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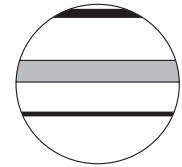
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Holocene seasonality changes in the central Mediterranean region reconstructed from the pollen sequences of Lake Accesa (Italy) and Tenaghi Philippon (Greece)

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Abstract

This study presents pollen-based climate reconstructions of Holocene temperature and precipitation seasonality for two high-resolution pollen sequences from the central (Lake Accesa, central Italy) and eastern Mediterranean (Tenaghi Philippon, Greece) regions. The quantitative climate reconstruction uses multiple methods to provide an improved assessment of the uncertainties involved in palaeoclimate reconstructions. The multimethod approach comprises Partial Least Squares regression, Weighted Average Partial Least Squares regression, the Modern Analogues Technique, and the Non-Metric Multidimensional Scaling/Generalized Additive Model method. We find two distinct climate intervals during the Holocene. The first is a moist period from 9500 to 7800 cal. BP characterised by wet winters and dry summers, resulting in a strongly seasonal hydrological contrast (stronger than today) that is interrupted by a short-lived event around 8200 cal. BP. This event is characterised by wet winters and summers at Accesa whereas at Tenaghi Philippon the signal is stronger, reversing the established seasonal pattern, with dry winters and wet summers. The second interval represents a later aridification phase, with a reduced seasonal contrast and lower overall precipitation, lasting from 7800 to 5000 cal. BP. Present-day Mediterranean conditions were established between 2500 and 2000 cal. BP. Many studies show the Holocene to have a complex pattern of climatic change across the Mediterranean regions. Our results confirm the traditional understanding of an evolution from wetter (early Holocene) to drier climatic conditions (late Holocene), but highlight the role of changing seasonality during this time. Our data yield new insights into the aspect of seasonality changes, and explain the apparent discrepancies between the previously available climate information based on pollen, lake-levels and isotopes by invoking changes in precipitation seasonality.

Keywords

climate changes, Holocene, Mediterranean, pollen, seasonality

Introduction

The Holocene is a period of special climatic interest characterised by relatively stable climate conditions but also by submillennial-scale climate fluctuations that affected the high and low latitudes of both hemispheres (e.g. Bond et al., 1997; Mayewski et al., 2004). Recent studies have detected minor climatic oscillations such as the 8.2 and 4.2 kyr events, and other short-lived events also in the Mediterranean region (e.g. Asioli et al., 1999; Cacho et al., 2001; Combourieu-Nebout et al., 2009; Frigola et al., 2007; Incarbona et al., 2008; Magny et al., 2003, 2009; Pross et al., 2009; Saffi et al., 2004), which is particularly sensitive to rapid climate change owing to an intermediate position between the higher-latitude (e.g. North Atlantic) and lower-latitude (e.g. monsoonally influenced) climate systems.

All these studies show the Holocene to have a complex pattern of climatic change across the Mediterranean regions, leading to different opinions as to the nature of this climate change (e.g. Magny et al., 2007a,b; Marchal et al., 2002; Sadori and Narcisi, 2001; Tzedakis, 2007; Zanchetta et al., 2007). Most authors assume that climatic conditions were cool and humid during the early Holocene due to precessional forcing (Cheddadi

et al., 1997; Huntley and Prentice, 1988), gradually becoming drier during the mid and late Holocene (e.g. Ariztegui et al., 2000; Carri n et al., 2001; Follieri et al., 2000; Frisia et al., 2006; Jalut et al., 2009; Pantaleon-Cano et al., 2003; P rez-Obiol and Sadori, 2007; Roberts et al., 2001; Sadori and Narcisi, 2001; Sadori et al., 2011, this issue). Hence, around 5000–4000

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yr BP, the expansion of sclerophyllous vegetation observed in many southern European pollen records has been interpreted as being due to aridification, leading to the establishment of modern Mediterranean climate (Follieri et al., 2000; Jalut et al., 2000, 2009; Sadori et al., 2011, this issue). Other studies suggest that the vegetation changes observed since the mid Holocene in numerous Mediterranean records are due to anthropogenic vegetation change or biogeographic factors (de Beaulieu et al., 2005). Human impact can be associated in some cases with forest clearance by fire and cutting which may have favoured Mediterranean taxa (Colombaroli et al., 2008; Pons and Quézel, 1998; Quézel, 1999).

In addition to these contradictory interpretations, recent studies have highlighted the role of seasonality in the Holocene climate system in the Mediterranean region (Davis and Brewer, 2009; Denton et al., 2005; Dormoy et al., 2009; Pross et al. 2009; Tzedakis, 2007) and in western Europe (Prasad et al., 2009). Magny et al. (2007a), Zanchetta et al. (2007) and Vanni ere et al. (2008) explain the apparent discrepancies derived from pollen, fire frequency, lake-levels and isotopes data for the early- to mid-Holocene climate in central Italy by precipitation seasonality. Given the scarcity of reliable palaeoclimatic and palaeoenvironmental records in the central south Mediterranean, new evidence is needed to test this hypothesis.

In light of the above, this study aims to provide robust and precise quantitative estimates of the Holocene climate in the Mediterranean region based on two high-resolution pollen records taken from Lake Accesa (Tuscany), and Tenaghi Philippon (Greece) with a special attention to reconstructions of precipitation and temperature seasonality. We investigate climatic trends during the Holocene, and we give particular emphasis to the early Holocene specifically addressing the question of humidity versus drought, and the degree of seasonality. Given that seasonal parameters seem to be the driving factor for Mediterranean climate (Finsinger et al., 2007; Rohling et al., 2002), this paper aims to provide reliable quantitative estimates for seasonal climatic variables, including summer and winter precipitation, in contrast to previous studies that examine largely annual climate parameters (e.g. Guiot, 1990; Peyron et al., 1998). We also test the sensitivity of the Mediterranean region to the climatic fluctuations recognised in the North Atlantic region (Bond et al., 1997) and other submillennial-scale climate events depicted in the Mediterranean region (e.g. Frigola et al., 2007; Incarbona et al., 2008; Magny et al., 2009; Triantaphyllou et al., 2009).

In the current study, we reconstruct climate for the Lake Accesa and Tenaghi Philippon high-resolution pollen sequences using a multimethod approach that takes into account the majority of the errors associated with palaeoenvironmental reconstructions (Brewer et al., 2008). We have chosen four methods to better assess the uncertainties in the predictions and the error of reconstruction: Partial Least Squares regression (Wold et al., 1984), Weighted Average Partial Least Squares regression (ter Braak and Juggins, 1993), Modern Analogues Technique (Guiot, 1990), and the more recent Non-Metric Multidimensional Scaling/Generalized Additive Model method (Goring et al., 2009).

This study is a part of a multiproxy project including Lake Accesa vegetation history (Colombaroli et al., 2008; Drescher-Schneider et al., 2007), fires (Vanni ere et al., 2008), lake-levels and tephra (Magny et al., 2006; 2007a,b), organic matter and chironomids records (Millet et al., 2007) throughout the Lateglacial and/or Holocene.

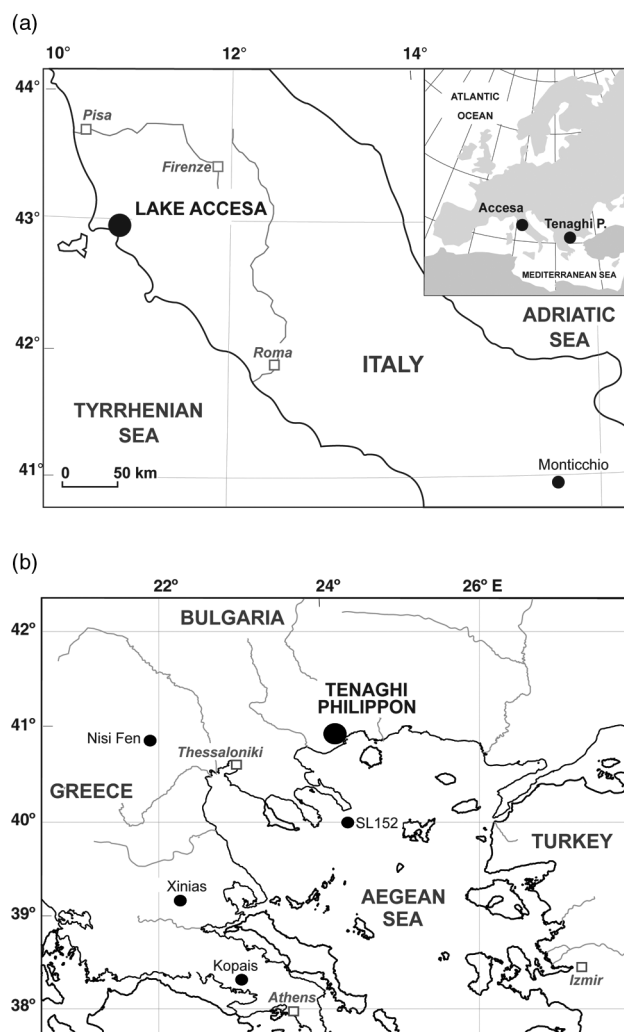


Figure 1. Geographical location of (a) Lake Accesa (north-central Italy) and (b) Tenaghi Philippon (Greece)

Sites, data and methods

Sites

The Lake Accesa sequence is located in Italy in the central Mediterranean basin and Tenaghi Philippon (Greece) sequence is located in the eastern part of the Mediterranean basin. The Mediterranean basin has a high level of climate diversity as a result of the orographic characteristics of the surrounding regions and the regional complexity of marine and atmospheric circulation patterns. The Mediterranean basin is situated within the transition zone between regions influenced by the North Atlantic Oscillation (NAO) to the north and the tropical convergence zone to the south. Today, the NAO controls winter precipitation in the western Mediterranean with less influence in the east and south. The role of the NAO in controlling winter temperatures is not as important in the western Mediterranean and is minor in the eastern part. The southern Mediterranean is mostly influenced by the descending branch of the Hadley cell (Lionello et al., 2006; Trigo et al., 2006).

