven by insolation changes and likely reflect the increasing influence of westerlies during the second half of Holocene, as demonstrated by the rise in winter precipitation in the upper part of our record.

The summer precipitation based on the MD 90-917 pollen record shows good fit to (i) sea surface salinity changes from the same core, interpreted as increasing runoff into the Adriatic deep sea basin (Siani et al., 2013) and (ii) changes in clay mineral composition (Fig. 8). Clays mineral records, presented as illite/kaolinite and smectite/kaolinite ratios (Fig. 8) reflect contributions from the eastern Apennine/Po rivers and dust input from Africa, respectively. These ratios clearly show a change in detrital input. Windblown dust (high kaolinite), supplied from the south by Sirocco winds, is more abundant during the first part of Holocene, while the rise of smectite after 9000 cal yr BP indicates the increasing contribution from Italian rivers to the basin.

A first rise in summer precipitation occurs at around 11 900 cal yr BP. Both I/K and S/K display a major peak at 12 500 cal yr BP, suggesting important discharges from both the Po and the eastern Apennine rivers. A single S/K peak at 12 000 cal yr BP suggests a major discharge from eastern Apennine rivers, synchronous with the precipitation maxima as reconstructed from pollen assemblages, related to the Preboreal event (Fig. 8).

Annual precipitation inferred from pollen data shows two maxima in the middle Holocene. During these two events, precipitation seasonality and temperature display two different patterns: (i) at 7700 cal yr BP, a longer humid season is combined with low summer and winter temperatures and (ii) at 7000 cal yr BP precipitation is equitable with no noticeable change in temperature. These two peaks occur at the same time that clay mineral composition changes, with two different signatures, indicative of two distinct sources. The 7700 cal yr BP event shows a major increase in the illite/kaolinite ratio, indicating major discharges from the Po River. This pattern of increasing inflow from the Po agrees well with increases in *Picea Abies* pollen in the sediments and confirms the role of Po discharge in the pollen signal, as well as its probable influence on declines in sea surface salinity during this event (Fig. 8). Both the origin and discharge rate of terrigenous inputs in the Adriatic Sea are seasonally modulated by precipitation distribution (Wheatcroft, 2001; Poulain, 2001). Modern seasonal precipitation influences discharge from the north Adriatic, as is shown for recent floods in the Po River basin (Zanchettin et al., 2008). Therefore, increases in precipitation seasonality probably occurred during the 7700 event, in particular in north and east Adriatic, leading to enhanced Po River discharges which would have driven salinity changes in the Adriatic sea surface and transported *Picea* pollen toward the core site. Such a process should explain why the vegetation change from 8200 to 7500 cal yr BP reported from Trifoglietti (Joannin et al., 2012a) is ascribed to a dry and cold phase, which does not appear in MD 90-917 which shows changes similar to those observed in other Mediterranean records (e.g. Sadori and Narcisi, 2001; Allen et al., 2002).

The second climatic event, around 7000 cal yr BP, shows increasing annual precipitation without increasing *Picea*. At this time, sea surface water are less saline based on δ^{18}O from MD 90-917 (Siani et al., 2013). The 7000 cal yr BP event occurs after the main peak of the illite/kaolinite ratio, indicating a reduced role for Po River discharges, but the event is synchronous with an increase in smectite/kaolinite ratio. Sedimentological studies suggest that the respective contribution of the Po and eastern Apennine rivers has varied through time (Cattaneo et al., 2003). Smectite is not presently supplied to the Adriatic through the Po River and rather originates from Italy slopes through the small but active eastern Apennine rivers flows (Fig. 6). Based on the depth at which the core was obtained, its sedimentation should be mostly under the influence of the illite-rich Po river plume which flows southeastward in the open sea. The smectite-rich southeastward Apennine plumes are generally restricted to shallower depths along the coast. Smectite is transferred toward the deep basin through turbidity and gravity currents when river discharge increases seasonally (Tomadin, 2000). As a consequence the 7000 cal yr BP event likely reflects a local pattern of change, reflecting increases in precipitation affecting the central Italian coast, nearest the core site. This suggests that decreases in salinity were caused by inflow from local rivers. These inputs persisted throughout the second half of Holocene but it is likely that they were then too weak to induce any significant decrease in salinity in Adriatic Sea surface.

