Precipitation changes in the Mediterranean basin during the Holocene from terrestrial and marine pollen records: A model/data comparison

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Abstract

Climate evolution of the Mediterranean region during the Holocene exhibits strong spatial and temporal variability which is notoriously difficult for models to reproduce. We propose here a new paleo-observations synthesis and its comparison – at regional (few ~100km) level – with a regional climate model to examine (i) opposing northern and southern precipitation regimes, and (ii) an east-to-west precipitation dipole during the Holocene across the Mediterranean basin. Using precipitation estimates inferred from marine and terrestrial pollen archives, we focus on the early to mid-Holocene (8000 to 6000 cal yrs BP) and the late Holocene (4000 to 2000 yrs BP), to test these hypotheses on a Mediterranean-wide scale. Special attention was given to the reconstruction of season-specific climate information, notably summer and winter precipitation. The reconstructed climatic trends corroborate the north-south partition of precipitation regimes during the Holocene. During the early Holocene, relatively wet conditions occurred in the south-central and eastern Mediterranean region, while drier conditions prevailed from 45°N northwards. These patterns then reverse during the late Holocene. With regard to the existence of a west-east precipitation dipole during the Holocene, our results show that the strength of this dipole is strongly linked to the seasonal parameter reconstructed; early Holocene summers show a clear east-west division, with summer precipitation having been highest in Greece and the eastern Mediterranean and lowest over the Italy and the western Mediterranean. Summer precipitation in the east remained above modern values, even during the late Holocene interval. In contrast, winter precipitation signals are less spatially coherent during the early Holocene but low precipitation is evidenced during the late Holocene. A general drying trend occurred from the early to the late Holocene, particularly in the central and eastern Mediterranean.

For the same time intervals, pollen-inferred precipitation estimates were compared with model outputs, based on a regional-scale downscaling (HadRM3) of a set of global climate-model simulations (HadAM3). The high-resolution detail achieved through the downscaling is intended to enable a better comparison between ‘site-based’ paleo-reconstructions and gridded model data in the complex terrain of the Mediterranean; the model outputs and pollen-inferred precipitation estimates show some overall correspondence, though modeled changes are small and at the absolute margins of statistical significance. There are suggestions that the eastern Mediterranean experienced wetter than present summer conditions during the early and late Holocene; the drying trend in winter from the early to the late Holocene also appears to be simulated. The use of this high-resolution regional climate model highlights how the inherently

patchy" nature of climate signals and palaeo-records in the Mediterranean basin may lead to local signals much stronger than the large-scale pattern would suggest. Nevertheless, the east to west division in summer precipitation seems more marked in the pollen reconstruction than in the model outputs. The footprint of the anomalies (like today or dry winters, wet summers) has some similarities to modern analogue atmospheric circulation patterns associated with a strong westerly circulation in winter (positive AO/NAO) and a weak westerly circulation in summer associated with anti-cyclonic blocking; although there also remain important differences between the palaeo-simulations and these analogues. The regional climate model, consistent with other global models, does not suggest an extension of the African summer monsoon into the Mediterranean; so the extent to which summer monsoonal precipitation may have existed in the southern and eastern Mediterranean during the mid-Holocene remains an outstanding question.

1 Introduction

The Mediterranean region is particularly sensitive to climate change due to its position within the confluence of arid North African (i.e. subtropically influenced) and temperate/humid European (i.e. mid-latitudinal) climates (Lionello, 2012). Palaeoclimatic proxies, including stable isotopes, lipid biomarkers, palynological data and lake-levels, have shown that the Mediterranean region experienced climatic conditions that varied spatially and temporally throughout the Holocene (e.g. Bar-Matthews and Ayalon, 2011; Luterbacher et al., 2012; Lionello, 2012; Triantaphyllou et al., 2014, 2016; Mauri et al., 2015; De Santis and Caldara 2015; Sadori et al., 2016a; Cheddadi and Khater, 2016) and well before (eg. Sadori et al., 2016b). Clear spatial climate patterns have been identified from east to west and from north to south within the basin (e.g. Zanchetta et al., 2007; Magny et al., 2009b, 2011, 2013; Zhornyak et al., 2011; Sadori et al., 2013; Fletcher et al., 2013). Lake-level reconstructions from Italy thus suggest contrasting patterns of palaeohydrological changes for the central Mediterranean during the Holocene (Magny et al., 2012, 2013). Specifically, lake level maxima occurred south of approximately 40^{o}N in the early to mid-Holocene, while lakes north of 40°N recorded minima. This pattern was reversed at around 4500 cal yrs BP (Magny et al., 2013). Quantitative pollen-based precipitation reconstructions from sites in northern Italy indicate humid winters and dry summers during the early to mid-Holocene, whereas southern Italy was characterised by humid winters and summers; the N-S pattern reverses in the late Holocene, with drier conditions at southern sites and wet conditions at northern sites (Peyron et al., 2011, 2013). These findings support a north–south partition for the central Mediterranean with regards to precipitation, and also confirm that precipitation seasonality is a key parameter in the evolution of Mediterranean climates. The pattern of shifting N-S precipitation regimes has also been identified for the Aegean Sea (Peyron et al., 2013). Taken together, the evidence from pollen data and from other proxies covering the Mediterranean region suggest a climate response that can be linked to a combination of orbital, ice-sheet and solar forcings (Magny et al., 2013).

