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

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Abstract. The high-resolution multiproxy study of the Adriatic marine core MD 90-917 provides new insights to reconstruct vegetation and regional climate changes over the southcentral Mediterranean during the Younger Dryas (YD) and Holocene. Pollen records show the rapid forest colonization of the Italian and Balkan borderlands and the gradual installation of the Mediterranean association during the Holocene. Quantitative estimates based on pollen data provide Holocene precipitations and temperatures in the Adriatic Sea using a multi-method approach. 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 evaluate precipitation changes in the Holocene.

Vegetation climate reconstructions show the response to the Preboreal oscillation (PBO), most likely driven by changes in temperature and seasonal precipitation, which is linked to increasing river inputs from Adriatic rivers recorded by increase in clay mineral contribution to marine sediments. Pollen-inferred temperature declines during the early–mid Holocene, then increases during the mid–late Holocene, similar to southwestern Mediterranean climatic patterns during the Holocene. Several short vegetation and 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 (170–200 mm) between 8000 and 7000 similar to the general pattern across southern Europe. Two important shifts in vegetation occur at 7700 cal yr BP (calendar years before present) and between 7500 and 7000 cal yr BP and are correlated with increased river inputs around the Adriatic Basin respectively from the northern (7700 event) and from the central Adriatic borderlands (7500–7000 event). During the mid-Holocene, the wet summers lead to permanent moisture all year resulting in a homogeneous seasonal precipitation regime. After 6000 cal yr BP, summer precipitation decreases towards present-day values while winter precipitation rises regularly showing the setting up of Mediterranean climate conditions.

Multiproxy evidence from core MD 90-917 provides 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 warming and drought stresses. Precipitation changes are of particular concern for the region. Increasing dryness predicted by models 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-latitude 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. Thus, reconstructions of past vegetation and climate in the different basins of the Mediterranean will produce information allowing us to draw a general framework to understand regional change and the drivers of environmental and climate change across the whole basin.

The southern Adriatic, with its central location in the Mediterranean Basin, provides an excellent opportunity to record high-resolution vegetation changes in Italy and the Balkans in response to Holocene climate variability. In fact, central Mediterranean ecosystems are highly sensitive to climate changes and help to understand the climate connections and conflicting influences between northwestern and southeastern atmospheric systems and their relative roles in mediating precipitation and runoff during the Holocene.

Holocene vegetation change in the central Mediterranean has been widely 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; Drescher-Schneider et al., 2007; Piva et al., 2008; Kotthoff et al., 2008a, b, 2011; Di Donato et al., 2008; Di Rita and Magri, 2009; Joannin et al., 2012, 2013; 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; Finné 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 cal yr BP (calendar years before present); (ii) a mid-Holocene transitional period from 8200 to 4200 cal yr BP; and, (iii) a late-Holocene period of aridification following 4200 cal yr BP. Climate reconstructions from Lake Accesa (northcentral Italy) distinguish two distinct intervals based on precipitation and emphasize the role of the seasonality during the Holocene (Peyron et al., 2011). Given the scarcity of reliable high-resolution pollen records

in the central Mediterranean and the peculiarities of this region, new evidence is needed to better understand the climate changes and the climate processes in this area.

The new pollen record from the marine MD 90-917 core provides new insights into vegetation and climate changes 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 bringing together continental and marine data to produce an integrated interpretation of the paleoenvironmental interpretation of 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 Balkan vegetation. By examining the 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 collected 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 cm 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 was previously given in Siani et al. (2010) and uses tephra layers and 21 AMS (accelerator mass spectrometry) ^{14}C dates performed on monospecific planktonic foraminifera. The conventional radiocarbon ages have been subsequently converted into calendar ages, based on INTCAL04 (Reimer et al., 2004) using the ^{14}C calibration software CALIB 6. The calibration integrates a marine ^{14}C reservoir age correction $R(t)$ at 390 ± 85 yr according to Siani et al. (2000, 2001). For this paper, only 13 AMS ^{14}C are used and provide 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 to the southwest. The Eurasian High retreats northward in the summer and is replaced by the northeastward expansion of the Azores 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

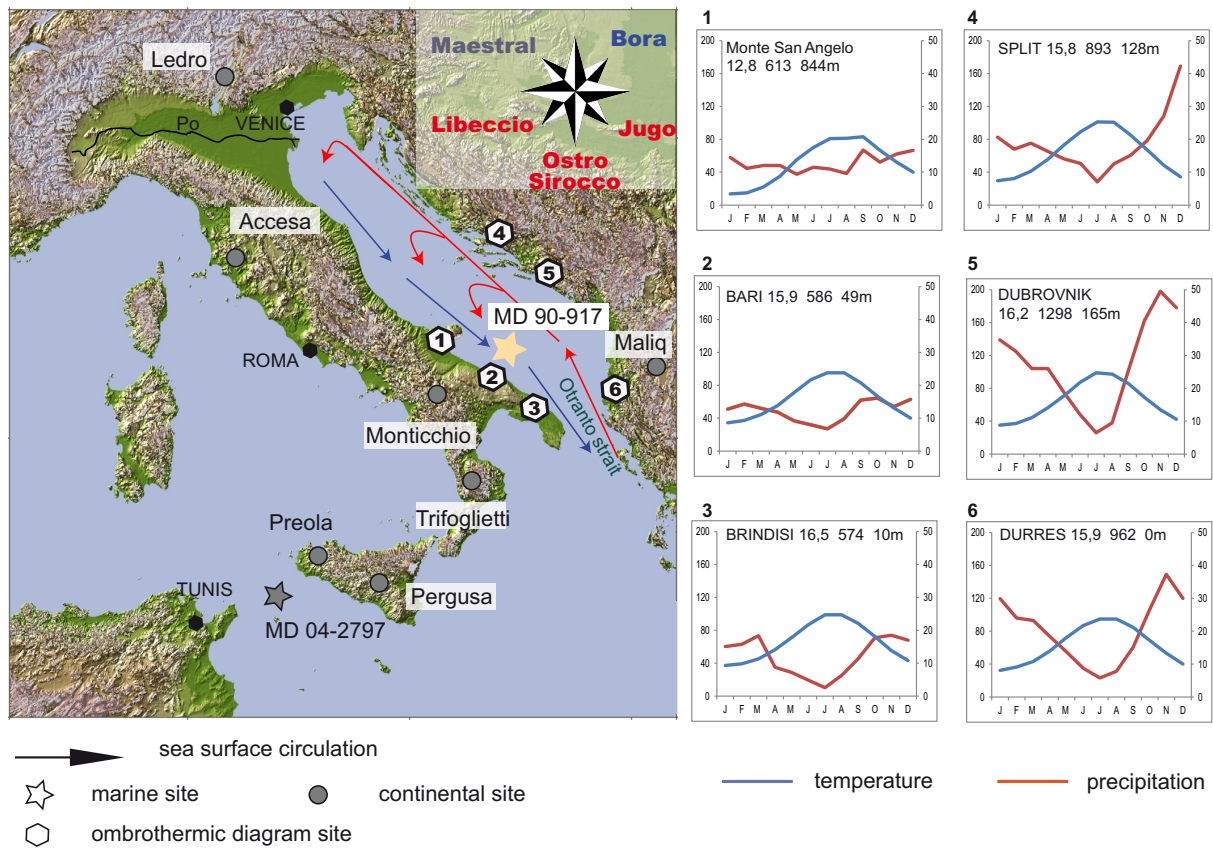


Fig. 1. Location of core MD 90-917. On the map is indicated sea surface circulation in Adriatic Sea and winds blowing over the Adriatic Basin. A selection of ombrothermic diagrams is presented on the right for the surrounding borderlands to show the climate of the studied area (Walter et al., 1975; New et al., 2000, New LoCClim software). For each ombrothermic diagram, near or below the site name is noted the annual mean temperature, the total annual precipitation and the altitude of the site. For each ombrothermic diagram, the left axis corresponds to precipitation values and the right axis to the temperature value. Red arrows represent the south–north sea surface water inflow; blue arrows draw the north–south sea surface outflow.

