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North–south palaeohydrological contrasts in the central Mediterranean during the Holocene: tentative synthesis and working hypotheses

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Abstract

On the basis of a multi-proxy approach and a strategy combining lacustrine and marine records along a north–south transect, data collected in the Central Mediterranean within the framework of a collaborative project have led to reconstruction of high-resolution and well-dated palaeohydrological records and to assessment of their spatial and temporal coherency. Contrasting patterns of palaeohydrological changes have been evidenced in the Central Mediterranean: south (north) of around 40° N of latitude, the middle part of the Holocene was characterised by lake-level maxima (minima), during an interval dated to ca. 10 300–4500 cal BP to the south and 9000–4500 cal BP to the north. Available data suggest that these contrasting palaeohydrological patterns operated throughout the Holocene, both on millennial and centennial scales. Regarding precipitation seasonality, maximum humidity in the Central Mediterranean during the middle part of the Holocene was characterised by humid winters and dry summers north of ca. 40° N, and humid winters and summers south of ca. 40° N. This may explain an apparent conflict between palaeoclimatic records depending on the proxies used for reconstruction as well as the synchronous expansion of tree species taxa with contrasting climatic requirements. In addition, south of ca. 40° N, the first millennium of the Holocene was characterised by very dry climatic conditions not only in the Eastern, but also in the Central and the Western Mediterranean zones as reflected by low lake levels and delayed reforestation. These results suggest that, in addition to the influence of the Nile discharge reinforced by the African monsoon, the deposition of Sapropel 1 has been favoured (1) by an increase in winter precipitation in the northern Mediterranean borderlands, and (2) by an increase in winter and summer precipitation in the southern Mediterranean area. The climate reversal following the Holocene climate optimum appears to have been punctuated by two major climate changes around 7500 and 4500 cal BP.

In the Central Mediterranean, the Holocene palaeohydrological changes developed in response to a combination of orbital, ice-sheet and solar forcing factors.

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The maximum humidity interval in the south-central Mediterranean started at ca. 10 300 cal BP, in correlation with the decline (1) of the possible blocking effects of the North Atlantic anticyclone linked to maximum insolation, and/or (2) of the influence of the remnant ice sheets and fresh water forcing in the North Atlantic Ocean. In the north-central Mediterranean, the lake-level minimum interval began only around 9000 cal BP when the Fennoscandian ice-sheet disappeared and a prevailing positive NAO-type circulation developed in the North Atlantic area. The major palaeohydrological oscillation around 4500–4000 cal BP may be a non-linear response to the gradual decrease, with additional key seasonal and interhemispherical changes, in insolation. On a centennial scale, the successive climatic events which punctuated the entire Holocene in the central Mediterranean coincided with cooling events associated with deglacial outbursts in the North Atlantic area and decreases in solar activity during the interval 11 700–7000 cal BP, and to a possible combination of NAO-type circulation and solar forcing since ca. 7000 cal BP onwards. Thus, regarding the centennial-scale climatic oscillations, the Mediterranean Basin appears to have been strongly linked to the North Atlantic area and affected by solar activity over the entire Holocene.

In addition to model experiments, a better understanding of forcing factors and past atmospheric circulation patterns behind the Holocene palaeohydrological changes in the Mediterranean area will require further investigation to establish additional high-resolution and well-dated records in selected locations around the Mediterranean Basin and in adjacent regions. Special attention should be paid to greater precision in the reconstruction, on millennial and centennial time scales, of changes in the latitudinal location of the limit between the northern and southern palaeohydrological Mediterranean sectors, depending on (1) the intensity and/or characteristics of climatic periods/oscillations (e.g. Holocene thermal maximum versus Neoglacial, as well as, for instance, the 8.2 ka event versus the 4 ka event or the Little Ice Age), and (2) on varying geographical conditions from the western to the eastern Mediterranean areas (longitudinal gradients).

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1 Introduction

At the interface between the European temperate and the African tropical zones, the Mediterranean area appears to be very sensitive to even low-amplitude variations in the hydrological cycle. This transitional zone is influenced by tropical circulation cells within the subtropical anticyclone belt and associated aridity, as well as by the mid-latitude westerlies and cyclogenesis (Tzedakis et al., 2009). This results in a marked precipitation seasonality that is crucial for both Mediterranean ecosystems and societies. Climate change projections over the Mediterranean show a pronounced decrease in precipitation and an increase in temperature especially during the summer season (Giorgi and Lionello, 2008), with considerable impact on water resources and consequently on biodiversity and human activities. Thus a deeper understanding of past climatic changes and their associated palaeohydrological variations in the Mediterranean area.

Over the last two decades, using various proxies and strategies, several studies have attempted to reconstruct palaeohydrological variations in the Mediterranean area over the entire Holocene. A first synthesis was proposed in 1993 by Harrison and Digerfeldt on the basis of lake-level fluctuations. Using a compilation of various proxy data from the literature, they reconstructed changes in lake status (high, intermediate, low) at 1000 yr intervals (Fig. 1). All together, in this study the Holocene appears to be characterised by two successive periods before and after ca. 6000 cal BP, i.e. the first more humid than the second. Regarding the early Holocene, the authors also pointed out an apparent opposition between relatively dry conditions in the eastern Mediterranean and greater moisture availability in the west. This general pattern was interpreted as a response to orbitally-driven changes in insolation.

More recently, on the basis of a comparison of various palaeoenvironmental (terrestrial and marine) data (e.g. lake levels, fluvial activity, pollen records, Mediterranean sea-water temperature and salinity, marine sedimentation), Jalut et al. (2000) have proposed that, in the entire circum-Mediterranean area, the Holocene can be divided into three periods: a lower humid Holocene (11 500–7000 cal BP), a transition phase

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(7000–5000 cal BP), and an upper Holocene (5500 cal BP–present) characterised by an aridification. In contrast to the multiproxy approach by Jalut et al. (2000), Roberts et al. (2008) endeavoured to establish a synthetic picture of the Holocene climate and hydrology in the Mediterranean using a single proxy, i.e. stable isotopic records from lakes. They concluded that, in the early Holocene, many east Mediterranean lakes were more depleted isotopically than in recent millennia. This coincides with marine sapropel formation, both chronologically and geographically, and implies an increase in regional rainfall responsible for lower isotopic values in lakes and marine anoxia. In contrast, isotope records from western Mediterranean lakes do not show such a pattern, suggesting a possible NW-SE bipolar contrast in climate history across the Mediterranean during the Holocene. In more recent syntheses of the mid-Holocene climatic transition in the Mediterranean, Roberts et al. (2011, 2012) observed that both model output and proxy data suggest an east-west division in the Mediterranean climate history. Regarding the western Mediterranean, they also noted that early Holocene changes in precipitation were smaller in magnitude and less coherent spatially, and that rainfall reached a maximum during the mid-Holocene, around 6000–3000 cal BP, before declining to present-day values.

Other recent studies are also of interest within the scope of the present paper. A comparison of hydrological records led Magny et al. (2003) to propose, as a working hypothesis, that mid-latitudes between ca. 50° and 43° N underwent wetter conditions in response to centennial-scale climate cooling phases, whereas northern and southern Europe were marked by shifts to drier climate. In this general hydrological tri-partition of Europe, the latitudinal amplitude of the middle zone could have varied in relation to the thermal gradient between the high and low latitudes. Later, Giraudi et al. (2011) and Zanchetta et al. (2012) showed the key significance of the palaeohydrological oscillation around 4000 cal BP in the general climatic trajectory of the Holocene in the Central Mediterranean region. In addition to these palaeohydrological studies, a thorough review by Tzedakis (2007) has pointed out the increasingly complex climatic scenarios invoked by authors to reconcile apparently conflicting data and interpretations. Among seven ambiguities in the Mediterranean palaeoenvironmental narratives produced by the literature, he specifically questioned the notion of an accentuated summer rain regime in the northern Mediterranean borderlands during the boreal insolation maximum.

To contribute to a better understanding of Holocene palaeohydrological changes in the Mediterranean area, this study presents a tentative synthesis of data recently collected in the central Mediterranean. This study forms part of a collaborative effort by LAMA ("*Holocene changes in environment and climate, and histories of human societies in Central Mediterranean as reflected by Lakes and Marines records*") working group members, to establish well-dated high-resolution records for the Holocene in the Central Mediterranean using both lacustrine and marine sediment archives. Study sites were strategically chosen along a north–south transect favoured by the geographical morphology of the Italian peninsula (Fig. 2). The investigations were developed using an integrated multi-proxy approach, based on a range of biotic and abiotic indicators. In this paper, after methodological preliminaries (i.e. Sect. 2), we first establish a synthesis of Holocene palaeohydrological changes as reflected by various proxies in the Central Mediterranean. This synthesis considers both millennial and centennial scales and aims to identify regionally coherent patterns of changes in this region with north–south palaeohydrological contrasts (i.e. Sect. 3). Using a comparison with records established in adjacent and more distant areas from North Africa to Scandinavia, we then discuss the possible climatic significance of these palaeohydrological oscillations in terms of forcing factors and general patterns of atmospheric circulation (i.e. Sect. 4).

Finally, this synthesis paper does not have the ambition of carrying out an exhaustive review and interpretation of all the palaeohydrological data available in the literature for the Mediterranean Holocene. More reasonably, it aims at offering a synthesis of data collected in the Central Mediterranean on the basis of a specific strategy, a multi-proxy approach, as far as possible homogeneous methods, and a comparison between strategically selected records from both neighbouring and more distant regions.

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2 Methodological preliminaries

Some preliminariy remarks will be helpful to better outline the methods and strategy behind the project LAMA. In addition to instrumental and historical data collected for the past recent centuries, various proxy data have been used to reconstruct and/or infer palaeohydrological changes which have punctuated the Holocene in the Mediterranean area, i.e. fluvial activity and alluvial sedimentation (e.g. Miramont et al., 2000; Giraudi, 2005a), lake-level fluctuations (e.g. Harrison and Digerfeldt, 1993; Giraudi, 1998, 2004; Magny et al., 2007), glacier variations (e.g. Orombelli and Mason, 1997; Giraudi 2005b), isotope studies from speleothems (e.g. Frisia et al., 2006; Drysdale et al., 2006; Zanchetta et al., 2007b), or lake sediments (e.g. Baroni et al., 2006; Zanchetta et al., 2007a; Roberts et al., 2008). Pollen data offer additional supports for such reconstructions using (1) taxa considered as indicators of more or less humid conditions (e.g. de Beaulieu et al., 2005), (2) ratio between taxa to infer the establishment of present-day Mediterranean climatic conditions (Jalut et al., 2000) or the develoment of drier conditions less favourable to the expansion of the Mediterranean forests (e.g. Fletcher et al., 2013), and (3) quantitative approaches to estimate various climatic parameters (e.g. Davis et al., 2003; Kotthoff et al., 2008; Peyron et al., 2011).

Roberts et al. (2011) distinguished between primary and secondary climate proxies. While primary proxies provide records which can be unambiguously attributed to climatic forcing, secondary ones such as pollen, geomorphological evidence of river incision, alluvation and fire regimes, produce records which may reflect either climatic changes or human activity, or a combination of the two, without excluding additional factors such as ecological dynamics. Thus, among primary proxies, lake and cave isotopes are assumed to offer one way to shed light on the causes of Holocene changes in the Mediterranean landscapes. The remarks by Roberts et al. (2011) call attention to the difficulties in disentangling natural and anthropogenic factors in the Mediterranean region where the human impact associated with the expansion of Neolithic societies appears to have come particularly early. However, as explained by Zanchetta et al. (2007b) and Develle et al. (2010), while being less sensitive to human impact than, e.g. pollen or charcoal, isotope records offer a complex picture of past climatic conditions, given that they reflect changes in the isotopic composition of water resulting from complex interactions between the so-called source-, amount-, and temperature-effects. In addition, apparent contradictions, on a regional scale, between isotope records and other palaeoclimatic data such as lake-level and glacial records (Sarikaya et al., 2008; Develle et al., 2010; Wagner et al., 2010) suggest an impact of seasonal conditions, the reconstruction of which also appears to be a central point for a better understanding of the Holocene trajectories of Mediterranean ecosystems and societies.