An east-west pattern of climatic change during the Holocene is also suggested in the Mediterranean region (e.g. Combourieu Nebout et al., 1998; Geraga et al., 2010; Colmenero-Hildago et al., 2002; Kotthoff et al., 2008; Dormoy et al., 2009; Finné et al., 2011; Roberts et al., 2011, 2012; Luterbacher et al., 2012; Guiot and Kaniewski, 2015). An east-west division during the Holocene is observed from marine and terrestrial pollen records (Dormoy et al., 2009; Guiot and Kaniewski, 2015), lake-level reconstructions (Magny et al., 2013) and speleothem isotopes (Roberts et al. 2011).

This study aims to reconstruct and evaluate N-S and E-W precipitations patterns for the Mediterranean basin, over two key periods in the Holocene, the early Holocene 8000-6000 cal yrs BP, corresponding to the “Holocene climate optimum” and the late Holocene 4000-2000 cal yrs BP corresponding to a trend towards drier conditions. Precipitation reconstructions are particularly important for the Mediterranean region given that precipitation rather than temperature represents the dominant controlling factor on the Mediterranean environmental system during the early to mid-Holocene (Renssen et al., 2012). Moreover, the reconstruction of precipitation parameters seems robust for the Mediterranean area (Combourieu-Nebout et al., 2009; Mauri et al., 2015; Peyron et al., 2011, 2013; Magny et al., 2013).

Precipitation is estimated for five pollen records from Greece, Italy and Malta, and for eight marine pollen records along a longitudinal gradient from the Alboran Sea to the Aegean Sea. Because precipitation seasonality is a key parameter of change during the Holocene in the Mediterranean (Rohling et al., 2002; Peyron et al., 2011; Mauri et al., 2015), the quantitative climate estimates focus on reconstructing changes in summer and winter precipitation.

Paleoclimate proxy data are essential benchmarks for model intercomparison and validation (e.g. Morrill et al., 2012; Heiri et al., 2014). This holds particularly true considering that previous model-data intercomparisons have revealed substantial difficulties for GCMs in simulating key aspects of mid-Holocene climate (Hargreaves et al., 2013) for Europe and notably for southern Europe (Davis and Brewer, 2009; Mauri et al., 2014). We also aim to identify and quantify the spatio-temporal climate patterns in the Mediterranean basin for the two key intervals of the Holocene (8000–6000 and 4000–2000 cal yrs BP) based on regional-scale climate model simulations (Brayshaw et al., 2011a). Finally, we compare our pollen-inferred climate patterns with regional-scale climate model simulations in order to critically assess the consistency of the climate reconstructions revealed by these two complimentary routes.

The first originality of our approach is that we estimate the magnitude of precipitation changes and reconstruct climatic trends across the Mediterranean using both terrestrial and marine high-resolution pollen records. The signal reconstructed is then more regional than in the studies based on terrestrial records alone. Moreover, this study aims to reconstruct precipitations patterns for the Mediterranean basin over two key periods in the Holocene while the existing large-scale quantitative paleoclimate reconstructions for the Holocene are often limited to the mid-Holocene - 6000 yrs BP- (Cheddadi et al., 1997; Bartlein et al., 2011; Mauri et al., 2014), except the climate reconstruction for Europe proposed by the study of Mauri et al. (2015).

The second originality of our approach is that we propose a data/model comparison based on (1) two time-slices and not only the mid-Holocene, a standard benchmark time period for this kind of data–model comparison; (2) a high resolution regional model (RCM) which provides a better representation of local/regional processes and helps to better simulate the localized, “patchy”, impacts of Holocene climate change, when compared to coarser global GCMs (e.g. Mauri et al., 2014); (3) changes in seasonality, particularly changes in summer atmospheric circulation which have not been widely investigated (Brayshaw et al., 2011).

2 Sites, pollen records, and models

The Mediterranean region is at the confluence of continental and tropical air masses. Specifically, the central and eastern Mediterranean is influenced by monsoonal systems, while the north-western Mediterranean is under stronger influence from mid-latitude climate regimes (Lionello et al., 2006). Mediterranean winter climates are strongly affected by storm systems originating over the Atlantic. In the western Mediterranean, precipitation is predominantly affected by the North Atlantic Oscillation (NAO), while several systems interact to control precipitation over the northern and eastern Mediterranean (Giorgi and Lionello, 2008). Mediterranean summer climates are dominated by descending high pressure systems that lead to dry/hot conditions, particularly over the southern Mediterranean where climate variability is strongly influenced by African and Asian monsoons (Alpert et al., 2006) with strong geopotential blocking anomalies over central Europe (Giorgi and Lionello, 2008; Trigo et al., 2006).