7 Conclusions

The MD 90-917 marine pollen record provides the regional signal of central Mediterranean vegetation to long-term and millennial climate fluctuations during the late-Glacial and Holocene, and provides an integrated picture of temperature and precipitation changes during that period:

- the early Holocene is clearly expressed in vegetation changes and, despite a short chronological time-lag with the ice core chronology, the Preboreal climate oscillation is recorded in the core by an expansion of central Mediterranean forest taxa, followed by the return of open vegetation. Shifts in vegetation during the Preboreal oscillation are probably driven by precipitation changes, especially summer precipitation, and are correlated with inputs from local and regional rivers since vegetation changes occurred prior to SST increases recorded in the MD 90-917 core.

- Pollen-based temperature reconstructions follow the pattern reconstructed of other proxies in the southern Mediterranean, with an increasing west and northwest climatic influence. Several cold events are recorded and may be linked to millennial scale variability during the Holocene.

- Precipitation reconstructed from the pollen record shows a trend of increasing annual and seasonal (winter, spring and autumn) precipitation during the Holocene. Summer precipitation reflects a trend seen elsewhere in the southern Mediterranean, with a maximum around 7000 cal yr BP and then a decline until 3000 cal yr BP. Two significant peaks in precipitation occur at 7700 cal yr BP and between 7500 and 7000 cal yr BP that are associated with peak runoff from the Po River and from local central Adriatic rivers, respectively.

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Table 1. Age model for core MD 90-917, AMS ^{13}C ages and corresponding calibrated ages from INTCAL04 (Reimer et al., 2009) integrating a ^{13}C marine reservoir correction (Siani et al., 2001).

Depth (cm)	Species	^{13}C age BP (yr)	Error ±1σ	Cal age BP (yr)
0–2	*G. bulloides*	1010	60	555–609
140–142	*G. ruber*	4180	70	4082–4290
167–169	*G. ruber*	4750	70	4855–4986
175–177	*G. bulloides*	5000	70	5344–5466
190–192	*G. bulloides*	5680	70	5990–6128
230–232	*G. bulloides*	6920	90	7413–7511
240–242	*G. bulloides*	7930	80	8171–8340
250–252	*G. ruber*	8170	70	8390–8482
275–277	*G. bulloides*	10 390	90	11 304–11 624
295–297	*G. bulloides*	10 800	90	12 116–12 399
305–307	*G. bulloides*	10 830	90	12 225–12 406
315–317	*G. bulloides*	11 140	90	12 721–12 853
335–337	*G. bulloides*	11 520	100	12 939–13 114

Table 2. Short description of the pollen zonation of the MD 90-917 pollen diagram.

Pollen zone	Interval cm	Age kyr	Pollen zone signature	Main biome	Climate
MD90 917-XII	80–120	2641–3671	*Pinus* (50 %); ↓ *Abies* (< 4 %) and *Picea* (< 6 %) *Quercus* (45 %), *Carpinus* (6 %) *Corylus* in low percentages, ↑ *Fagus* (4 %) Mediterranean taxa, *Q. ilex* (↑ 12 %), *Olea* (3–4 %) and *Pistacia* (↑4 %) ↑ *Cichoriodeae*; ↑ *Artemisia* (15 %)	Warm temperate Mediterranean oak forest	Warm and humid stability in T° ↑ seasonal Pmm
MD90 917-XI	128–140	3877–4186	*Pinus* (50 %); ↑ *Abies* (< 15 %), *Picea* (3 %) *Quercus* (40 %), *Carpinus* (6 %), *Corylus* and *Fagus* in low percentages, Mediterranean taxa in low percentages, *Q. ilex* (4 %)	Cool mixed forest	Cool and relatively humid
MD90 917-X	142–179	4244–5579	*Pinus* low (20–40 %); Low percentages in *Abies* and *Picea* (< 6 %) ↓ *Quercus* (45 %), ↑ *Carpinus* (↑ 10 %) and *Corylus* (↑ 10 %) Mediterranean taxa in stable percentages, Herbs in stable percentages; slight increase in steppic taxa (5–10 %)	Warm temperate oak forest	Warm and humid stability in T° Pmm slight decrease
MD90 917-IX	180–220	5623–6960	*Pinus* low (20–40 %); low percentages in *Abies* and *Picea* (< 6 %), Temperate trees stable, ↑ *Quercus* (↑ 45–65 %), ↓ *Carpinus* (~ 5 %) and *Corylus* (~ 5 %), ↑ Mediterranean taxa, *Q. ilex* (6–7 %), *Olea*, *Phillyrea* and *Pistacia* ↑ in herbs; *Cichoriodeae* (5–10 %); steppic taxa low	Warm temperate oak forest	Warm and humid – stability in T° and Pmm slightly reiincrease
MD90 917-VIIIb	221–232	7010–7620	*Pinus* (20–50 %), ↓ *Abies* (< 10 %) and *Picea* (< 5 %) decrease, ↑ Temperate trees, *Quercus* stable (< 45 %), *Corylus* (5–20 %), *Carpinus* (4–10 %), *Fagus* (↑ 5 %), *Ulmus*, (↑ 5 %), *Alnus* (3–8 %), Mediterranean taxa stable (*Q. Ilex* mainly, *Olea* and *Pistacia* presence), ↓ Herbs (*Asteraceae* < 5 %, *Poaceae* < 5 %), steppic taxa low (10 %)	Warm temperate oak forest	Warm and humid – increase in T° and Pmm slight decrease