In consequence, the strategy and methods used for the present study may be summarised as follows:

– The study sites have been chosen along a north–south transect in the Central Mediterranean to better capture possible influences of a latitudinal gradient. Thus, the project LAMA includes the sediment sequences from Lakes Ledro in Trentino, northern Italy, Accesa in Tuscany, central Italy, Trifoglietti in Calabria, southern Italy, Preola and Pergusa in Sicily, as well as the two marine cores MD90-917 in the southern Adriatic Sea and MD04-2797 in the Siculo-Tunisian strait (Fig. 2).

– The approach is based on an integrated multi-proxy analysis in the aim of reconstructing precipitation seasonality, by independant but complementary means. Thus, regarding the palaeohydrological changes which are the main topic of this paper, their reconstructions are mainly based on lake-level fluctuations and pollen-based quantitative estimates of climatic parameters, according to specific techniques described in detail and validated elsewhere (Overpeck et al., 1985; Guiot, 1990; Magny 1992, 1998, 2004, 2006; Peyron et al., 2011). While the Modern Analogue Technique (MAT) allows seasonal precipitation to be inferred from pollen data, the lake-level records established from variations in lithology and carbonate concretion assemblages are assumed to be mainly representative of summer moisture conditions (Magny, 1992; Magny et al., 2012c). However, the palaeohydrological signal given by the lake-level records probably also includes an influence of the winter rainfall which may results in reinforced water volume in the lake basins before the summer dryness. This is supported by correlations between changes in lake level and NAO indice over the last millennium (Magny et al., 2011c). Micro or macro-charcoal and pollen data offer additional supports to recognize drought periods favourable to increasing frequency of fires as well as to forest declines or the expansion of dry-tolerant plants (Vannière et al., 2008, 2011; Desprat et al., 2013; Combourieu Nebout et al., 2009, 2013). In addition, in the case of Lake Ledro, sedimentological analyses of deep cores enabled us to establish a flood frequency record (Vannière et al., 2013).

- The approach is also based on the production of high-resolution records to capture not only millennial trends of past environmental and climatic changes, but also centennial-scale events and possible abrupt changes.

- This is coupled with strong efforts to establish a robust chronology which is a prerequisite for inter-regional correlations between records. Moreover, special attention has been paid to the recognition of tephras, which support precise long-distance correlations between palaeoclimatic records (Zanchetta et al., 2012).

Before concluding the methodological preliminaries, it is worth noting the relative confusion which often characterises the terminology used for the subdivision of the Holocene in the Mediterranean area. Various terms are used from early/late to lower/upper Holocene. While the most frequent usage is a tripartite division of the Holocene (early, mid or middle, and late), the literature reveals that this distinction refers to various meanings both in terms of chronology and palaeoclimate/palaeoenvironment. Thus “early Holocene” may correspond to the period’s very beginning phase, or also include its maximum humidity phase, in contrast to “late Holocene” characterised by drier climate conditions as soon as they initiated, for instance at ca. 7000–6000 cal BP, or when they have already sufficiently developed, i.e. after ca. 5000–4000 cal BP. The term “late Holocene” may also refer to a period

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characterised by an increasing human impact on the vegetation cover, in contrast to the early Holocene characterised by absent or limited human imprint. The two usages of term may converge chronologically but also show differences depending on the region considered. Walker et al. (2012) have proposed formalizing the tri-partition division of the Holocene by reference to the 8.2 ka and the 4.2 ka climatic events. Below, we will discuss how the data presented in this paper may help to test how well this new formal subdivision coincides (or not) with palaeoclimate records available for the Central Mediterranean. So as to avoid any confusion, in this paper we will use the terms of "*early part*", "*middle/mid part*" and "*late part of the Holocene*" to refer to time intervals different from those precisely defined by Walker et al. (2012). When used, the terms of "*early Holocene*", "*middle/mid Holocene*" and "*late Holocene*" systematically refer to the intervals 11 700–8200, 8200–4200 and 4200–0 cal BP defined by Walker et al. (2012).

3 Contrasting patterns of Holocene palaeohydrological changes in the Central Mediterranean: a tentative synthesis

3.1 Millennial trends

We chose four lake-level records along a north–south transect from the Jura Mountains in west-central Europe (north of the Alps) to the south-central Mediterranean to exemplify the changes along a latitudinal gradient (Fig. 3). These records have been established from littoral cores using the same sedimentological approach, making the comparison easier. Lakes Ledro in northern Italy and Saint-Point in the Jura Mountains offer for comparison two additional palaeohydrological records established from deep cores: (1) that from Lake Ledro shows variations in flood frequency in general agreement with the pattern of lake-level fluctuations reconstructed from littoral cores in Lake Ledro (Magny et al., 2012b; Vannière et al., 2013), and (2) that from Lake Saint-Point presents palaeohydrological variations based on the estimation of detrital inputs into the lake using the ratio authigenic carbonate deposits/silicate input which reflects the hydrological activity of the lake inlets (Magny et al., 2013). In addition, Fig. 3 shows oxygen-isotope data and pollen- and sediment-inferred lake-level data from Lake Pergusa (Zanchetta et al., 2007a,b; Sadori and Narcisi, 2001; Sadori et al., 2008), as well as oxygen-isotope data from Corchia Cave (Zanchetta et al., 2007b).

Considered as a whole, Fig. 3 gives clear, overall evidence of two opposing patterns in the Central Mediterranean, with a middle part of the Holocene characterised by (1) a minimal wetness at Ledro and Accesa to the north, and (2) a maximal humidity at Lake Preola to the south. The direct comparison of the Lake Saint-Point and Preola records (Fig. 3h) gives a more striking illustration of the opposition between the Holocene palaeohydrological patterns that characterise two distinct zones, north and south of ca. 40° N. Specific characteristics of the outlet area of Lake Ledro probably explain the generally low lake level prevailing from the early to the mid-Holocene (Magny et al., 2012b).

As illustrated by Fig. 4, such an opposition is fully supported by the differences between the patterns of fire activity reconstructed for the western Mediterranean by Vannière et al. (2011), with a maximum (minimum) fire frequency during the middle part of the Holocene to the north (south) of ca. 40° N.

Regarding the chronology, the lake-level records presented in Fig. 3 lead to a definition of three successive phases within the Holocene as follows:

– Taken together, north of ca. 40° N, the lake-level records of Accesa, Ledro and Cerin (Jura Mountains; Fig. 2) suggest a distinction of two humid periods before ca. 9000 cal BP and after ca. 4500 cal BP. They were characterised by relatively wet summer conditions, and separated by a middle phase marked by drier summer conditions. The Ledro and the Accesa lake-level records show strong similarities with the Lake Cerin record north of the Alps in west-central Europe. This general palaeohydrological subdivision is close to that established by Moreno et al. (2011) at Lake Enol in northern Spain (ca. 41° N).

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- South of ca. 40° N, the Preola lake-level record gives evidence of very dry summer conditions during the early part of the Holocene, with an absence of the lake until ca. 10 300 cal BP, more humid conditions between ca. 10 300 and 4500 cal BP, and an increase in summer dryness (in addition to a possible decrease in winter precipitation) after ca. 4500 cal BP. In addition, wide lake-level fluctuations characterise two transition phases at ca. 10 300–9000 and 6400–4500 cal BP. This pattern is consistent (1) with oxygen-isotope data and lake-level changes inferred from sedimentological and pollen data at Lake Pergusa in Sicily (Fig. 3g; Zanchetta et al., 2007a,b; Sadori and Narcisi, 2001; Sadori et al., 2008), and (2) with the maximum discharge of the Sele River in southern Italy (ca. 40° N) between 10 800 and 6900 cal BP, reconstructed from a marine core in the Gulf of Salerno (Naimo et al., 2005).

Due to the absence of carbonate lake marl (metamorphic rocks in the catchment area), the sediment sequence of Lake Trifoglietti in Calabria did not allow a similar sedimentological method to reconstruct past Holocene lake-level changes in southern Italy. Nevertheless, variations in the water depth in the lake basin have been reconstructed using pollen data, i.e. a specific ratio between hygrophilous and terrestrial taxa (Joannin et al., 2012) (see below, Fig. 5). The results suggest relatively shallow water before 11 000 cal BP, a maximum water depth between 11 000 and 6500 cal BP (deep water between 11 000 and 9000 cal BP, intermediate water depth between 9000 and 6500 cal BP), and a decreasing water depth after 6500 cal BP. While the Lake Trifoglietti water-depth record partly reflects the progressive infilling and the overgrowth of this small lake basin, the general pattern shown by Lake Trifoglietti appears to be in general agreement with a humidity maximum during the middle part of the Holocene in southern Italy (Naimo et al., 2005) and show similarities with the Lake Dojran record in the Balkan region (Francke et al., 2013).

While some differences appear, for the palaeohydrological transition chronology, between the early and middle parts of the Holocene, all the records presented in Fig. 3 clearly show the key importance of the oscillation around 4500 cal BP in initiating relatively abrupt changes towards more humid (drier) summer conditions north (south) of ca. 40° N. However, it is worth noting that the Preola record also shows that a trend towards lowering initiated as early as ca. 6500 cal BP, in good agreement with the record of Lake Trifoglietti (see below, Fig. 5).

3.2 Centennial-scale events

A series of successive centennial-scale events punctuated the entire Holocene (Figs. 3 and 5). Regarding the north-central Mediterranean, the Ledro and Accesa lake-level records benefit from a robust chronology: that of Accesa is based on 43 radiocarbon dates and four tephra layers (Magny et al., 2007), and that of Ledro on 51 radiocarbon dates (Magny et al., 2012b). On both sites, the study of several littoral cores allowed to well constrain the magnitude and the chronology of the lake-level fluctuations.

Keeping in mind the age uncertainties inherent in radiocarbon dating, the centennial-scale events evidenced at Accesa and Ledro offer a consistent pattern not only on the regional scale of the north-central Mediterranean, but also in comparison to the west-central European record established north of the Alps (Magny, 2013). Thus, all together, these records display phases of increasing humidity around 10 200, 9300, 8200, 7300, 6200, 5700–5300, 4800, 4400–3800, 3300, 2700–2300, 1700, 1200 and 300 cal BP. Regarding the 11 500–11 000 cal BP interval, differences appear with a more complex pattern of lake-level variations recognised at Ledro and Accesa (a lowstand bracketed between highstand episodes; Figs. 3 and 5). Instead the west-central European lakes show a major highstand around 11 350–11 100 cal BP (Magny, 2013). In general, the phases of higher lake-level conditions in west-central Europe have been shown to coincide with cooling events in the North Atlantic area (Bond et al., 2001; Magny, 1999, 2004, 2006, 2013).

In the south-central Mediterranean, it seems more difficult to define a series of centennial-scale events from Lake Preola. Although the two cores studied at Preola display a general agreement for the millennial trends and the abrupt fall in lake level around 4500 cal BP, they show discrepancies in the details for the period after

4500 cal BP due to possible influence of overgrowth process (Magny et al., 2011b). Regarding the period before 4500 cal BP, the littoral core LPA gives evidence of major lowstands at around 10 100, 9500, 8500–8200, 7500, 6400–6000, and 5500–5000 cal BP. Core LPBC taken in the centre of the lake basin gives nearly similar results except for the lowstand dated to 8900–8600 instead of 8500–8200 cal BP in core LPA (Magny et al., 2011b).