The palynological component of our study combines results from five terrestrial and eight marine pollen records to provide broad coverage of the Mediterranean basin (Fig. 1, Table 1). The terrestrial sequences comprise pollen records from lakes along a latitudinal gradient from northern Italy (Lakes Ledro and Accesa) to Sicily (Lake Pergusa), one pollen record from Malta (Burmarrad) and one pollen record from Greece (Tenaghi Philippon). The marine pollen sequences are situated along a longitudinal gradient across the Mediterranean Sea; from the Alboran Sea (ODP Site 976 and core MD95-2043), Siculo-Tunisian strait (core MD04-2797), Adriatic Sea (core MD90-917), and Aegean Sea (cores SL152, MNB-3, NS14, HCM2/22). For each record we used the chronologies as reported in the original publications (see Table 1 for references).

Climate reconstructions for summer and winter precipitation (Figs. 2 and 3) inferred from the terrestrial sequences and marine pollen records were performed for two key intervals of the Holocene: 8000–6000 cal yrs BP and 4000–2000 cal yrs BP; the climate values available during each period have been averaged. We use here the Modern Analogue Technique (MAT; Guiot, 1990), a method which compares fossil pollen assemblages to modern pollen assemblages with known climate parameters. The MAT is calibrated using an expanded surface pollen dataset with more than 3600 surface pollen samples from various European ecosystems (Peyron et al., 2013). In this dataset, 2200 samples are from the Mediterranean region, and the results shows that the analogues selected here are limited to the Mediterranean basin. Since the MAT uses the distance structure of the data and essentially performs local fitting of the climate parameter (as the mean of *n*-closest sites), it may be less susceptible to increased noise in the data set, and less likely to report spurious values than others methods (for more details on the method, see Peyron et al., 2011). *Pinus* is overrepresented in marine pollen samples (Heusser and Balsam, 1977; Naughton et al., 2007), and as such *Pinus* pollen was removed from the assemblages (both modern and fossil) for the calibration of marine records using MAT. The reliability of quantitative climate reconstructions from marine pollen records has been tested using marine core-top samples from the Mediterranean in Combourieu-Nebout et al. (2009), which shows an adequate consistency between the present day observed and MAT estimations for annual and summer precipitations values, however the MAT seems to overestimate the winter precipitation reconstructions in comparison with the observed values. More top-cores are needed to validate these results at the scale of the Mediterranean basin, particularly in the eastern part where only one marine top core was available (Combourieu-Nebout et al., 2009).

The climate model simulations used in the model-data comparison are taken from Brayshaw et al. (2010, 2011a, 2011b). The HadAM3 global atmospheric model (resolution 2.5^{o} latitude x 3.75^{o} longitude, 19 vertical levels; Pope et al., 2000) is coupled to a slab ocean (HadSM3, Hewitt et al., 2001) and used to perform a series of time slice experiments. Each time-slice simulation corresponds to 20 model years after spin up (40 model years for pre-industrial). The time slices correspond to “present-day” (1960-1990), 2000 cal BP, 4000 cal BP, 6000 cal BP and 8000 cal BP conditions, and are forced with appropriate insolation (associated with changes in the Earth’s orbit), and atmospheric CO_2 and CH_4 concentrations. The heat fluxes in the ocean are held fixed using values taken from a pre-industrial control run (i.e., the ocean ‘circulation’ is assumed to be invariant over the time-slices) and there is no sea-level change, but sea-surface temperatures are allowed to evolve freely. The coarse global output from the model for each time slice is downscaled over the Mediterranean region using HadRM3 (i.e. a limited area version of the same atmospheric model; resolution 0.44° x 0.44°, with 19 vertical levels). Unlike the global model, HadRM3 is not coupled to an ocean model; instead, sea-surface temperatures are derived directly from the HadSM3 output.

Following Brayshaw et al. (2011a), time slice experiments are grouped into "mid Holocene" (8000 BP and 6000 cal yrs BP) and "late Holocene" (4000 BP and 2000 cal yrs BP) experiments because (1) these two periods are sufficiently distant in the past to be substantially different from the present but close enough that the model boundary conditions are well known; (2) these two periods are rich in high resolution and well-dated palaeoecological sequences, providing a good spatial coverage suitable for large-scale model-data comparison. The combination of the simulations into two experiments (Mid- and Late- Holocene) rather than assessing the two extreme time slices (2000 and 8000 cal yrs BP) is intended to increase the signal-to-noise ratio by doubling the quantity of data in each experiment. This is necessary and possible as the change in forcing between adjacent time-slices is relatively small, making it difficult to detect differences between each individual simulations. To aid comparison with proxies, changes in climate are expressed as differences with respect to the present day (roughly 1960-1990) rather than the pre-industrial control run: therefore the climate anomalies shown thus include a component which is attributable to anthropogenic increases in greenhouse gases in the industrial period, as well as longer term 'natural' changes (e.g., orbital forcing). We suggest it may be better to use 'present day' to be in closer agreement with the pollen data (modern samples) which use the late 20th century long-term averages (1961-1990). However, there are some quite substantial differences between model runs under 'present day' and 'preindustrial' forcings (Figure 4). Statistical significance is assessed with the Wilcoxon-Mann-Whitney significance test (Wilks, 1995).