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 northeast during winter. The mistral (Italian: maestral) is a northwestern 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 southeast dry wind that blows most often in the winter. The west to southwest 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. Flow progresses counterclockwise from the east coast of the Adriatic to the 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 dominated by Po River discharges. The Po is primarily fed by snowmelt in the spring and high runoff in the autumn, particularly in the northern reaches of the watershed (Cattaneo et al., 2003;

Table 1. Age model for core MD 90-917, AMS ^{14}C ages and corresponding calendar ages from INTCAL04 (Reimer et al., 2004) integrating ^{14}C reservoir age correction $R(t)$ at 390 ± 85 yr BP (Siani et al., 2000, 2001).

Depth (cm)	Species	^{14}C age BP (yr)	Error $\pm 1\sigma$	Cal age BP (yr)
0–2	<i>G. bulloides</i>	1010	60	555–609
140–142	<i>G. ruber</i>	4180	70	4082–4290
167–169	<i>G. ruber</i>	4750	70	4855–4986
175–177	<i>G. bulloides</i>	5000	70	5344–5466
190–192	<i>G. bulloides</i>	5680	70	5990–6128
230–232	<i>G. bulloides</i>	6920	90	7413–7511
240–242	<i>G. bulloides</i>	7930	80	8171–8340
250–252	<i>G. ruber</i>	8170	70	8390–8482
275–277	<i>G. bulloides</i>	10 390	90	11 304–11 624
295–297	<i>G. bulloides</i>	10 800	90	12 116–12 399
305–307	<i>G. bulloides</i>	10 830	90	12 225–12 406
315–317	<i>G. bulloides</i>	11 140	90	12 721–12 853
335–337	<i>G. bulloides</i>	11 520	100	12 939–13 114

Frignani et al., 2005; Orange et al., 2005; Palinkas and Nittrouer, 2007).

3.3 Present-day vegetation

Vegetation is organized along altitudinal belts on the Adriatic borderlands according to the ecological requirements of the plants. 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* and *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 colonized by pine forest. Inland, forests are dominated by supramediterranean vegetation at higher altitudes, composed of deciduous trees such as *Carpinus*, *Ostrya*, *Fraxinus* and *Quercus*. At higher elevation, where summer precipitation is higher, mountain 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.

4 Methods

4.1 Pollen record

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 the Holocene, from $\sim 13\,000$ to ~ 2500 cal yr BP.

Pollen was obtained from marine sediments following 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 concentrated pollen residues. Pollen grains were counted on slides with an Olympus light microscope at x500 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 that exclude *Pinus* pollen. *Pinus* percentages were calculated using the total sum of identified grains. Pteridophyta percentages are 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, b).

Fossil pollen assemblages from the MD 90-917 core show similarities to a range of vegetation types from semi-desert to

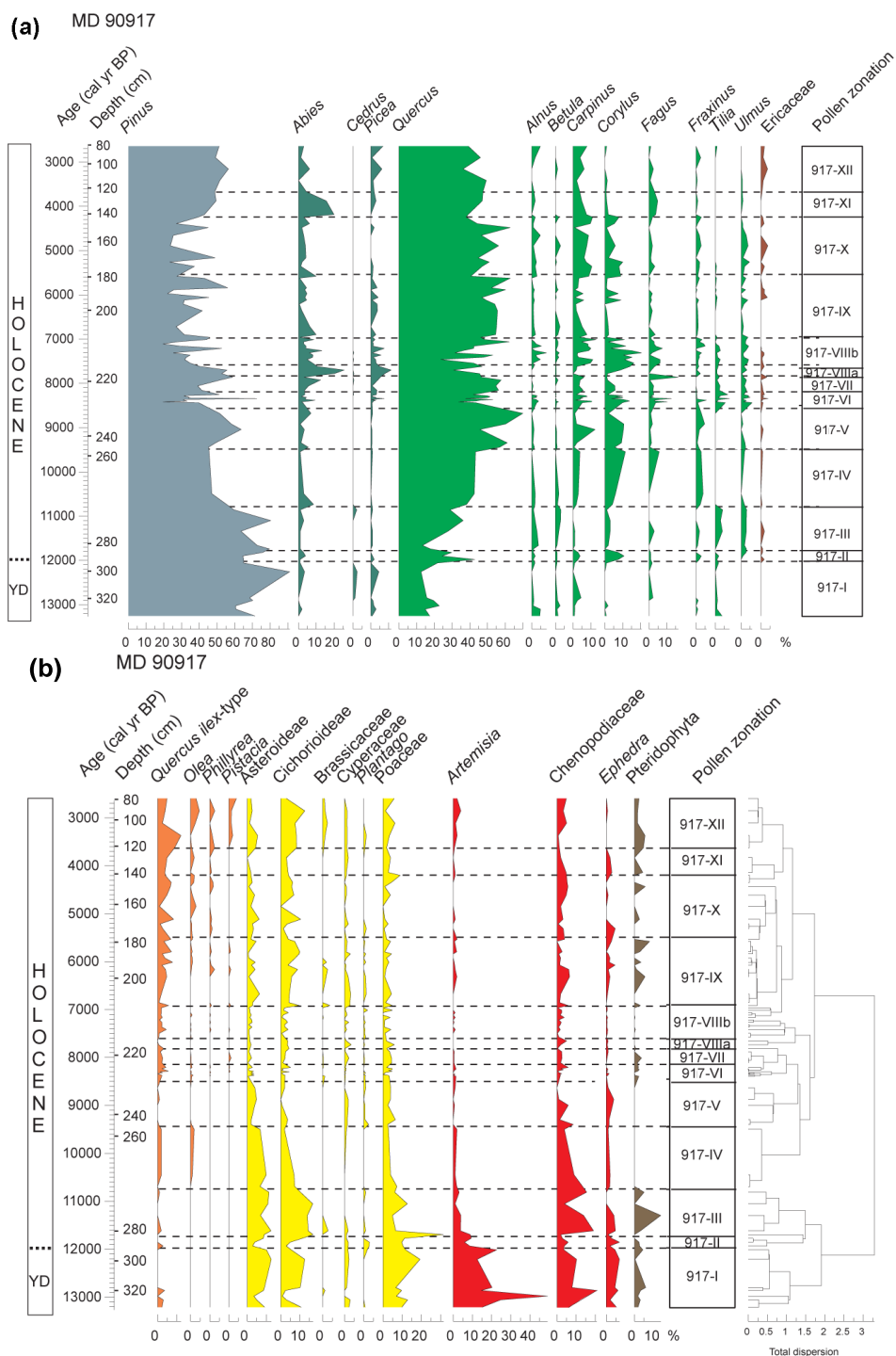


Fig. 2. Pollen diagram of the core MD 90-917. **(a)** arboreal taxa; **(b)** Mediterranean and herbaceous taxa. Pollen percentages are calculated on a sum excluding Pinus; Pinus percentages are calculated on the total pollen sum. Pteridophyta percentages are calculated on the total pollen sum. Pollen curves are presented in calendar yr BP (correspondence between age and depth is presented on the left). On the right of the diagram are represented the pollen zones and results of the cluster analysis (CONISS software, Grimm, 1987).