Table 2. Continued.

Pollen zone	Interval cm	Age kyr	Pollen zone signature	Main biome	Climate
MD90 917-VIIIa	233–234	7700–7779	*Pinus* (50 %), ↑ *Abies* (↑ 25 %) and *Picea* (↑ 11 %), ↓ Temperate trees, *Quercus* (< 45 %), *Corylus*, *Carpinus* absent, *Fagus* (↑ 10 %), Mediterranean taxa low, Herbs low, steppic taxa low (slight ↑ *Chenopodiaceae*; 2–5 %)	Cool mixed forest	Cool and humid
MD90 917-VII	235–238	7859–8058	*Pinus* (30–60 %); *Abies* and *Picea* low, Temperate trees: *Quercus* (30–60 %), *Corylus* (< 5 %), *Carpinus* (4 %), *Fagus* (↑ 10 %), Mediterranean taxa low (*Q. Ilex* mainly, *Olea* presence), ↓ Herbs (*Asteraceae* < 5 %, *Poaceae* < 5 %), steppic taxa nearly absent	Warm temperate oak forest	Warm and humid – Max T° and Pmm slight re-increase
MD90 917-VI	239–250	8157–8456	*Pinus* (30–60 %); *Abies* and *Picea* low, Temperate trees: *Quercus* (40 %), *Corylus* (5–10 %), *Carpinus* (4–10 %), *Fagus* (↑ 8 %), Mediterranean taxa ↑ (*Q. Ilex* mainly, *Olea* and *Pistacia* presence), ↓ Herbs (*Asteraceae* < 5 %, *Poaceae* < 5 %), steppic taxa low	Warm temperate oak forest	Warm and humid – Max T° and Pmm slight decrease
MD90 917-V	252–258	8678–9445	*Pinus* (around 50 %), *Abies* and *Picea* low, ↑ temperate trees, maximum *Quercus* (45–70 %), *Corylus* (5–10 %), *Carpinus* (2–10 %), Mediterranean taxa low (*Q. Ilex* only), ↓ Herbs (*Asteraceae* < 5 %, *Poaceae* < 5 %) and steppic taxa low	Warm temperate oak forest	Warm and humid – Max T° and Pmm
MD90 917-IV	259–269	9546–10 737	Large decrease in *Pinus* (< 50 %), *Abies* and *Picea* nearly absent, Increase in temperate trees, *Quercus* (40 %), *Corylus* (5–10 %), *Carpinus* (2–4 %), Mediterranean taxa low (*Q. Ilex* and first occurrence in *Olea*), ↓ Herbs (*Asteraceae* < 12 %, *Poaceae* < 7 %), steppic taxa very low	Warm temperate oak forest	Progressive ↑ T° and Pmm

Table 2. Continued.