To enlarge the documentation for the south-central Mediterranean, Fig. 5 presents pollen data obtained from marine core MD04-2797 in the Siculo-Tunisian strait (Desprat et al., 2013). In close agreement with the palaeohydrological pattern given by the Preola lake-level record, the general background is characterised first by a dominance by steppic taxa (dry climatic conditions), followed by an extension of temperate trees and shrubs between 10 100 and 6600 cal BP (wetter conditions), and finally by a development of Mediterranean plants from ca. 6600 cal BP onwards (increasing dryness). Superimposed on this general background supported by mineralogical and geochemical analyses of core MD04-2797 (Bout-Roumazeilles et al., 2012), recurrent episodes of Mediterranean forest reduction or changes in the herbaceous layer such as an increase in semi-desert plants (indicator of dryness) and/or a decrease in Cyperaceae (indicator for humidity) which are synchronous with alkenone-inferred cooling phases, give evidence of successive dry centennial-scale events marked by cooler and drier climatic conditions at ca/ 11 300, 10 100, 9300, 8200, 7000, 6200, 5500 and 4200 cal BP (Fig. 5). This series of centennial-scale events finds an equivalent in episodes of forest declines reconstructed from core MD90-917 in the Southern Adriatic Sea (Combourieu Nebout et al., 2013).

This suggests that, in response to centennial-scale cooling events, drier climatic conditions developed in the south-central Mediterranean, while an opposite pattern prevailed in the north-central Mediterranean with wetter climatic conditions. As illustrated in Fig. 5, the water-depth record of Trifoglietti (ca. 39° N) supports these conclusions with phases of shallower water around 5500 and 4000 cal BP. As discussed by Joannin et al. (2012), if we take into account the radiocarbon age uncertainty (standard

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deviation), the lowering which developed between 2500 and 1800 cal BP may be equivalent to the well-known phase identified around 2700–2500 cal BP at the Subboreal-Subatlantic transition (van Geel et al., 1996). Another relevant interpretation, if we consider the relatively northern latitudinal location of Lake Trifoglietti at more than 39° N, may be to infer a possible slight migration south to 40° N of the boundary between the north- and the south-central Mediterranean sectors characterised by contrasting palaeohydrological patterns.

Farther in the western Mediterranean, but still south of 40° N, pollen data from sites of Siles in southeastern Spain (ca. 38° N) reveal successive dessication episodes at ca. 9300, 8400, 5200, 4100, 2900, 1900, 600–300 cal BP, i.e. in general agreement with data obtained at similar latitudes in the south-central Mediterranean except for phases around 2900 and 1900 cal BP (Carrión, 2002). A pollen record from marine core MD95-2043 in the Alboran Sea, at the extremity of the western Mediterranean around 36° N (Fletcher et al., 2013) displays a series of successive episodes of forest decline as shown by Fig. 5. It is noteworthy that no dry event appears around 4000 cal BP in the MD95-2043 pollen record, in contrast to core MD04-2797, but the temporal resolution of the record around this time interval is relatively poor. Using a smoothed curve of Mediterranean forest taxa, Fletcher et al. (2013) proposed to synchronise the forest decline episodes with phases of mid-European lake-level highstands during the interval 10 500–7000 cal BP, and to the contrary, with phases of mid-European lake-level lowstands for the interval 7000–1000 cal BP. However, Magny (2013) has shown how the mid-European record of lake-level highstands is more representative of past palaeohydrological changes in the European mid-latitudes and should preferably be used as being reference for the lake-level changes in west-central Europe, whereas a reference limited to lowstands may be a source of confusion and mistakes. Moreover, as discussed in detail below (see Sect. 4.3), the comparison of the MD95-2043 record with data from adjacent areas (Carrión, 2002; Combourieu Nebout et al., 2009) suggests a possibly more complex interpretation, likely due to a fluctuating limit between the southern and the northern palaeohydrological Mediterraean sectors.

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Though human impact may have provoked vegetation change in the late Holocene, the two successive peaks of Mediterranean tree taxa, dated to ca. 2700 and 2300 cal BP in the MD95-2043 pollen record, reflect wetter climatic conditions (Fletcher et al., 2013), in good agreement with the Siles record in which a more humid interval developed between two dessication phases dated to ca. 2900 and 1900 cal BP (Carrión, 2002). This suggests a migration south to 40° N of the boundary between the opposing north and south Mediterranean hydrological sectors at the edge of the western Mediterranean around 2500 cal BP. The same interpretation does not appear to be pertinent to high values of Mediterranean tree taxa around 4400–3800 cal BP since the hypothesis of a migration of the boundary between northern and southern Mediterranean hydrological sectors southwards to ca. 36° N is inconsistent with the dry conditions reconstructed at Siles (ca. 38° N) for the same period. This suggests that new records with higher temporal resolution are needed for a better understanding of climatic conditions in this region around 4400–3800 cal BP. Later, during the Little Ice Age (LIA), this boundary may have been located north of ca. 38° N in southern Spain as suggested by dry conditions at Siles (Carrión, 2002).

3.3 Contrasting patterns of precipitation seasonality between the north- and the south-central Mediterranean

As discussed in Sect. 3.1, lake-level and fire event data provide robust and consistent records to shed light on the summer moisture availability: when not determined by anthropogenic activities, fire frequency depends on the duration and intensity of the dry season (Pausas, 2004; Vannière et al., 2011), while the main proxies used for lake-level reconstruction in this study are characteristic of the warm season (Magny, 2006). Thus, the fire records shown in Fig. 4 confirm the contrasting patterns between the north- and the south-western Mediterranean for the mid-Holocene (Vannière et al., 2011), with higher frequency of fires to the north (summer dryness) and less frequent fires to the south (more humid summers). The fire record of Lake Eski Acigöl in central Turkey, at ca. 38° N (Turner et al., 2008) fully supports this general pattern with minimum fire frequency between 9000 and 7000 cal BP.

Quantitative estimates inferred from pollen data offer useful complementary data (indirect proxy following Roberts et al., 2011) to reconstruct the precipitation seasonality in the Central Mediterranean. Figure 4 presents quantitative estimates of winter and summer precipitation for the Holocene in the north- and the south-central Mediterranean using MAT from pollen data of Lakes Accesa (Peyron et al., 2011) and Pergusa (Sadori and Narcisi, 2001; Magny et al., 2012c). First, the values obtained for the summer precipitation show general trends in good agreement with the lake-level records, i.e. they support the assumption that the south-central Mediterranean underwent a phase of maximum summer wetness between ca. 10 500 and 4500 cal BP, while the north-central Mediterranean was marked by a maximal summer dryness between ca. 9500 and 4500 cal BP. Regarding the winter season, pollen-inferred estimates suggest that both the northern and the southern areas underwent a precipitation maximum during the middle part of the Holocene, and more particularly during the interval 10 000/9500–7500/7000 cal BP, i.e. broadly during the deposition of Sapropel 1 (Mercone et al., 2000). Comparisons with climatic data obtained in northern Greece in the Boras mountains (Lawson et al., 2005) and from Tenaghi Philippon in northern Greece (Peyron et al., 2011) as well as marine cores in the Aegean Sea suggests that the climate trends and the north–south contrasts observed in the Central Mediterranean show strong similarities with those recognised in the Balkans (Peyron et al., 2013).

According to Magny et al. (2007, 2011b, 2012c), such a combination of differences and similarities between the north- and the south central Mediterranean during the middle part of the Holocene, depending on the season under consideration, may explain the apparent conflict between palaeoclimatic records depending on the proxy used for the reconstructions. For example, the stable isotope record from a speleothem of Corchia Cave in north-central Italy reveals enhanced rainfall between ca. 8900 and 7300 cal BP which probably reflects an increase in the winter precipitation originating from the North Atlantic Ocean (Zanchetta et al., 2007b). All together, these data also support the discussion by Tzedakis (2007) who (1) questioned the notion of an accentuated summer rain regime in the northern Mediterranean borderlands contributing to a freshening of the Mediterranean Sea during the boreal insolation maxima, and (2) hypothesised a summer aridity at that time. Such a contrasting seasonality in the Mediterranean during the Holocene interglacial has recently been reconstructed for the Eemian interglacial by Milner et al. (2012). To sum up, in addition to the monsoon-related enhanced Nile discharge (Revel et al., 2010), the deposition of Sapropel 1 has been favoured by an increase (1) in winter precipitation in the northern Mediterranean borderlands, and (2) in winter and summer precipitation in the southern Mediterranean area.

Moreover, reference to contrasting patterns of precipitation seasonality reconstructed in the central Mediterranean has shed new light on the Holocene development and vegetation trajectories in the western Mediterranean. Palaeoecologists have proposed various hypotheses about the possible factors driving the increase in broadleaf evergreen vegetation during the Holocene, i.e. wildfires (e.g. Carcaillet et al., 1997), human impact (e.g. Lang, 1994), or summer drought (Jalut et al., 2000). As discussed by Colombaroli et al. (2009) for the central Mediterranean, analyses suggest that the expansion of *Quercus ilex* developed as a response to contrasting hydrological conditions in the north. *Quercus ilex* expanded as early as 8500 cal BP at Accesa and replaced deciduous forests when the climatic conditions became drier. This is well illustrated by synchronous *Q. ilex* peaks and lake-level lowstands at Accesa (Magny et al., 2007). In the south, it began to expand only at 7000 cal BP at Preola (Tinner et al., 2009; Calò et al., 2011) and Biviere di Gela in low-elevated coastal areas of southern Sicily, but as early as 9000 cal BP at the higher elevation site of Pergusa (Sadori and Narcisi, 2001), where it replaced maquis or steppe vegetation when climatic conditions became moister. In addition, precipitation seasonality may help to explain synchronous expansion of taxa with apparent opposite requirements in humidity. Thus, the contemporaneous maxima of *Abies* and *Q. ilex* at Accesa in the mid-Holocene may be explained by a combination of maximal (minimal) winter (summer) humidity.

3.4 Climato- and tephro-stratigraphies

Several lacustrine and marine sediment sequences studied within the LAMA project have revealed tephra layers (Figs. 3 and 5) which offer the opportunity to better constrain correlations between palaeoclimatic/palaeohydrological- and tephrostratigraphies. Inter-regional correlations between records on a centennial scale are often limited due to chronological uncertainties linked to inaccuracies inherent in the radiocarbon dating (calibration time-window, marine reservoir effect) (Zanchetta et al., 2011). In this general context, tephra layers offer key time-marker horizons to physically correlate different records. From this point of view, the sediment sequence of Lake Accesa and that of core MD90-917 provide important contributions to establishing possible correlations between climato- and tephro-stratigraphies as set out below.

Three tephra layers have been recognised in the Holocene sediment sequence of core AC03-04 of Lake Accesa (Magny et al., 2007, 2009; Fig. 3):

- The Agnano Monte Spina (AMST) and the Avellino (AVT) tephras, from the Phlegrean fields and from the Vesuvius respectively, offer key horizons for the beginning of the Neoglacial in the Central Mediterranean around 4500–3800 cal BP. As summarised by Zanchetta et al. (2012), major environmental changes such as rise in lake level at Accesa, and glacier advance in the Gran Sasso Massif (central Italy), occurred just after the deposition of the AMST and predate that of the AVT. Moreover, a second distinct layer (Pr1) corresponding to the end phase of the Avellino event (interplinian events AP2-AP4; Wulf et al., 2004; Rolandi et al., 1998) was deposited during a short-lived lowstand between the two successive high lake-level phases which characterise the starting Neoglacial at Lake Accesa (Magny et al., 2007, 2009).

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At Lake Preola, core LPBC gives evidence of a tephra layer dated to ca. 7300 cal BP from the age-depth model (Magny et al., 2011b). It corresponds to an eruption from Pantelleria Island and was deposited during a maximal dryness phase marked by a lake-level lowering and an accumulation of eolian sand (Fig. 3).

In core MD90-917, Siani et al. (2010, 2013) have identified several tephras of interest for correlation between tephro- and climato-stratigraphies (Fig. 5).