Lake Accesa (42°59'N, 10°53'E, 157 m a.s.l.) is a small lake (16 ha, 39 m max. depth) located in central Italy, 10 km from the eastern shore of the Tyrrhenian Sea (Figure 1). Although the present-day vegetation is marked by human impact, vegetation around Lake Accesa is generally ascribed to perennial grassland, transitional woodland shrubs and broadleaved forests, with the presence of widespread evergreen vegetation in sparse areas around

the lake. Climate is typically Mediterranean with an annual precipitation of *c.* 780 mm/yr, highest in autumn with marked summer drought. Mean annual temperature is *c.* 13°C, ranging from 4.5°C in the coldest month to 22°C in the warmest (New et al., 2002).

A core transect was carried out from the western shore of the lake. Pollen data used in the current study were extracted from two overlapping twin cores, AC3 and AC4 (AC3/4), obtained in a littoral mire, 50 m from the present-day lake shore. The chronology, spanning the last 16 000 years, is based on 21 ¹⁴C dates and 8 tephra layers with a temporal resolution sufficient to trace climatic oscillations with duration of *c.* 200 yr (Magny et al., 2006, 2007a).

The Tenaghi Philippon site (40°58.40'N, 24°13.42'E; 40 m a.s.l.) is located in the near-coastal Drama Basin, NE Greece (Figure 1). The Drama Basin is bounded by the Phalakron range (2232 m) to the west and southwest and Mt Lekani (1150 m) to the east; it is separated from the northern Aegean Sea by the Symvolon range (477 m). Little of the original vegetation remains as a result of human activity, both in the Drama Basin and the surrounding mountain slopes but vegetation in the region would likely be characterised as a mixture of Mediterranean and transitional deciduous forest (Tzedakis et al., 2006). The Drama Basin is characterised by Mediterranean climate conditions, with colder winters and wetter summers than southern Greece. The nearby Amygdaleonas meteorological station reports mean January and July temperatures of 3.4°C and 23.9°C, respectively, with a mean annual precipitation of 600 mm (Tzedakis et al., 2006). The Tenaghi Philippon archive was first investigated by Wijmstra (1969). In an effort to improve the temporal resolution of the Tenaghi Philippon pollen sequence, a new core was retrieved in 2005 (Pross et al., 2007, 2009). Because the new core lacks high-quality ¹⁴C-datable material, age control comes from the correlation of key events in its pollen record with corresponding features in the well-dated marine pollen record of core SL152 from the northern Aegean Sea (Kotthoff et al., 2008a, b). One hundred pollen samples were studied in a resolution of ~30 yr across the interval spanning the 8.2 kyr event.

Pollen diagrams

Lake Accessa. Two pollen records have been obtained from different localities within the lake: a littoral core, AC3/4, provides a record from 16 000 cal. BP to the present (Drescher-Schneider et al., 2007), while a profundal core, AC05, spans an interval from 11 000 to 6500 cal. BP (Colombaroli et al., 2008; Finsinger et al., 2010). The profundal and the littoral cores give a roughly similar vegetation picture. Only the littoral core has been used in this study (Figure 2).

Quercus pollen (probably *Q. pubescens* at the beginning of the Holocene) dominates the Holocene record for Lake Accessa, alternating between deciduous and evergreen taxa (Figure 2). The pollen record shows three zones characterised by evergreen oaks which are accompanied by peat layers, indicating lower lake-levels (Magny et al., 2007a), at *c.* 8600–7900 cal. BP, 4600–4300 cal. BP and 3700–2800 cal. BP. High percentages of evergreen oaks and low lake-levels from 9500 to 7700 cal. BP indicate warm, dry conditions, contrasting with contemporaneous high values of *Abies* (20%) and other taxa that might otherwise suggest high precipitation. This combination suggests the influence of precipitation seasonality (Drescher-Schneider et al., 2007). The pollen percentages for *Abies* at this time are different between littoral (20%) and profundal (5%) cores, leading

to the conclusion that higher concentration in the littoral core may be due to over-representation owing to pollen buoyancy on the water surface that would result in higher concentration near the shore or due to local stands of *Abies alba* near the shore (Colombaroli et al., 2008). A persistent decline of *Quercus ilex* occurs around 7700 cal. BP.

Human presence is detectable at Lake Accessa through the Neolithic period (Drescher-Schneider et al., 2007), but becomes significant at the beginning of the Bronze Age (*c.* 4300 cal. BP) when cultivation of cereals and pasturing can be detected in the pollen record. Pollen taxa of deciduous oaks, *Fraxinus* and *Alnus* indicate temperate climatic conditions from 4300 to 3700 cal. BP, while high amounts of evergreen oaks suggest hot and dry climate conditions from 3700 to 3400 cal. BP.

Quantitative climate reconstructions for Lake Accessa are only performed from 11 000 to 2000 cal. BP since human impact dominates the signal and masks the reaction of the vegetation to climatic changes after 2000 cal. BP.

Tenaghi Philippon. The Tenaghi Philippon core provides a record from 10 500 to 6500 cal. BP, for which temporally highly resolved (~30 to ~120 yr) pollen data are available (Pross et al., 2009). The early-Holocene vegetation was dominated by broadleaved forests, with high abundances of evergreen *Quercus* (Figure 2). Shortly after 8200 cal. BP, percentages of pollen from broadleaved trees (particularly evergreen *Quercus*) strongly declined, while percentages of Poaceae and steppic (*Artemisia*, Chenopodiaceae, *Ephedra*) pollen taxa increased. Tree pollen percentages reached their minima at ~8100 cal. BP. The recovery of broadleaved arboreal pollen taxa shortly after 8000 cal. BP was accompanied by a reduction in steppe taxa, ultimately leading to pollen assemblages comparable with those preceding the perturbation, suggesting that the perturbation lasted for ~200 yr. It is only after *c.* 7800 cal. BP that pronounced vegetation changes began to emerge again. These changes suggest a continued, albeit less pronounced vegetation variability during the remainder of the early Holocene, although our high-resolution record for Tenaghi Philippon extends only as far as 6500 cal. BP.

Climate reconstruction methods

Quantitative climate reconstructions for both pollen sequences were performed for summer and winter precipitation to emphasize changes in precipitation seasonality. To assess reconstruction errors, multiple methods for pollen-based climate reconstruction were used. Since pollen-based climate reconstruction methods each have their own set of advantages and limitations (Birks and Birks, 2006; Brewer et al., 2008), we chose four methods, including most standard methods used in climate reconstruction. Here, Partial Least Squares regression (PLS; Wold et al., 1984), Weighted Averaging Partial Least Squares (WAPLS; ter Braak and Juggins, 1993), the Non-Metric Multidimensional Scaling/Generalized Additive Model (NMDS/GAM; Goring et al., 2009) and the Modern Analogue Technique (MAT; Guiot, 1990) are used. The three first methods are true transfer functions based on a calibration between environmental variables and modern pollen assemblages whereas the MAT does 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 a modern pollen data set that contains more than 3500 modern spectra (lacustrine top-cores, moss polsters and terrestrial