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
MD 90 917-XII	80–120	2641–3671	<i>Pinus</i> (50%), ↓ <i>Abies</i> (<4%) and <i>Picea</i> (<6%) <i>Quercus</i> (45%), <i>Carpinus</i> (6%) <i>Corylus</i> in low percentages, ↑ <i>Fagus</i> (4%) Mediterranean taxa, <i>Q. ilex</i> (↑12%), <i>Olea</i> (3–4%) and <i>Pistacia</i> (↑4%) ↑ Cichoriodeae; ↑ <i>Artemisia</i> (15%),	Warm temperate Mediterranean oak forest	Warm and humid stability in T° ↑ seasonal P mm
MD90 917-XI	128–140	3877–4186	<i>Pinus</i> (50%), ↑ <i>Abies</i> (<15%), <i>Picea</i> (3%) <i>Quercus</i> (40%), <i>Carpinus</i> (6%), <i>Corylus</i> and <i>Fagus</i> in low percentages, Mediterranean taxa in low percentages, <i>Q. ilex</i> (4%)	Cool mixed forest	Cool and relatively humid
MD90 917-X	142–179	4244–5579	<i>Pinus</i> low (20–40%), low percentages in <i>Abies</i> and <i>Picea</i> (<6%) ↓ <i>Quercus</i> (45%), ↑ <i>Carpinus</i> (↑10%) and <i>Corylus</i> (↑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° P mm slight decrease
MD90 917-IX	180–220	5623–6960	<i>Pinus</i> low (20–40%); low percentages in <i>Abies</i> and <i>Picea</i> (<6%) Temperate trees stable, ↑ <i>Quercus</i> (↑45–65%), ↓ <i>Carpinus</i> (5%) and <i>Corylus</i> (5%), ↑ Mediterranean taxa, <i>Q. ilex</i> (6–7%), <i>Olea</i> , <i>Phillyrea</i> and <i>Pistacia</i> ↑ in herbs; Cichoriodeae (5–10%); steppic taxa low	Warm temperate oak forest	Warm and humid stability in T° and P mm slightly reincrease
MD90 917-VIIIb	221–232	7010–7620	<i>Pinus</i> (20–50%), ↓ <i>Abies</i> (<10%) and <i>Picea</i> (<5%) decrease ↑ Temperate trees, <i>Quercus</i> stable (<45%), <i>Corylus</i> (5–20%), <i>Carpinus</i> (4–10%), <i>Fagus</i> (↑5%), <i>Ulmus</i> , (↑5%), <i>Alnus</i> (3–8%), Mediterranean taxa stable (<i>Q. ilex</i> mainly, <i>Olea</i> and <i>Pistacia</i> presence) ↓ Herbs (Asteraceae <5%, Poaceae <5%), steppic taxa low (10%)	Warm temperate oak forest	Warm and humid increase in T° and P mm slight decrease
MD90 917-VIIIa	233–234	7700–7779	<i>Pinus</i> (50%), ↑ <i>Abies</i> (↑25%) and <i>Picea</i> (↑11%) ↓ Temperate trees, <i>Quercus</i> (<45%), <i>Corylus</i> , <i>Carpinus</i> absent, <i>Fagus</i> (↑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	<i>Pinus</i> (30–60%); <i>Abies</i> and <i>Picea</i> low Temperate trees: <i>Quercus</i> (30–60%), <i>Corylus</i> (<5%), <i>Carpinus</i> (4%), <i>Fagus</i> (↑10%) Mediterranean taxa low (<i>Q. ilex</i> mainly, <i>Olea</i> presence) ↓ Herbs (Asteraceae <5%, Poaceae <5%), steppic taxa nearly absent	Warm temperate oak forest	Warm and humid Max T° and P mm slight reincrease
MD90 917-VI	239–250	8157–8456	<i>Pinus</i> (30–60%); <i>Abies</i> and <i>Picea</i> low Temperate trees: <i>Quercus</i> (40%), <i>Corylus</i> (5–10%), <i>Carpinus</i> (4–10%), <i>Fagus</i> (↑8%) Mediterranean taxa ↑ (<i>Q. ilex</i> mainly, <i>Olea</i> and <i>Pistacia</i> presence) ↓ Herbs (Asteraceae <5%, Poaceae <5%), steppic taxa low	Warm temperate oak forest	Warm and humid Max T° and P mm slight decrease
MD90 917-V	252–258	8678–9445	<i>Pinus</i> (around 50%), <i>Abies</i> and <i>Picea</i> low ↑ Temperate trees, maximum <i>Quercus</i> (45–70%), <i>Corylus</i> (5–10%), <i>Carpinus</i> (2–10%) Mediterranean taxa low (<i>Q. ilex</i> only) ↓ Herbs (Asteraceae <5%, Poaceae <5%) and steppic taxa low	Warm temperate oak forest	Warm and humid – Max T° and P mm
MD90 917-IV	259–269	9546–10737	Large decrease in <i>Pinus</i> (<50%), <i>Abies</i> and <i>Picea</i> nearly absent Increase in temperate trees, <i>Quercus</i> (40%), <i>Corylus</i> (5–10%), <i>Carpinus</i> (2–4%) Mediterranean taxa low (<i>Q. ilex</i> and first occurrence in <i>Olea</i>) ↓ Herbs (Asteraceae <12%, Poaceae <7%), steppic taxa very low	Warm temperate oak forest	Progressive ↑ T° and P mm
MD90 917-III	270–282	10858–11742	<i>Pinus</i> abundant (60–80%), <i>Abies</i> and <i>Picea</i> percentages low <i>Quercus</i> (20–40%), ↓ <i>Corylus</i> and <i>Carpinus</i> , slight ↑ <i>Alnus</i> , <i>Betula</i> , <i>Tilia</i> ↑ Herbs (Asteraceae 20%), ↑ Chenopodiaceae >10%	Grassland mixed to open oak forest	Cool and moderately dry
MD90 917-II	284–288	11821–11980	<i>Pinus</i> abundant (65–75%), <i>Abies</i> and <i>Picea</i> percentages low ↑ <i>Quercus</i> (15–40%), <i>Corylus</i> (↑10%), <i>Carpinus</i> (3%) ↓ Herbs (Asteraceae <20%, Poaceae around 10%), ↓ steppic taxa low	Open Warm mixed forest	Slight increase in T° and P mm
MD90 917-I	290–350	12060–13257	<i>Pinus</i> abundant (65–90%), <i>Abies</i> and <i>Picea</i> percentages low Low percentages in temperate trees, <i>Quercus</i> <20%, <i>Alnus</i> , <i>Betula</i> , <i>Carpinus</i> present Herbs abundant, Asteraceae 10–20%, Poaceae around 10% Steppic taxa abundant (<i>Artemisia</i> 15%, Chenopodiaceae 10%, <i>Ephedra</i> up to 7%)	Steppe	Cold and dry

mountain deciduous and coniferous forest. The interpretation of these assemblages follows the modern plant–climate relationships in Eurasia and northern Africa (Woodward, 1987; Peyron et al., 1998).