- The Palinuro tephra from Seamount Palinuro was deposited just at the Younger Dryas/Holocene transition (Siani et al., 2006). It is dated at 9990 ± 90 ^{14}C yr BP (i.e. ca. 11 460 cal BP).
- The E1 tephra (Paterne et al., 1998; Fontugne et al., 1989) is correlated with the Gabellotto-Fiumebianco eruption from the Lipari Islands. It marks the top of the interval S1a, just before the interruption of Sapropel 1 deposition which corresponds to the 8.2 ka event in the Mediterranean.
- In agreement with the terrestrial records from Central Italy (Zanchetta et al., 2012), the AMST predates the beginning of a cooling event which developed around 4300–3800 cal BP, while the Astroni tephra from the Phlegrean fields marks its final part.

Further to the east, in the Balkan region, the Mercato tephra constrains the age of the 8.2 cooling event (Aufgebauer et al., 2012; Vogel et al., 2010; Wagner et al., 2009), while the FL tephra constrains the age of a dry and cold period around 4000 cal yr BP at Lake Ohrid (Wagner et al., 2009, 2012; Vogel et al., 2010), and the AD472/512 tephra constrains the onset of the MWP at lakes Ohrid and Prespa (Aufgebauer et al., 2012; Wagner et al., 2009, 2012; Vogel et al., 2010).

4 Forcing factors and past atmospheric circulation patterns

4.1 Preliminary remarks

As noted by Tzedakis (2007), the wealth of palaeoenvironmental/palaeoclimatic data collected from the Mediterranean area has led to increasingly complex (sometimes conflicting) scenarios which reflect the possible complexity of climatic mechanisms that have operated in a region at the interface between high- and low-latitude influences as well as between western (North Atlantic Ocean) and eastern (Eurasia, Indian Ocean) interactions.

Given that the Mediterranean region is located at the transition between the temperate and tropical zones, it is influenced by the dynamics of both the tropical circulation cells and the mid-latitude westerlies. Today, the mechanisms which control the marked seasonal precipitation contrasts in the Mediterranean area offer a possible modern analogue for palaeoclimatic studies (Tzedakis et al., 2009). While the northward migration of the Intertropical Convergence Zone (ITCZ) across the Equator determines the development of the rainy season in the Tropics (monsoonal systems) in the boreal summer, it brings the Mediterranean under the influence of the subtropical anticyclone belt and, as a result, widespread aridity. In contrast, its southward migration in winter allows the influences of mid-latitude westerlies to penetrate the Mediterranean basin. This also results in a north–south humidity gradient in the Mediterranean with the dry summer season lasting less (more) than five months north (south) of ca. 40° N (Quézel and Medail, 2003).

Geographical characteristics may reinforce this general complexity. The Mediterranean Basin is composed of two distinct basins separated by the Italian Peninsula and Sicily, with a western basin located at more northerly latitudes between ca. 45° and 35° N and closer to the influences of the North Atlantic Ocean, and an eastern basin located at more southerly latitudes between ca. 40° and 30° N, farther away from the North Atlantic Ocean but more exposed to influences from continental Europe such

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as the Siberian High (Rohling et al., 2002; Pross et al., 2009), or to possible interactions with the African and south Asian monsoon (Staubwasser and Weiss, 2006).

The Mediterranean area is also affected by atmospheric circulation patterns responsible for regionally contrasting hydrological conditions. Many studies have demonstrated that the North Atlantic Oscillation (NAO) coupled with the Arctic Oscillation (AO) is the most prominent mode of variability of the North Atlantic and Mediterranean region winter climate (e.g. Hurrell, 1995; Wanner et al., 2001; Xoplaki, 2002). In winter, the atmospheric circulation in this area is characterised by a strong north–south pressure contrast (expressed by the NAO index) between the Icelandic Low and the Azores High. This pressure gradient drives the strength of the westerly flow bringing more (positive NAO) or less (negative NAO) mild moist air to north-western Europe. Regarding the Mediterranean area, the NAO provokes marked regional hydrological contrasts. Thus, under positive NAO, the Mediterranean northern borderlands experience dry conditions when the southern Mediterranean benefits from increasing precipitation like in north-western Europe (see below) (Marshall et al., 2001; Dünkeloh and Jacobeit, 2003). Opposite contrasts develop under negative NAO conditions. It is worth noting that the boundary between the two opposite hydrological sectors of the Mediterranean may be affected by latitudinal fluctuations. Thus, in recent times, depending on the reference period considered, northern Morocco and the region of the Gibraltar Strait to the west, and southern Turkey to the east, may or may not both included in the northern Mediterranean sector (Marshall et al., 2001; Lamy et al., 2006; Lionello et al., 2006). As noted by Dünkeloh and Jacobeit (2003), the so-called Mediterranean Oscillation (MO), associated with similar hydrological contrasts between north-western and south-eastern Mediterranean sectors, must not be seen as independent large-scale circulation modes since they correlate significantly with the Northern Hemisphere modes of the AO/NAO, and may be considered as the Mediterranean expression of the NAO in terms of precipitation variability.

In addition to the NAO, various (secondary) circulation patterns acting over the Mediterranean area (such as the East Atlantic-West Russian and North Sea-Caspian

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patterns) have been recognised by means of recent time-series of meteorological data (e.g. Xoplaki, 2002). Interestingly, Dünkeloh and Jacobeit (2003) have established maps of precipitation anomalies associated in the Mediterranean Basin to main circulation patterns distinguished for the period 1948–1998. These maps reveal the complex hydrological patchworks which may result on regional scale from these different atmospheric circulation patterns. This may be a source of additional difficulties in identifying regionally coherent patterns from palaeoclimatic data.

A further complexity originates from changes which affect boundary conditions during the Holocene interglacial. This includes orbitally-driven changes in insolation and its seasonal as well as interhemispheric distribution (Berger, 1978; Berger and Loutre, 1991; Wanner et al., 2011). The insolation maximum coincided with a northward migration of ITCZ and a reinforcement of the African and Indian monsoons (Tzedakis et al., 2009; Revel et al., 2010; Fleitman et al., 2007), as well as a prevailing positive mode of the NAO (Gladstone et al., 2005; Davis and Brewer, 2009; Dyck et al., 2010). The deglaciation is also responsible for substantial changes in the boundary conditions with the successive disappearance of the Fennoscandian and Laurentide ice-sheets around 9500–9000 and 7500–7000 cal BP respectively (Lundqvist and Saarnisto, 1995; Renssen et al., 2009; Carlson et al., 2008). At a centennial scale, rapid deglaciation freshwater outbursts were still associated during the early Holocene with successive abrupt cold events in the North Atlantic area, such as the well-known 8.2 ka event (Alley et al., 1997).

Last (but not least), a final difficulty may be seen in the wide variety of proxies used for the establishment of palaeoenvironmental/palaeoclimatic records from both marine and terrestrial cores in the Mediterranean basin. This leads to a plethora of palaeodata which theoritically may favour the reconstruction of various (seasonal) aspects of past changes in environmental/climatic conditions. But this also may be responsible for difficulties in cross-correlations between records due to differences in the signal recorded by proxies (or in their sensitivity threshold) resulting in possible leads and lags between proxies and apparently in no synchronous changes in the records.

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Taking into account the main features and the complexity which may characterise the Holocene in the Mediterranean area, Figs. 6–9 present a comparison of selected records to place the Mediterranean in a more general context and help to recognise possible key factors, on both millennial and centennial scales, responsible for hydrological changes in this area over the last 11 700 yr.

4.2 Millennial trends

To replace the palaeohydrological records from the Mediterranean in a large-scale context, they may be compared with selected records from northern Africa to northern Europe as illustrated by Figs. 6 and 7. In Fig. 6, the lake-level records from Preola, Accesa and Cerin have been reconstructed by Magny et al. (2007, 2011a,b). The record established at Jostedalsbreen by Nesje et al. (2000) displays variations in precipitation in western Norway, while the annual precipitation record at Lake Svanåvatnet (northern Norway) has been produced by Bjune and Birks (2008) using pollen-inferred quantitative estimates. Finally, the upper panel of Fig. 6 shows records indicating general climatic conditions in the Finnish Lapland as reflected by (1) the altitude of the highest pine megafossil in 200 yr intervals and (2) a chironomid-inferred temperature record (Seppä et al., 2008). In Fig. 7, the Fe record from core MS27PT off the Nile Delta has been established by Revel et al. (2010) and reflects the sediment input from the Blue Nile as resulting from the African monsoon. The lake-level pattern of the northern part of Africa has been established using various data from the region between 8° and 28° N (Hoelzmann et al., 1998; Gasse and Roberts, 2004). The Ti record from Lake Tana in Ethiopia has been established by Marshall et al. (2011) to infer variations in effective precipitation in the area of the source of the Blue Nile. The oxygen-isotope record from Soreq Cave gives evidence of variations in the wetness in the south-eastern Mediterranean (Bar-Matthews et al., 1998). Finally, the Preola lake-level record has been added in the upper panel of Fig. 7 to facilitate the comparison between the palaeohydrological records from the south-central and eastern Mediterranean.

Taken together, Figs. 6 and 7 reveal several mean features as follows.

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– The palaeohydrological records show (1) a general increase in humidity during the middle part of the Holocene in tropical North Africa, in the south-central Mediterranean and in Norway, and (2), in contrast, drier conditions (lake-level minimum) in the north-central Mediterranean and in west-central Europe.

– Like the lake-level records from Lakes Tanganyika, Turkana and Chew Bahir in equatorial Africa (Marshall et al., 2011; Garcin et al., 2012; Foerster et al., 2012), the MS27PT record off the Nile Delta shows a maximum of humidity (monsoon rainfall) as early as the beginning of the Holocene which prolongs a strong Late Glacial Bölling-Alleröd increase interrupted by the dry Younger Dryas event (Revel et al., 2010). In contrast, the other palaeohydrological records presented in Figs. 6 and 7 give evidence of increasing time lags of the hydrological signal towards northern latitudes, with a maximum (or a minimum in the north-central Mediterranean and in west-central Europe) of humidity starting around 10 500 cal BP in North African lakes (in agreement with Lézine et al., 2011), at Lake Preola and at Soreq Cave, around 9000 cal BP at Lakes Accesa and Cerin, and finally at ca. 7500 cal BP at Jostedalsbreen and Stanåvatnet in northern Norway. This suggests a shortening of the duration of the Holocene climatic optimum from the southern to the northern latitudes.

– Regarding the mid- to late Holocene, the palaeohydrological records in Figs. 6 and 7 highlight two phases of major changes around 8000–7000 cal BP and 4500–4000 cal BP.

The data presented in Figs. 6 and 7 suggest that palaeohydrological changes reflect a combination of two major forcing factors, i.e. orbitally-driven insolation and deglaciation:

– According to Davis and Brewer (2009), the maximal strength of the African monsoon shows a close relationship with the peak of insolation near the Equator in the North African tropics. This is in agreement with the early maximum of sediment

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input (i.e. Blue Nile discharge) observed off the Nile Delta by Revel et al. (2010) and the early Holocene maximum of humidity shown by the lake-level records from equatorial Africa (Marshall et al., 2011; Garcin et al., 2012; Foerster et al., 2012).