The details of the climate model simulations are discussed at length in Brayshaw et al (2010, 2011a, 2011b). These includes a detailed discussion of verification under present climate, the model's physical/dynamical climate responses to Holocene period 'forcings', and comparison to other palaeoclimate modelling approaches (e.g., PMIP projects) and palaeo-climate syntheses. The GCM used (HadAM3 with a slab ocean) is comparable to the climate models in PMIP2, but a key advantages of the present dataset is: (a) the inclusion of multiple time-slices across the Holocene period; and (b) the additional high-resolution regional climate model downscaling enables the impact of local climatic effects within larger-scale patterns of change to be distinguished (e.g., the impact of complex topography or coastlines; Brayshaw et al

2011a), potentially allowing clearer comparisons between site-based proxy-data and model output.

3 Results and Discussion

A North-South precipitation pattern?

Pollen evidence shows contrasting patterns of palaeohydrological changes in the central Mediterranean. The early- to mid-Holocene was characterized by precipitation maxima south of around 40°N while at the same time, northern Italy experienced precipitation minima; this pattern reverses after 4500 cal yrs BP (Magny et al., 2012b; Peyron et al., 2013). Other proxies suggest contrasting north-south hydrological patterns not only in central Mediterranean but also across the Mediterranean (Magny et al., 2013), suggesting a more regional climate signal. We focus here on two time periods (early to mid-Holocene and late Holocene), in order to test this hypothesis across the Mediterranean, and to compare the results with regional climate simulations for the same time periods.

Early to mid-Holocene (8000 to 6000 cal yrs BP)

Climatic patterns reconstructed from both marine and terrestrial pollen records seem to corroborate the hypothesis of a north-south division in precipitation regimes during the Holocene (Fig 2a). Our results confirm that northern Italy was characterized by drier conditions (relative to modern) while the south-central Mediterranean experienced more annual, winter and summer precipitation during the early to mid-Holocene (Fig. 2a). Only Burmarrad (Malta) shows drier conditions in the early to mid-Holocene (Fig 2a), although summer precipitation reconstructions are marginally higher than modern at the site. Wetter summer conditions in the Aegean Sea suggest a regional, wetter, climate signal over the central and eastern Mediterranean. Winter precipitation in the Aegean Sea is less spatially coherent than summer signal, with dry conditions in the North Aegean Sea and or near-modern conditions in the Southern Aegean Sea (Figs. 2a and 3).

Non-pollen proxies, including marine and terrestrial biomarkers (terrestrial n-alkanes), indicate humid mid-Holocene conditions in the Aegean Sea (Triantaphyllou et al., 2014, 2016). Results within the Aegean support the pollen-based reconstructions, but non-pollen proxy data are still lacking at the basin scale in the Mediterranean, limiting our ability to undertake independent evaluation of precipitation reconstructions.

Very few large-scale climate reconstruction of precipitation exist for the whole Holocene (Guiot and Kaniewski, 2015; Tarroso et al., 2016) and, even at local scales, pollen-inferred reconstructions of seasonal precipitation are very rare (e.g. Peyron et al., 2011, 2013; Combourieu-Nebout et al., 2013; Nourelbait et al., 2016). Several « large-scale » studies focused on the 6000 cal years BP period (Cheddadi et al., 1997 ; Wu et al., 2007 ; Bartlein et al., 2011; Mauri et al., 2014). Wu et al. (2007) reconstruct regional seasonal and annual precipitation and suggest that precipitation did not differ significantly from modern conditions across the Mediterranean; however, scaling issues render it difficult to compare their results with the reconstructions presented here. Cheddadi et al. (1997) reconstruct wetter-than-modern conditions at 6000 yrs cal BP in southern Europe; however, their study uses only one record from Italy and measures the moisture availability index, which is not directly comparable to precipitation *sensu stricto*, since it integrates temperature and precipitation. At 6000 yrs cal BP, Bartlein et al. (2011) reconstruct Mediterranean precipitation at values between 100 and 500 mm higher than modern. Mauri et al. (2015), in an updated version of Davis et al. (2003), provide a quantitative climate reconstructions comparable to the seasonal precipitation reconstructions presented here. Compared to Davis et al. (2003), which focused on reconstruction of temperatures, Mauri et al. (2015) reconstructed seasonal precipitation for Europe and analyse their evolution throughout the Holocene. Mauri et al. (2015) results differ from the current study in using MAT with plant functional type scores and in producing gridded climate maps. Mauri et al. (2015) show wet summers in southern Europe (Greece and Italy) with a precipitation maximum between 8000 and 6000 cal yrs BP, where precipitation was ~20 mm/month higher than modern. As in our reconstruction, precipitation changes in the winter were small and not significantly different from present-day conditions. Our reconstructions are in agreement with Mauri et al. (2015), with similar to present day summer conditions above 45°N during the early Holocene and wetter than today summer conditions over much of the south-central Mediterranean south of 45°N, while winter conditions appear to be similar to modern values. Mauri et al. (2015) results inferred from terrestrial pollen records and the climatic trends reconstructed here from marine and terrestrial pollen records seem to corroborate the hypothesis of a north-south division in precipitation regimes during the early to mid-Holocene in central Mediterranean. However, more high-resolution above 45°N are still needed to validate this hypothesis.