4.2 Pollen-based climate reconstructions

To obtain a robust quantitative reconstruction of Holocene climate changes in the Adriatic Sea, two methods have been used to reconstruct climate parameters: modern analogues technique (MAT: Hutson, 1980; Guiot, 1990) and weighted average partial least squares regression (WAPLS: Ter Braak and Juggins, 1993). Both methods have been used extensively for the Holocene climate reconstruction from terrestrial and marine pollen records located in the Mediterranean region (e.g. Davis et al., 2003; Pross et al., 2009; Peyron et al., 2011, 2013; Joannin et al., 2012; Kotthoff et al., 2008a, b; Combourieu-Nebout et al., 2009; Dormoy et al., 2009; Desprat et al., 2013; Sadori et al., 2013) with results that are generally supported by other independent proxies (e.g. lake levels, alkenones, charcoals, etc.) and other regional records.

Like most classic 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). In contrast to the MAT, the WAPLS is a true transfer function that requires a statistical calibration between environmental variables (climate parameters) and modern pollen assemblages. WAPLS is a common regression method which supposes that the relationships between pollen percentages and climate parameters are unimodal. More details on the MAT and on the WAPLS are given in Peyron et al. (2013).

Both methods are calibrated using the high-quality and taxonomically consistent dataset compiled by Dormoy et al. (2009). This dataset contains more than 2000 samples from the Mediterranean region to which were added 26 modern surface samples from around Lake Trifoglietti (Calabria, southern Italy) collected by Joannin et al. (2012), and from around Mount Altesina and Lake Preola (Sicily). *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 using annual (TANN), coldest month (MTCO) and warmest month (MTWA) temperature, and annual (PANN), spring (Pspr), summer (Psum), autumn (Paut) and winter (Pwin) precipitation to emphasize changes in seasonality. Results are expressed as reconstructed values and anomalies (reconstructed values minus present-day values) (Fig. 3).

4.3 Sediment clay fraction

Samples were prepared following standard protocols described in Bout-Roumazeilles et al. (2007). All samples were first decalcified with 0.2N hydrochloric acid. Excess acid was removed by repeated centrifugations. The clay-sized fraction ($< 2\ \mu\text{m}$) 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), and (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 Å–3.53 Å), was performed using the software MacDiff developed by Petschick (2001). 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 Origin of the continental proxy data

5.1 Pollen inputs

Paleoenvironmental interpretation of the changes depicted in the marine 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 kilometers (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 MD 90-917 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 in the modern vegetation community structure between coasts (Ozenda, 1975; Horvat et al., 1974). However, natural stands of *Olea* are nearly absent on the Dalmatian coast today and are only

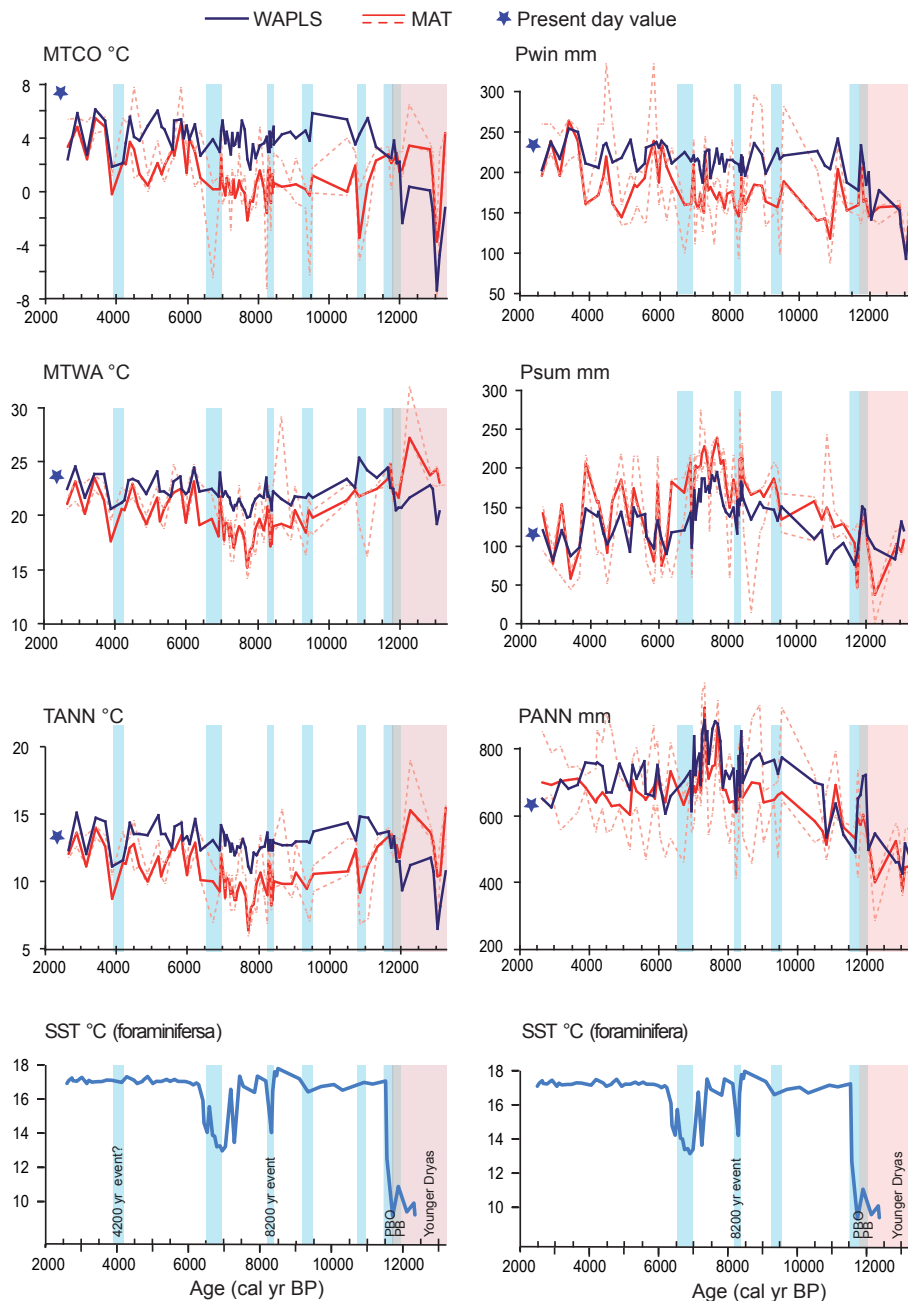


Fig. 3. Quantitative climate reconstructions from pollen analyses obtained by the MAT (red: dotted line corresponds to error) and WAPLS (blue) methods. Present-day values for temperature (MTCO, MTWA and TANN) and precipitation (Pwin, Psum and PANN) are represented by blue stars. SSTs (blue) from the same core are reported at the base of the figure for comparison with the pollen inferred reconstruction. All curves are presented in cal yr BP. Colored bars underline climate events: YD (pink), PB (grey), PBO and Holocene events (blue).

found in southern Greece on the Balkan Peninsula (Ozenda, 1975), thus *Olea* pollen grains are more likely to arrive from the Italian coast. Nevertheless, olive cultivation by human societies during the last millennia (Mercuri et al., 2013) 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 coasts to the highlands.