– On the basis of Western and Central Mediterranean records it has been suggested that dry conditions during the early Holocene in the (southern) Mediterranean may have resulted from the strong Hadley Cell activity in response to the orbitally-driven insolation maximum (Tinner et al., 2009). This is corroborated by our new compilation, which shows that dry conditions prevailed south of ca. 40° N during the early part of the Holocene along a west–east transect in the Mediterranean (Magny et al., 2011b), as reflected by the lake-level record of Preola but also by those of Medina in southern Spain (Reed et al., 2001), Xinias in Greece (Digerfeldt et al., 2007), and Gölhisar in south-western Turkey (Eastwood et al., 2007), as well as by the Soreq isotope record (Bar-Matthews et al., 1998). The latter records show that this explanation may also be applied to the Eastern Mediterranean which is also influenced by the Asian monsoon. However the African and Asian monsoons are strongly coupled (Fleitmann et al., 2008) through the Hadley Cell activity. Indeed Gaetani et al. (2007) have shown how an intense African monsoon reinforces the Hadley circulation, and consecutively strengthens the North Atlantic anticyclone (with a wider extension of the descending branch of the Hadley cell) and its blocking effect for the western (Atlantic) wet air flow towards the Mediterranean. This interpretation is supported by data obtained from marine core ODP site 658 C off Mauritania which shows the effects of the declining summer insolation maximum as early as ca. 10 000 cal BP at ca. 20° N in the eastern North Atlantic area (deMenocal et al., 2000; Berger and Loutre, 1991). Links between a strong monsoon system and an increased summer dryness are also supported by recent observations for the last two millennia in the eastern Mediterranean (Jones et al., 2006). It is worth to note that even the North African lake-level record (Hoelzmann et al., 1998; Damnati, 2000; Gasse and Roberts,

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2004; Lézine et al., 2011) shows such a slightly delayed humidity maximum as do the Preola and Soreq records. In addition, model experiments have shown how the presence of remnant ice sheets (with associated fresh water input into the North Atlantic Ocean and lake-drainage episodes) may have been responsible for a southward shift of the monsoon rainbelt as discussed by Lézine et al. (2011) about Holocene palaeohydrological records from the Sahara and Sahel, and provoked dry conditions during the early part of the Holocene. Such an evolution of combined orbital and ice-sheet forcing may have favoured the general delay of the forest expansion observed in the pollen records from Trifoglietti (Joannin et al., 2012), core MD04-2797 in the Siculo-Tunisian Strait (Desprat et al., 2013; Bout-Roumazeilles et al., 2012) and core MD95-2043 in the Alboran Sea (Fletcher et al., 2013), as well as in the eastern Mediterranean region (Roberts et al., 2001; Valsecchi et al., 2012), with west–east and north–south gradients probably due to an increasing distance from the North Atlantic Ocean and from the northern mid-latitude westerlies.

– As discussed above in Sect. 3, contrasting hydrological patterns have been recognised in the central Mediterranean south and north of 40° N. Interestingly, Davis and Brewer (2009) have shown that, at the mid-Holocene, the latitude around 40° N also corresponds to a temperature limit with negative temperature anomalies (climate cooling) to the south, and positive values to the north. This may have favoured a positive water balance to the south and a negative one to the north, in agreement with the lake-level records presented in Fig. 3. Furthermore, the final steps of the deglaciation in a general context of high insolation provoked a decrease in the latitudinal temperature gradient (LTG) (not directly in phase with the maximum insolation), and favoured the installation of a positive NAO-type circulation in the North Atlantic area (Davis and Brewer, 2009). Thus, the initiation of the lake-level minimum at Lakes Accesa and Cerin around 9000 cal BP coincided with the disappearance of the Fennoscandia ice-sheet (Magny et al., 2011a) and a first installation of a general atmospheric circulation which mimics a positive NAO-type

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circulation (Gladstone et al., 2005; Wanner et al., 2008; Dyck et al., 2010). In the south-central Mediterranean, the wide amplitude of the lake-level fluctuations during the unstable transition period 10 300–9000 cal BP (see above, Sect. 3.1) may reflect a diminished influence of the Fennoscandian deglaciation period. Finally, the second major step of the deglaciation, with a rapid melting of the Laurentide ice-sheet (LIS) between 8000 and 7000 cal BP punctuated by a marked increase in sea-level rise around 7600 cal BP (Carlson et al., 2008), led to the expansion of a predominant positive NAO-type circulation towards higher latitudes (weaker LTG; Davis and Brewer, 2009). This resulted in warm/humid air advection into northern Europe (northward movement of westerlies) as reflected by the increasing humidity observed in western Norway and the rapid tree-line rise in Finnish Lapland around 7500 cal BP (Fig. 6; Bjune and Birks, 2008; Nesje et al., 2000; Seppä et al., 2008). On the basis of palaeoclimatic data, the map in Fig. 8 presents an illustration of the possibly prevailing positive NAO-type circulation over Europe and the Mediterranean and its contrasting palaeohydrological pattern for the middle part of the Holocene. While a decrease in the LTG favoured a northward migration of westerlies which brought milder and wetter climate conditions over northern Europe, the development of more humid conditions in the Mediterranean during the middle part of the Holocene may have resulted from (1) orbital conditions, i.e. decreased summer insolation and reduced blocking effect of the North Atlantic anticyclone for the western (Atlantic) wet air flow towards the Mediterranean, (2) the development of lows induced by stronger sea-land temperature contrasts in winter along the relief of the northern and southern Mediterranean coastlines (Trigo et al., 2002; Harding et al., 2009), (3) sub-saharian cyclones over the western-central Mediterranean (Knippertz, 2005) favoured by a more northerly position of ITCZ during the insolation maximum, as well as rain-stroms originating from the Tropics over the Eastern Mediterranean (Ziv et al., 2005), and (4) a substantial increase in precipitation in response to generally higher sea-surface temperature (Marchal et al., 2002).

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However, the prevailing positive NAO-type circulation during the middle part of the Holocene remains a matter of debate. The winter mid-latitude circulation and associated storms reaching Europe may have been determined by a complex interplay between the mid-latitude temperature gradient, the tropical convection and the surface contrast at the North American East coast, which have varied along the Holocene due to changes in insolation and ice-sheet extent (Brayshaw et al., 2011). In particular, in order to explain an increased winter precipitation during the 10 000–7000 cal BP interval, Desprat et al. (2013) pointed to a possible southern location of the mid-latitudes jet, strengthening the Mediterranean cyclogenesis, in agreement with model simulations in response to a weaker boreal winter insolation (Brayshaw et al., 2011) and to a rapid LIS melting associated with a suppression of the deep convection in the Labrador Sea and a cooling the eastern North Atlantic (Carlson et al., 2008).

– After ca. 7500 cal BP, the LTG began to increase (Davis and Brewer, 2009) and favoured both (1) the southward migration of the ITCZ and monsoon system, in agreement with the Cariaco record (Haug et al., 2001), and (2) that of the westerlies. However, the records presented in Figs. 6 and 7 suggest that, in response to the progressive decline in insolation and LTG, the climate reversal may have been characterised by abrupt climatic changes. As early as ca. 7500 cal BP, a major climate reversal occurred as suggested (1) to the south by an abrupt fall in the Nile discharge (Revel et al., 2010; Fig. 7f), and a peak in the eolian dust record of Kilimanjaro due to enhanced aridity (Thompson et al., 2002), and (2) to the north by the development of colder SST in the Norwegian Sea (Fronval and Jansen, 1996) and the beginning of a drying trend at Jostedalsbreen in western Norway (Nesje et al., 2000; Fig. 6e). In the southern Mediterranean, the lake-level records from Preola in Sicily, Medina in Spain, and Xinias in Greece, as well as the oxygen-isotope record from Gölhissar in Turkey, show a marked negative anomaly around 7500 cal BP followed by a general decline in humidity after ca. 6000 cal BP (see Fig. 10 in Magny et al., 2011b). In addition, the Preola sediment

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sequence gives evidence of a provisional resumption of eolian sand deposition during the dry phase around 7300 cal BP (Fig. 7b), while the Soreq Cave record marks an abrupt fall in wetness after ca. 7500 cal BP. However, the comparison of the Preola and North African lake-level records (Fig. 7e) suggests that the African lakes were more affected by the climatic oscillation around 7500 cal BP than the Mediterranean ones, while they show nearly synchronous rises in water table around 10 500 cal BP. In the northern Mediterranean (Lake Accesa) and in west-central Europe (Lake Cerin), the period around 7500 cal BP coincided with the beginning of a trend toward higher lake-level conditions, while marine core MD90-917 in the South Adriatic Sea shows a marked decline in salinity around 7500–7000 cal BP probably due to increased discharge from the Po River in northern Italy (Combourieu Nebout et al., 2013; Siani et al., 2013).

The event around 7500–7000 cal BP could be a non-linear response of the climate system to the gradual decrease in insolation. The period around 8000–7000 cal BP appears to be synchronous with the maximum rate of change (decline) in annual insolation (MRCAI, see Figs. 6a and 7a) for the Holocene (Zhao et al., 2010) while a prolonged period of decrease in residual atmospheric ^{14}C developed between ca. 8200 and 7200 cal BP (Stuiver et al., 1998). Finally, this interval also coincided with a major final step of the deglaciation as pointed out by Törnqvist and Hijma (2012), with the Lake Ungava and Labrador outburst events (Jansson and Kleman, 2004). Thus, the large magnitude of the event around 7500–7000 cal BP may have resulted from a combination of three factors, i.e. the orbital forcing, the final deglaciation, and a change in solar activity.

– The records presented in Figs. 6 and 7 point to a second major event around 4500–4000 cal BP, which marks another key step in the climate reversal following the Holocene climate optimum. It may be considered as the end of the general dominance of positive NAO-type circulation, as suggested by the end of the humid interval in western Norway (Bjune and Birks, 2008), the marked decline in temperature and in timberline in northern Scandinavia (Fig. 6; Seppä et al., 2008),

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i.e. all indicators of a southward migration of westerlies and their associated influence for mild/wet climatic conditions. To the south, in Northern Africa, the interval 4500–4000 cal BP coincided with a major fall in temperature in the Kilimanjaro region (Schmiedl et al., 2010), and corresponded to the most salient event (double peak) in the Holocene eolian dust record of Kilimanjaro (Thompson et al., 2002), and to the end of the high lake-level period in the North African lakes (Hoelzmann et al., 1998; Gasse and Roberts, 2004; Kröpelin et al., 2008). In the southern Mediterranean, an abrupt decrease in wetness at Lake Preola and at Soreq Cave developed south of 40° N. In the northern Mediterranean and in west-central Europe, Lakes Accesa and Cerin show an accentuated rise in lake level. Such an abrupt change in environmental and climatic conditions around 4500 cal BP has been reconstructed in central Italy (Zanchetta et al., 2012; Ramrath et al., 1999), at Lake Maliq (Magny et al., 2009; Fouache et al., 2010) and at Lakes Prespa and Dojran (Wagner et al., 2010; Francke et al., 2013) in the Balkans. As observed for the climate reversal at ca. 7500–7000 cal BP, this second major climate reversal around 4500–4000 cal BP which marks the transition between the middle and late Holocene (Walker et al., 2012) may be a non-linear response to a gradual decrease in insolation (Zhao et al., 2010) and LTG. It is worth to note that it also coincided with a key period of seasonal and interhemispherical changes in insolation (Fig. 7) and with a reorganisation of the general atmospheric circulation underlined by a pronounced southward shift of ITCZ in the Tropics (Haug et al., 2001; Magny et al., 2012b). Marchant and Hooghiemstra (2004) and Booth et al. (2005) have shown how this severe climatic anomaly may have been global in extent. In the northern Mediterranean, the rising lake levels probably reflect the increasing influence of westerlies, and instead of drier conditions developed in the southern Mediterranean and the Tropics in response to climate cooling, i.e. lower sea-surface temperature and weaker evaporation (Magny et al., 2003; Mayewski et al., 2004).

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4.3 Centennial-scale events

According to Davis and Brewer (2009), the LTG controls the location of the main climate zones, as well as the position of the Hadley cell and the ITCZ. Every year, the Hadley cell moves northwards (southwards) in summer (winter) when the LTG is weak (strong). These annual migrations offer modern analogues for mechanisms associated to high-latitude Holocene cooling events, and their consequences in terms of wetter (drier) conditions in the subtropics and in northern latitudes when the systems migrate northwards (southwards). In addition to the effects of the system migrations, cooling events also favour a decrease in wetness in southern latitudes due to lower sea-surface temperature and weaker evaporation.

