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Climate of the Past Discussions

Contrasting patterns of climatic changes during the Holocene in the Central Mediterranean (Italy) reconstructed from pollen data

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Abstract

Lake-level records from Italy suggest a north–south climatic partition in the Central Mediterranean during the Holocene with respect to precipitation, but the scarcity of reliable palaeoclimatic records in the North and Central-Southern Mediterranean means new evidence is needed to validate this hypothesis. Here, we provide robust quantitative estimates of Holocene climate in the Mediterranean region based on four high-resolution pollen records from Northern (Lakes Ledro and Accesa) and Southern (Lakes Trifoglietti and Pergusa) Italy. Multiple methods are used to provide an improved assessment of the paleoclimatic reconstruction uncertainty. The multi-method approach uses the pollen-based Weighted Averaging, Weighted-Average-Partial-Least-Squares regression, Modern Analogues Technique, and the Non-Metric-Multidimensional Scaling/Generalized-Additive-Model methods. The precipitation seasonality reconstructions are validated by independent lake-level data, obtained from the same records.

A climatic partition between the north and the south during the Holocene confirms the hypothesis of opposing mid-Holocene summer precipitation regimes in the Mediterranean. During the early-to-mid-Holocene the northern sites (Ledro, Accesa) are characterized by minima for summer precipitation and lake-levels while the southern sites (Trifoglietti, Pergusa) are marked by maxima for precipitation and lake-levels. During the late Holocene, both pollen-inferred precipitation and lake-levels indicate the opposite pattern, a maximum in North Italy and a minimum in Southern Italy/Sicily. Summer temperatures also show partitioning, with warm conditions in Northern Italy and cool conditions in Sicily during the early/mid-Holocene, and a reversal during the Late-Holocene.

Comparison with marine cores from the Aegean Sea suggests that climate trends and gradients observed in Italy shows strong similarities with those recognized from the Aegean Sea, and more generally speaking in the Eastern Mediterranean.

1 Introduction

The Mediterranean region lies in a transitional zone grading from mid-latitude to subtropical climate regimes, with high apparent sensitivity to changing climate. The peculiarities of the region and its response to climate change have driven intense research into Mediterranean climate over the last decade (Lionello et al., 2012). The regional response to large-scale climate forcings is complex (Giorgi and Lionello, 2008). Consequently, future climate change can be expected to be particularly strong in this region and will likely have a marked impact on terrestrial ecosystems and on human societies. Growing interest in the region has focused on both the study of future and past climates.

The Holocene climate and ecology of the Mediterranean is particularly well investigated, with a large amount of data including palynological, speleothem, lake isotope and lake-level evidence (e.g. Magri and Sadori, 1999; Allen et al., 2002; Sadori et al., 2004, 2011; Zanchetta et al., 2007a,b; Colonese et al., 2011; Finne et al., 2011; Giraudi et al., 2011; Zhornyak et al., 2011; Magny et al., 2009, 2011, 2012a,b; Di Rita et al., 2012; Calo et al., 2012). These data show a complex pattern of climatic change across the Mediterranean during the Holocene, with strong spatial and temporal variability (e.g. Tzedakis et al., 2007; Peyron et al., 2011; Roberts et al., 2011). Recent studies based on lake-level records from Italy suggest a partitioning of Holocene climate across a north-south boundary in the Central Mediterranean (Magny et al., 2012b). During the mid-Holocene the northern sites are characterized by a minimum in summer precipitation while the southern sites (south of 40° N) experience precipitation maxima. The north–south climatic partition highlighted by the Italian lake-level data is also apparent in the Central and Western Mediterranean, based on independent fire records (Vannière et al., 2011)

Recent pollen-based reconstructions of precipitation from Lakes Accesa in North-Central Italy, and Pergusa in Sicily support this interpretation of a north–south climatic partition during the mid-Holocene (Peyron et al., 2011; Magny et al., 2012b). Climate reconstructions from Lake Accesa (North-Central Italy) based on a multi-method

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approach distinguish two distinct intervals based on precipitation regimes: the mid-Holocene is characterized by a winter precipitation maximum and a summer precipitation minimum, while the late Holocene coincides with a decrease in winter precipitation and a slight increase in summer precipitation (Peyron et al., 2011). The Lake Pergusa pollen record (Southern Italy, Sicily) reconstructs the opposite pattern: maximum precipitation in winter and in summer during the early to mid-Holocene and a very moderate drying trend towards modern climatic conditions during the late Holocene (Magny et al., 2012b). The Sicilian record is supported by isotopic evidence from snail shells (Colonese et al., 2011), lacustrine records (Zanchetta et al., 2007a; Sadori et al., 2008) and stalagmites (Frisia et al., 2006). The Sicilian record also shows similarities to records from the Eastern Mediterranean (Bar-Matthews et al., 1998, 2011; Kouli et al., 2012) and the Western Mediterranean (Pérez-Obiol and Sadori, 2007).

The recent pollen-based reconstructions from Lakes Accesa (Tuscany) and Pergusa (Sicily) seem support the interpretation of opposing northern and southern climatic regimes in the Mediterranean during the mid-Holocene. However, given the scarcity of reliable palaeoclimatic records in the Central Mediterranean, new evidence is needed to validate this hypothesis. In light of the above, this study aims to provide robust and precise quantitative estimates of Holocene climate for the Central Mediterranean region based on four high-resolution pollen records taken from lakes located along a latitudinal gradient from Northern to Southern Italy. Three lakes are from peninsular Italy (Lake Ledro, Lake Accesa, Lake Trifoglietti), and one is from Sicily (Lake Pergusa). We investigate climatic trends during the Holocene to test whether reconstructions from pollen records can support opposing mid-Holocene summer precipitation regimes across the North-Central (minimum precipitation) and Southern (maximum precipitation) Mediterranean (Magny et al., 2012b).

Special attention will be given to reconstructions of precipitation and temperature seasonality as was the case for Lake Accesa (Peyron et al., 2011). Reconstructions of seasonal precipitation and temperature from Accesa brought new insight into the role of seasonality in this region and proposed an explanation of the apparent discrepancies observed in North-Central Italy between pollen, lake-levels and isotope data by invoking changes in precipitation seasonality (Peyron et al., 2011; Magny et al., 2007; 2012b). In the current study, we aim to emphasize the effects of seasonality by examining Holocene changes in precipitation seasonality across Italy. We will provide reliable quantitative estimates for seasonal climatic variables (summer and winter precipitation and temperature) from the four pollen records located in Northern and Southern Italy. Our purpose is to produce a climate reconstruction which can be directly compared to former investigations of Peyron et al. (2011). Here too, a multi-method approach is favoured for the reconstruction to better assess the error of reconstruction inherent in pollen-based climate predictions. We have chosen four methods: Weighted Averaging method (ter Braak and Van Dam, 1989), Weighted Average Partial Least Squares regression (ter Braak and Juggins, 1993), Best Modern Analogues Technique (Guiot, 1990), and the Non-Metric Multidimensional Scaling/Generalized Additive Model method (Goring et al., 2009).

Changes in the regional atmospheric circulation in the Mediterranean have clear consequences for precipitation and temperature during the Holocene (Tzedakis et al., 2009; Vannière et al., 2011). Forcings such as the boreal insolation maximum (Tinner et al., 2009) and changes in the mean position of the ITCZ may influence the intensity and position of monsoons in the region through the position and size of Hadley cells. Thus, this study also aims to better understand which climate processes can explain the inferred climate changes and the north–south partition.

2 Sites and data

The core transect used in this study runs from north to south through Italy (Fig. 1), linking Lake Ledro, located on the southern slope of the alps, to Lake Pergusa on Sicily. The sites are grouped into northern sites (Lake Ledro and Lake Accesa) and southern sites (Lake Trifoglietti and Lake Pergusa) for the purposes of most subsequent analysis. For all sites we provide information on the radiocarbon dates used in constructing the

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chronologies (Table 1). Chronology construction is reported in the initial publications for each site, referenced below.

2.1 Lake Ledro (Northern Italy)

Lake Ledro (45°87′ N, 10°76′ E, 652 m a.s.l.) is a small lake (area: 2.2 km^2, max. depth: 48 m, catchment: 131 km^2) in Northern Italy on the southern slope of the Alps. Mean temperature of the coldest and the warmest months are 0 °C and 20 °C respectively at Molina di Ledro, close to the lake's outlet; annual precipitation ranges from ca. 750 to 1000 mm. Vegetation in the catchment is dominated by *Fagus* along with *Abies*. Higher in the Ledro Valley, the montane belt (650–1600 m) is characterized by *Picea*. The sub-alpine belt (1600–2000 m) is replaced by grasslands above 2000 m. Lake Ledro over-hangs and flows into the nearby Lake Garda (65 m a.s.l.). There, mild climate allows the development of a mixed oak forest with lime and elm trees, and Mediterranean vegetation such as *Quercus ilex*, Ericaceae and olive trees that can reach 300 m a.s.l. in the form of groves. More details about the site can be found in Magny et al. (2009).