Pollen zone	Interval cm	Age kyr	Pollen zone signature	Main biome	Climate
MD90 917-III	270–282	10 858–11 742	*Pinus* abundant (60–80 %), *Abies* and *Picea* percentages low, *Quercus* (20–40 %), ↓ *Corylus* and *Carpinus*, slight ↑ *Alnus*, *Betula*, *Tilia*, ↑ Herbs (*Asteraceae* 20 %), ↑ *Chenopodiaceae* > 10 %)	Grassland mixed to open oak forest	Cool and moderately dry
MD90 917-II	284–288	11 821–11 980	*Pinus* abundant (65–75 %), *Abies* and *Picea* percentages low, ↑ *Quercus* (15–40 %), *Corylus* (↑ 10 %), *Carpinus* (3 %), ↓ Herbs (*Asteraceae* < 20 %, *Poaceae* around 10 %), ↓ steppic taxa low	Open Warm mixed forest	Slight increase in T° and Pmm
MD90 917-I	290–350	12 060–13 257	*Pinus* abundant (65–90 %), *Abies* and *Picea* percentages low, Low percentages in temperate trees, *Quercus* < 20 %, *Alnus*, *Betula*, *Carpinus* present, Herbs abundant, *Asteraceae* 10–20 %, *Poaceae* around 10 %, Steppic taxa abundant (*Artemisia* 15 %, *Chenopodiaceae* 10 %, *Ephedra* up to 7 %)	Steppe	Cold and dry

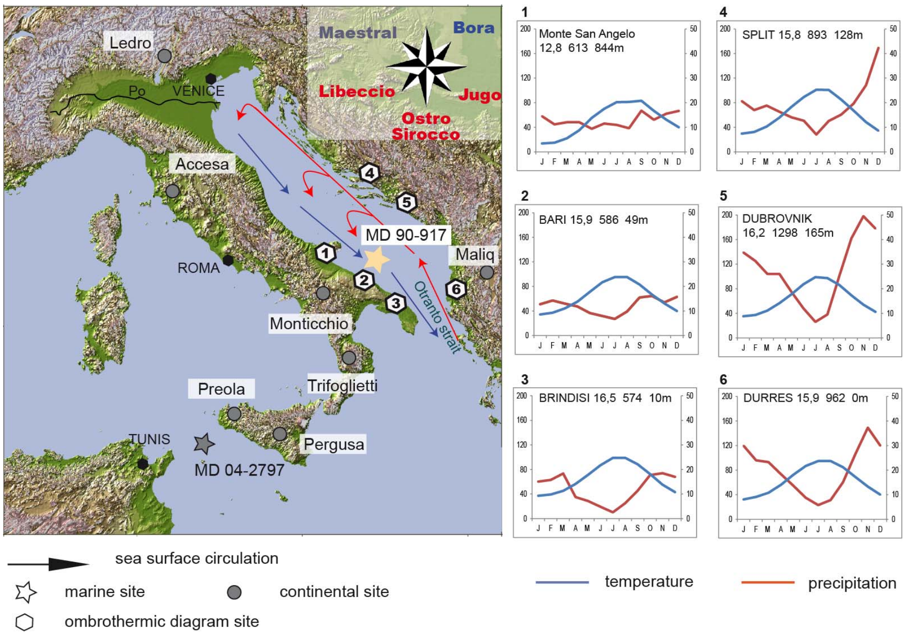

Fig. 1. Location of core MD 90-917. On the map is indicated sea surface circulation in Adriatic Sea and winds blowing over the Adriatic basin. A selection of ombrothermic diagrams are presented on the right for the surrounding borderlands to show the climate of the studied area (Walter et al., 1975; New et al., 2000; New LoCClim software).