It is well known that the early Holocene has been punctuated by a series of freshwater outbursts from deglacial lakes in northern Europe and in North America, resulting in successive cooling events in the North Atlantic area at ca. 11 300 (Preboreal oscillation), 10 200, 9200, 8200 and 7500–7000 cal BP (Alley et al., 1997; Björck et al., 1997, 2001; Fleitmann et al., 2008; Magny et al., 2001; Magny and Bégeot, 2004; Jansson and Kleman, 2004; Yu et al., 2010). Authors have also shown how these events may have been associated with cooling in the North Atlantic and have resulted from a possible combination of freshwater outbursts and decrease in solar activity (Magny, 1999, 2004, 2006; Bond et al., 2001; Björck et al., 2001; van der Plicht et al., 2004; Magny and Bégeot, 2004). Palaeohydrological data collected in Europe suggest that the cooling events have coincided at mid-latitudes with wetter climate conditions in response to an increasing strength of the Atlantic westerly jet (increasing LTG), while latitudes south of ca. 40° N experienced drier climate conditions (Magny et al., 2003). The cold and dry conditions associated to the interruption of Sapropel 1 during the 8.2 ka event offer a well-known illustration for these mechanisms (Kotthoff et al., 2008; Pross et al., 2009).

Previous studies have revealed possible imprints of deglacial cooling events in the western and central Mediterranean from marine and terrestrial (lacustrine) cores (e.g.

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Cacho et al., 2001; Asioli et al., 2001; Magny et al., 2006a; Fletcher et al., 2010). Data collected within the LAMA project clearly show how these cooling events in the Central Mediterranean corresponded to wetter conditions marked by higher lake level to the north of ca. 40° N and to drier conditions to the south. The drier conditions south of ca. 40° N are marked by a retreat of forest taxa in core MD04-2097 at ca. 11 300, 10 100, 9300, 8200, and 7000 cal BP (Desprat et al., 2013) (Fig. 5), in good agreement with phases of forest retreat recognised from core MD95-2043 in the Alboran Sea (Fletcher et al., 2013).

Regarding the mid- to late Holocene period, Fig. 9 presents a comparison between selected records around the Mediterranean (Fig. 9, upper panel) to test the hypothesis of a possible impact of NAO-type circulation in driving centennial-scale climatic events as proposed by Lamy et al. (2006). Lake-level records present phases of higher water tabel (wetter conditions) reconstructed in west-central Europe and in the north-central Mediterranean (Magny, 2013; Magny et al., 2007, 2012b). Records from cores GeoB7622 and GeoB5804-4 have been established by Lamy et al. (2006). Core GeoB7622 in the south-western Black Sea off the Sakarya River mouth gives evidence of variations in the frequency of clay layers which reflect variations in rainfall in northern Anatolia. Core GeoB5804-4 in the Gulf of Aqaba (northern extremity of the Red Sea) provides a record of terrigenous sand accumulation as a marker of the eolian input (dryness) from neighbouring deserts. Cores GA-112/GA110 off southern Israel have been studied by Schilman et al. (2001) and give evidence of Nile flood fluctuations on the basis of variations in eastern Mediterranean productivity over the last 3500 yr. Three pollen records (1) from marine cores MD04-2797 in the Siculo-Tunisian strait (Desprat et al., 2013), MD95-2043 in the Alboran Sea (Fletcher et al., 2013) and (2) from Lake Siles in southern Spain (Carrión, 2002) document drought phases in the south-central and south-western Mediterranean. Finally, Fig. 9 shows a series of dry events identified in Central Tunisia from major peaks in fluvial activity linked to a decrease in vegetation cover (Zielhofer and Faust, 2008).

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The general picture which emerges from Fig. 9 is that of a succession of centennial-scale climatic oscillations which punctuated the mid- to late Holocene period in the Mediterranean and are associated with contrasting hydrological patterns characteristic of NAO-type circulation as first hypothesised by Lamy et al. (2006). Thus, within the radiocarbon age uncertainty, phases of increasing wetness in the north-central Mediterranean and in northern Anatolia appear to be broadly synchronous with phases of increasing dryness in the southern Mediterranean borderlands and reduced Nile flood frequencies. Taken together, these data show a regional pattern coherent with that of the negative phase of NAO. Despite the relatively weak temporal resolution of core MD95-2043 for the late Holocene, this general pattern is supported by the well-dated high-resolution record of Siles, near the Alboran Sea. Davis and Brewer (2009) have shown close relationships between winter LTG across Europe and AO during the 20th century, with positive (negative) AO-type circulation linked to weaker (stronger) LTG. This is consistent with Wanner et al. (2001) and Trouet et al. (2009), which show that during negative NAO phases, the Azores High is weakened, resulting in a southward move of westerlies and an increase in moisture transported over the European mid-latitudes. This is supported by the reconstruction of Holocene storm activity in the north-western Mediterranean (Sabatier et al., 2012), in addition to a 200 yr time series of recent Po River discharges which confirms the link between negative NAO, higher Po discharge and stronger precipitation in northern Italy (Zanchettin et al., 2008). These results, hypothesising a possible major impact of NAO (MO) on the Holocene climate in the Mediterranean, support interpretations from previous studies of the climate oscillation around 4500–4000 cal BP in the central Mediterranean (Magny et al., 2009) or concerning the last millennium in the Mediterranean (Roberts et al., 2011). This points out similar mechanisms such as those described for millennial trends (see above, preceding Sect. 4.2), with cooling events responsible (1) for wetter conditions over the northern Mediterranean more affected by a southward migration of westerlies due to a stronger LTG, and (2) for drier conditions in the southern Mediterranean and the

Tropics in response to cooler sea-surface temperature and weaker evaporation (Magny et al., 2003; Mayewski et al., 2004).

Moreover, on the basis of spectral analyses, Lamy et al. (2006) have suggested that the marine records from cores GeoB7622 and GeoB5804-4 show a likely solar origin for the AO-NAO-like atmospheric variability in the Mediterranean during the mid-to late Holocene. This is supported by correlations recognised between (1) phases of high lake-level (or increasing flood frequency) in the north-central Mediterranean and west-central Europe, (2) IRD events in the North Atlantic Ocean, and (3) peaks in atmospheric residual ^{14}C (Bond et al., 2001; Magny, 1999, 2013; Magny et al., 2003, 2007, 2012b; Vannière et al., 2013). Such a relationship is consistent with model studies (Shindell et al., 2001). All together, in agreement with Lamy et al. (2006), this suggests a prominent role of NAO-type circulation and solar forcing in the centennial-scale climate variability in the Mediterranean area during the last seven millennia.

In addition, data presented in Fig. 9 suggest possible latitudinal changes in the limit between the contrasting hydrological sectors in the Mediterranean in response to changing NAO. Thus, during the LIA, fluvial data from Tunisian rivers (Zielhofer and Faust, 2008) and pollen data from the Spanish site of Siles (Carrión, 2002) suggest drier conditions, though pollen data from Pergusa in Sicily (Sadori et al., 2013) give evidence of more humid conditions. During the interval 2700–2300 cal BP, the regions of southern Spain and the Alboran Sea may have been included in the northern hydrological sector characterised by more humid conditions in response to negative NAO as shown by the records from Siles and marine core MD95-2043. This is supported by pollen-inferred quantitative estimates at Pergusa, Sicily (Sadori et al., 2013) and by the Trifoglietti water-depth record discussed above in Sect. 3.2 (Joannin et al., 2012), while, in contrast, the Tunisian area belongs to the southern hydrological sector marked by drier conditions (Zielhofer and Faust, 2008). Taken together, available data suggest a southward migration of the limit between the northern and the southern hydrological sectors during the intervals 2700–2300 and 500–200 cal BP (i.e. the LIA) in the central Mediterranean.

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Looking at the climate oscillation pattern, the double peaks that appear around 2500 cal BP in cores GeoB5804-4, MD95-2043 and GeoB7622 may find an equivalent in the two successive lake-level highstands recognised in west-central Europe during this interval (Magny, 2004, 2013). The possible complexity of the oscillation around 4300–3700 cal BP, well illustrated by the lake-level records of Lakes Ledro and Accesa and of west-central Europe (Magny et al., 2009, 2012a), is also supported by the records from Lake Dojran (Francke et al., 2013) core GeoB7622 in the Black Sea and core GeoB5804-4 in the Red Sea (Lamy et al., 2006), and by a double peak of eolian dust in the Kilimanjaro record (Thompson et al., 2002). However, the pollen data from Siles and core MD95-2043 appear to be conflicting (dryness at Siles and higher humidity in the Alboran Sea region). The lake-level records from Ledro, Accesa and west-central Europe (Magny et al., 2006b) reveal a possible complexity of the oscillation around 5700–5200 cal BP with three successive events. The pollen- and sediment-records from cores MD04-2797 and GeoB5804-4 also show a possible tripartite pattern but, in core MD04-2797, the second retreat of Mediterranean tree taxa and the second and third sand peaks in core GeoB5804-4 are weakly marked. Thus, clearly, the schema outlined in Fig. 9 must be tested through further investigations to establish additional high-resolution and well-dated records in selected locations around the Mediterranean basin.

5 Conclusions

On the basis of a multi-proxy approach and a strategy combining lacustrine and marine records along a north–south transect, data collected in the Central Mediterranean within the framework of the LAMA project have led to the reconstruction of palaeohydrological records with specific efforts to establish robust chronologies and attain high temporal resolutions. Several conclusions and working hypotheses emerge from these investigations as follows.

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- Lacustrine and marine sediment sequences studied within the LAMA project offer a new contribution to better constrained correlations between tephro- and palaeo-hydrological/palaeoclimatic stratigraphies.

- South of ca. 40° N, the first millennium of the Holocene was characterised by very dry climatic conditions, not only in the eastern Mediterranean, but also in the central and the western Mediterranean as reflected by low lake levels and delayed afforestation.

- Contrasting patterns of palaeohydrological changes have been evidenced in the central Mediterranean: north (south) of around 40° N, the middle part of the Holocene was characterised by lake-level minima (maxima), during an interval dated to ca. 10 300–4500 cal BP to the south and 9000–4500 cal BP to the north. Available data suggest that these contrasting palaeohydrological patterns operated during the entire Holocene, both on millennial and centennial scales.

- The use of a multi-proxy approach supports the reconstruction of contrasting precipitation seasonality. Thus, the maximum humidity in the Central Mediterranean during the middle part of the Holocene was characterised by humid winters and dry summers north of ca. 40° N, and humid winters and summers south of 40° N. This may explain an apparent conflict between palaeoclimatic records depending on the proxies used for the reconstruction, as well as a synchronous expansion of tree species with contrasting climatic requirements.

Thus, instead of a west–east opposition often proposed by previous studies, the results obtained within the project LAMA point to north–south contrasts in the Mediterranean Basin. From this point of view, the latitudes around 40° N appear to be particularly important but, in the details, the precise location of this limit between north and south hydrological sectors in the Mediterranean area may have

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fluctuated in time and space. Moreover, the results presented in this paper suggest that the deposition of Sapropel 1 has been favoured by an increase (1) in winter precipitation in the northern Mediterranean borderlands, and (2) in winter and summer precipitation in the southern Mediterranean area.

- The climate reversal following the Holocene climate optimum appears to have been punctuated by two major climate oscillations around 7500 and 4500 cal BP. In addition to previous studies about the 4.2 ka event in the eastern Mediterranean and Tropics, the high-resolution palaeohydrological reconstructions established within the project LAMA reveal a pronounced climatic change around 4500–4000 cal BP in the Central Mediterranean, with contrasting changes in the hydrological cycle (drought trend to the south, and more humid conditions to the north). Thus, these new data show the clear climatic (palaeohydrological) significance, for the central Mediterranean, of the formal distinction between the middle and the late Holocene proposed by Walker et al. (2012). However, even if useful, the reference to the 8.2 ka event to distinguish between the early and the middle Holocene does not find a major climatic significance in the Central Mediterranean where the maximum (minimum) of summer humidity started around 10 500 cal BP (9000 cal BP) in the south- (north-) central Mediterranean.