A deep master core (LL081) was built using twin cores from an undisturbed sediment zone recognised using seismic-reflection. Others cores have been obtained from Lake Ledro (Ledro I, Ledro II and Ponale: Magny et al., 2012a) but only the profundal LL081 is used in this study. The chronology spans the last 17 000 yr using 13 ^{14}C dates (Table 1) and one date from the Ledro II littoral site (Magny et al., 2012a) aligned using stratigraphic comparison. The temporal resolution is estimated to 66 yr $sample^{-1}$ throughout the Holocene.

Holocene vegetation at the site shows the development of a mixed-oak forest followed by successive expansion of trees in the montane belt and beech forest (Fig. 2). Human land-use activity and forest exploitation begins at ca. 7500 cal BP. This accelerates during the Late Holocene (from 4100 cal BP onwards) through continuous records of anthropogenic pollen indicators and drops in arboreal pollen percentages. More details on the Lake Ledro pollen, vegetation and lake-level history are given in Joannin et al. (2012a) and in Magny et al. (2009, 2012a).

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2.2 Lake Accesa (Tuscany, Central Italy)

Lake Accesa (42°59′ N, 10°53′ E, 157 m a.s.l.: Magny et al., 2007; Drescher-Schneider et al., 2007; Vannière et al., 2008; Peyron et al., 2011; Finsinger et al., 2010) is a small lake (area: 16 ha, max. depth: 40 m, catchment area ca. 5 km^2) located in Tuscany, Italy, close the eastern shore of the Tyrrhenian Sea, surrounded by low hills (ca. 300 m). The catchment area is characterised by gentle slopes, although steeper slopes around the outlet area may be sensitive to the accumulation of colluvial deposits. Lake Accesa has a typically Mediterranean climate with ca. 780 mm yr^{-1} annual precipitation, highest in autumn with marked summer drought. Mean annual temperature is ca. 13 °C, ranging from 4.5 °C in the coldest month to 22 °C in the warmest.

Although the Lake Accesa region is widely cultivated (cereals, vineyards and olive trees), vegetation in the region would likely be dominated by *Quercus ilex* (Ozenda, 1979). Existing woodland vegetation is sparsely distributed on the tops of hills, on some northern and north-western slopes and in small shady valleys. Vegetation is characterized by open brush with *Erica arborea*, *Arbutus unedo*, *Phillyrea, Pistacia, Juniperus oxycedrus, Viburnum tinus, Spartium junceum, Cistus monspeliensis, C. salviifolius* or open wood with *Pinus pinaster*, *Quercus ilex*, *Q. cerris, Fraxinus ornus,* depending on the frequency and intensity of human impact. The lake is surrounded by a small belt of *Phragmites/ Carex*.

A core transect was carried out from the western shore of the lake (discussed in Peyron et al., 2011). Pollen data for the current study were extracted from two overlapping cores, AC3 and AC4 (AC3/4), obtained in a littoral mire, 50 m from the present-day lake shore. The chronology spans the last 11 000 yr based on 17 ^{14}C dates and 4 tephra layers with a temporal resolution of 85 yr $sample^{-1}$ (Table 1). Holocene vegetation at Lake Accesa (Fig. 2) was dominated by deciduous *Quercus* (probably *Q. pubescens* at the beginning of the Holocene) and characterised by alternating dominance of deciduous and evergreen oaks. From 9500 to 7700 cal BP, high percentages of evergreen oaks are recorded, associated with high values of *Abies* (20 %). Regional *Abies* abundance may be overestimated from the littoral core, and may represent only local abundance since increases in *Abies alba* pollen recorded in the deep Lake Accesa core are small (Colombaroli et al., 2008). A persistent decline of *Quercus ilex* occurs around 7700 cal yr BP. The Lake Accesa core indicates human presence since the Neolithic, but cereal cultivation and pasturing becomes more pronounced at ca. 4300 yr BP (early Bronze Age). More details on Lake Accesa pollen, lake-levels and climate history can be found in Drescher-Schneider et al. (2007), Colombaroli et al. (2008), Magny et al. (2007), Vannière et al. (2011), Finsinger et al. (2010), Sadori et al. (2011) and Peyron et al. (2011).

2.3 Lake Trifoglietti (Calabria, Southern Italy)

Lake Trifoglietti (39°33′ N, 16°1′ E; 1048 m a.s.l.) is a small, shallow lake (area: 0.97 ha, depth: 1.5 m, catchment area: 0.37 km^2) located 10 km from the Tyrrhenian coast in the Catena Costiera Mountain, Southern Italy, near Monte Caloria (1183 m). Climate at nearby Fagnano Castello (Cosenza province) has a mean annual temperature of 15 °C, (24 °C for August and 7.5 °C for January). Despite the strictly Mediterranean latitude of the studied area, annual precipitation (including cloudiness) is high (1849 mm yr^{-1}), A relatively short dry period occurs in the summer season (Joannin et al., 2012b). Forest surrounding Lake Trifoglietti is dominated by *Fagus* with some *Pinus nigra* subsp. *laricio*. Scrub vegetation with *Erica arborea* and *Cistus salvifolius* trees, develops in more open forest. *Quercus cerris* and *Castanea sativa* trees occur at lower altitude.

A core transect was carried out from the north-eastern shore of the lake. Pollen data were extracted from overlapping cores (Joannin et al., 2012b). The chronology, spanning the last 11 500 yr, is based on 11 ^{14}C dates with a mean temporal resolution of 68 yr $sample^{-1}$ (Table 1). Holocene vegetation history at Lake Trifoglietti (Fig. 2) shows relatively stable *Fagus* forest during the Holocene. Prevailing westerly winds may have driven pollen taxa such as oak, hazel and other Mediterranean taxa to the site from lower vegetation belts. Changes in algae, aquatic taxa and alder proportions at Lake Trifoglietti are characteristic of changes in water-depth associated with climatic change

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and the development of peatland at the site. The Trifoglietti pollen record shows only a weak signal of human impact, apart from those indicating pastoralism beneath forest cover. The selective exploitation of *Abies* appears to have been the strongest human impact in the region surrounding Lake Trifoglietti.

2.4 Lake Pergusa (Sicily)

Lake Pergusa (37°31′ N; 14°18′ E, 667 m a.s.l. : Sadori and Narcisi, 2001; Sadori et al., 2008, 2011; Magny et al., 2012b; Zanchetta et al., 2007a; Ortu et al., 2012) is a larger lake (area: 1.4 km^2, depth: 12 m, catchment area: 7.5 km^2) located in Central Sicily, Italy, about 5 km from the town of Enna. Artificial drainage and lower lake levels, related to reduced rainfall in the region has resulted in the progressive salination of the lake. Records from Enna show a local mean annual precipitation between 500 and 700 mm and a mean annual temperature of 13.4 °C, ranging from 6 °C in the coldest month to 24 °C in the warmest. Potential vegetation at Lake Pergusa is mesophilous Mediterranean evergreen forest with prevailing *Quercus ilex* L., but the Lake Pergusa region is among the most open landscapes of Sicily, widely cultivated and dominated by xerophytic grasslands. The only traces of natural woody vegetation are sparse stands of deciduous and evergreen oaks (*Quercus virgiliana*, *Q. ilex*, *Q. pubescens*, *Q. suber* and *Rhamnus alaternus*).

Pollen records have been obtained from two different locations within Lake Pergusa: a 4.5 m long core (PRG1) provided a record from 12 500 cal BP to the present (Sadori and Narcisi, 2001) while a second core (PG2) spans an interval from 6700 cal BP to the present (Ortu et al., 2012). Results from the PRG1 pollen record have been extensively reported (Sadori and Narcisi, 2001; Sadori and Giardini 2007; Sadori et al., 2011; Magny et al., 2011). The PRG1 core is used in this study since it covers the entire Holocene (for more details on Late Holocene vegetation and climate history based on the PG2 record see Ortu et al., 2012). The chronology, based on eight ^{14}C dates and one tephra layer, provides a mean temporal resolution of 131 yr sample^{-1} throughout the Holocene (Table 1). Holocene vegetation history (Fig. 2) shows that deciduous and evergreen oaks dominated from 10 000 to 5000 yr BP (Sadori et al., 2011). Tree cover declined briefly from ca. 8900 and 8700 yr BP. Soon after 8000 yr BP, *Olea* begins to increase, indicating the beginning of a climatic trend towards more arid conditions. The regional vegetation appears to have been open following 8000 yr BP, with deciduous and evergreen oaks and olive as the main taxa, although *Quercus* forest briefly expanded at ca. 5500 cal BP (Sadori and Narcisi, 2001).

3 Climate reconstruction methods

Individual pollen-based climate reconstruction methods have their own set of advantages and limitations (Birks and Birks, 2006; Brewer et al., 2008; Birks et al., 2010). For this reason we adopted a multi-method approach that would allow us to better assess reconstruction error and provide more precise and robust climate estimates than those based on only one method (e.g. Klotz et al., 2003; Peyron et al., 2005, 2006; Kühl et al., 2010). Such an approach has been successfully tested for the Holocene from Mediterranean marine and terrestrial pollen records (Dormoy et al., 2009; Peyron et al., 2011; although see Birks et al., 2010). We chose four methods, including most standard methods, and based on different ecological concepts. Here, Modern Analogues Technique (MAT: Guiot, 1990), Weighted Averaging method (WA: Ter Braak and Van Dam, 1989), Weighted Average Partial Least Squares regression (WAPLS: Ter Braak and Juggins, 1993), and the Non-Metric Multidimensional Scaling/Generalized Additive Model method (NMDS/GAM: Goring et al., 2009) are used. The WA, WAPLS and the NMDS/GAM are true transfer functions based on a calibration betweenenvironmental variables and modern pollen assemblages whereas the MATdoes not require real calibration, and is based on a comparison of past assemblages to modern pollen assemblages. For all the methods presented here, we use the modern pollen dataset developed by Dormoy et al. (2009), containing more than 2000 samples from the Mediterranean region with climate estimates for sites developed by New et al. (2002). To improve reconstruction, we have updated the dataset by adding 26 modern surface samples from around Lake Trifoglietti (Joannin et al., 2012b), Mount Altesina close to Lake Pergusa (Sicily) and Lake Preola (Sicily).