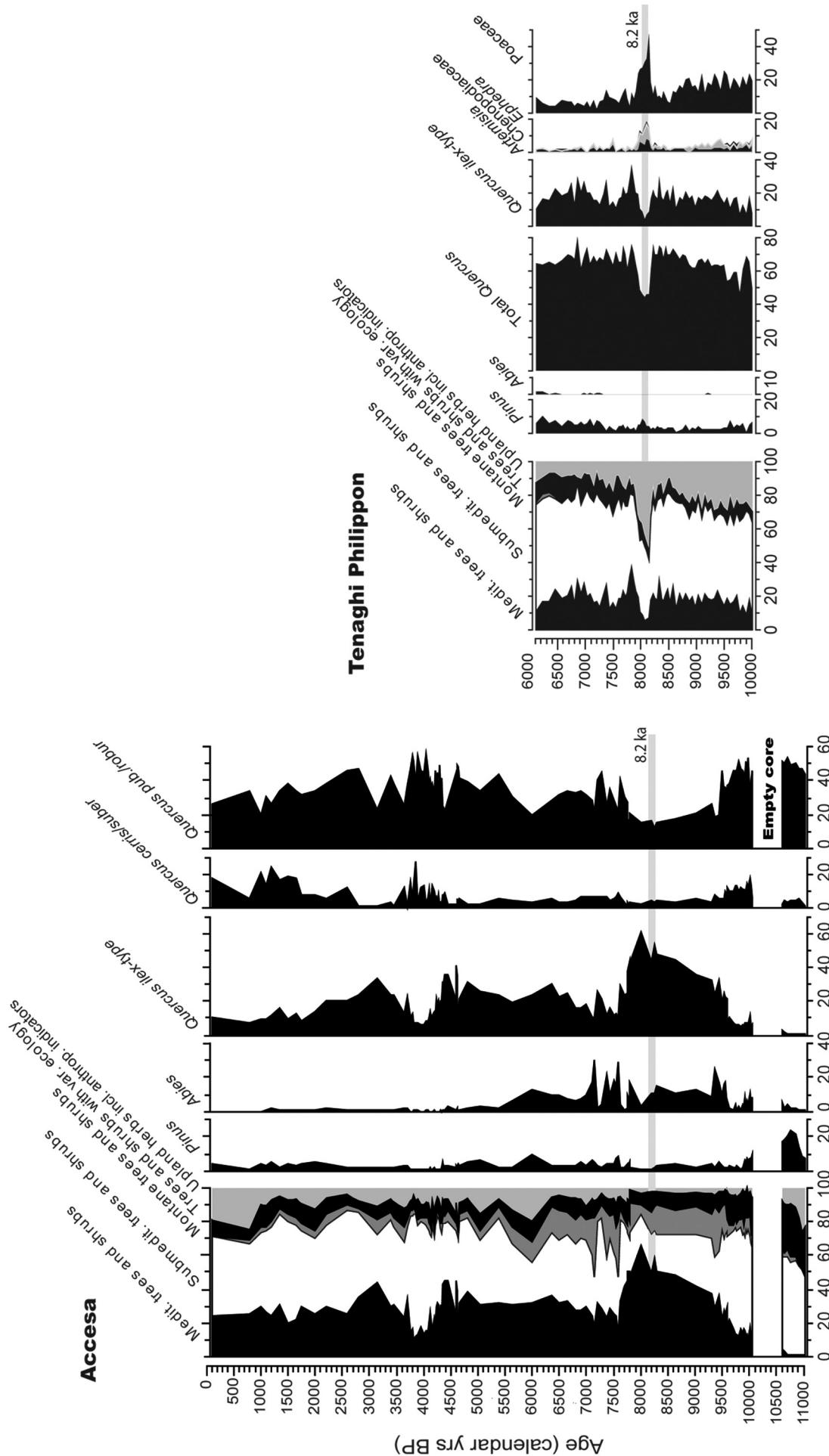


Figure 2. Simplified pollen diagrams for Lake Accessa (littoral core AC3/4) and Tenaghi Philippon (Drescher-Schneider et al., 2007; Pross et al., 2009). More details on the pollen diagrams and on the vegetation history at Lake Accessa and Tenaghi Philippon are given in Drescher-Schneider et al. (2007), Colombaroli et al. (2008), Magry et al. (2007a), Wijmstra (1969), Tzedakis et al. (2006) and Pross et al. (2009). There are no pollen data for Lake Accessa around 10 000 cal. BP due to core loss (empty cores). The chronology of the Lake Accessa pollen record is based on 21 ¹⁴C dates and 8 tephra layers (Magry et al., 2006, 2007a). Radiocarbon dates were obtained from aquatic plant macrofossils in the lower sections of the core. Radiocarbon ages were calibrated using IntCal 5 (Stuiver et al., 1998), and the calibrated ages have been adjusted using a constant 4700-yr hard-water effect. The Tenaghi Philippon chronology is anchored by correlations to key events in its palynological record with corresponding features in the marine, ¹⁴C-dated core SL152 from the Mount Athos Basin, Aegean Sea (Kotthoff et al., 2008a; Pross et al., 2009)

samples) with 2000 samples from the Mediterranean region (Dormoy et al., 2009; Bordon et al., 2009).

The regression methods PLS and WAPLS operate by compressing the overall data structure onto latent variables. The modern pollen data set used may be considered a large matrix with 103 dimensions, corresponding to each of the pollen taxa within the data set. Since there is some colinearity among the pollen taxa, and since some taxa will be related to climate parameters of interest, it is possible to reduce the data set 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 data set 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. Both PLS and WAPLS are often used in pollen-based climate reconstruction (Lotter et al., 2000) and are more commonly used in chemometric analysis (Wold et al., 2001).

The NMDS/GAM method is a newer pollen-based climate reconstruction method that was developed from pollen assemblage data in British Columbia, Canada, a region that is relatively poorly sampled and that experiences very sharp climate gradients (Goring et al., 2009). This method begins by reducing the dimensionality of the data set 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 (Hastie and Tibshirani, 1990) to the 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. The potential improvement on the MAT comes if we consider a point at the centre of a circle to be a sample; two points equidistant from this central point may be located anywhere along the circumference of the circle, either directly opposite from one another (distance = $2r$), or at the same place on the circumference (distance = 0). MAT treats these two possible orientations as equivalent, whereas a GAM model fit to the NMDS ordination output can recognise latent gradients across the surface of this hypothetical circle.

The Modern Analogue Technique (MAT) uses the squared-chord distance, effective with percentage data (Overpeck et al., 1985), 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 parameter for the unknown sample it is common practise to calculate the climate parameter as the weighed mean of the closest n samples or 'analogues'. A minimum 'analogue' threshold is often established beforehand using a Monte Carlo method (Guiot, 1990). For this analysis we retain the 8–10 nearest analogues with a distance inferior to this minimum. If less than 8 analogues are found, no climate reconstruction is attempted for that sample. Paleoenvironmental reconstructions

using MAT are based on a small subset of samples from the much larger data set. Thus, uncertainty estimates only provide a partial estimate of error when they are obtained from the dispersion of climate variables for the n -closest analogues (the standard deviation). A full estimate of error requires the uncertainty that relates the new estimates to the underlying climate variable for samples with known climate. In practice this may mean that a sample with n modern analogues from a very small region with nearly identical climate variables will produce a standard deviation that grossly underestimates the true sample error. For this reason we test model error using cross-validation across the entire set of modern samples.

Each of these methods is subject to error. To some degree all methods are subject to error resulting from 'noise' in the data set. This noise may result from variation in basin characteristics, differential degradation of pollen taxa resulting from the deposition substrate, differences in pollen transport and local anthropogenic effects. In general, as noise in the pollen data set increases model error increases. Methods such as PLS and WAPLS may be more susceptible to this noise since they rely on a direct and linear relationship between the underlying climate parameter and the pollen data set. Since both MAT and NMDS/GAM use the distance structure of the data and essentially perform local fitting of the climate parameter (either as the mean of n -closest sites, or predictions from a fitted spline function) they may be less susceptible to increased noise in the data set, and less likely to report spurious values. A disadvantage of MAT that is not found in the other techniques may be that since parameters are calculated as the mean of n samples within the data set it is often impossible to calculate parameters beyond the ranges contained within the data set (except with the revised analogues method developed by Waelbroeck et al., 1998). However, the size of the data set used in this analysis should be sufficient to cover most of the climate parameters expected to have occurred at these two sites throughout the Holocene. Additionally, although MAT generally is found to have lower RMSE/RMSEP values than other common reconstruction methods (Dormoy et al., 2009; Paterson et al., 2002; Peros and Gajewski, 2008), caution should be exercised as it is possible that MAT achieves lower RMSE/RMSEP by internalizing the spatial structure of climatic parameters associated with the pollen assemblages that are not being directly reconstructed, resulting in lower apparent error (Telford and Birks, 2005).

Results and discussion

Model error

We calculated model error as a function of sample size using a split-sampling method (Birks, 1995) modified to vary the predictive sample size from 215 to 3252 modern surface samples. For 223 randomly selected data sets we calculated climate variables for 50 randomly selected modern samples. This allowed us to generate a predictive model for Root Mean Squared Error of Prediction (RMSEP) as a function of sample size and to calculate error for models that use the entire data set (Table 1). This method of error estimation allows us to understand potential sources of error among the models since it generates both RMSEP and an error estimate for RMSEP. Thus, models that generate similar RMSEP estimates but have differences in error variance can be judged appropriately (e.g. WAPLS and PLS error estimates).