- Regarding the possible forcing factors, the palaeohydrological changes reconstructed in the Central Mediterranean appear to have occurred in response to a combination of orbital, ice-sheet and solar forcing factors. Considering palaeohydrological records along a latitudinal gradient, increasing time lags are evidenced from the Tropics to northern Europe, with maximum (or minimum) of humidity starting as early as the beginning of the Holocene in equatorial Africa and not before 7500 cal BP in northern Norway. In this general framework, the interval of the humidity maximum in the south-central Mediterranean started at ca. 10 300 cal BP, in correlation with the decline of (1) the blocking effects of the North Atlantic anticyclone linked to the maximum insolation and (2) the influence

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of the remnant ice sheets and fresh water forcing in the North Atlantic Ocean. Its duration until ca. 4500 cal BP broadly coincides with that observed for the high lake-level status of North African lakes between 8° and 28° N. In the north-central Mediterranean, the interval of lake-level minimum began only around 9000 cal BP when the Fennoscandian ice-sheet disappeared and a prevailing positive NAO-type circulation developed in the North Atlantic area. The major palaeohydrological oscillation around 4500–4000 cal BP may be a non-linear response to the gradual insolation decrease in addition to key seasonal and interhemispherical changes in insolation. At a centennial scale, the successive climatic events which punctuated the entire Holocene in the central Mediterranean coincided with cooling events associated with decreases in solar activity and deglacial outbursts in the North Atlantic area during the interval 11 700–7000 cal BP, and to a possible combination of NAO-type circulation and solar forcing from ca. 7000 cal BP onwards.

Further investigations are still needed to test the conclusions proposed in this paper. It is clear that the hypothesis of a possible influence of a NAO-type circulation operating on a centennial scale appears to be a relevant way to explain contrasting palaeohydrological patterns in the Mediterranean Basin as suggested by available data. However, in addition to possible local effects which bias the climatic signal, the inter-regional correlations between records and their interpretation in terms of past atmospheric circulation patterns like NAO are often hampered by insufficient temporal resolution and/or chronological controls of the records. These observations should encourage developing new investigations to establish additional palaeohydrological/environmental records, based on high-resolution analyses and a robust chronology, and using a strategy favouring a careful selection of study sites locations. In particular, future studies should outline with greater precision, on both millennial and centennial time scales, changes in the latitudinal location of the limit between the northern and southern palaeohydrological Mediterranean sectors, depending (1) on the intensity and/or characteristics of

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climatic periods/oscillations (e.g. Holocene thermal maximum versus Neoglacial, as well as the 8.2 ka event versus the 4 ka event or Little Ice Age), and (2) on varying geographical conditions from the western to the eastern Mediterranean regions.

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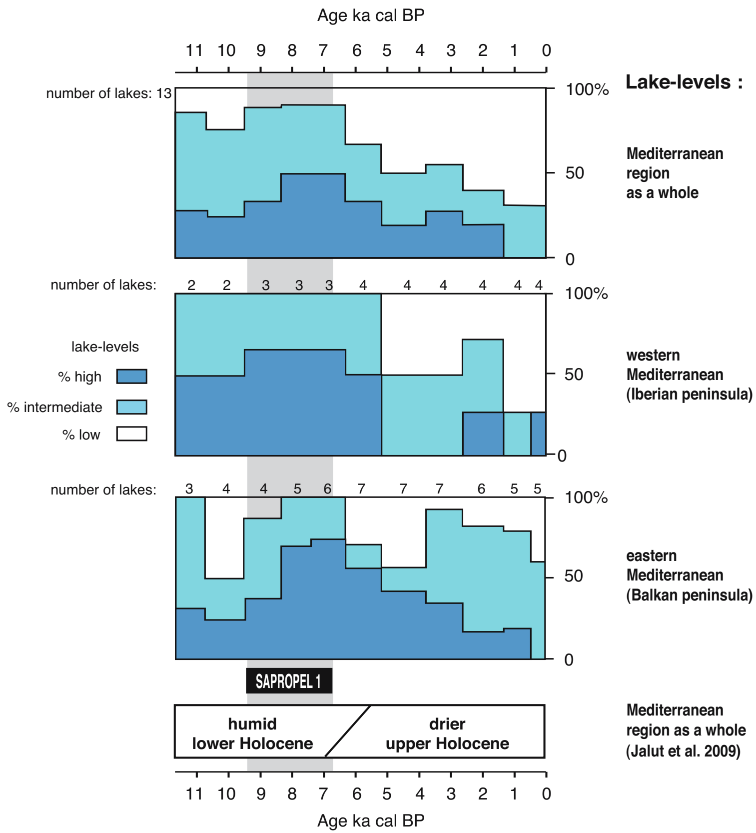

Fig. 1. Holocene changes in lake-level status and humidity in the Mediterranean as reconstructed by Harrison and Digerfeldt (1993) (upper three diagrams) and Jalut et al. (2009). The date of Sapropel 1 deposition in the Mediterranean was taken from Mercone et al. (2000). LC: Lake Cerin; LSP: Lake Saint-Point.

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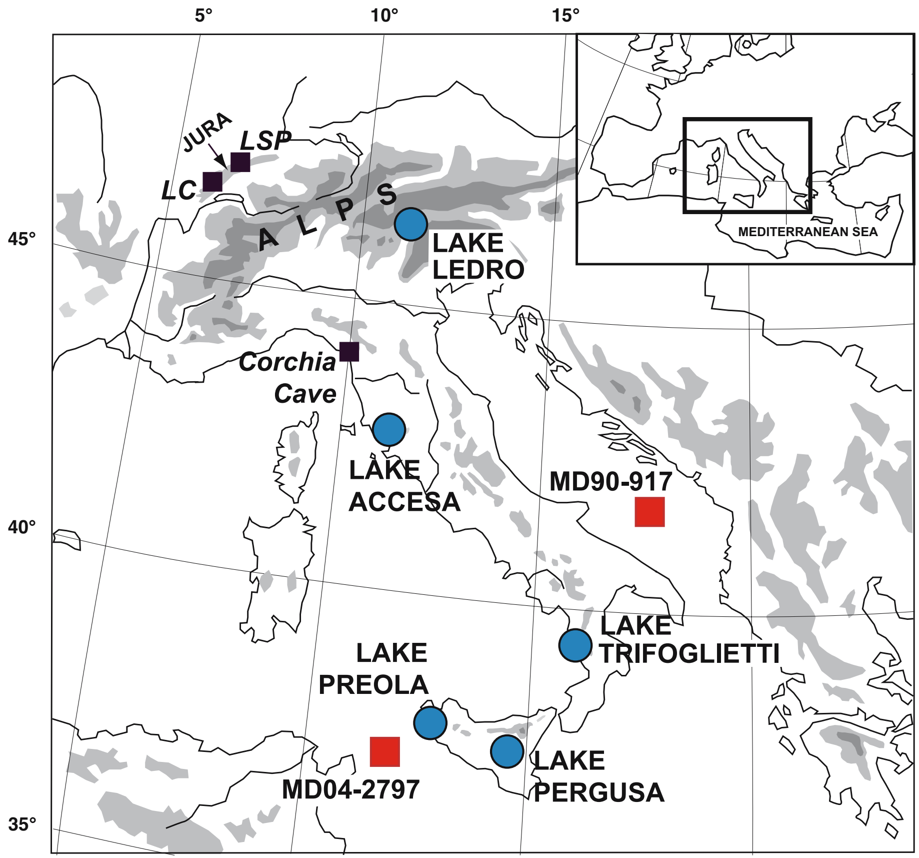

Fig. 2. Geographical location of marine and lacustrine study sites of the LAMA project in the Central Mediterranean. LC: Lake Cerin; LSP: Lake Saint-Point.

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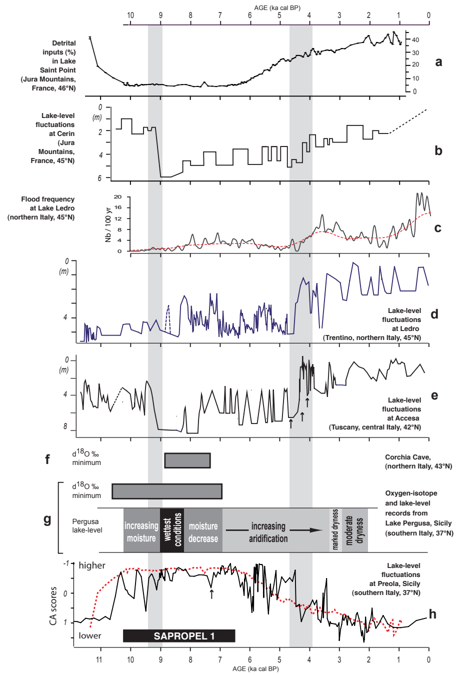

Fig. 3. Comparison between palaeohydrological records along a north–south transect from west-central Europe to the south-central Mediterranean, i.e. **(a)** Lake Saint-Point (Magny et al., 2013), **(b)** Lake Cerin (Magny et al., 2011a), **(c** and **d)**: Lake Ledro (Vannière et al., 2013; Magny et al., 2012b), **(e)** Lake Accesa (Magny et al., 2007), **(f)** Corchia Cave (Zanchetta et al., 2007b), **(g)** Lake Pergusa (Sadori and Narcisi, 2001; Zanchetta et al., 2007a; Sadori et al., 2008), and **(h)** Lake Preola (Magny et al., 2011b). The red curve in **(h)** is the Saint-Point palaeohydrological record after inversion (see **a**). The two vertical grey bands point out two major phases of palaeohydrological changes around 9000 and 4500 cal BP. Labels AMST, AVT and Pr1T in **(e)** correspond to the Agnano Mt Spina, Avellino and Pr1 tephras respectively, and PT in **(h)** to the Pantelleria tephra.

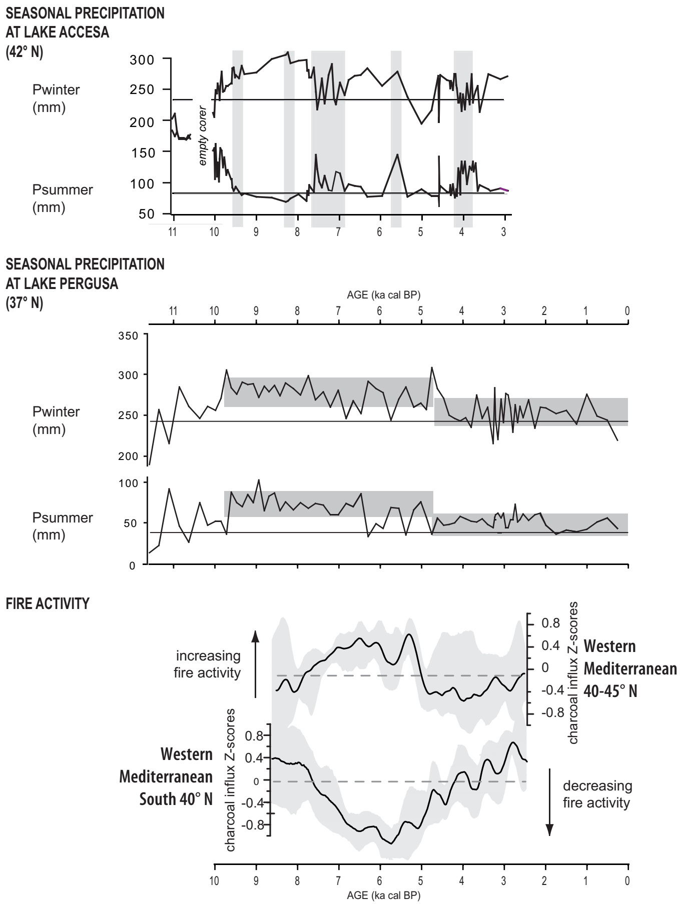

Fig. 4. Upper panel: pollen-inferred estimates of seasonal precipitation at Lake Accesa (Peyron et al., 2011) and Lake Pergusa (Magny et al., 2012c; Peyron et al., 2013). Lower panel: changes in fire regimes in north- and south-western Mediterranean (Vannière et al., 2011).