3.1 MAT

The Modern Analogue Technique (MAT) reconstructs past climate parameters by considering proportion of pollen assemblages (Guiot, 1990). The MAT uses the squared-chord distance, effective with percentage data, to determine the degree of similarity between samples with known climate parameters (modern pollen samples) to a sample for which climate parameters are to be estimated (fossil pollen sample). The smaller the chord distance is, the greater the degree of analogy between the two samples. To calculate the climate parameters for each fossil sample it is common practice to calculate the climate parameters as the weighed mean of the present-day climate of the closest n modern samples or "analogues". A minimum "analogue" threshold is often established beforehand using a Monte Carlo method. Finally, based on the present-day climate data of the closest meteorological stations to the modern analogues, the palaeoclimate is reconstructed by weighted averaging.

3.2 WA

Weighted averaging (ter Braak and van Dam, 1989) is a transfer function that uses the (implied) unimodal responses of pollen taxa (in this case) along environmental gradients to infer climate by weighting taxon abundances from target assemblages using the calibrated optima. While the assumption of unimodality is, in practice, violated by a large number of pollen taxa (see figures in Williams et al., 2006), Birks et al. (2010) have described the ways in which the strengths of WA might outweigh some of its limitations, accounting for its popularity in many modern studies.

3.3 WAPLS

WAPLS is a "classic" regression method which assumes that the relationships between pollen percentages and climate are unimodal: each taxon grows best at a particular optimal value of an environmental variable and cannot survive when the value of that variable is too low or too high. If taxon ecology can be assumed to be constant through time, then, even if the overall pollen assemblage has no modern analog, a reasonable reconstruction can be given. WAPLS operates by compressing the overall data structure onto latent variables. The modern pollen dataset used may be considered a large multidimensional matrix. Since there is some co-linearity among pollen taxa, and since some taxa will be related to climate parameters of interest, it is possible to reduce the dataset into a smaller number of components based on both linear predictors of the parameter of interest and the residual structure of the data when those predictors are removed. The modification of PLS proposed by ter Braak and Juggins (1993) requires transformation of the initial dataset using weighted averaging (ter Braak and van Dam, 1989) along a gradient defined by the climate parameter of interest, such that the pollen taxa that best define the climate gradient are weighted more heavily than those that show little specificity to the gradient.

3.4 NMDS/GAM

This method, first developed from pollen assemblages in British Columbia, Canada (Goring et al., 2009), has recently been successfully tested on Mediterranean pollen assemblages (Dormoy et al., 2009; Peyron et al., 2011). This method begins by reducing the dimensionality of the dataset using non-metric multidimensional scaling, a non-parametric ordination method that retains the dissimilarity structure of the data to generate low-dimensionality representations. In this way it is somewhat similar to the MAT, although the ordination recovers not only the degree of dissimilarity between samples, but also the direction of dissimilarity. Once the low-dimensionality representation is generated, the NMDS/GAM method fits a generalized additive model to the

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ordination space to reconstruct the climate parameter of interest. Since this method uses non-parametric methods, specific statistical violations, such as the non-linearity of the relationship between climate parameters and pollen taxa, may be avoided.

3.5 Validation of the methods and error calculation

To some degree all methods are subject to error resulting from "noise" in the dataset. This noise may result from variation in basin characteristics, co-variance of climate variables, differential degradation of pollen taxa resulting from the deposition substrate, differences in pollen transport and local anthropogenic effects. The ecological noise is internalized differently in each pollen-based reconstruction method, although overlap exists among more closely related methods (e.g. effects of spatial autocorrelation: Telford and Birks, 2005; effects of sample depositional environments: Goring et al., 2010). In general, as noise in the pollen dataset increases, model error increases. But, as dataset size increases, many models become more robust (Birks et al., 2010). More details on the validation procedure used for pollen-climate calibration with the European pollen dataset are given in Peyron et al. (2011).

4 Results and discussion

Quantitative climate reconstructions for each pollen sequence were performed for summer and winter temperature in Fig. 3, and summer and winter precipitation in Fig. 4 to emphasize changes in seasonality.

4.1 A north–south climatic pattern? Looking at the temperature reconstruction

Climate reconstructions suggest the partitioning of Holocene summer temperature regimes between Northern (Lakes Ledro and Accesa) and South-Central (Lakes Trifoglietti and Pergusa) Mediterranean sites (Figs. 3 and 5). Warm conditions in Northern Italy and cool conditions in Sicily are reconstructed during the early to mid-Holocene;

the pattern reverses in the late-Holocene. The partitioning of temperature trends is evident when results are expressed as anomalies (Fig. 5). Pollen-inferred temperatures from Lake Ledro (north) show two distinct periods: relatively high temperatures before 7200 cal BP that are followed by a summer cooling trend from 7000 cal BP to 4600 cal BP. Pollen-inferred temperatures from Lakes Trifoglietti and Pergusa (south; Figs. 3 and 5) show two distinct periods of temperature, but the pattern opposes Lake Ledro: cold temperatures before 6400–7000 cal BP that are followed by an abrupt change towards warm summer conditions from 6400 cal BP to the present.

The pattern of climate partitioning defined here from Northern Italy and Sicily shows strong similarities to similar partitioning recognized in the Eastern Mediterranean, particularly in the Northern and Southern Aegean Sea (Dormoy et al., 2009, Kotthoff et al., 2008, 2011). The climate pattern observed in Northern Italy from Lake Ledro (warm Early-to-Mid Holocene followed by a summer cooling trend after 7200 cal BP) is supported by pollen-based climate reconstruction from the North Aegean Sea (marine core SL52, Fig. 5c: Dormoy et al., 2009). Further to the north, the Tenaghi Philippon pollen-based temperature reconstruction (Fig. 5b) also provides evidence of high early-Holocene temperatures declining to the mid-Holocene (Pross et al., 2009). Moreover, Kouli et al. (2012) use a temperature index based on the ratio of cool to warm-temperate broadleaved taxa to show a Holocene summer temperature regime with strong differences between the Northern and Southern Aegean Sea based on three cores from the region. The north (core MNB3) is marked by warm conditions during the early to mid-Holocene, while the south (core NS14) remains cool. Following 6500–7000 cal BP, the pattern appears to reverse, with cold conditions in the north culminating around 4500 cal BP while warm conditions exist in the south. The northern temperature index fits with the summer cooling trend reconstructed from Lake Ledro (Fig. 5a,d) while the temperature index from the South-Eastern Aegean fits with the warming trend reconstructed from Lakes Accesa, Trifoglietti and Pergusa pollen data (Fig. 5d–g). This pattern is supported by alkenone based SST curves from both records (Gogou et al., 2007; Triantaphyllou et al., 2009b). Alkenone derived SSTs range between 20 and

23 °C in the North Aegean MNB3 record during the early-to-mid Holocene and drop to 20 °C after 6000 BP (Gogou et al., 2007). In contrast, the South Aegean record of core NS14 displays SSTs ranging from 17 to 22 °C for the early-to-mid Holocene, rising to ~ 24.8 °C at about 5000 BP (Triantaphyllou et al., 2009b). Terrestrial biomarkers (*n*-alkanes) indicate the dominance of warm species in South Aegean during the mid-to-late Holocene confirming the pollen signal (Kouli et al., 2012) and agreeing with our pollen-based reconstructions. Even at a regional scale, the Holocene climate signal reconstructed at Lakes Accesa, Trifoglietti and Pergusa fits with the summer temperature trend over Southern Eastern Europe (south of 45° N, east of 15° E), reconstructed by Davis et al. (2003) and Davis and Brewer (2009) in Fig. 5e–h, confirming interpretations of relatively cool summer conditions over Southern Europe.