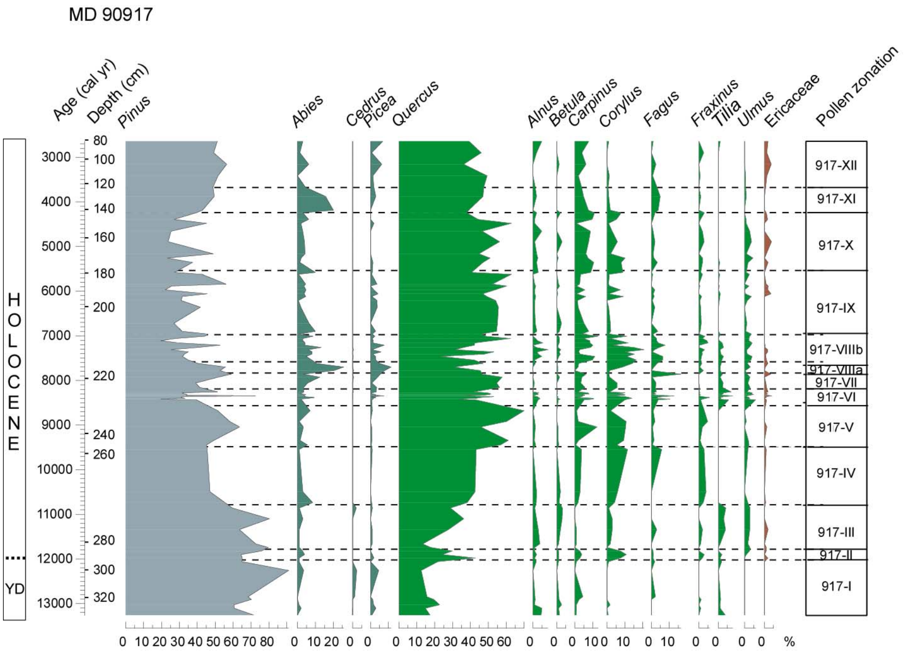

Fig. 2a. Pollen diagram of the Core MD 90-917: arboreal taxa. Pollen percentages are calculated on a sum excluding *Pinus*; *Pinus* percentages are calculated on the total pollen sum.

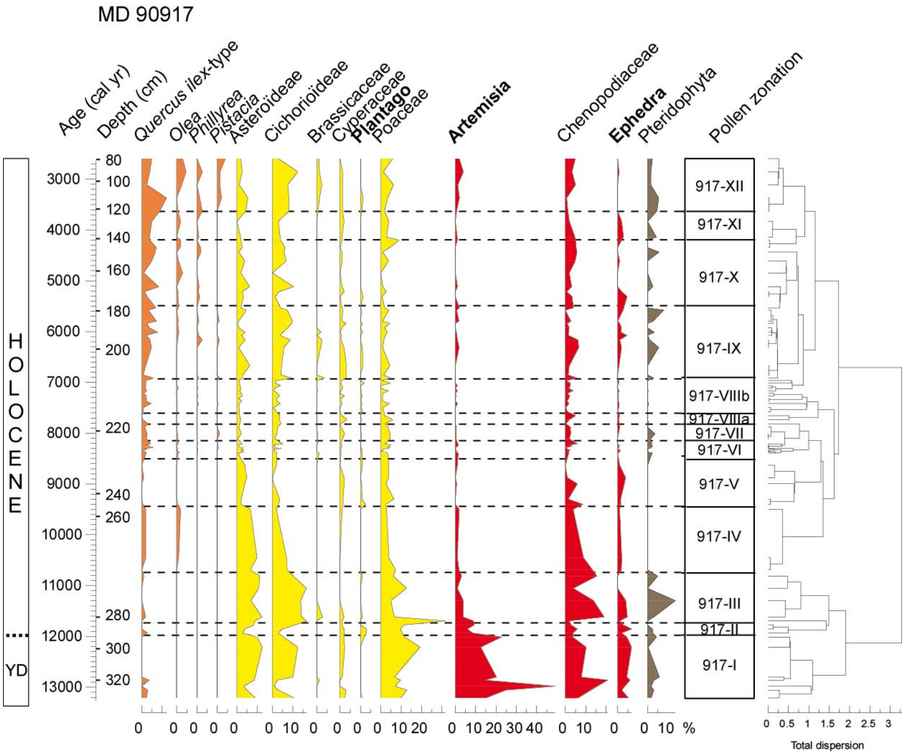

Fig. 2b. Pollen diagram of the core MD 90-917. Mediterranean and herbaceous taxa. Pollen percentages are calculated on a sum excluding *Pinus*. Pteridophyta percentages are calculated on the total pollen sum.