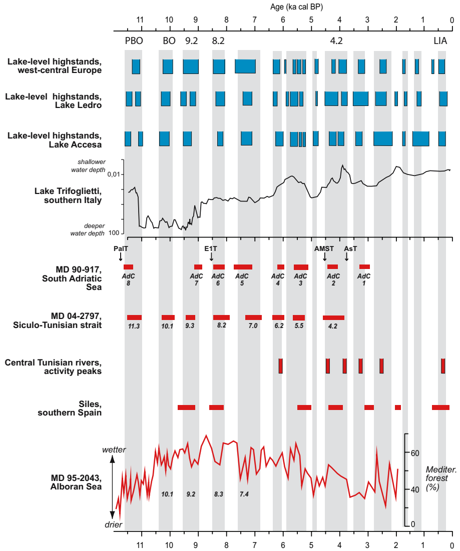

Fig. 5. Comparison between centennial-scale variations in humidity as reflected by lake-level, fluvial, and pollen records in west-central Europe and in the north- and south-western Mediterranean. To the north, wetter climatic conditions are marked by lake-level highstands (blue boxes) reconstructed in west-central Europe (Magny, 2004, 2006, 2013), at Lake Ledro (Magny et al., 2012b), Lake Accesa (Magny et al., 2007), and Lake Trifoglietti (Joannin et al., 2013a). To the south, dry phases (red boxes) are marked by activity peaks of Central Tunisian rivers (Ziehlhofer and Faust, 2008), and pollen data at Siles (Carrión, 2002), and marine cores MD 90-917 (Combourieu Nebout et al., 2013), MD04-2797 (Desprat et al., 2013) and MD95-2043 (Fletcher et al., 2013). PBO: Preboreal oscillation; BO: Boreal oscillation; LIA: Little Ice Age. For the MD90-917 record, the labels PalT, E1T, AMST and AsT correspond to the Palinuro, E1, Agnano Mt Spina and Astroni tephras, respectively.

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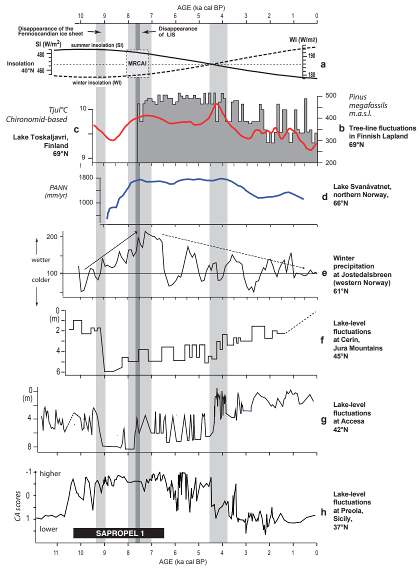

Fig. 6. Comparison between palaeohydrogical and palaeoclimatic records along a north–south transect from the Scandinavia to the south-central Mediterranean. **(a)** Curve of summer and winter insolation at 40° N (Berger and Loutre, 1991; MRCAI: maximum rate of change in annual insolation, Zhao et al., 2010), **(b)** tree-line altitude in Finnish Lapland and **(c)** chironomid-based summer temperature record from Lake Toskaljavri in Finland (Seppä et al., 2008), **(d)** annual precipitation at Lake Svanåvatnet in northern Norway (Bjune and Birks, 2008), **(e)** winter precipitation at Jostedalsbreen in western Norway (Nesje et al., 2000), **(f)** lake-level records at Cerin in west-central Europe (Magny et al., 2011a), **(g)** at Lake Accesa in north-central Mediterranean (Magny et al., 2007), and **(h)** at Lake Preola in south-central Mediterranean (Magny et al., 2011b). Vertical grey bands indicate (1) the periods of disappearance of the Fennoscandian and Laurentide ice sheets according to Renssen et al. (2009), Jansson and Kleman (2004) and Törnqvist and Hijma (2012) with an episode of increasing sea-level rise around 7600 cal BP (Carlson et al., 2008), and (2) a period of major climatic/palaeohydrological change around 4500–4000 cal BP.

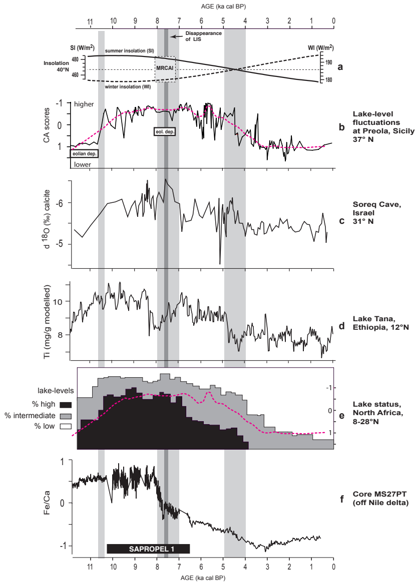

Fig. 7. Comparison between palaeoclimatic and palaeohydrogical records from the Mediterranean area and North Africa, i.e. **(a)** curve of summer and winter insolation at 40° N (Berger and Loutre, 1991; MRCAI: Maximum rate of change in annual insolation, Zhao et al., 2010), **(b)** lake-level record from Lake Preola in south-central Mediterranean (Magny et al., 2011b; smoothed curve in red), **(c)** oxygen-isotope record from Soreq Cave (Bar-Matthews et al., 1998), **(d)** Ti record from Lake Tana in Ethiopia (Marshall et al., 2011), **(e)** lake-level status of North African lakes between 8° and 28° N (Hoelzmann et al., 1998; Gasse and Roberts, 2004), and **(f)** Fe/Ca record from core MS27PT off the Nile delta (Revel et al., 2010). The red dotted curve in **(e)** is the smoothed Preola lake-level record (see **b**). Vertical grey bands indicate (1) the periods of disappearance of the Fennoscandian and Laurentide ice sheets according to Renssen et al. (2009), Jansson and Kleman (2004) and Törnqvist and Hijma (2012) with an episode of increasing sea-level rise around 7600 cal BP (Carlson et al., 2008), and (2) periods of major climate change around 10 500 and 5000–4000 cal BP.

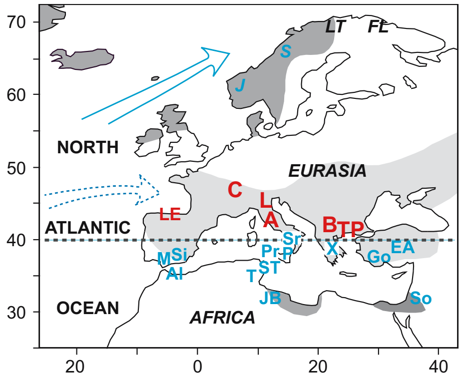

Fig. 8. Positive NAO-like palaeohydrological/palaeoclimatic pattern during the Holocene climatic optimum as suggested by milder (black letters) and wetter (blue letters) versus drier (red letters) climatic conditions around the Mediterranean Basin and in Western Europe. A: Lake Accesa in central Italy (Magny et al., 2007); Al: core MD95-2043 in Alboran Sea (Fletcher et al., 2013); B: Boras Mountains in northern Greece (Lawson et al., 2005); C: Lake Cerin (Magny et al., 2011a); EA: Lake Eski Acigöl in central Turkey (Turner et al., 2008); FL: Finnish lapland (Seppä et al., 2008); Go: Lake Gölhisar in south-western Turkey (Eastwood et al., 2007); J: Jostedalsbreen in western Norway (Nesje et al., 2000); JB: Jebel Gharbi in north-western Libya (Giraudi et al., 2012); L: Lake Ledro in northern Italy (Magny et al., 2012b); LE: Lake Enol in northern Spain (Moreno et al., 2011); LT: Lake Toskaljavri, Finland (Seppä et al., 2008); M: Lake Medina in southern Spain (Reed et al., 2007); P: Lake Pergusa in Sicily (Magny et al., 2011b); Pr: Lake Preola in Sicily (Magny et al., 2011b); S: Lake Svanåvatnet, northern Norway (Bjune and Birks, 2008); Si: Siles in southern Spain (Carrión, 2002); So: Soreq Cave in southern Israel (Bar-Matthews et al., 1998); Sr: Sele river in southern Italy (Naimo et al., 2005); ST: core MD04-2797 in the Siculo-Tunisian strait (Desprat et al., 2013); T: central Tunisian rivers (Ziehlhofer and Faust, 2008); TP: Tenaghi Philippon in northern Greece (Kotthoff et al., 2008); X: Lake Xinias in northern Greece (Digerfeldt et al., 2007). (Dotted) arrow indicates westerlies in positive (negative) NAO-type circulation in response to weaker (stronger) LTG. The present day areas affected by increasing (decreasing) humidity in response to positive (negative) NAO are represented by dark (light) grey zones (from Lamy et al., 2006; Marshall et al., 2001).

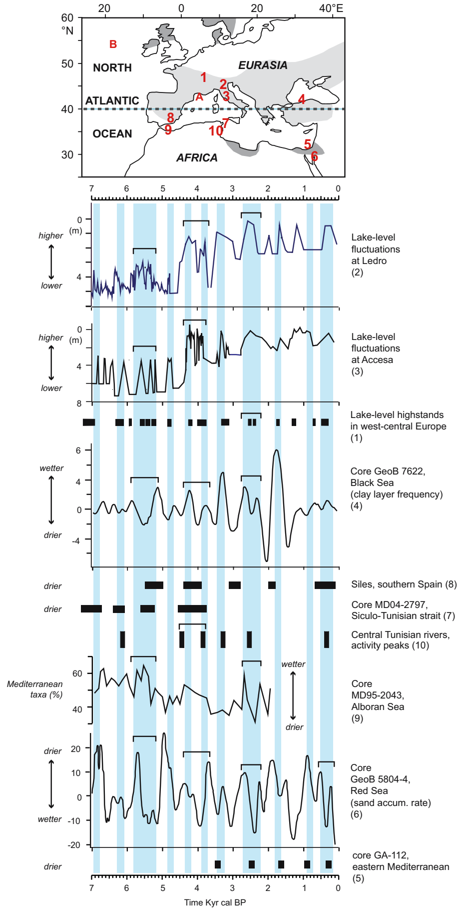

Fig. 9. Caption on next page.

Fig. 9. Upper panel: location of records used in the lower panel. (1) lake-level record from west-central Europe (Magny, 2013); (2) Lake-level record from Lake Ledro (Magny et al., 2012b); Lake-level record from Lake Accesa (Magny et al., 2007); (4) core GeoB7622 (Lamy et al., 2006); (5) core GA-112 (Schilman et al., 2001); (6) core GeoB5804-4 (Lamy et al., 2006), (7), (8) and (9) pollen records from core MD04-2797 (Desprat et al., 2013), from Siles (Carrión, 2002), and from core MD95-2043 (Fletcher et al., 2013), respectively; 10: central Tunisian rivers (Ziehlhofer and Faust, 2008). A: record of storm frequency from a lagoonal sediment sequence in the Gulf of Lions (Sabatier et al., 2012); B: IRD record from the North Atlantic ocean (Bond et al., 2001). The present day areas affected by increasing (decreasing) humidity in response to positive (negative) NAO are represented by dark (light) grey zones (from Lamy et al., 2006; Marshall et al., 2001). Lower panel: centennial-scale hydroclimatic changes around the Mediterranean basin during the last seven millennia. The numbers in brackets after the names of the sites on the right hand side of the figure refer to the points located on the map in the upper panel. The Ledro, Accesa and west-central Europe lake-level records are from Magny et al. (2007, 2012b) and from Magny (2013), the records from cores GeoB 7622 and GeoB 5804-4 are from Lamy et al. (2006), the record from Siles is from Carrión (2002), that from core MD04-2797 is from Desprat et al. (2013), that from central Tunisian Rivers is from Zieh lhofer and Faust (2008), that from core MD95-2043 is from Fletcher et al. (2013), and that from core GA-112 is from Schilman et al. (2001). Horizontal brackets point out a possible complexity of events (see discussion in the text).

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