4.2 A North–South climatic pattern? Looking at the precipitation reconstruction

Pollen-inferred precipitation from Lakes Ledro, Accesa, Trifoglietti and Pergusa suggests a partitioning of the precipitation regime between the North and South Mediterranean during the Holocene (Figs. 4, 6 and 7). Relatively dry conditions in summer characterise the Lake Ledro area from 11 500 to 8500 cal BP, while precipitation in South Italy and Sicily reaches a maximum (Figs. 4 and 6). Precipitation increases at Lake Ledro area from 8200 cal BP to 4000 cal BP, reaching a maximum from 4000 cal BP to the present. The inferred climate from Lakes Trifoglietti and Pergusa differs from Lake Ledro, showing two distinct periods of precipitation change: with wet conditions prior to 6500 cal BP, followed by a trend towards dryer conditions from 6500 cal BP to 4500, and a period post 4000 cal BP with dry conditions. A contrasting precipitation pattern between the North and South Mediterranean is also seen for winter precipitation, even if relatively moist winter conditions seem to characterise the four sites areas during the Holocene (Fig. 4). The winter and summer precipitation trends reconstructed at Lake Ledro fit well; winter precipitation increases from 10 000 cal BP to 4000 cal BP, reaching a precipitation maximum from 4000 to the present, similar to the summer precipitation record. Lake Trifoglietti presents a problematic reconstruction,

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much below modern winter precipitation values for all methods, possibly due to specific aspect of its location (Joannin et al., 2012b). Given the low reconstructions we are still able to reconstruct a precipitation trend which fits well with Pergusa and Accesa with an "Holocene Optimum" between 9500 and 5000 cal BP followed by a trend towards aridification. At Trifoglietti, the two periods marked by high precipitations at ~ 7200–6500 and 4900–4500 cal BP (Fig. 6) are almost synchronous with phases of high fluvial activity and floods recorded at 7200–6800 and 4800–4550 cal BP in the nearby region of Basilicata, Southern Italy (Piccarreta et al., 2011). The correlation between the precipitation reconstruction and independent assessments of hydrological activity may indicate that, while the reconstruction values may be offset strongly at Lake Trifoglietti the anomaly trends are consistent with long term change in regional precipitation.

One goal of this study is to test the hypothesis proposed by Magny et al. (2012b) that mid-Holocene summer precipitation regimes are partitioned and in opposition between the North-Central and Southern Mediterranean. This assumption is based on lake-level variations established for Italy from carbonate concretions produced during summer (Magny et al., 2011). Figure 6 shows a direct comparison between independent Holocene lake-level changes and the pollen-inferred summer precipitation for Lakes Ledro and Accesa. Summer precipitation estimated for the Southern Lakes Trifoglietti and Pergusa are compared to the Lake Preola lake-level reconstruction from coastal Sicily (Fig. 6; Magny et al., 2011). The lake-level and pollen-based climate reconstructions both suggest a climatic partition during the Holocene. Two opposite patterns appear (1) during the early to mid-Holocene, the northern sites (Ledro, Accesa) are characterized by a minimum in summer precipitation and associated lake-level minimum while the sites located south of ca. 40° N (Trifoglietti, Pergusa) are marked by high precipitation and associated high lake-levels and (2) during the late Holocene, both pollen-inferred precipitation and lake-levels indicate the opposite pattern with maximums in Northern Italy and minimums in the south. These findings are supported by a synthesis of fire activity for the Mediterranean basin (Vannière et al., 2011). During the Mid-Holocene (ca. 7500–4500 cal BP), low fire activity was observed in the Southern

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Mediterranean region (south of 40° N) while Northern Mediterranean records suggest a contemporaneous increase in fire activity. The North–South climatic partition in Italy highlighted in our study is also apparent in the Central and Western Mediterranean from independent fire records (Vanniere et al., 2011). Relatively abrupt changes in fire activity are observed ca. 5500–5000 cal BP which fit well with the climate transition recorded around 5000 cal BP by the lake-level and summer precipitation records from Italy (Fig. 6).

The climate trend observed in Southern Italy and Sicily show strong similarities to the Soreq Cave speleothem record (Israel; Bar-Matthews et al., 1998) from the Eastern Mediterranean (Magny et al., 2012b, Fig. 6). Moreover, a similar climate pattern is particularly clear in the Aegean Sea (Fig. 7) based on (1) a relative "humidity index" established from the three marine pollen records located across a north-south transect in the Aegean Sea (Kouli et al., 2012), and (2) the pollen-based climate reconstruction from marine core SL52 located in the North Aegean Sea (Dormoy et al., 2009). The humidity index (Fig. 7) shows a climatic partition through the Holocene which fit remarkably well with the pollen-based precipitation reconstructions: the Mid-Holocene is characterised by dry summer conditions in Northern Italy and the North Aegean Sea, while wet conditions are reconstructed in Southern Italy, Sicily and South Crete. Warm and humid conditions that prevailed during this period are verified in the South Aegean marine NS14 record by the deposition of a distinguishable sapropel-like layer (Sapropel Mid Holocene/SMH, Triantaphyllou et al., 2009b). This trend reverses during the late Holocene, after 6000 cal BP.

A shift in climate at ca. 4500 cal BP is clear from summer precipitation, lake-level and speleothems records from the region (Fig. 6). This shift is also seen in Eastern Mediterranean by Finné et al. (2011). Paleoclimate records in the Eastern Mediterranean reconstruct wet conditions from 6000 to 5400 cal BP followed by a period of drying that develops into aridity by ca. 4600 cal BP. Climate changes around 4500 cal BP may have resulted from large-scale changes in the atmospheric circulation affecting the Southern Mediterranean area over the mid- to late-Holocene transition (Magny et al., 2009).

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Changes could be linked to a non-linear response of the climate system to the gradual decrease in insolation in addition to other key seasonal and inter-hemispherical related directly to changes in insolation.

4.3 Short-term events around 8000, 6500 and 4200 cal BP

Short-term Holocene climate events are evident in the pollen-inferred climate reconstruction for Lakes Ledro and Trifoglietti (and to a less extent at Lake Pergusa). These short-lived events occur at ca. 8000, 6500 and 4200 cal BP and they correspond to strong shifts in the humidity index reconstructed from the Aegean cores.

The earliest event seems to correspond with the regional expression of the 8.2 kyr event (Alley et al., 1997) in the Mediterranean region (Magny et al., 2003, 2007; Kotthoff et al., 2008, 2011; Pross et al., 2009; Triantaphyllou et al., 2009b). This event is commonly explained through atmospheric circulation changes induced by freshwater pulses that produced a weakening of the thermohaline circulation in the North Atlantic. This allowed an expansion of the Eurasian/Siberian High, ultimately resulting in colder and drier winters (Renssen et al., 2002; Rohling et al., 2002). The multi-method approach for Lake Ledro indicates a winter temperature drop > 3 °C (Fig. 3) and a summer temperature decrease of 1.5 °C (Figs. 3 and 5). This strong cooling is corroborated by the ∼ 4 °C abrupt winter cooling evidenced in Tenaghi Philippon (Greece) from pollen data (Pross et al., 2009; Peyron et al., 2011), and by pronounced cooling between 8.2 and 7.8 in the Northern Aegean based on alkenone data (Gogou et al., 2007). Summer cooling also occurs at Tenaghi Philippon (Pross et al., 2009) and in the North Aegean Sea core SL152 (Fig. 5a,b; Dormoy et al., 2009). Dry winters and wet summers are reconstructed from the Lake Ledro core (Figs. 4, 6 and 7), fitting well with wet summer conditions reconstructed from the SL152 marine core in the Northern Aegean Sea (Fig. 7). At Accesa, the 8.2 kyr event is marked by a well-identified lithological change but is weakly expressed in the pollen-based reconstruction (Fig. 4). However, wet summer conditions around this time period can be seen with the multi-method approach

(Fig. 4), associated with a short-term lake-level rise centred at 8200 yr BP (Fig. 6), and a decline in the fire regime (Vannière et al., 2008) also suggesting wet conditions.

There is no clear hydrological signal for the 8.2 kyr event in Southern Italy obtained from the Lake Trifoglietti reconstruction, although lower summer temperatures (2 °C, Figs. 3 and 5f) and dry summer conditions are suggested (Fig. 6). The 8.2 kyr event signal from Pergusa, is very weak but seems to correspond to dry summer conditions at ∼ 8300 cal BP associated to a 1.5 °C decline in summer and winter temperature (Fig. 3). Although the signal of short-term change is weak in Southern Italy, the broader changes in climate seem to confirm the hypothesis by Magny et al. (2003) of a hydrological partition in Central Europe for the 8.2 kyr event, with Southern Europe marked by dry climate and northern latitudes (from ca. 43–50° N) marked by wet conditions. Similarly in the South Aegean this event does not reflect a very cold and dry spell as evidenced in higher latitude locations, although recorded by a drop in precipitation (Triantaphyllou et al., 2009b).

The second short-lived cool and dry event at ca. 6500 cal BP is recorded in the pollen reconstructions for Lakes Trifoglietti and Pergusa (Fig. 5). The cooling and drying at the two core sites corresponds remarkably well to a number of independent studies from the region. At ca. 6500 terrestrial biomarkers from marine cores in the Aegean Sea reflect less humid conditions and a "cooler" vegetation type, supported by pollen from the same marine cores (Fig. 7; Kouli et al., 2012). This cool-dry event is also characterized by a strong decrease in SST and the termination of the S1 sapropel in the Southern Aegean Sea (Gogou et al., 2007) and is coeval with pronounced cooling in Southern Adriatic and Aegean Seas (Geraga et al., 2010; Sangiorgi et al., 2003; Triantaphyllou et al., 2010). Kouli et al., (2012) suggest short-term episodes of climatic instability during this time interval associated with enhanced runoff conditions from 6600 to 6400 ka BP (Triantaphyllou et al., 2009a)

We also present evidence of a strong climatic change around 4200 cal BP (Figs. 7 and 8). Pollen-inferred climate reconstructions from Lakes Ledro, Accesa and Pergusa highlight a marked cooling event at ca. 4300–3800 BP, corresponding to declines in winter and summer temperature decrease of 2 °C (Fig. 8). This event, also evidenced in North Aegean Sea (Fig. 5c), is possibly the regional expression of the so-called "4.2 kyr event" observed in various regions of the world (e.g. Geraga et al., 2010). In the Southeastern Aegean Sea, the H-index records a humid phase between 5400 and 4300 ka BP that coincides with the deposition of a distinct sapropel-like layer and that is interrupted at ~ 4.2 ka BP (Triantaphyllou et al., 2009b). Additionally, some Italian sites south of 43° N have shown temporary mid-Holocene deforestation at 4000 cal BP that may have been caused by drought (Di Rita and Magri, 2009).