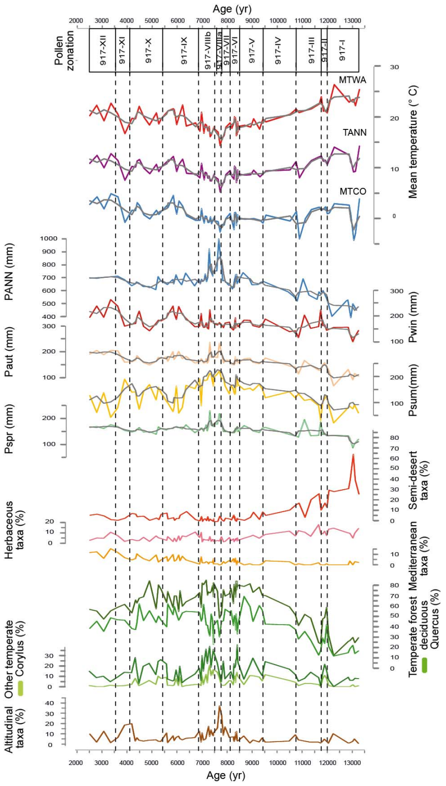

Fig. 3. Selected pollen curves of core MD 90-917 and pollen based reconstruction of precipitation (seasonal – Pspr, Psum, Paut, Pwin – and annual – Pann) and temperature (winter Twin, annual Tann and summer Tsum).

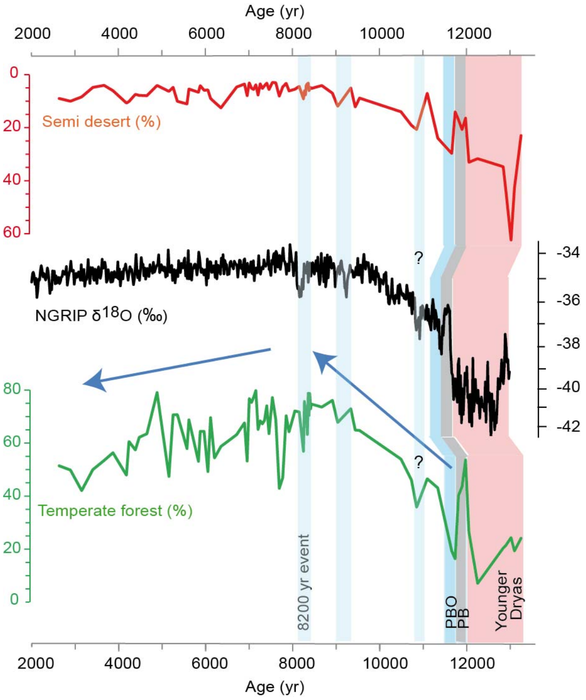

Fig. 4. Comparison between two main pollen groups; temperate trees (green) and semi-desert (red) and NGRIP oxygen isotope record (NGRIP members, 2004; Lemieux Dudon, 2011).

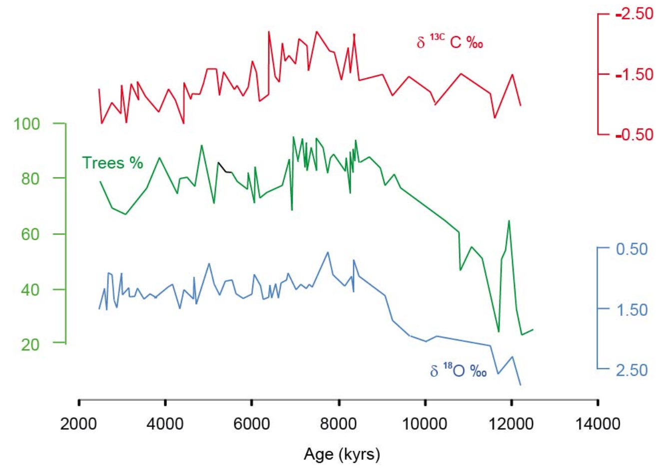

Fig. 5. Comparison of the total tree percentage curve (green) (this paper) and the δ^{18}O (blue) and δ^{13}C (red) record from the MD 90-917 core (Siani et al., 2013).

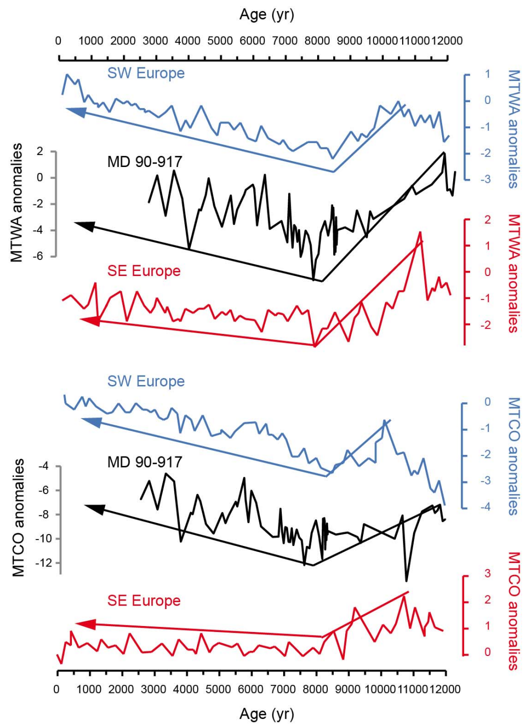

Fig. 6. Comparison between MD 90-917 pollen-based winter and summer temperature reconstructions and the combined climate records of south-eastern and south-western Europe (from Davis and Brewer, 2003).