5.2 Clay mineral origin

The Po River and the eastern Apennine rivers are the main sources of clay-sized particles in the western Adriatic. Although 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 components (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 particles 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 desert dust plumes export clay-mineral particles toward the Mediterranean (Rea et al., 1985; Guerzoni and Chester, 1996) *via* regional meridional wind systems (Prospero, 1981; Loÿe-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-Padrón et al., 2002; Ginoux et al., 2004). Illite and kaolinite can also be transported through eolian processes. Kaolinite abundance is highest in the southeastern 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 dusts from North Africa to the Adriatic Sea during spring and summer (Goudie and Middleton, 2001).

6 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 MD90-917 is similar to other Italian and Balkan sequences for the Holocene, which suggests the pollen from MD 90-917 can reveal the consequences of the regional climatic change during the last 13 000 cal yr BP on central Mediterranean vegetation (Table 2, Fig. 2a, b)

The Younger Dryas event (GS-1 event – YD) is characterized by the dominance of semi-desert elements such as *Artemisia*, Chenopodiaceae and *Ephedra* (Fig. 2b) accompanied by Poaceae and Asteraceae, 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 (e.g. Watts et al., 1996; Magri and Sadori, 1999; Denèfle et al., 2000; Allen et al., 2002; Bordon et al., 2009; Kotthoff et al., 2011; Combourieu-Nebout et al., 2009; Fletcher et al., 2010; Desprat et al., 2013). Steppic pollen taxa indicate that cold-arid climate conditions prevailed over the whole Mediterranean Basin and especially in the Adriatic Basin during the Younger Dryas (Figs. 3, 4).

Between 12 000 and 11 700 cal yr BP, semi-desert elements are replaced by arboreal associations composed by *Quercus*, *Carpinus*, *Corylus* and *Abies* showing the afforestation driven by climatic warming at the beginning of the Holocene (Fig. 2a). Although it begins at an older age in the MD 90-917 marine core, such a spread of temperate taxa may be related to what is observed in several pollen sequences across the central Mediterranean (e.g. Watts et al., 1996; Sadori and Narcisi, 2001; Allen et al., 2002; Sadori et al., 2011; Di Rita et al., 2013) and corresponds to the Preboreal (PB) improvement at the Younger Dryas/Holocene transition (Björk et al., 1996). 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 Cichorioideae) and semi-desert taxa, excluding *Artemisia* (Fig. 2a, b). Climate reconstructions using pollen data show a decrease in temperature and precipitation at this time for the two methods (Figs. 3, 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 (e.g. Lake Trifoglietti – Joannin et al., 2012; Valle di Castiglione – Di Rita et al., 2013). Thus, the climate oscillation recorded in the MD90-917 appears to follow the pattern observed in the Greenland ice cores' $\delta^{18}\text{O}$ record (Fig. 5; Rasmussen et al., 2007) and probably corresponds to the $\sim 11\,300$ cal yr BP Preboreal oscillation recorded in the Greenland ice cores (PBO: Björk et al., 2001; Magny et al., 2012).

In the early Holocene, the general trend of the vegetation data and pollen-based climate reconstructions precede the foraminifer-based SST (sea surface temperature) from the same core (Siani et al., 2013) (Figs. 3, 5) in the same pattern

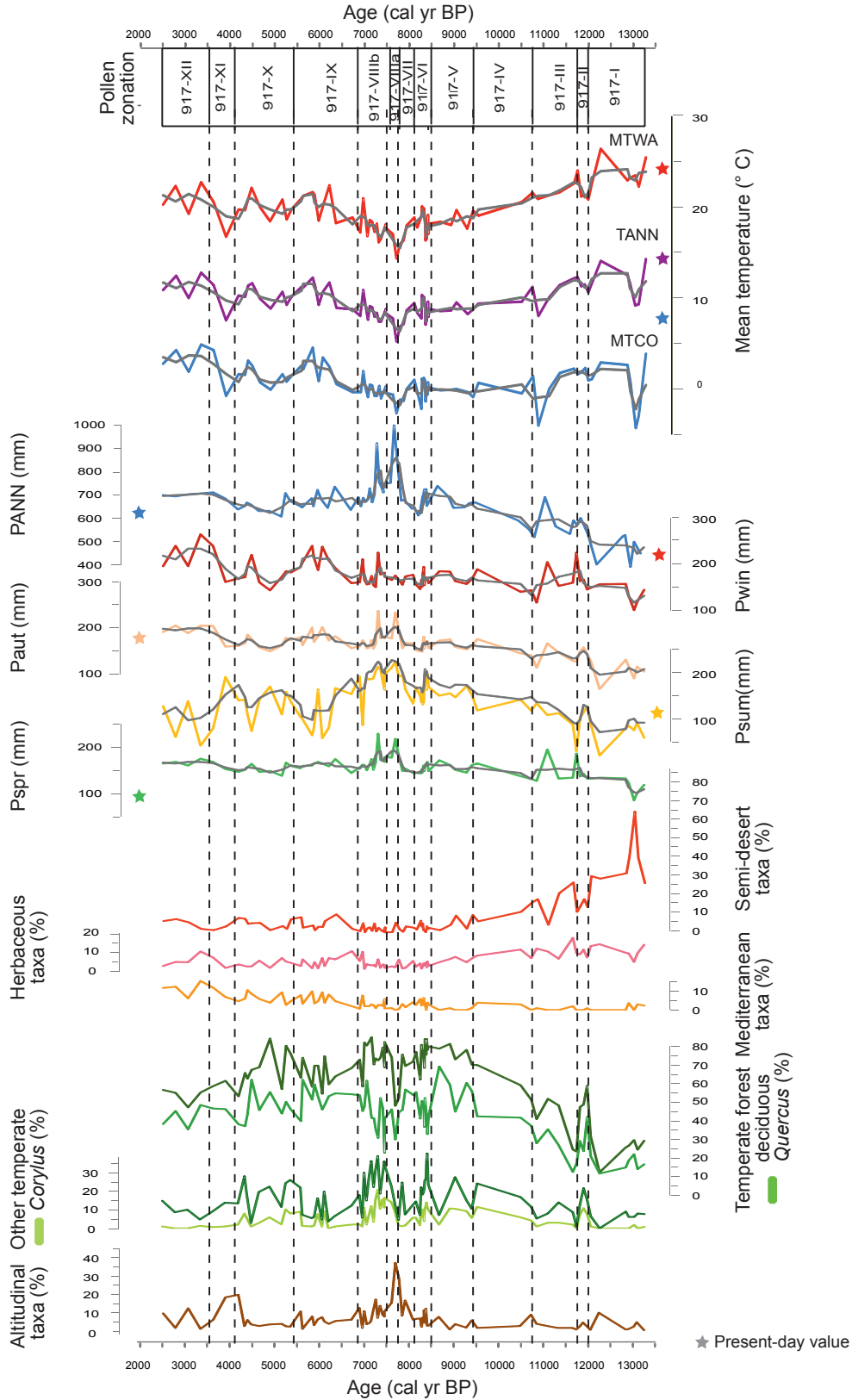


Fig. 4. Selected pollen curves of core MD 90-917 and pollen based reconstruction of precipitation (seasonal: Pspr, Psum, Paut, Pwin and annual: PANN) and temperature (MTCO, MTWA and TANN). All curves are presented in cal yr BP. Grey curves are the 3 pts-smoothed curves. Colored stars represent the present-day values for each climate parameter.