Magny et al. (2009) recognise a complex tripartite climatic oscillation between ca. 4300–3800 cal BP based on the Lake Accesa lake-level variations (Fig. 8). The three phases entail a phase characterised by dry conditions at ca. 4100–3950 cal BP that is bracketed by marked by wet conditions, dated to ca. 4300–4100 and 3950–3850 cal BP, respectively. Pollen-based summer precipitation reconstructions for lakes Accesa, Ledro and Trifoglietti (Fig. 8) confirms the presence of such a dry event and provide some insight into the possible complexity of this climatic oscillation around the 4.2 ka event. The dry episode centred at ca. 4150–3950 cal BP that is detected in Accesa, Ledro and Trifoglietti may be related to this short-lived dry phase bracketed by two wet phases in the Central Mediterranean. This event, documented as the 4.2 kyr event in the subtropical zone, is a single short-lived event which may have corresponded to a climatic episode controlled from low latitudes (Marchant and Hooghiemstra, 2004) and can be associated with an expansion or northward displacement of the North African high pressure zone.

4.4 Precipitation seasonality, proxy sensitivity, and climate reconstruction

Enhanced rainfall near Lake Accesa between ca. 8900 and 7300 cal BP has been interpreted from speleothems recovered from Corchia Cave in the Apuan Alps (Zanchetta et al., 2007b) and from ca. 8200 to 7100 cal BP from Renella Cave, close to Corchia Cave (Zhornyak et al., 2011). The Renella record suggests that during this period this region experienced very wet conditions associated to a substantial increase in

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flood activity (Zhornyak et al., 2011). However, during the first part of this period, the nearby lakes of Accesa and Fucino (e.g. Giraudi et al., 2011; Magny et al., 2007) experienced low-stand phases. Changes in precipitation seasonality may explain the apparent discrepancy between wetter conditions from speleothem records and drier conditions reported from lake-level reconstructions (Peyron et al., 2011; Magny et al., 2007, 2012b). This hypothesis is supported by the contrasting seasonal patterns of precipitation (strong Mediterranean conditions, with wet winters and dry summers) reconstructed for the early to mid-Holocene at Accesa from pollen data (Fig. 4; Peyron et al., 2011).

In the current study, we emphasize changes in precipitation seasonality by examining them at the regional scale. A direct comparison of pollen-inferred summer precipitation and lake-level changes at Lakes Ledro and Accesa from North-Central Italy is shown in Fig. 6. Mediterranean conditions only appear to exist at Lake Ledro prior to 8500 cal BP (Fig. 4). Mediterranean conditions terminate with increases for both summer and winter precipitation between 8300 and 7000 cal BP. These results fit well with the relatively high lake-levels at Ledro (Fig. 6), with the speleothem results from Corchia and Renella (Zanchetta et al., 2007b; Zhornyak et al., 2011), and with Southern Alpine speleothems (Spötl et al., 2010). Southern and Eastern Alpine speleothem records appear to register a humid period that is contemporraneous with the wettest phase identified at Corchia (i.e. ca. 8000 to 7300 cal BP) (Spötl et al., 2010). This humid period was interpreted as an increase in moisture sourced from the Mediterranean as oposed to the drier northwesterly air masses that affect the Alps (Spötl et al., 2010). At Accesa, winter precipitation is particularly high around 8000 cal BP (Fig. 4). This evolution is consistent with the increase in flood activity due to increased storminess in the region as suggested by Zhornyak et al. (2011), and is confirmed by a significant increase in winter precipitation between ca. 9500 and 7000 cal BP in North Aegean Sea (Kotthoff et al., 2008, 2011).

Proxy records of precipitation from Sicily show higher rainfall between ca. 8500 and 7500 cal BP (Carburangeli Cave speleothems: Frisia et al., 2006; land snail shells

Favignana Island: Colonese et al., 2011). Colonese et al. (2011) take the thermal limits controlling periods of snail activity into account to suggest that the increased precipitation at this time may not have been an exclusive winter phenomenon, but may have extended into spring and autumn. The two southern sites reported in this current study (Trifoglietti, Pergusa) both show higher winter precipitation, which is corroborated by Colonese et al. (2011) and Frisia et al. (2006), providing support that changes in seasonality may be major drivers for the high precipitation values from 10 000 to 6500 cal BP and the high lake-levels recorded at these sites (Figs. 4 and 6).

The current study confirms that lake-levels appear to be good indicators of summer precipitation changes (Magny et al., 2007) and supports the assumption that lake-levels, pollen, and isotopic data likely reflect processes linked to seasonality. Possible discrepancies between data could be reconciled considering the relative sensitivity of each site to changes in the seasonality of precipitation (Giraudi et al., 2011; Peyron et al., 2011), and the different residence times of water in their respective hydrological systems, but further evidence is needed to improve the general framework of climate evolution at this time, both at local and regional (Mediterranean-basin) scales.

4.5 Climate processes and north–south partition

To fully understand the timings and the relationships between regions and lakes within the Mediterranean basin, we must understand the climatic mechanisms driving changes in moisture across the Central Mediterranean during the Holocene. Tinner et al. (2009) have suggested that increasing humidity in coastal Sicily during the mid-Holocene reflects a decrease in the Hadley circulation (trade winds) and monsoonal activity after the boreal insolation maximum. This is in agreement with processes suggested for other areas of the Mediterranean (Tzedakis et al., 2009). An intense African monsoon strengthens the Hadley circulation (Gaetani et al., 2007), resulting in a reinforcement of the North Atlantic anticyclone and its blocking effect for possible intrusions of humid western airflow towards the Mediterranean. However, recent observations have also given evidence of possible influences of (1) sub-Saharian cyclones over the Western-Central Mediterranean (Knippertz and Wernli, 2010) and (2) rainstorms originating from the Tropics over the Eastern Mediterranean (Ziv et al., 2005). Moreover, Tzedakis et al. (2007) and Tinner et al. (2009) have also pointed out the possible influence of local convective precipitation in response to the orbitally driven insolation maximum. The comparison of lake-level data and pollen-inferred estimates of climatic parameters along a north-south transect in the Central Mediterranean clearly suggests that, over the Holocene period, the Northern Mediterranean borderlands belong to a North-Atlantic domain and show strong similarities with the European mid-latitudes (Magny et al., 2011, 2012a), while the Southern Mediterranean borderlands appear to be more affected by sub-tropical influences.

Data in this study show progressive, millenial-scale changes in climate in response to progressive changes in insolation. Data also show major centennial-scale climatic events, most evident at 8000 and 4500 cal BP. The 8000 cal BP event may be related to the influence of the well-known 8.2 ka event associated with a final step of the deglaciation in the North Atlantic area (Alley et al., 1997). The climatic oscillation around 4500–4000 cal BP appears to have been a major climate change, not only in the Eastern Mediterranean (Weiss et al., 1993; Enzel et al., 2003; Arz et al., 2006; Drysdale et al., 2006) but also in the Western Mediterranean.

Zhao et al. (2010) indicate that the climatic oscillation at 4000 cal BP may reflect a non-linear response of the climate system to (1) a gradual decrease of insolation, and (2) key seasonal and inter-hemispherical changes in insolation. On the one hand, this orbital forcing resulted in a reorganization of the general atmospheric circulation leading to a further southward migration of the Intertropical Convergence Zone in the tropics (Haug et al., 2001; Denton et al., 2005). The southward migration of the ITCZ would have driven the westerlies southward, bringing more humidity to the mid-European latitudes and the North-Central Mediterranean. On the other hand, in response to the decrease in insolation, cooling sea surface temperatures (Marchal et al., 2002) may have favoured the development of drier conditions over the South-Central and Eastern

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Mediterranean, south of ca. 40° N, leading to the development of modern climate conditions.

5 Conclusions

There is strong agreement between summer precipitation and lake-level reconstructions at Lakes Accesa and Ledro in Northern Italy and Lake Pergusa (Lake Preola for the lake-levels) in Sicily throughout the Holocene. The strong relationship between the two confirms that lake-level is most strongly a reflection of summer temperatures in the Central Mediterranean.

The results presented here for precipitation and temperature reconstructions from the four lakes appear to confirm that northern and southern sites in the Mediterranean have opposing precipitation regimes during the Holocene (Magny et al., 2012b). The summer temperature curves appear to show the same pattern as for precipitation: Warm/dry conditions in North Italy and cool/wet conditions in Sicily are reconstructed during the Early/Mid-Holocene, and conditions reversed during the Late-Holocene. The Holocene climate history of the region was punctuated by centennial-scale events at ca. 8000, 6500 and 4200 cal BP. These short-term events and the North/South climate partition observed in Italy shows strong similarities with those recognized in the Aegean Sea. The connections to short-lived climate events in the Aegean indicate that the climate events detected in the pollen-based climate reconstructions are in fact part of a broader regional climate forcing.