Late Holocene (4000 to 2000 cal yrs BP)

Late Holocene reconstructions of winter and summer precipitation indicate that the pattern established during the early Holocene was reversed by 4000 cal yrs BP, with similar to present day or lower than present day precipitation in southern Italy, Malta and Siculo-Tunisian strait (Figs. 2b and 3). Annual precipitation reconstructions suggest drying relative to the early Holocene, with modern conditions in northern Italy, and modern conditions or drier than modern conditions in central and southern Italy during most of the late Holocene. Reconstructions for the Aegean Sea still indicate higher than modern summer and annual precipitation (Fig. 2b). Winter conditions reverse the early to mid-Holocene trend, with modern conditions in the northern Aegean Sea and wetter than modern conditions in the southern Aegean Sea (Fig. 3). Our reconstructions from all sites show a good fit with Mauri et al. (2015), except for the Alboran Sea where we reconstruct relatively high annual precipitations, whereas Mauri et al. (2015) reconstruct dry conditions, but here too, more sites are needed to confirm or refute this pattern in Spain. Our reconstruction of summer precipitation for the eastern Mediterranean is very similar to Mauri et al. (2015) where wet conditions are reported for Greece and the Aegean Sea.

An East-West precipitation pattern?

A precipitation gradient, or an east-west division during the Holocene has been suggested for the Mediterranean from pollen data and lakes isotopes (e.g. Dormoy et al., 2009; Roberts et al., 2011; Guiot and Kaniewski, 2015). However, lake-levels and other hydrological proxies around the Mediterranean Basin do not clearly support this hypothesis and rather show contrasting hydrological patterns south and north of 40°N particularly during the Holocene climatic optimum (Magny et al., 2013).

Early to mid-Holocene (8000 to 6000 cal yrs BP)

The pollen-inferred annual precipitation indicates unambiguously wetter than today conditions south of 42°N in the western, central and eastern Mediterranean, except for Malta (Fig. 3). A prominent feature of the summer precipitation signal is an east-west dipole with increasing precipitation in the eastern Mediterranean (as for annual precipitation). In contrast, winter conditions show less spatial coherence, although the western basin, Sicily and the Siculo-Tunisian strait appear to have experienced higher precipitation than modern, while drier conditions exist in the east and in north Italy (Fig. 2a).

Our reconstruction shows a good match to Guiot and Kaniewski (2015) who have also discussed a possible east-to-west division in the Mediterranean with regard to precipitation (summer and annual) during the Holocene. They report wet centennial-scale spells in the eastern Mediterranean during the early Holocene (until 6000 years BP), with dry spells in the western

Mediterranean. Mid-Holocene reconstructions show continued wet conditions, with drying through the late Holocene (Guiot and Kaniewski, 2015). This pattern indicates a see-saw effect over the last 10,000 years, particularly during dry episodes in the Near and Middle East. Similar to in our findings, Mauri et al. (2015) also reconstruct high annual precipitation values over much of the southern Mediterranean, and a weak winter precipitation signal. Mauri et al. (2015) confirm an east-west dipole for summer precipitation, with conditions drier or close to present in south-western Europe and wetter in the central and eastern Mediterranean (Fig 2b). These studies corroborate the hypothesis of an east-to-west division in precipitation during the early to mid-Holocene in the Mediterranean as proposed by Roberts et al. (2011). Roberts et al. (2011) suggest the eastern Mediterranean (mainly Turkey and more eastern regions) experienced higher winter precipitation during the early Holocene, followed by an oscillatory decline after 6000 yrs BP. Our findings reveal wetter annual and summer conditions in the eastern Mediterranean, although the winter precipitation signal is less clear. However, the highest precipitation values reported by Roberts et al. (2011) were from sites located in western-central Turkey; these sites are absent in the current study. Climate variability in the eastern Mediterranean during the last 6000 years is also documented in a number of studies based on multiple proxies (Finné et al., 2011). Most palaeoclimate proxies indicate wet mid-Holocene conditions (Bar-Matthews et al., 2003; Stevens et al., 2006; Eastwood et al., 2007; Kuhnt et al., 2008; Verheyden et al., 2008) which agree well with our results; however most of these proxies are not seasonally resolved.