Table 1. Model error calculated using modified leave-*n*-out validation based on root mean squared error (RMSEP) values from sample sets of 50 pollen assemblages, predicted with data sets of between 213 and 3252 pollen assemblages from the Modern Pollen Dataset. Final RMSEP values and error are extrapolated from the slope relating the sampled RMSEP to sample size for each pollen-based climate reconstruction method and each climate variable

Method	Summer precipitation	Winter precipitation	Annual precipitation	Evaporation: precipitation ratio	Temperature of the coldest month	Temperature of the warmest month	Mean annual temperature	GDD5
MAT	40.5 ± 0.7 mm	55.3 ± 1.6 mm	166.6 ± 5.1 mm	8.9 ± 0.2	3.6 ± 0.1°C	2.3 ± 0.1°C	2.5 ± 0.1°C	653.9 ± 14.1
NMDS/GAM	51.0 ± 1.0 mm	64.7 ± 1.9 mm	203.8 ± 5.0 mm	12.0 ± 0.3	4.9 ± 0.1°C	3.2 ± 0.1°C	3.4 ± 0.1°C	846.3 ± 16.1
PLS	57.5 ± 1.3 mm	71.7 ± 2.6 mm	203.1 ± 7.0 mm	13.5 ± 0.3	5.3 ± 0.1°C	3.2 ± 0.1°C	3.7 ± 0.1°C	884.2 ± 21.5
WAPLS	56.7 ± 1.1 mm	70.5 ± 1.8 mm	214.8 ± 4.6 mm	12.9 ± 0.3	5.0 ± 0.1°C	3.3 ± 0.1°C	3.4 ± 0.1°C	893.4 ± 16.4

Initially PLS had lower error than WAPLS for most climate variables. This was a surprising result since WAPLS is meant to perform better than PLS (ter Braak and Juggins, 1993), however the PLS method generated spurious results at low sample sizes resulting in very high RMSEP values. This produced models of error for the PLS method that had steep slopes for model error as a function of sample size. To correct for this we removed all RMSEP values above the third quantile, regardless of the method used. This had little effect on the remaining three models and appeared to correct the problems relating to the PLS model.

We found MAT to have the lowest error for all climate variables (Table 1). This result should be taken with some caution as Telford and Birks (2005) have suggested that spatial autocorrelation within the data set may result in artificially low error values. NMDS/GAM has the second lowest error for all climate variables, except for annual precipitation where PLS had the lowest error. Although we corrected for spurious RMSEP values from the PLS method it appears that PLS still produces lower RMSEP values than WAPLS for a number of climate variables including winter precipitation, E/PE, mean temperature of the coldest month and mean annual temperature.

If all models behave similarly with respect to both individual pollen taxa and pollen assemblages we might expect model outputs for the various climate parameters to match well throughout the climate reconstructions. It is clear (Figures 3, 4) that although similarities exist, there are distinct differences between models. The most dramatic difference between models occurs at approximately 5000 cal. yr BP in the Accessa record, where the NMDS/GAM model indicates winter precipitation levels of ~300 mm, while the MAT, PLS and WAPLS models all indicate arid conditions with precipitation between 150 and 200 mm.

To determine the cause of differences between the other models and the NMDS/GAM model we began by examining the locations of modern analogue sites for which NMDS/GAM predicted high winter precipitation and MAT predicted low winter precipitation. We found no spatial pattern for this difference, indicating that it is not likely to be an artefact of regional processes such as taxa distributions or the underlying climate gradients. A significant relationship does exist between the residual for the NMDS/GAM winter precipitation predictions and the difference between the model outputs. This relationship indicates that as the difference between model outputs increases the NMDS/GAM residual is also likely to increase ($F_{1,3535} = 2626, p < 0.001, R^2 = 0.42$). This relationship is stronger and accounts for more variance for the PLS ($F_{1,3535} = 3258, p < 0.001, R^2 = 0.48$) and WAPLS ($F_{1,3535} = 3770, p < 0.001, R^2 = 0.52$) methods. These results indicate that for both the Accessa and Tenaghi Philippon reconstructions, sections of the reconstruction where the NMDS/GAM, WAPLS or

PLS models portions of the reconstruction are dissimilar to all other models are likely to have higher residuals.

Climate reconstructions

The pollen records and inferred climate from Lake Accessa and Tenaghi Philippon (Figures 3,4) show two distinct periods of precipitation changes: a period before 7800 cal. BP with strong Mediterranean conditions (wet winters and dry summers), followed by a trend towards aridification from 7800 cal. BP to the present, where seasonality becomes less defined. Short-term events, including the 8.2 kyr event appear in both records (although this event is clearly better depicted at Tenaghi Philippon).

From 9500 to 7800 cal. BP: a 'Holocene optimum' with Mediterranean conditions. Relatively moist conditions, with mild winters and warm, dry summers characterise the Tenaghi Philippon and Lake Accessa areas during the early Holocene (Figures 3,4,5). From 9500 to 7800 cal. BP, the reconstructed climate at Accessa and Tenaghi Philippon meets the Köppen definition of Mediterranean climate (Csa), in which the winter precipitation is three times higher than summer precipitation, the temperature of the warmest month is above 10°C, and the temperature of the coldest month is between -3°C and 18°C (Köppen, 1936). Winter precipitation during this time reached a maximum while summer precipitation reached a minimum (60–80 mm), close to or even below modern values (Figures 3,4,5), resulting in the highest degree of seasonality found within both records. These findings are supported by lake-level records for Lake Accessa (from the same core), based on carbonate concretions produced during the summer. They indicate a lake-level minimum at *c.* 9200–8000 cal. BP (Magny et al., 2007a) reflecting dry conditions, followed by higher lake-levels (Figure 3). Additional fire records from the profundal core show evidence of increased fire activity at 9500, 8700, 7600 and 6200 cal. BP, likely driven by drier (summer?) climatic conditions (Vannièrè et al., 2008, 2011, this issue). The oxygen-isotope composition of shells analysed from Lake Frassino (northern Italy) also provides evidence of dry conditions from 9100 to 7000 yr BP, followed by a rapid increase in moisture at 7000/6800 yr BP that continues to 5000 yr BP (Baroni et al., 2006).

However, lake-level, fire and oxygen-isotope proxies are in contrast to isotopic evidence from a stalagmite situated close to Lake Accessa (Corchia cave, Apuan Alps, Italy) that suggest increased rainfall during the deposition of sapropel S1 (8800–6700 cal. BP in the Adriatic Sea), with maximum rainfall from 8900 to 7300 cal. BP (Zanchetta et al., 2007). Tzedakis (2007) suggests that an enhanced summer rainfall regime in the northern