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Table 1. chronologies: information on the radiocarbon dates used, for each site.

Depth (cm)	Material	AMS ^{14}C Age BP	Cal. yr BP (2σ)
		Ledro	
17.5	Wood-Peat-Charcoal	255 ± 30	0–430
82.6	Wood-Peat-Charcoal	290 ± 30	280–460
142.6	Wood-Peat-Charcoal	1020 ± 30	800–1050
193.9	Wood-Peat-Charcoal	1445 ± 30	1290–1390
238.9	Wood-Peat-Charcoal	1945 ± 30	1820–1970
299.5	Wood-Peat-Charcoal	2520 ± 35	2480–2740
403.3	Wood-Peat-Charcoal	3030 ± 35	3080–3360
462.3	Wood-Peat-Charcoal	4080 ± 35	4440–4810
498.9	Wood-Peat-Charcoal	4550 ± 35	5050–5320
560.4	Wood-Peat-Charcoal	5720 ± 40	6410–6640
614	Wood-Peat-Charcoal	7270 ± 50	7980–8180
639.5	Wood-Peat-Charcoal	8385 ± 35	9300–9390
757.4	Wood-Peat-Charcoal	11 480 ± 60	13 210–13 440
		Accesa	
31–32	peat	820 ± 35	789–670
120–121	peat	1770 ± 35	1814–1569
219–220	peat	3000 ± 25	3322–3079
268–269	peat	3075 ± 30	3362–3174
305–307	peat	3355 ± 30	3687–3475
643–644	peat	3910 ± 30	4421–4243
739–740	peat	4675 ± 25	5568–5318
774–775	peat	5565 ± 35	6410–6290
823–824	peat	6330 ± 50	7415–7100
904–905	peat	7220 ± 40	8154–7944
906–907	peat	7235 ± 25	8156–7961
915–916	peat	7765 ± 40	8605–8422
920–921	peat	7580 ± 30	8411–8349
924–925	peat	8295 ± 35	9468–9134
935–936	peat	8610 ± 50	9697–9500
1040–1041	peat	8830 ± 50	10 154–9689
1158–1159	wood fragments	9890 ± 40	11 540–11 199

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Table 1. Continued.

Depth (cm)	Material	AMS^{14}C Age BP	Cal. yr BP (2σ)
		Trifoglietti	
87	Wood-Peat-Charcoal	125 ± 30	0–270
172	Wood-Peat-Charcoal	2675 ± 35	2740–2850
295	Wood-Peat-Charcoal	3970 ± 40	4290–4530
371	Wood-Peat-Charcoal	4890 ± 35	5580–5710
497	Wood-Peat-Charcoal	6660 ± 50	7430–7610
571	Wood-Peat-Charcoal	7920 ± 50	8600–8980
685	Wood-Peat-Charcoal	8600 ± 50	9490–9680
761	Wood-Peat-Charcoal	9335 ± 60	10 290–10 710
806	Wood-Peat-Charcoal	9630 ± 60	10 760–11 190
843	Wood-Peat-Charcoal	9850 ± 50	11 190– 11 388
843	Wood-Peat-Charcoal	9940 ± 60	11 220–11 690
		Pergusa	
65	Sediment	1995 ± 65	1818–2127
97	Plant remains	2420 ± 97	2333–2736
192	Sediment	3055 ± 75	3061–3411
245	Sediment	4400 ± 105	4816–5318
317	Sediment	7475 ± 65	8178–8395
369	Sediment	8950 ± 90	9742–10 246
378	Sediment	9235 ± 95	10 229–10 605
456	Plant remains	10 815 ± 160	12 418–13 101

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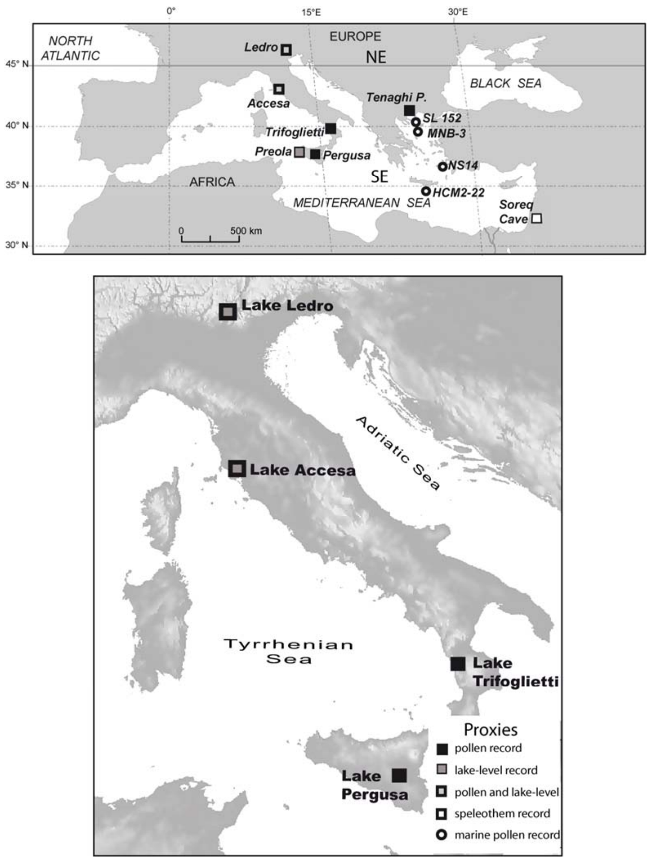

Fig. 1. Geographic location of the study sites along a latitudinal gradient from Northern Italy to Southern Italy: Lakes Ledro in North Italy (45°87′ N, 10°76′ E, 652 m), Accesa (42° 59′ N, 10°53′ E, 157 m) in North-Central Italy, Trifoglietti in South Italy (39°33′ N, 16°1′ E; 1048 m), and Pergusa (37°31′ N; 14°18′ E, 667 m) in Central Sicily. Other sites mentioned in the text (marine cores located in the Aegean Sea, Tenaghi Philippon, Soreq Cave) are also plotted. SE = South Eastern Europe (south of 45° N and east of 15° E) and NE = North Eastern Europe as defined in Davis and Brewer (2003).

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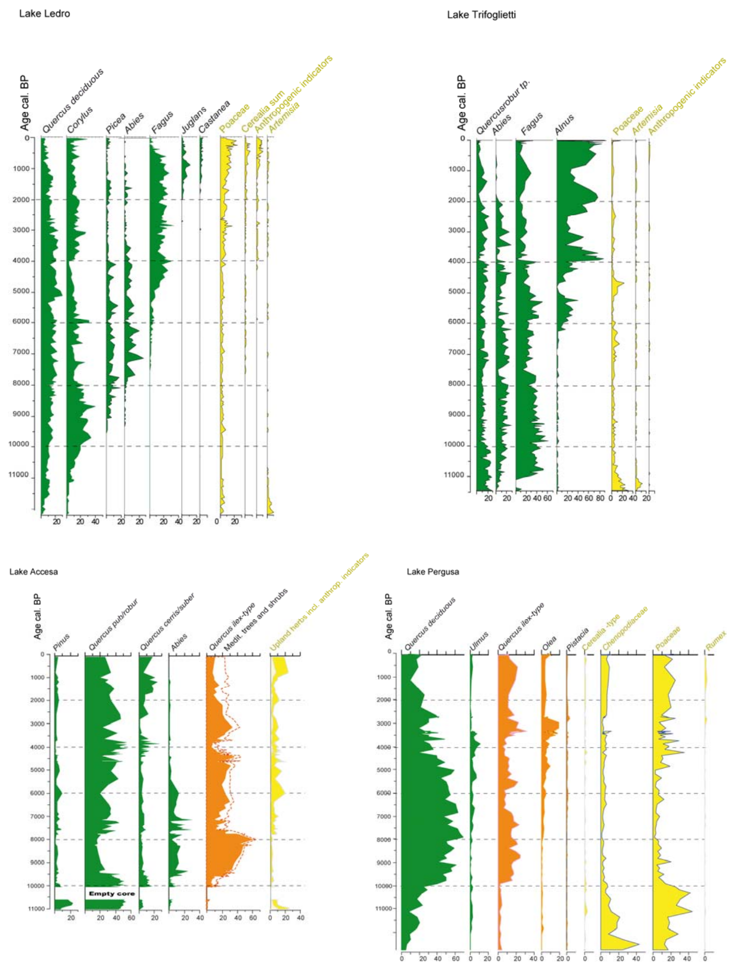

Fig. 2. Caption on next page.

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Fig. 2. Simplified pollen diagrams for: Lake Ledro deep core "LL081" (Joannin et al., 2012a), Lake Accesa littoral core "AC3/4" (Drescher-Schneider et al., 2007), Lake Trifoglietti (Joannin et al., 2012b), and Lake Pergusa (Sadori and Narcisi, 2001). The chronology of the four pollen records is based on radiocarbon dates compiled in Table 1. More details on each chronology are given in the references papers.