Roberts et al. (2011) and Guiot and Kaniewski (2015) suggest that changes in precipitation in the western Mediterranean were smaller in magnitude during the early Holocene, while the largest increases occurred during the mid-Holocene, around 6000-3000 cal BP, before declining to modern values. Speleothems from southern Iberia suggest a humid early Holocene (9000-7300 cal BP) in southern Iberia, with equitable rainfall throughout the year (Walczak et al., 2015) whereas our reconstructions for the Alboran Sea clearly show an amplified precipitation seasonality (with higher annual/winter and similar to modern summer rainfall) for the Alboran sites. It is likely that seasonal patterns defining the Mediterranean climate must have been even stronger in the early Holocene to support the wider development of sclerophyll forests than present in south Spain (Fletcher et al., 2013).

Late Holocene (4000 to 2000 cal yrs BP)

Annual precipitation reconstructions suggest drier or near-modern conditions in central Italy, Adriatic Sea, Siculo-Tunisian strait and Malta (Figs. 2b and 3). In contrast, the Alboran and

Aegean Seas remain wetter. Winter and summer precipitation produce opposing patterns; a clear east-west division still exists for summer precipitation, with a maximum in the eastern and a minimum over the western and central Mediterranean (Fig. 2b). Winter precipitation shows the opposite trend, with a minimum in the central Mediterranean (Sicily, Siculo-Tunisian strait and Malta) and eastern Mediterranean, and a maximum in the western Mediterranean (Figs. 2b and 3). Our results are also in agreement with lakes and speleothem isotope records over the Mediterranean for the late Holocene (Roberts et al., 2011), and the Finné et al. (2011) palaeoclimate synthesis for the eastern Mediterranean. There is a good overall correspondence between trends and patterns in our reconstruction and that of Mauri et al. (2015), except for the Alboran Sea. High-resolution speleothem data from southern Iberia show Mediterranean climate conditions in southern Iberia between 4800 and 3000 cal BP (Walczak et al., 2015) which is in agreement with our reconstruction. The Mediterranean climate conditions reconstructed here for the Alboran Sea during the late Holocene is consistent with a climate reconstruction available from the Middle Atlas (Morocco), which show a trend over the last 6000 years towards arid conditions as well as higher precipitation seasonality between 4000 and 2000 cal yrs BP (Nourelbait et al., 2016). There is also good evidence from many records to support late Holocene aridification in southern Iberia. Paleoclimatic studies document a progressive aridification trend since ~7000 cal yr BP (e.g. Carrion et al., 2010; Jimenez-Moreno et al., 2015; Ramos-Roman et al., 2016), although a reconstruction of the annual precipitation inferred from pollen data with the Probability Density Function method indicate stable and dry conditions in the south of the Iberian Peninsula between 9000 and 3000 cal BP (Tarroso et al., 2016).

The current study shows that a prominent feature of late Holocene climate is the east-west division in summer precipitation: summers were overall dry or near-modern in the central and western Mediterranean and clearly wetter in the eastern Mediterranean. In contrast, winters were drier or near-modern in the central and eastern Mediterranean (Fig. 3) while they were wetter only in the Alboran Sea.

Data-model comparison

Figure 3 shows the data-model comparisons for the early to mid-Holocene (a) and late Holocene (b) compared to the Present day control run (in anomalies, with statistical significance hatched. Encouragingly, there is a good overall correspondence between patterns and trends in pollen-inferred precipitation and model outputs. Caution is required when interpreting climate model results, however, as many of the changes depicted in Fig. 3 are very small and of marginal statistical significance, suggesting a high degree of uncertainty around their robustness.

For the early to mid-Holocene, both model and data indicate wet annual and summer conditions in Greece and in the eastern Mediterranean, and drier than today conditions in north Italy. There are indications of an east to west division in summer precipitation simulated by the climate model (e.g., between the ocean to the south of Italy and over Greece/Turkey), although the changes are extremely small (not significant with a p-value<0.30). Furthermore, in the Aegean Sea, the model shows a good match with pollen-based reconstructions, suggesting that the increased spatial resolution of the regional climate model may help to simulate the localized, “patchy”, impacts of Holocene climate change, when compared to coarser global GCMs (Fig. 3). In Italy, the model shows a good match with pollen-based reconstructions with regards to the contrasting north-south precipitation regimes, but there is little agreement between model output and climate reconstruction with regard to winter and annual precipitation in southern Italy. The climate model suggests wetter winter and annual conditions in the far western Mediterranean (i.e. France, western Iberia and the NW coast of Africa) – similar to pollen-based reconstructions – and near-modern summer conditions during summers (except in France and northern Africa). A prominent feature of winter precipitation simulated by the model and partly supported by the pollen estimates is the reduced early Holocene precipitation everywhere in the Mediterranean basin except in the south east.