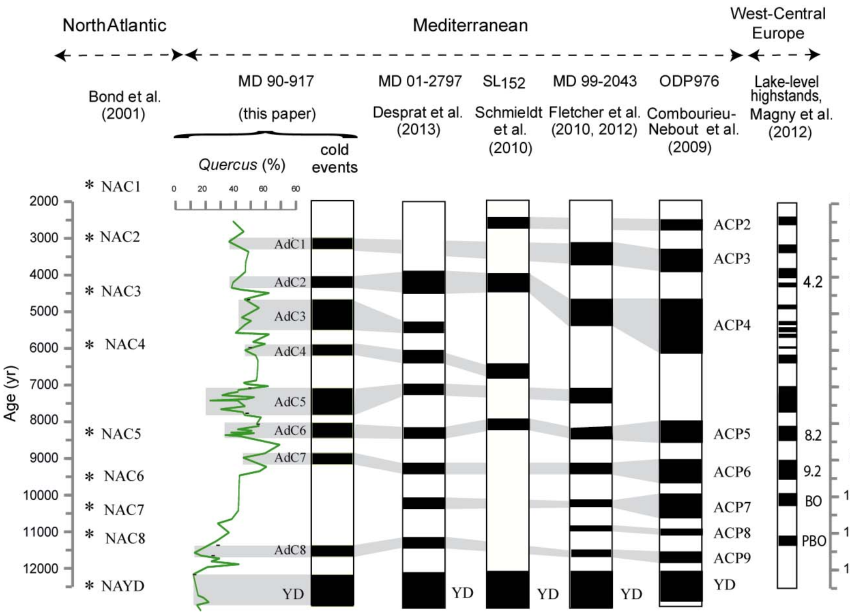

Fig. 7. Comparison of millennial cold events recorded in MD 90-917 with the cold events recorded from vegetation changes in other Mediterranean marine cores (Desprat et al., 2013; Schieldt et al., 2010; Fletcher et al., 2010, 2013; Combourieu Nebout et al., 2009). On the left are pointed the North Atlantic Bond events (Bond et al., 2001) and, on the right, the periods of high lake levels recorded in the Southern Alps (Magny et al., 2012).

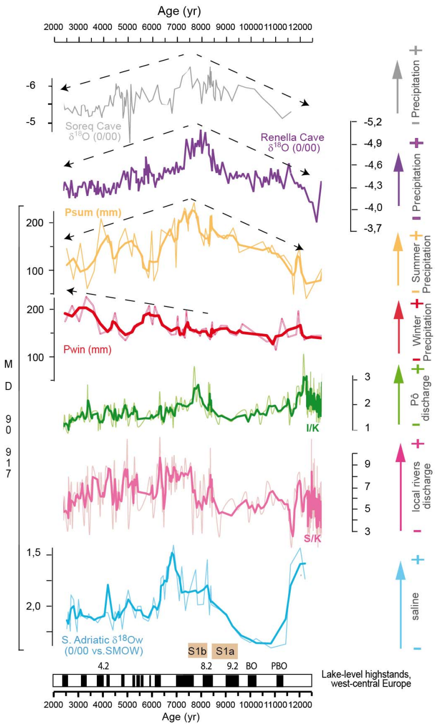

Fig. 8. Comparison of the summer precipitation changes reconstructed from MD 90-917 pollen data and high lake levels in the alps (Magny et al., 2012), sea surface salinity reconstructed from MD 90-917 δ^{18}O record (Siani et al., 2013), Illite/Kaolinite (I/K) and Smectite/Kaolinite (S/K) ratios from MD 90-917 and δ^{18}O speleothem records from the Renella cave (Italy) (Zhornyak, 2011) and Soreq cave (Israel) (Bar-Matthews et al., 2011).