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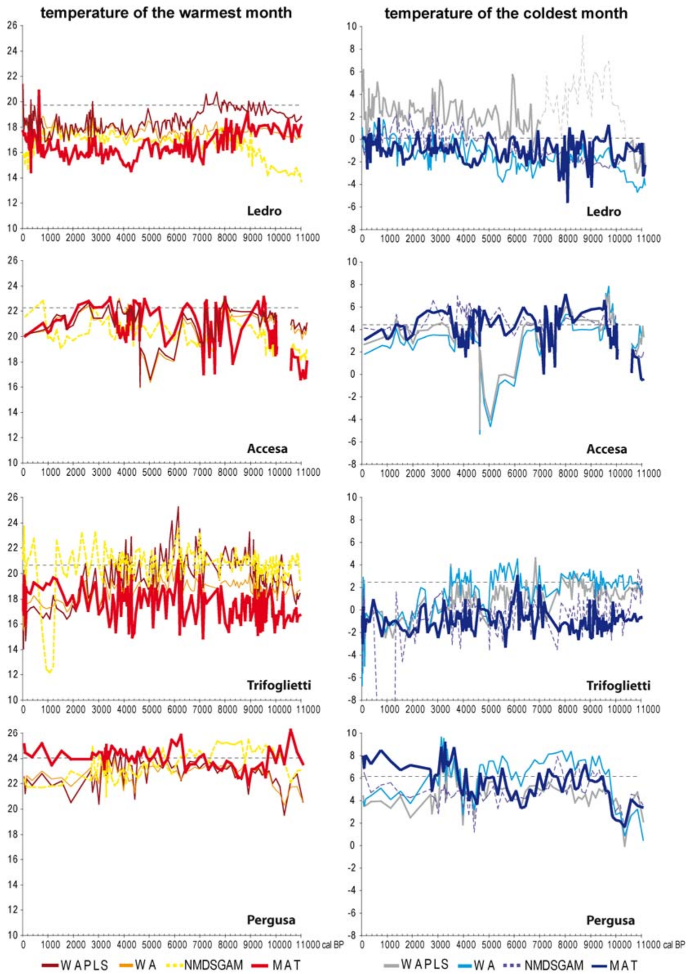

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Fig. 3. Pollen-based climate reconstructions for the four lakes with special attention to reconstructions of temperature seasonality. Climate values are estimated using 4 methods: the Modern Analogues Technique (MAT), the Non-Metric Multidimensional Scaling/Generalized Additive Model method (NMDS/GAM), Weighted Averaging (WA), and Weighted Average Partial Least Squares regression (WAPLS). Warmest and coldest month temperatures (°C) are plotted. Modern values are indicated with a horizontal dotted line. The thin dotted grey curve (temperature of the coldest month, Ledro) corresponds to unrealistic values.

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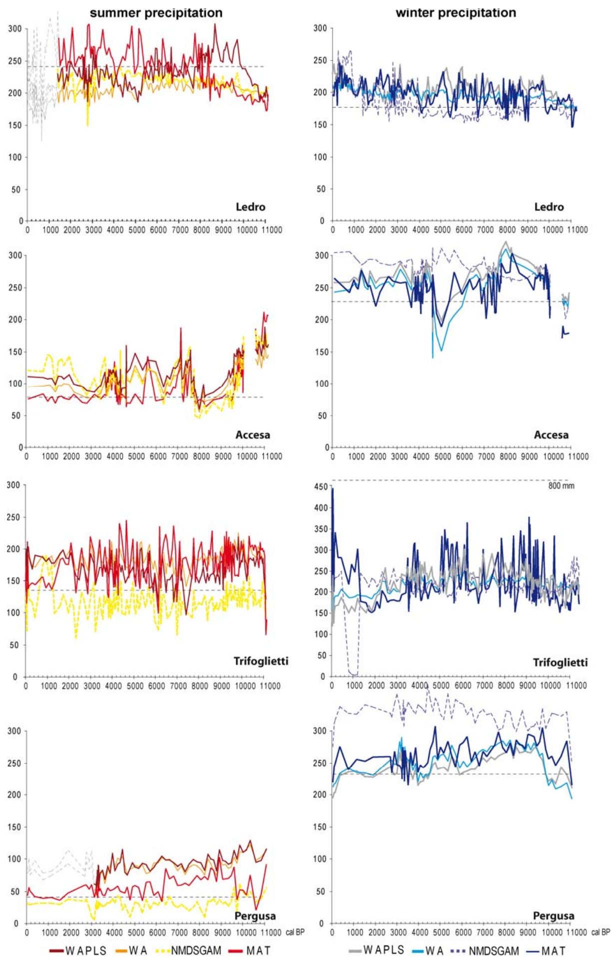

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Fig. 4. Pollen-based seasonal precipitation (winter = sum of December, January, February precipitation, and summer = sum of June, July, August precipitation, in mm) values for the four lakes estimated with the methods listed in Fig. 3. Modern values are indicated with a horizontal grey dotted line. The thin dotted grey curve (summer precipitation, Ledro and Pergusa) corresponds to unrealistic values.

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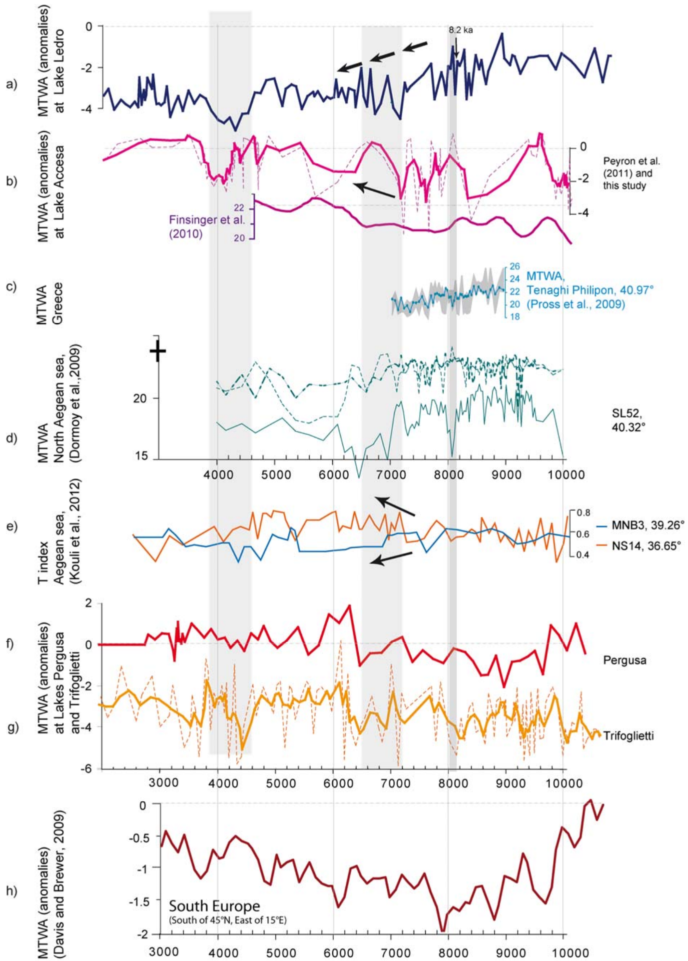

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Fig. 5. Synthesis figure for selected Mediterranean temperature records. **(a)** Pollen-inferred temperature of the warmest month for Lake Ledro (as for Fig. 3), MAT only. **(b)** Pollen-inferred temperature of the warmest month for (1, pink curve) Lake Accesa littoral core, MAT only (as for Fig. 3), and (2, purple curve) Lake Accesa profundal core, WAPLS only (Finsinger et al., 2010). **(c)** Pollen-inferred temperature of the warmest month for Tenaghi Philippon, Greece, MAT only (Pross et al., 2009). **(d)** Pollen-inferred temperature of the warmest month for the marine core SL152, Aegean Sea, (Dormoy et al., 2009) with three methods (short dotted line: MAT; blue line: PLS; long dotted line: NMDS/GAM). **(e)** Pollen-based temperature index "T index" for the marine cores MNB3 (North Aegean Sea), and NS14 (South Aegean Sea) (Kouli et al., 2012). **(f)** Pollen-inferred temperature of the warmest month for Lake Pergusa (as for Fig. 3), MAT only. **(g)** Pollen-inferred temperature of the warmest month for Lake Trifoglietti (as for Fig. 3), MAT only; the curve of temperature is calculated with a moving average (bold curve) and raw values are also plotted (dotted curve). **(h)** Reconstruction of temperatures of the warmest month (anomalies) for South Europe based on pollen data from over 500 pollen sites from across Europe, MAT only (Davis and Brewer, 2009; Davis et al., 2003).