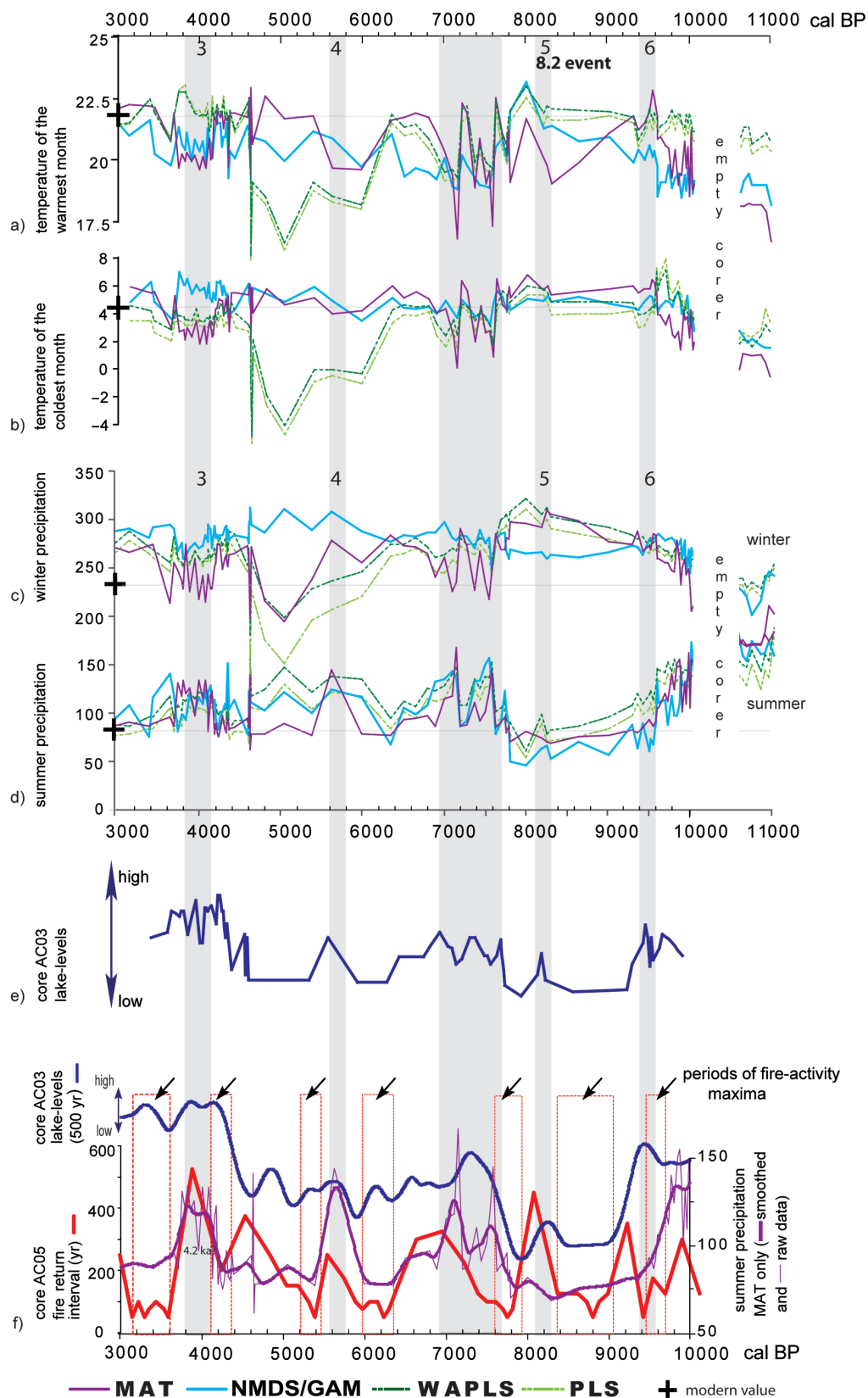


Figure 3. Pollen-based climate reconstructions for Lake Accessa with special attention to reconstructions of temperature and precipitation seasonality. Climate values have been estimated using four methods: the Modern Analogues Technique (MAT), the Non-Metric Multidimensional Scaling/Generalized Additive Model method (NMDS/GAM), Partial Least Squares regression (PLS), and Weighted Average Partial Least Squares regression (WAPSL). Temperatures of the warmest month (a) and coldest month (b) in °C are plotted together with winter (December, January, February) precipitation (c) and summer (June, July, August) precipitation (d) in mm. Modern values are indicated with crosses. Climate estimates are compared with the independent lake-level fluctuation curve (e) from (Magny et al., 2007b), and the Fire Return Interval (f) reconstructed from charcoal analyses (Vanni re et al., 2008). Littoral core AC3/4 is used for the climate reconstructions and the lake-levels changes, and profundal core AC05 is used for Fire Return Interval. In (f), the lake-level changes and MAT estimated summer precipitation are smoothed with a 500 yr window (tendency on a 500 yr running time window). Peaks in the Fire Return Interval curve correspond to the periods of fire-activity minima (period of fire-activity maxima are also plotted). Bond events 3, 4, 5, 6, dated respectively at 4200, 5900, 8100, and 9400 BP (Bond et al., 1997) are also plotted (grey zones)

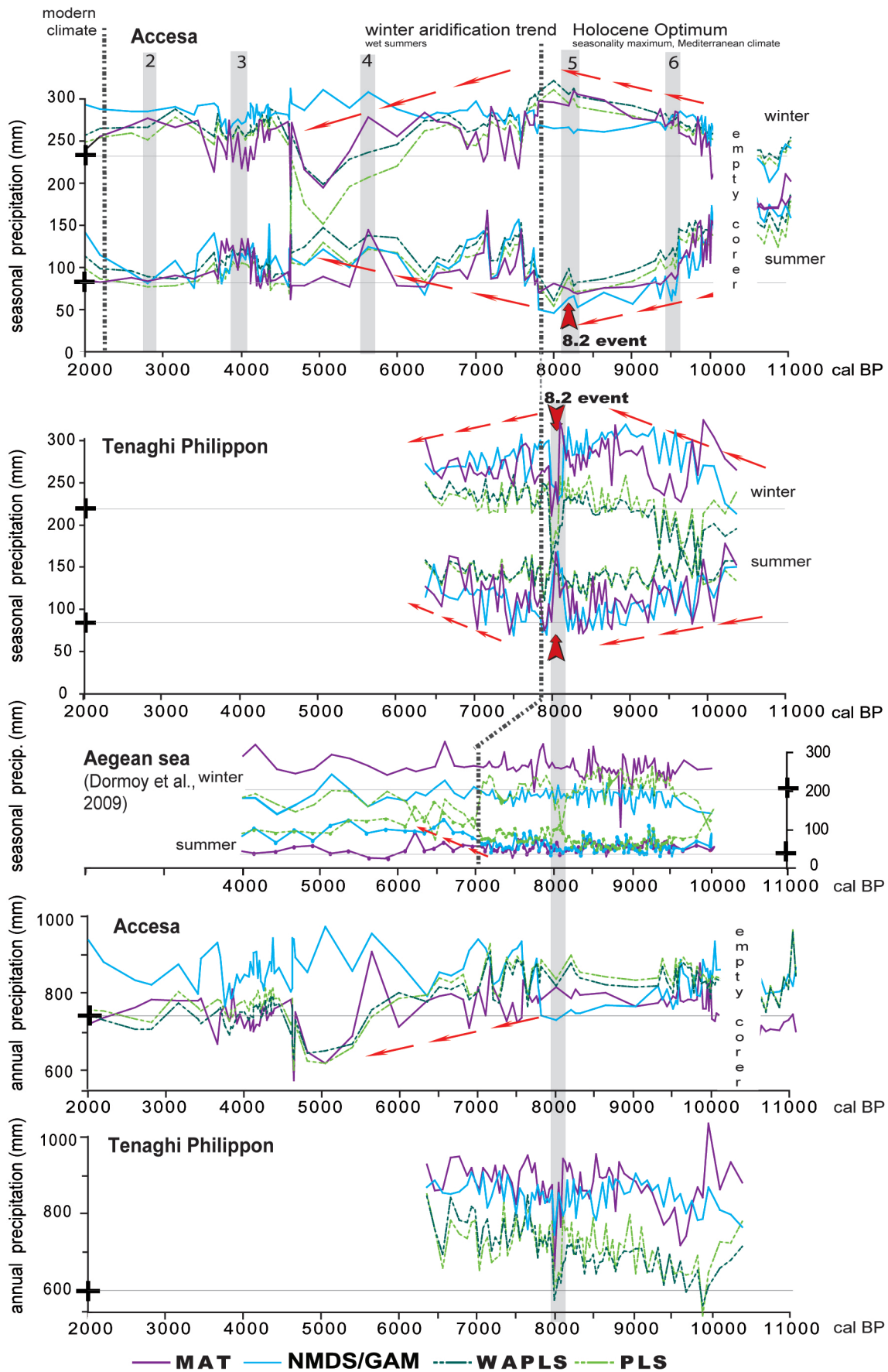


Figure 4. Pollen-based annual precipitation and seasonal precipitation (winter = sum of December, January, February precipitation, and summer = sum of June, July, August precipitation) values for Lake Accesa and Tenaghi Philippon estimated with the four methods as given in Figure 3. Seasonal precipitation values for the marine core SLI52 (Aegean Sea, Dormoy et al., 2009) are also shown for comparison. Bond events 2, 3, 4, 5, 6 are also plotted