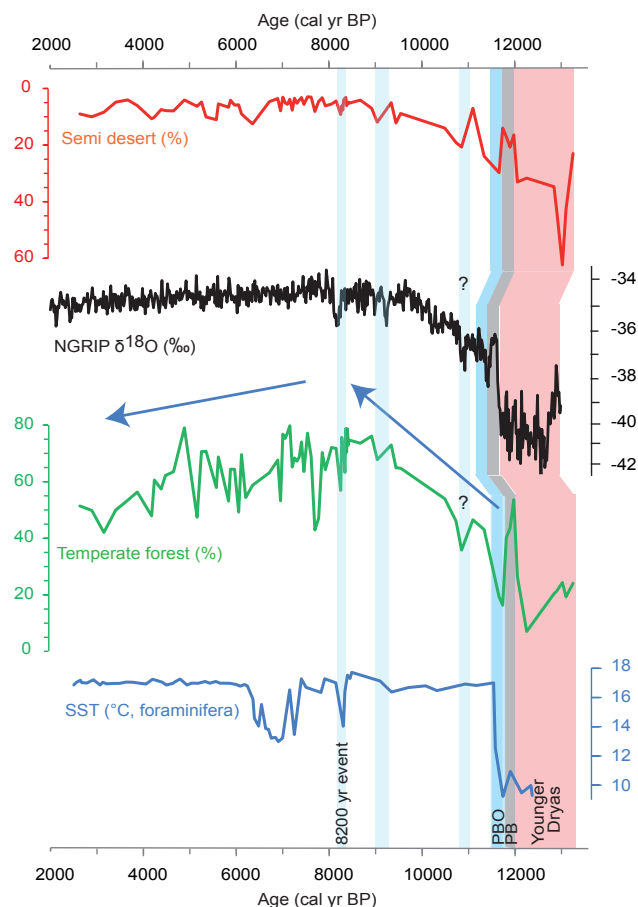


Fig. 5. Comparison between two main pollen groups (this paper); temperate trees (green), semi-desert (red) and SST (blue) from the core MD 90-917 and NGRIP oxygen isotope record (NGRIP members, 2004; Lemieux Dudon, 2011). Colored bars underline climate events: YD (pink), PB (grey), PBO and 8200 cal yr BP event (purple). Curves are plotted according to their respective age models in cal year BP. The time lag observed between MD 90-917 and NGRIP records during the YD–Holocene transition is probably due to ^{14}C age uncertainties displayed in the MD 90-917 age model. The question marks indicate potential events not sufficiently documented in the record.

as the alkenone-inferred SST response (Sicre et al., 2013). To explain such discrepancies, Sicre et al. (2013) suggest a local response in alkenone-inferred SST record. In fact, the temporal lead shown in MD 90-917 vegetation and pollen-based climate reconstruction records relative to foraminifer-based SST should not be related to local behavior as it would imply a time lag with other Italian records such as Lake Trifoglietti (Joannin et al., 2012) and Lake Vico (di Rita et al., 2013) records; which would be amazing. Of course, the MD 90-917 record represents the regional vegetation changes of the central Mediterranean and thus integrates vegetation changes evidenced in these contemporary Italian records. Another explanation might be that the lead in vegetation response rela-

tive to foraminifer inferred SST from the same core suggests that the vegetation response to the Preboreal oscillation in the region could be driven by precipitation changes rather than temperature variations, which is quite different to the classic feature of climate changes observed at the beginning of interglacials (temperature rise generally preceding precipitation increase). Thus, the discrepancy between the different proxies obtained in the core MD 90-917 can be related to the sampling resolutions, which are not strictly similar in this part of the core, and the delay of SST response compared to vegetation may be due to the lack of samples in the PB–PBO interval. Given this, age discrepancies between continental, ice records and the MD 90-917 marine core vegetation proxy may be due to ^{14}C age control uncertainties in this part of the core; and that the vegetation event at 11 700 cal yr in MD 90-917 may be related without doubt to the Preboreal event.

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, b). The mixed forest peaks around 7000 cal yr BP corresponding to the “Holocene climate optimum”. Deciduous forest 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 $\delta^{18}\text{O}$ from planktonic foraminifers (Fig. 6) and the foraminifer inferred SST increase from the MD 90-917 core (Siani et al., 2013). Increases in regional forest biomass also concur with $\delta^{13}\text{C}$ depletion in the MD 90-917 sediments, linked to sea-level rise (Siani et al., 2013) in the early-Holocene since depletion in $\delta^{13}\text{C}$ in core sediments may also be interpreted as an intensification of nutrient supply from the continent to the Adriatic Sea.

Although temperate forest dominates the vegetation record from 11 000 until ~ 7000 cal yr BP there are several compositional shifts in that time (Figs. 2a, 4). 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 forests 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 (Fig. 3) or changes in the spring and autumn (Fig. 4). 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 seasonality 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 northern Adriatic slopes and/or (ii) from northern Italy and Alps by Po River

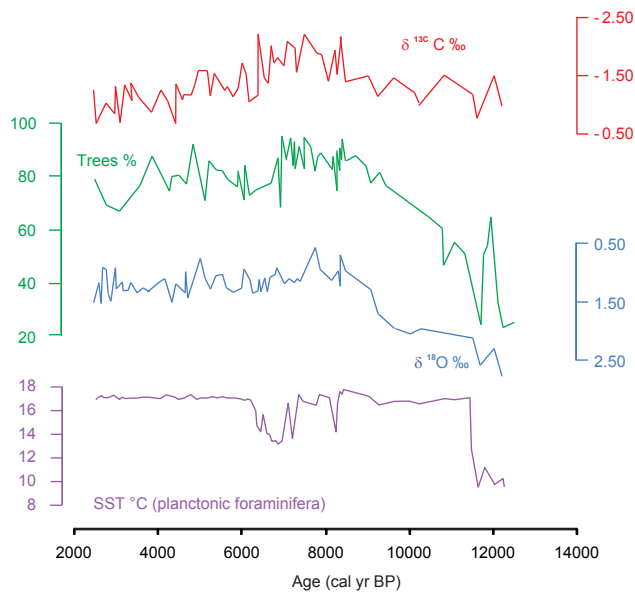


Fig. 6. Comparison of the total tree percentage curve (green) (this paper) and the $\delta^{18}\text{O}$ (blue), $\delta^{13}\text{C}$ (red) and SST ($^{\circ}\text{C}$, purple) records from the MD 90-917 core (Siani et al., 2013). All curves are presented in cal yr BP.

discharges and then by marine flows. *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). *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; Sjögren et al., 2008). As a result, the *Abies* and *Picea* increase at ~ 7700 cal yr BP could therefore express the development of mixed *Abies* and *Picea* forests in the north and northeast mountains around the Adriatic Basin, with the pollen being transported through river flows.

Temperate forest dominated by *Quercus* have fluctuated between 7000 and 5000 cal yr BP, decreasing after 4500 cal yr BP. *Quercus* became less abundant while *Carpinus*, *Corylus* and *Alnus* increased. This marks progressive opening of the forest, corresponding to decreases in summer precipitation, reflected in the pollen-based climate reconstructions based on the MAT and the WAPLS (Fig. 3). A cold, moist event is inferred from the rise in *Abies*, *Fagus*, and to a lesser extent *Picea* around 4000 cal yr BP (Fig. 4). 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 Balkan. 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 sum-

mer 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 (Figs. 3, 4). *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. Lake Pergusa, Mercuri et al., 2013; Sadori et al., 2013) and possibly in the Balkans.