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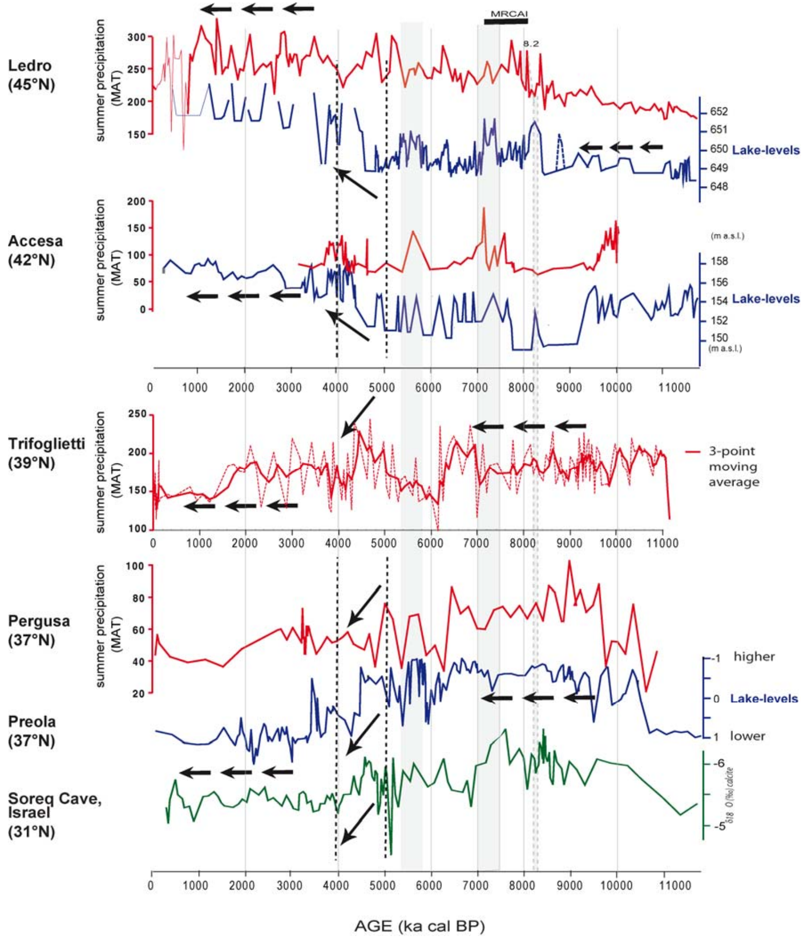

Fig. 6. Caption on next page.

Fig. 6. Comparison between pollen-inferred summer precipitation (MAT only) and lake-levels variations at Lakes Ledro, Accesa, Trifoglietti and Pergusa. More details on the lake-levels data are given in Magny et al., (2012a) for Lake Ledro, Magny et al. (2007) for Lake Accesa, and Magny et al. (2011) for Lake Preola (Sicily). Oxygen isotope data based on speleothem from Soreq Cave, Israel, is also plotted for comparison with Eastern Mediterranean sites (Bar-Matthews et al., 1998, 2011; Vaks et al., 2006). MRCAI = Period of maximal rate of change in annual insolation.

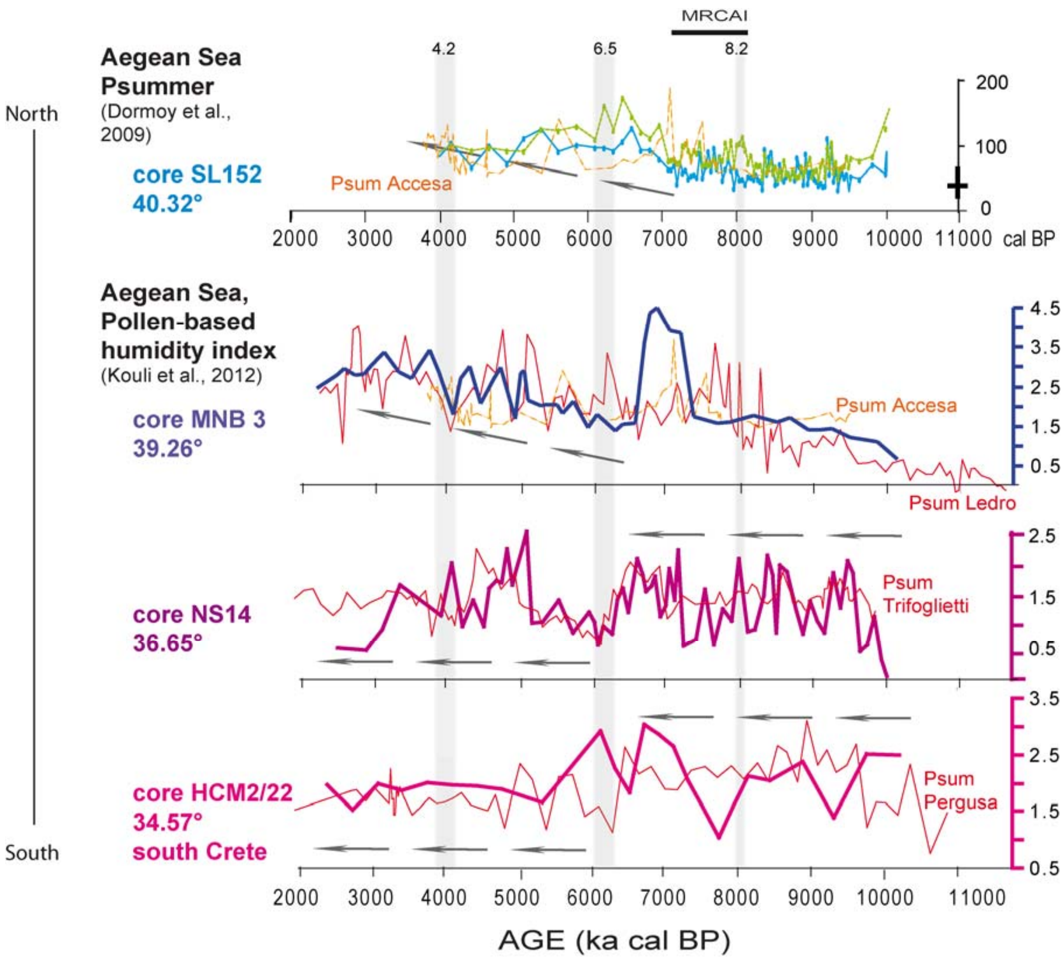

Fig. 7. Caption on next page.

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Fig. 7. Contrasting precipitation patterns in Italy and in Aegean Sea. during the Holocene. Psum = Psummer (MAT only) as in Fig. 4, from each lake pollen record (dotted orange: Accesa; red: Ledro, Trifoglietti and Pergusa; units same as Fig. 6). Comparison with the Aegean Sea records (1) Pollen-inferred summer precipitation (in mm) for the marine core SL152, North Aegean Sea, (Dormoy et al., 2009) obtained with the PLS method (green curve), and the NMDS/GAM (blue curve); (2) Pollen-based humidity index established by Kouli et al., (2012) from three marine pollen records located across a north-south transect in the Aegean Sea: cores MNB3 (blue curve), core NS14 (purple curve) and core HCM2/22 (dark pink curve). Short-events at around 8200, 6500 and 4200 cal BP are also plotted. MRCAI = Period of maximal rate of change in annual insolation.

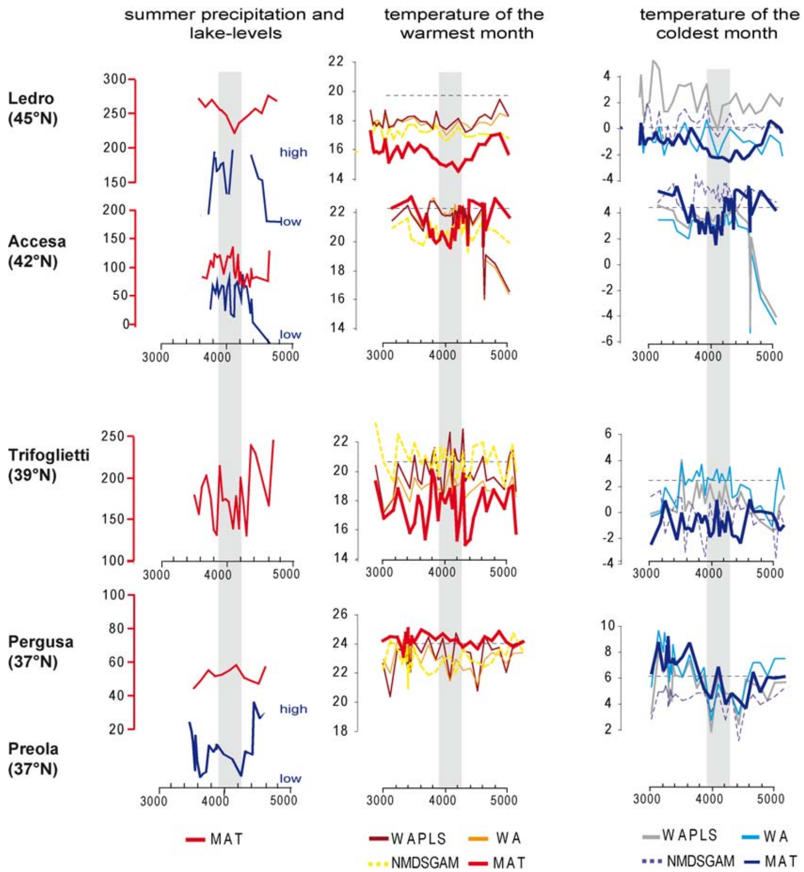

Fig. 8. Synthesis figure for the 4.2 ka event in Italy, and comparison with lake-level data.

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