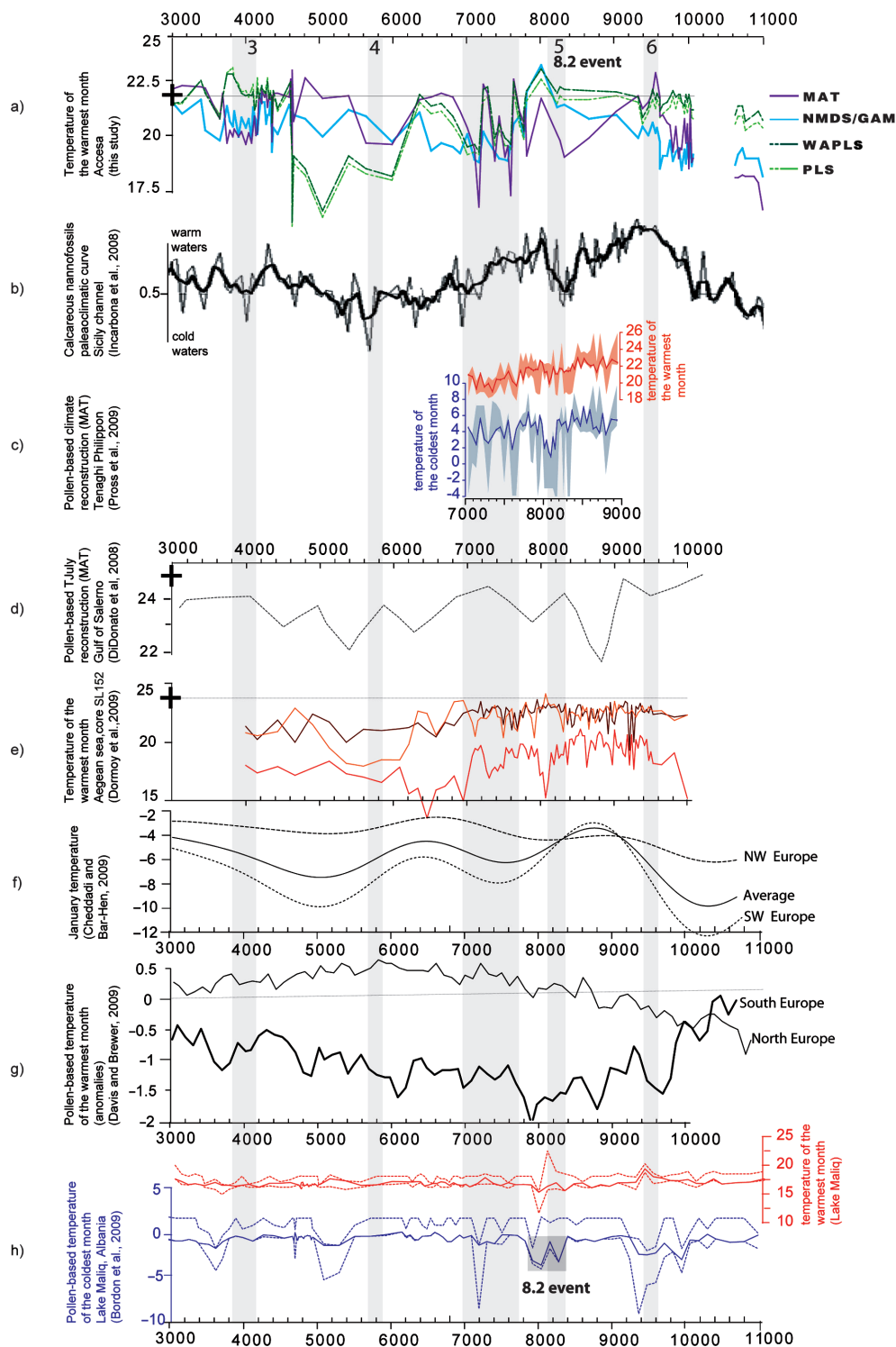


Figure 5. Synthesis figure for selected Mediterranean climate records. (a) Pollen-inferred temperature of the warmest month for Lake Accessa (as for Figure 3). (b) Calcareous nannofossils climatic curve from ODP Site 963 (Sicily Chanel), with a three-point moving average curve, in bold (Incarbona et al., 2008). (c) Pollen-inferred temperature of the coldest and warmest month for Tenaghi Philippon (same core as this study) as published by Pross et al. (2009), MAT only. (d) Pollen-inferred T_{July} for core GNS84-C106 (Gulf of Salerno, Tyrrhenian Sea), MAT only (Di Donato et al., 2008). (e) Pollen-inferred temperature of the warmest month for the marine core SL152, Aegean Sea, (Dormoy et al., 2009) with three methods (orange, MAT; red, PLS; brown, NMDS/GAM). (f) Pollen-inferred January temperature (Cheddadi and Bar-Hen, 2009) using a statistical method based on the probability density function of plant species. The solid line is the T_{Jan} average over the 216 European pollen data used, the short-dashed and the long-dashed lines are the averages of T_{Jan} over those sites with coefficients of the functional principal component greater (SW Europe) and smaller (NW Europe) than zero, respectively. (g) Reconstruction of Holocene temperatures of the warmest month (anomalies) for the European region based on pollen data from over 500 pollen sites from across Europe, MAT only (with a PFT approach; Davis and Brewer, 2009; Davis et al., 2003). The temperatures over Northern Europe show a warming while temperatures over Southern Europe show a mid-Holocene cooling. (h) Pollen-inferred temperature of the coldest and warmest month for Lake Maliq (Albania), MAT only (Bordon et al., 2009)

Mediterranean borderlands, especially between the first 2000–2500 years of sapropel deposition, is not supported by palynological, lake isotopic or lake-level evidence, lending support for increased summer aridity during this period. To reconcile the pollen, lake-level, fire, and isotope data we must invoke precipitation seasonality, where the net increase in precipitation occurs during the autumn and winter months (Magny et al., 2006, 2007a,b; Tzedakis, 2007; Vanni re et al., 2008). Our pollen-based climate reconstructions (Figures 3,4) confirm this hypothesis and explain the apparent discrepancies between proxies by invoking changes in precipitation seasonality: Climate conditions reconstructed at Accessa and Tenaghi Philippon from 9500 to 7800 cal. BP were Mediterranean, with wet winters (and also probably wet autumns and springs) confirming the speleothem signal, and dry summers, agreeing with the lake-level and fire signal. Lake-levels appear to be good indicators of summer precipitation change (Magny, 2007). Fires are linked in Mediterranean area to summer length and intensity of seasonal-drought (Vanni re et al., 2011, this issue). We confirm the assumption that lake levels, pollen, and isotopic data may reflect processes linked to seasonality. We also confirm the necessity of multiproxy approaches to access to climate seasonality which is the base of Mediterranean climate definition.

Regionally, a similar seasonal climate pattern (Figure 5) based on a pollen-based climate reconstruction is found in a marine core from the Aegean Sea during the early Holocene to 7200 cal. BP (Dormoy et al., 2009). Jalut et al. (2009) found evidence of a short-lived climate event resulting in dry summer conditions during the early Holocene, however the duration of the dry summers reconstructed at Accessa and Tenaghi Philippon seems to be longer than this short-lived event which appears to correspond to the 8.2 kyr event (see discussion below). A marked seasonal contrast is also found in isotopic and micropaleontological data from the upper continental Tyrrhenian slope, near the Ombrone River mouth, very close to Lake Accessa (Carboni et al., 2005). These data show a marked seasonality from 9900 to 8300 cal. BP, leading to paleoceanographic conditions characterised by efficient vertical mixing during the winter and a stratified water column with warm surface waters during the summer. The SST trend in Tyrrhenian Sea at the Gulf of Salerno (Figure 5) shows a seasonality comparable with modern values between 9200 and 8200 BP (Di Donato et al., 2008).

Results obtained at Accessa and Tenaghi Philippon bring new insight on the role of seasonality in the debate about Holocene climate history of the Mediterranean region. Most authors assume that climatic conditions were moist during the early Holocene and gradually became drier during the mid to late Holocene (e.g. Ariztegui et al., 2000; Frisia et al., 2006; Jalut et al., 2009; Sadori and Narcisi, 2001; Sadori et al., 2008, 2011, this issue), with the establishment of present-day Mediterranean climate around 5000–4500 cal. BP. However, this notion has been seriously questioned recently (Magny et al., 2007a; Tzedakis, 2007; Vanni re et al., 2011, this issue). Many terrestrial records across the Mediterranean preserve evidence of a ‘climate optimum’ with high rainfall during the early to middle Holocene. This period, well known by palynologists, corresponds to the maximum expansion of deciduous forests and is traditionally interpreted as the period with the highest precipitation during the Holocene. The early Holocene at Accessa and Tenaghi Philippon is characterised by wet/warm winters and dry/warm summers, which supports this hypothesis and also the interpretation of a sapropel period, traditionally considered an ‘optimum’ climatic period.

Jalut et al. (2009) indicate wet conditions in circum-Mediterranean during the early Holocene (11500–7000 cal. BP), and Mediterranean conditions in SE Spain from the beginning of the Holocene in their recent synthesis. This contrast is also found in Sicily. Early-Holocene conditions in coastal Sicily (Gorgo Basso, 6 m a.s.l.) were most likely drier than today until 7000 cal. BP while a site further inland (Pergusa, Sicily, 667 m a.s.l.) experienced wetter conditions (Sadori and Narcisi, 2001; Tinner et al., 2009). In the Near East, palynological, archaeobotanical and lake isotopic evidence suggest summer aridity in the early Holocene until 8000 cal. BP (e.g. van Zeist and Bottema, 1991; Wick et al., 2003). Given these contrasting signals it seems unlikely that moist conditions prevailed everywhere in the Mediterranean prior to 8000–6000 cal. BP, a period corresponding to the weakening of monsoonal activity.

Recent results (de Beaulieu et al., 2005; Reed et al., 2001; Tzedakis, 2007; Vanni re et al., 2008) question the notion of a moist early Holocene in the entire Mediterranean region. Jalut et al. (2009) show that various regional climates prevailed in the circum-Mediterranean during the early Holocene. The western and central Mediterranean experienced abundant precipitation in autumn, spring and winter associated with short dry summer periods (supra-Mediterranean type) while in other zones, irregular summer drought with more or less high precipitation during spring, autumn and winter (sub-Mediterranean type) could have existed. Tzedakis (2007) suggests that a Mediterranean-type seasonal precipitation rhythm may have appeared intermittently during the course of the Tertiary (or indeed before) as a result of the modulating influence of mean climate state (e.g. moisture balance), which could have accentuated the effects of orbital variations, especially during boreal summer insolation maxima. This orbital influence would proceed directly through the effects of insolation in the Mediterranean basin, thus amplifying eastern Mediterranean summer aridity.