7 Climate interpretation

7.1 Temperature pattern

Temperature estimates from the MD 90-917 pollen sequence (Figs. 3, 4) 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 TANN, MTCO and MTWA temperature reconstructions from MD 90-917 provided by two methods: the MAT and the WAPLS (Fig. 3). The lowest MTCO in the record occurs before 12000 cal yr BP, when temperatures are $5\text{--}7^{\circ}\text{C}$ lower than preceding and subsequent periods. After these coldest values, MTCO increases towards higher values and then oscillate around 0°C with a slight decreasing trend. The temperatures obtained with the WAPLS were lower during the YD than during the Holocene, which makes sense and suggests that the MAT may provide lower quality results during the Younger Dryas and Preboreal (Ortu et al., 2010a, b). However, Holocene results are consistent between methods. Temperatures (TANN and MTWA) minima are observed 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 anomaly ($T^{\circ}\text{C}$ reconstructed – $T^{\circ}\text{C}$ present-day) record from MD 90-917 also mirrors the southwestern European temperature curve reconstructed using more than 500 continental pollen records by Davis et al. (2003) (Fig. 7), who also indicate low temperature anomalies during the mid-Holocene. This confirms that the pollen record in the Adriatic reflects southwestern Mediterranean climate influences, more so than southeastern influences. The low anomalies likely reflect the strength of the north–south Mediterranean gradient (Magny et al., 2012) and an increase in the influence of westerlies in the northcentral Mediterranean during the late 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, 4200 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 the Mediterranean (Fig. 8; e.g. Combourieu-Nebout et al., 2009; Schmiedl et al., 2010; Fletcher et al., 2010, 2012; Desprat et al., 2013) and may be linked to the millennial-scale cold events recorded in the North Atlantic (Bond et al., 1997, 2001; Kotthoff et al., 2008a; Combourieu-Nebout et al., 2009; Schmiedl et al., 2010; Fletcher et al., 2010, 2012; 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 midlatitude 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 respectively cold/cool winters and warm summer); 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).

7.2 Precipitation pattern

Pollen-inferred annual precipitation for MD 90-917 shows an increasing trend from 12 000 to 7000 cal yr BP reaching highest values between 8000 and 7500 cal yr BP (Figs. 3, 4). This trend is mirrored by P_{spr} and P_{aut} precipitation, but, while P_{sum} and P_{ANN} precipitation show similar trends of increasing precipitation from the early Holocene to 7500 cal yr BP, summer precipitation declines more strongly than annual precipitation towards 3000 cal yr BP. The MAT and the WAPLS results show an unambiguous increase in summer precipitation during the mid-Holocene (Fig. 3) even if the MAT may slightly overestimate the summer precipitation and underestimate the winter precipitation (Combourieu-

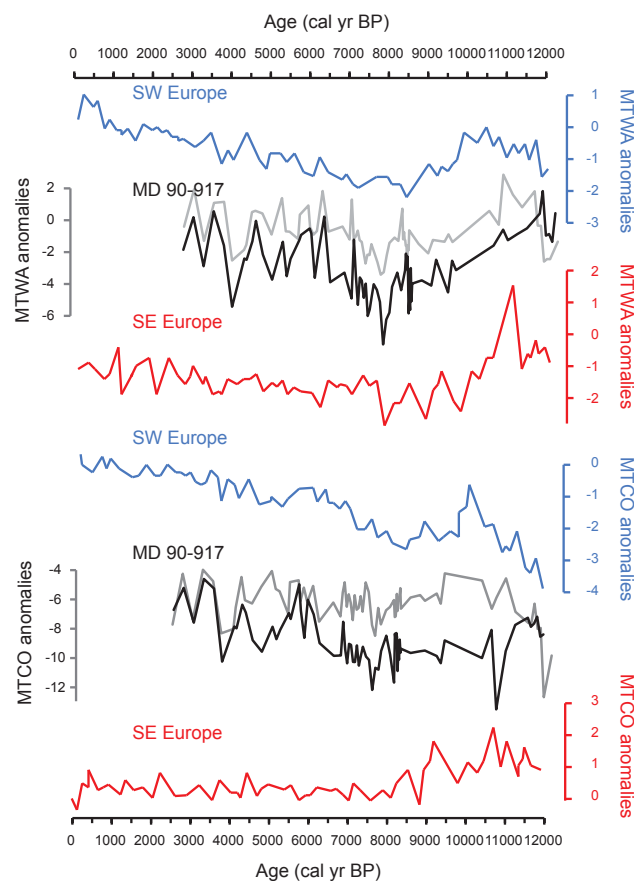


Fig. 7. Comparison between MD 90-917 pollen-based MTCO and MTWA temperature reconstructions (MAT in black, WAPLS in grey) and the combined climate records of southeastern and southwestern Europe (from Davis et al., 2003). Curves are presented in temperature anomalies (reconstructed values minus present-day values).

Nebout et al., 2009). The Holocene's summer precipitation trend inferred from our pollen data is similar to speleothem records in central Italy (Zhorniak et al., 2011) and the eastern Mediterranean (Bar-Matthews et al., 1998; Bar-Matthews and Ayalon, 2011), although speleothem-record features should be linked to changes in winter precipitation. However interpretations of speleothem records in terms of precipitation seasonality in the central and eastern Mediterranean remain a matter of debate (Zhorniak, 2011) (Fig. 9).

The summer precipitation record also matches the lake-levels pattern described by Magny et al. (2012), which suggests that lakes located southward of 40° N experienced high lake levels during precipitation maxima in 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

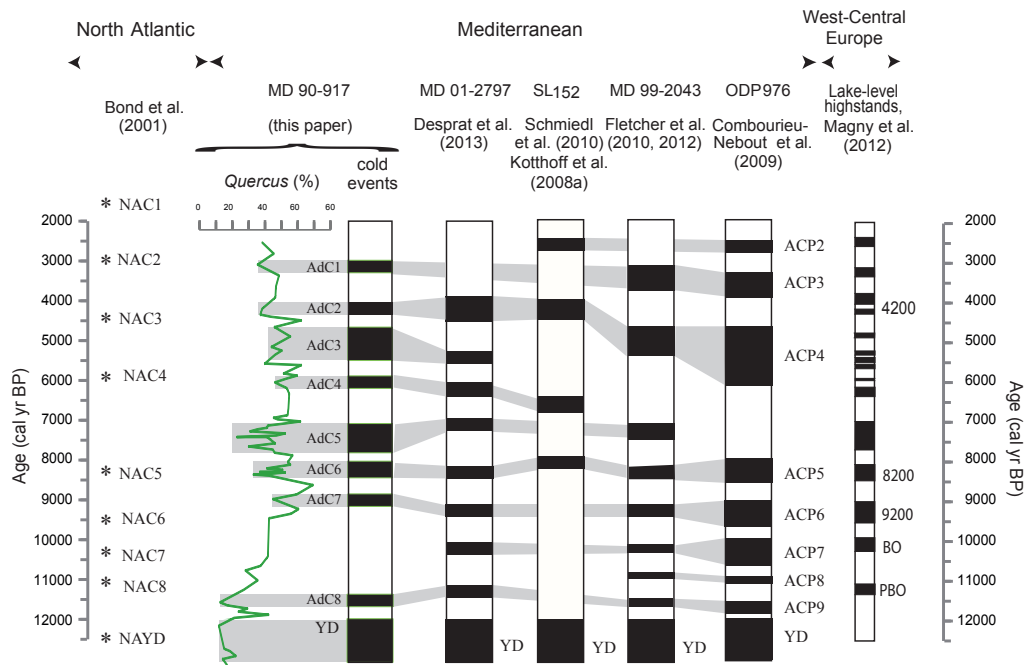


Fig. 8. Comparison of millennial cold events recorded in MD 90-917 with the cold events recorded from vegetation changes in other Mediterranean marine cores (Kotthoff et al., 2008a; Schmiedel et al., 2010; Fletcher et al., 2010, 2012; Combourieu-Nebout et al., 2009; Desprat et al., 2013). On the left are 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).