Model and pollen-based reconstructions for the late Holocene indicate declining winter precipitation in the eastern Mediterranean and southern Italy (Sicily and Malta) relative to the early Holocene. In contrast, late Holocene summer precipitation is higher than today in Greece and in the eastern Mediterranean and near-modern in the central and western Mediterranean, and relatively lower than today in south Spain and north Africa. The east-west division in summer precipitation is strongest during the late Holocene in the proxy data and there are suggestions that it appears to be consistently simulated in the climate model; the signal is reasonably clear in the eastern Mediterranean (Greece and Turkey) but non-significant in central and western Mediterranean (Fig. 3).

Our findings can be compared with previous data-model comparisons based on the same set of climate model experiments; although here we take our reference period as ‘present-day’ (1960-1990) rather than preindustrial and thus include an additional ‘signal’ from recent anthropogenic greenhouse gas emissions. Previous comparisons nevertheless suggested that the winter precipitation signal was strongest in the northeastern Mediterranean (near Turkey) during the early Holocene and that there was a drying trend in the Mediterranean from the early Holocene to the late Holocene, particularly in the east (Brayshaw et al., 2011a; Roberts et al., 2011). This is coupled with a gradually weakening seasonal cycle of surface air temperatures towards the present.

It is clear that most global climate models (PMIP2, PMIP3) simulate only very small changes in summer precipitation in the Mediterranean during the Holocene (Braconnot et al., 2007a,b, 2012; Mauri et al., 2014). The lack of a summer precipitation signal is consistent with the failure of the northeastern extension of the West African monsoon to reach the southeastern Mediterranean, even in the early to-mid-Holocene (Brayshaw et al., 2011a). The regional climate model simulates a small change in precipitation compared to the proxy results, and it can be robustly identified as statistically significant. This is to some extent unsurprising, insofar as the regional climate simulations presented here are themselves "driven" by data derived from a coarse global model (which, like its PMIP2/3 peers, does not simulate an extension of the African monsoon into the Mediterranean during this time period). Therefore, questions remain about summer precipitation in the eastern Mediterranean during the Holocene. The underlying climate dynamics therefore need to be better understood in order to confidently reconcile proxy data (which suggest increased summer precipitation during the early Holocene in the Eastern Mediterranean) with climate model results (Mauri et al., 2014). Based on the high-resolution coupled climate model EC-Earth, Bosmans et al. (2015) show how the seasonality of Mediterranean precipitation should vary from minimum to maximum precession, indicating a reduction in precipitation seasonality, due to changes in storm tracks and local cyclogenesis (i.e. no direct monsoon required). Such high-resolution climate modeling studies (both global and regional) may prove a key ingredient in simulating the relevant atmospheric processes (both local and remote) and providing fine-grain spatial detail necessary to compare results to palaeo-proxy observations.

Another explanation proposed by Mauri et al. (2014) is linked to the changes in atmospheric circulation. Our reconstructed climate characterized by dry winters and wet summers shows a spatial pattern that is somewhat consistent with modern day variability in atmospheric circulation rather than simple direct radiative forcing by insolation. In particular, the gross NW-SE dipole of reconstructed winter precipitation anomalies is perhaps similar to that associated with a modern-day positive AO/NAO. The west coast of Spain is, however, also wetter in our early Holocene simulations which would seem to somewhat confound this simple picture of a shift to an NAO+ like state compared to present. In summer, an anti-cyclonic blocking close to Scandinavia may have caused a more meridional circulation, which brought dry conditions to northern Europe, but relatively cooler and somewhat wetter conditions to many parts of southern Europe. It is of note that some climate models which have been used for studying palaeoclimate have difficulty reproducing this aspect of modern climate (Mauri et al., 2014). Future work based on transient Holocene model simulations are important, nevertheless, transient-model simulations have also shown mid-Holocene data-model discrepancies (Fischer and Jungclaus, 2011; Renssen et al., 2012). It is, however, suggested that further work is required to fully understand changes in winter and summer circulation patterns over the Mediterranean (Bosmans et al., 2015).

Data limitations

Classic ecological works for the Mediterranean (e.g. Ozenda 1975) highlight how precipitation limits vegetation type in plains and lowland areas, but temperature gradients take primary importance in mountain systems. Also, temperature and precipitation changes are not independent, but interact through bioclimatic moisture availability and growing season length (Prentice et al., 1996). This may be one reason why certain sites may diverge from model outputs; the Alboran sites, for example, integrate pollen from the coastal plains through to mountain (+1500m) elevations. At high elevations within the source area, temperature effects become be more important than precipitation in determining the forest cover type. Therefore, it is not possible to fully isolate precipitation signals from temperature changes. Particularly for the semiarid areas of the Mediterranean, the reconstruction approach probably cannot distinguish between a reduction in precipitation and an increase in temperature and PET, or vice versa.