The 8.2 kyr event. Shortly after 8200 cal. BP, a short-lived event can be seen in the pollen reconstruction for Tenaghi Philippon, and to a lesser extent at Lake Accessa. This event seems to correspond with the regional expression of the 8.2 kyr event (Alley et al., 1997) in the Mediterranean region (Davis and Stevenson, 2007; Kotthoff et al., 2008a,b; Magny et al., 2003, 2006, 2007a; Pross et al., 2009). At Accessa, this event is weakly expressed while at Tenaghi Philippon, the signal is stronger, reversing the seasonal pattern, with dry winters and wet summers (Figures 3, 4, 5). The pollen record indicates relatively weak vegetation change at Accessa, which seems to agree with the subdued evidence for the 8.2 kyr event from the Corchia speleothems (Zanchetta et al., 2007). At Accessa, this well-dated event (three radiocarbon dates, Magny et al., 2007a) is very weak, but is unambiguously associated with a well-identified lithological change (registered as a temporary return to carbonate lake-marl sedimentation), a short lake-levels rise centred at 8200 yr BP, and a fire-regime decrease (Figure 3).

In contrast to Accessa, the pollen data from Tenaghi Philippon provide evidence for a strong climate-induced vegetation turnover shortly after 8200 yr BP. Most arboreal pollen taxa (*Quercus ilex*) decline strongly, while low-temperature-adapted tree taxa (*Betula*, *Pinus*), steppe elements (*Artemisia*, Chenopodiaceae, *Ephedra*), and Poaceae increase (Figure 2). This pattern implies a strong climatic perturbation, and the near-disappearance of evergreen *Quercus* suggests low winter temperatures. A climate reconstruction using MAT indicates a winter temperature drop of >4°C (Figure 5),

associated with an annual precipitation decrease from ~800 to ~600 mm/yr (Pross et al., 2009). The decrease in annual precipitation seems likely biased towards the colder season since deciduous *Quercus*, which is sensitive to summer drought, was little affected by the change in climate. Our study confirms the results of Pross et al. (2009): the multimethod approach indicates an annual precipitation decrease of 100–150 mm (Figure 4) and a shift in seasonality, resulting from a drop in winter precipitation and a strong increase in summer precipitation (–100 mm and +75 mm, respectively). This change in seasonality is followed by a weakening of the seasonal hydrological contrast (Figure 4).

Few quantitative climate reconstructions of the seasonal hydrological parameters are available from the Mediterranean region for a direct comparison with Accesa and Tenaghi Philippon estimates. Paleoclimate reconstructions (Figure 5) have recently been performed for Lake Maliq (818 m a.s.l., Balkans Peninsula, similar latitude as Tenaghi Philippon) and Aegean Sea pollen sequences (Bordon et al., 2009; Dormoy et al., 2009; Kotthoff et al., 2008b). Available reconstructions for the 8.2 kyr event are generally in good agreement with the seasonal pattern suggested by our results (Figure 5). In the Balkans, the Lake Maliq reconstruction (Figure 5) shows cool and dry conditions at 8300–8100 cal. BP, especially in wintertime, interrupting the relatively stable climate conditions of the Holocene (Bordon et al., 2009). A clear hydrological signal is not produced in the Aegean Sea reconstruction for the 8.2 kyr event (Figure 4) from a multimethod approach (Dormoy et al., 2009), although lower temperature and/or humidity centred at 8.2 kyr are evidenced in the central Aegean Sea (Geraga et al., 2010).

A synthesis of hydrological records in western Europe for the 8.2 kyr event suggests that southern (and northern) Europe was marked by drier climate, whereas latitudes from c. 43° to 50°N experienced wet conditions (Magny et al., 2003). Our results allow us to test whether this hydrological tripartition exists in central Europe; however while the wet summers reconstructed at Accesa confirm the Magny et al. (2003) hypothesis, results based on the Tenaghi Philippon pollen record located further east in the Mediterranean do not reflect a negative summer anomaly below 43°N. A possible explanation might be that the lakes compiled in the Magny et al. (2003) synthesis are all located in the central and western Mediterranean region, not in eastern Mediterranean regions that may have experienced different climate processes and undergo influence of different climatic factors (Lionello et al., 2006; Tzedakis, 2007). Eastern Mediterranean, and especially Greece, experiences a stronger influence of the Siberian High than western Mediterranean. Annual/winter dry conditions reconstructed at Tenaghi Philippon (Figures 4,5) are consistent with a dry event recorded near 8100 cal. BP at the same latitude in central Italy, at Lake Vico (Magri and Parra, 2002; Magri and Sadori, 1999), and with the recent synthesis of Jalut et al. (2009) focusing on Mediterranean pollen data during the Holocene. Jalut et al. (2009) show the existence of a dry episode from 8400 to 7600 cal. BP in the southwestern Mediterranean, at Tigmamine (Morocco, Lamb et al., 1995), Salinas (Jalut et al., 1997, 2000), Siles (south-eastern Spain, Sierra de Segura, Carrion et al., 2001, 2003), and at many other regional sites from 8200 to 7800 cal. BP (Ramrath et al., 2000). However, most of the sites listed above are located further south than Accesa and Tenaghi Philippon, and are not seasonally resolved.

Additional comparisons of seasonality parameters can be made with recent models simulations (Brewer et al., 2009; Wiersma and

Renssen, 2006). Available model-data comparisons for the 8.2 kyr event are generally in good agreement for a number of climate parameters, including annual precipitation as well as winter precipitation. The pollen-based annual and winter precipitation reconstructed for Tenaghi Philippon show trends similar to the ECBilt–CLIO model simulation, a three-dimensional atmosphere–sea-ice–ocean model (Wiersma and Renssen, 2006). Specifically, reconstructed winter precipitation anomalies (–0 to –100 mm, depending on the method) compare favourably in magnitude with the model predictions for Greece (anomalies of ~0 to –100 mm over North Africa, the Middle East, and southern Europe), however, the wet summers suggested by our reconstructions are not reproduced in the ECBilt–CLIO model (Wiersma and Renssen, 2006). The decline in annual precipitation (~100–150 mm) during the 8.2 kyr event compares favourably with the Renssen et al. (2002) model simulations for the Aegean region (50–100 mm/yr).

Pollen-based reconstruction of winter temperatures by Pross et al. (2009) suggests a drop of >4°C (Figure 5), significantly stronger than the model-inferred anomaly for the Aegean region, which does not exceed –1°C (Renssen et al., 2002). This strong cooling is corroborated by the abrupt winter SST minimum evidenced in the Aegean Sea by Marino et al. (2009). Pross et al. (2009) explain the magnitude of the winter temperature decline at Tenaghi Philippon through an amplification of the original signal by topographically induced mesoclimatic conditions that are not resolved in model simulations due to their limited horizontal and altitudinal resolution. The climate changes occurring during the 8.2 kyr event are commonly explained through atmospheric circulation changes induced by freshwater pulses that produced a weakening of the thermohaline circulation in the North Atlantic. The slowdown of the thermohaline circulation resulted in increased sea-ice coverage of the Nordic seas, reducing the penetration of mild, moist Atlantic air masses into Europe. This allowed an expansion of the Eurasian/Siberian High, ultimately resulting in colder, drier winters and springs (Renssen et al., 2002; Vellinga and Wood, 2002). This outcome is in agreement with the Tenaghi Philippon climate reconstruction.

Finally, Prasad et al. (2009) emphasize the role of the seasonality through the 8.2 kyr event. They suggest that at Lake Holzmaar (Germany), the onset of the 8.2 kyr event cooling occurred c. 28 years before the onset of drier winters, and the cooler temperature interval persisted longer than the period of winter dryness. However, only few proxies are readily available for a comparison of the *seasonal* signal as in the Prasad et al. (2009) study. Seasonal precipitation inferred from pollen data is not a ‘direct’ seasonal signal and may be biased by autocorrelation, thus additional speleothem, mollusc and varved sediment records able to resolve seasonal changes are needed to clarify the nature and timing of the Mediterranean precipitation changes during the 8.2 kyr event and the early part of the Holocene. This also points to the crucial need for multiproxy studies to capture the seasonality signal.

Post 7800 cal. BP: an ‘aridification trend’ with high summer precipitation. After the 8.2 kyr event, from c. 7800 to 5000 cal. BP, palynological data from Lake Accesa and Tenaghi Philippon indicate continued wet conditions, at this time however, a drying trend begins that culminates at c. 5000 cal. BP. Winter and annual precipitation during this time are higher than modern values but decline progressively, while summer precipitation increases (Figure 4). These findings match independent lake-level changes and the fire frequency at Lake Accesa (Figure 3). Drying phases

have been reported from Italy at 7900 cal. BP at Lagaccione (Magri, 1999) and at *c.* 7800 cal. BP at Vico (Magri and Sadori, 1999; Sadori et al., 2011, this issue), from 8000 to 7600 cal. BP at Lago di Pergusa in Sicily (Sadori and Narcisi, 2001), from marine pollen cores at 7800 and 7200 cal. BP in the Alboran and Aegean Seas, respectively (Dormoy et al., 2009), and at 8600–7600 yr BP in the southeastern Aegean Sea from pollen, coccolithophores, planktonic foraminifers, and dinoflagellate cysts (Triantaphyllou et al., 2009). In their synthesis of the circum-Mediterranean region, Jalut et al. (2009) suggest a tripartition for the Holocene climate in central Mediterranean; they distinguish a ‘climate transition phase’ from 7000 to 5500 cal. BP, and an aridification process from 5500 cal. BP to the present. Our results confirm these three time-slices, although our findings indicate that the aridification process began earlier, around 7700 cal. BP. This aridification is characterised by a weakening of the seasonal contrast (corresponding to an increase in summer precipitation and a decrease in winter precipitation), culminating around 5000 cal. BP.