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. The MD 90-917 summer precipitation curve shows similarities to the northern Italy Lake Ledro record 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). The MD 90-917 precipitation pattern may support, at the mid-Holocene, a correlative increase in winter and summer precipitations with high summer precipitation and cooler temperatures at time of the boreal insolation maximum. Such a signal may illustrate the possible conflict of mid-latitudinal and subtropical monsoonal climatic systems in the Mediterranean area (Tzedakis, 2007; Revel et al., 2010; Desprat et al., 2013; Magny et al., 2013) and surely 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 the Holocene, as demonstrated by the rise in winter precipitation in the upper part of our record.

Summer precipitation 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. 9). Clay mineral records, presented as illite/kaolinite (I/K) and smec-

tite/kaolinite (S/K) ratios (Fig. 9) reflect contributions from the eastern Apennine/Po Rivers and dust input from Africa respectively. These ratios clearly show a change in detrital input during the late-glacial and Holocene. Wind-blown dust (high kaolinite), supplied from the south by sirocco winds, is more abundant during the first part of the Holocene, while the rise of smectite after 9000 cal yr BP indicates the increasing contribution from Italian rivers to the basin.

Both I/K and S/K display a major peak at 12 500 cal yr BP (Fig. 9), associated with an early rise in summer precipitation, 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 that is synchronous with the precipitation maxima, likely related to the Preboreal event.

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 River

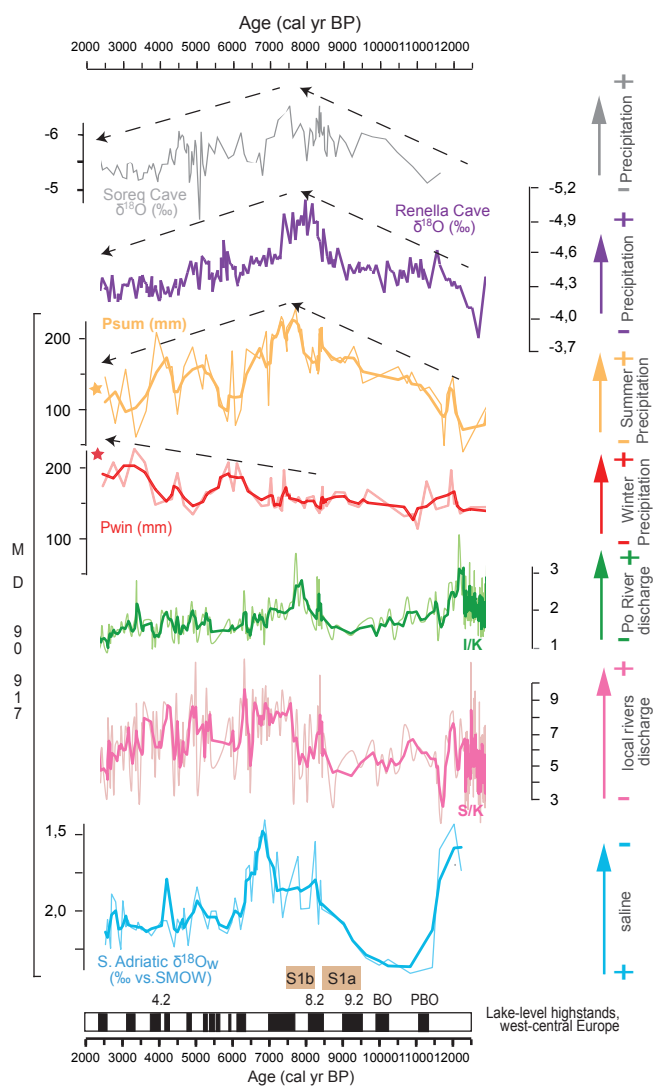


Fig. 9. Comparison of the Psum (yellow) and Pwin (red) precipitation changes reconstructed from MD 90-917 pollen data (MAT) and from bottom to top: lake level highstands in western Europe (Magny et al., 2012 column); sea surface salinity reconstructed from MD 90-917 $\delta^{18}\text{O}$ record (Siani et al., 2013; blue), I/K (pink) and S/K (green) ratios from MD 90-917 and $\delta^{18}\text{O}$ speleothem records from the Renella cave (Italy) (Zhornyak et al., 2011; purple) and Soreq cave (Israel) (Bar-Matthews et al., 1998; Bar-Matthews and Ayalon, 2011; grey). For MD 90-917 records, thin, light curves represent the original data and accentuated curves are the 3 pts-smoothed curves.

agrees well with increases in *Picea* and *Abies* pollen in the sediments and confirms the role of Po River discharge in the pollen signal, as well as its probable influence on declines in sea surface salinity during this event (Fig. 9). Both the origin and discharge rate of terrigenous inputs in the Adriatic Sea are seasonally modulated by precipitation distribution (Wheatcroft et al., 2001; Poulain, 2001). Modern seasonal precipitation influences discharge from the northern Adriatic, as is shown for recent floods in the Po River basin (Zanchet-

tin et al., 2008). Therefore, increases in precipitation seasonality probably occurred during the 7700 cal yr BP event, particularly in the northern and eastern Adriatic, leading to enhanced Po River discharges that would have driven salinity changes in the Adriatic Sea surface and transported *Picea* pollen toward the core's site. Such a process should explain why vegetation change from 8200 to 7500 cal yr BP reported from Trifoglietti (Joannin et al., 2012) is ascribed to a dry and cold phase. This dry phase 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 waters are less saline based on $\delta^{18}\text{O}$ 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 the smectite/kaolinite ratio. Sedimentological studies suggest that the respective contribution of the Po River and eastern Apennine rivers has varied through time (Cattaneo et al., 2003). Smectite is not presently supplied to the Adriatic through the Po River, originating from Italy's slopes through the small but active eastern Apennine rivers (Fig. 7). Based on the depth at which the core was obtained, 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's 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 sea surface salinity in the Adriatic Sea.

8 Conclusions

The MD 90-917 marine pollen record illustrates the regional response of central Mediterranean vegetation to long-term and millennial climate fluctuations during the late-glacial and Holocene, and gives an integrated signal 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 patterns reconstructed using 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) precipitation during the Holocene. Summer precipitation reflects a trend seen elsewhere in the southern Mediterranean, with maximum values (around 180–200 mm from the two methods) around 7000 cal yr BP and then declining until 3000 cal yr BP towards nearly present-day values (< 100 mm). 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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