From 7700 to 5000 cal. BP, a marked summer cooling is reconstructed at Lake Accesa (Figures 3, 5). Figure 5 shows that this cooling fits remarkably well with the summer cooling trend reconstructed from pollen data in southern Italy, (Gulf of Salerno, Di Donato et al., 2008), and in Aegean Sea (Dormoy et al., 2009; Geraga et al., 2010). It also fits well with the summer cooling trend over southern Europe reconstructed (Figure 5) from pollen data by Davis et al. (2003) and Davis and Brewer (2009), thus confirming previous interpretations of opposing Holocene climate patterns, with summer cooling over southern Europe while northern Europe warmed from 9000 cal. BP. Reconstructions focusing on the mid-Holocene climate (6000 yr BP) for Europe also show that the climatic response varied along a north–south gradient (Cheddadi and Bar-Hen, 2009; Cheddadi et al., 1997; Davis et al., 2003). In the Mediterranean region, winter and summer temperatures were reduced (Figure 5), but in the north, winter warming occurred, due to a strengthening of the high pressure system over the Azores and an advection of warm air masses from the Atlantic Ocean (Masson et al., 1999). Variations in water budget also show a latitudinal trend (Brewer et al., 2009). South Europe experienced wetter conditions at 6000 yr BP (Brewer et al., 2007; Cheddadi et al., 1997). Our results confirm this ‘mid-Holocene’ pattern by showing a drying trend, but with higher precipitation than today, in agreement with reconstructions by Wu et al. (2007) for Italy.

Atmospheric general circulation models (GCMs) and data match well over northern Europe during the mid Holocene, but are at odds in the south, where no GCM simulates a reduction in summer temperatures and wetter conditions (Brewer et al., 2007; Davis and Brewer, 2009). Based on past climate scenarios and sensitivity studies, Brewer et al. (2009) showed significant differences between northern and southern Europe and also between the eastern and western Mediterranean. The models indicated increased summer precipitation in the western Mediterranean, explaining vegetation changes through increased precipitation and a reduction in growing season length, controlled by a reduction in winter temperatures. In the east, the models simulate a more seasonal climate with a summer precipitation decrease coupled to a winter precipitation increase, and cool winters. This simulation agrees well with our seasonal reconstruction, although summer temperatures differ.

Jalut et al. (2000, 2009) suggest that the Mediterranean climate became established through time along a latitudinal gradient. They assume that the Mediterranean conditions prevailing in the western Mediterranean region during the early Holocene

expanded northward at 7600 cal. BP to 39–40°N and reached 41°N before 5700 cal. BP. Their synthesis identified changes in the seasonal pattern of precipitation from 5300 to 4200 cal. BP that indicated an aridification process, coeval to the strong decrease in tree pollen concentration recorded at *c.* 5500 cal. BP at Lake Pergusa in Sicily (Sadori et al., 2011, this issue), as well as a decline in deciduous oak pollen around 5500 cal. BP in Peloponnese and 5600 cal. BP in Turkey.

Our data indicate that from 4600 to 3000 cal. BP, a new climate pattern emerged at Lake Accesa resulting in a trend toward drier and warmer conditions (Figure 3) with wet summers, from 4300 to ~3700 cal. BP (early Bronze Age). Figure 5 suggests that summer temperatures trend fit well with the warming trend reconstructed for the Gulf of Salerno by Di Donato et al. (2008), for the Aegean Sea by Dormoy et al. (2009), and for southern Europe by Davis et al. (2003) and Davis and Brewer (2009).

We also observe a weakening of the seasonal hydrological contrast (Figure 4). There is strong agreement between reconstructed summer precipitation and independent lake levels until *c.* 3800 cal. BP (Magny et al., 2007a, 2009), after which agreement declines with high lake-levels and a pronounced decline in summer precipitation until they reach modern values. From 3700 to ~3400 cal. BP (middle Bronze Age), high proportions of *Quercus ilex* pollen associated with low anthropogenic impact suggest hot, dry climatic conditions consistent with the pollen-inferred dry and warm summer conditions and fire return interval (Figure 3). Dry conditions from 3800 to 3600 cal. BP are supported by the Accesa lake-level record and have been recorded also in Italy at Lake Mezzano (Sadori et al., 2004), Castiglione (Alessio et al., 1986), Monticchio, and in the northern Apennines (Lowe, 1992). Quantitative climate reconstructions of recent periods should nevertheless be taken with caution given the possible disturbance due to anthropogenic activities. Since human activity has influenced natural vegetation in the past, distinguishing between vegetation change induced by man and climatic change in the Mediterranean is a challenge. At Accesa, the cultivation of cereals and pasture activities are evident during the early Bronze Age while the anthropogenic indicators suggest low human impact during the middle and late Bronze Ages (3700 to *c.* 2800 cal BP). Drescher-Schneider et al. (2007) advance the hypothesis that dry climatic conditions explain reduced cereal cultivation; our results confirm this interpretation. Nevertheless, Bronze Age climate reconstructions based on pollen proxies should be taken with caution given the extent of human activity. Although this activity may affect reconstructions there remains strong agreement between the summer precipitation curve and the independently reconstructed lake-level curve. Moreover, many southern Mediterranean pollen records show substantial differences in vegetation development starting around 4400 cal. BP, suggesting a general trend from wetter to drier climatic conditions (e.g. Ariztegui et al., 2000; Carrión et al., 2001; Pantaleon-Cano et al., 2003; Pérez-Obiol and Sadori, 2007; Roberts et al., 2001, 2008; Sadori, 2007; Sadori and Narcisi, 2001). There is no doubt that humans cannot have been solely responsible for these changes since they have occurred synchronously across a wide geographical range (Magny et al., 2009).

The present-day Mediterranean climate, characterised by marked seasonality, seems to begin at Lake Accesa around 2500–2000 cal. BP (Figure 4), in agreement with other sites from around the Mediterranean (Jalut et al., 2000; Terral and Mengual, 1999).

The quantitative reconstruction gives evidence of a marked cool climatic event at *c.* 4300–3800 *c.* BP (Figures 3,4,5), 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). Based on the Lake Accesa lake-level variations, Magny et al. (2009) recognise a tripartite climatic oscillation between *c.* 4300 and 3800 cal. BP with a phase characterised by drier conditions at *c.* 4100–3950 cal. BP bracketed by two phases marked by wetter conditions and dated to *c.* 4300–4100 and 3950–3850 cal. BP, respectively. The Accesa summer precipitation pattern confirms the possible complexity of this climatic oscillation around the 4.2 ka event. The dry episode centred at *c.* 4000–3950 cal. BP may be related to this short-lived dry phase bracketed by two humid phases in the western and 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).

In addition, most of the short-lived climate events depicted in our reconstruction throughout the Holocene are associated with lake-level high-stands at Accesa at *c.* 9500, 8200, 7500, 5800 and 4200 cal. yr BP (Figure 3), possibly regional expressions of Bond events (Bond et al., 1997). This timing appears to be in agreement with patterns established for the North Atlantic and Europe. This suggests that these short-lived cool, wet summer events at Accesa are synchronous to the cooling phases associated with the final steps of the deglaciation (and IRD events) in the North Atlantic area and/or to decreases in solar activity. This observation confirms the presence of strong climatic linkages between the North Atlantic and Mediterranean regions throughout the Holocene (Dormoy et al., 2009).

Conclusions

- The multimethod approach shows that while the reconstructed climate signal is roughly consistent throughout the Holocene, clear differences in model response can be seen at several times throughout the records.
- Throughout the Holocene, there is strong agreement at Lake Accesa between the summer precipitation curves and both lake-level curve (based on carbonate concretions produced during the summer season) and the reconstruction of fire activity (which is relative to climate conditions of the summer season). This confirms that in the central Mediterranean region, lake-level and fire-regime changes probably reflect changes in summer precipitation rather than in winter precipitation.
- Many studies show the Holocene to have a complex pattern of climatic change across the Mediterranean regions. The notion that climatic conditions were cool and moist during the early Holocene, gradually becoming drier during the mid and late Holocene, leading to the establishment of the present-day Mediterranean climate has recently been seriously questioned. The results of our study confirm the traditional evolution of climate in the Mediterranean from wetter (early Holocene) to drier climatic conditions (late Holocene), but highlight the importance of seasonality (such as Mediterranean conditions from 9500 to 7800 cal. BP, i.e. 4000 years before traditional interpretations although this hypothesis needs to be tested by further investigations) in understanding the effects of Holocene climate change on vegetation. The pollen-based climate reconstructions of seasonal precipitation from the Lake Accesa and Tenaghi Philippon records brings new insight on the seasonality

process and explain the apparent discrepancies between pollen, lake-level and oxygen-isotope data by invoking changes in precipitation seasonality.

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