Along similar lines, while the concept of reconstructing winter and summer precipitation separately is very attractive, it may be worth commenting on some limitations. Although different levels of the severity or length of summer drought are an important ecological limitation for vegetation, reconstructing absolute summer precipitation can be difficult because the severity/length of bioclimatic drought is determined by both temperature and precipitation. We are dealing with a season that has, by definition, small amounts of precipitation that drop below the requirements for vegetation growth. Elevation is also of concern, as lowland systems tend to be recharged by winter rainfall, but high mountain systems may receive a significant part of precipitation as snowfall, which is not directly available to plant life. This may be important in the long run for improving the interpretation of long-term Holocene changes and contrasts between different proxies, such as lake-levels and speleothems. Although these issues may initially appear to be of marginal importance, they may nevertheless have a real influence leading to problems and mismatches between different proxies (e.g. Davis et al., 2003; Mauri et al., 2015).

Another important point is the question of human impact on the Mediterranean vegetation during the Holocene. Since human activity has influenced natural vegetation, distinguishing between vegetation change induced by humans and climatic change in the Mediterranean is a challenge requiring independent proxies and approaches. Therefore links and processes behind societal change and climate change in the Mediterranean region are increasingly being investigated (e.g. Holmgren et al., 2016; Gogou et al, 2016; Sadori et al., 2016a). Here, the behavior of the reconstructed climatic variables between 4000 and 2000 cal yrs BP is likely to be influenced by non-natural ecosystem changes due to human activities such as the forest degradation that began in lowlands, progressing to mountainous areas (Carrión et al., 2010). These human impacts add confounding effects for fossil pollen records and may lead to slightly biased temperature reconstructions during the late Holocene, likely biased towards warmer temperatures and lower precipitation. However, if human activities become more marked at 3000 cal yrs BP, they increase significantly over the last millennia (Sadori et al., 2016) which is not within the time scale studied here. Moreover there is strong agreement between summer precipitation and independently reconstructed lake-level curves (Magny et al., 2013). For the marine pollen cores, human influence is much more difficult to interpret given that the source area is so large, and that, in general, anthropic taxa are not found in marine pollen assemblages.

Conclusions

The Mediterranean is particularly sensitive to climate change but the extent of future change relative to changes during the Holocene remains uncertain. Here, we present a reconstruction of Holocene precipitation in the Mediterranean using an approach based on both terrestrial and marine pollen records, along with a model-data comparison based on a high resolution regional model. We investigate climatic trends across the Mediterranean during the Holocene to test the hypothesis of an alternating north-south precipitation regime, and/or an east-west precipitation dipole. We give particular emphasis to the reconstruction of seasonal precipitation considering the important role it plays in this system.

Climatic trends reconstructed in this study seem to corroborate the north-south division of precipitation regimes during the Holocene, with wet conditions in the south-central and eastern Mediterranean, and dry conditions above 45°N during the early Holocene, while the opposite pattern dominates during the late Holocene. This study also shows that a prominent feature of Holocene climate in the Mediterranean is the east-to-west division in precipitation, strongly linked to the seasonal parameter reconstructed. During the early Holocene, we observe an east-to-west division with high summer precipitation in Greece and the eastern Mediterranean and a minimum over the Italy and the western Mediterranean. There was a drying trend in the Mediterranean from the early Holocene to the late Holocene, particularly in central and eastern regions but summers in the east remained wetter than today. In contrast, the signal for winter precipitation is less spatially consistent during the early Holocene, but it clearly shows similar to present day or drier conditions everywhere in the Mediterranean except in the western basin during the late Holocene.

The regional climate model outputs show a remarkable qualitative agreement with our pollen-based reconstructions, although it must be emphasised that the changes simulated are typically very small or of questionable statistical significance. Nevertheless, there are indications that the east to west division in summer precipitation reconstructed from the pollen records do appear to be simulated by the climate model. The model results also suggest that parts of the eastern Mediterranean experienced similar to present day or drier conditions in winter during the early and late Holocene and wetter conditions in annual and summer during the early and late Holocene (both consistent with the paleo-records).

Although this study has used regional climate model data, it must always be recalled that the regional model's high-resolution output is strongly constrained by a coarser-resolution global climate model, and the ability of global models to correctly reproduce large-scale patterns of change in the Mediterranean over the Holocene remains unclear (e.g. Mauri et al 2015). The generally positive comparison between model and data presented here may therefore simply be fortuitous and not necessarily replicated if the output from other global climate model simulations was downscaled in a similar way. However, it is noted that the use of higher-resolution regional climate models can offer significant advantages for data-model comparison insofar as they assist in resolving the inherently "patchy" nature of climate signals and palaeo-records. Notwithstanding the difficulties of correctly modeling large-scale climate change over the Holocene (with GCMs), we believe that regional downscaling may still be valuable in facilitating model-data comparison in regions/locations known to be strongly influenced by local effects (e.g., complex topography).

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Figure captions

Figure 1: Locations of terrestrial and marine pollen records along a longitudinal gradient from west to east and along a latitudinal gradient from northern Italy to Malta. Ombrothermic diagrams are shown for each site, calculated with the NewLoclim software program and database, which provides estimates of average climatic conditions at locations for which no observations are available (ex.: marine pollen cores).

Figure 2: Pollen-inferred climate estimates as performed with the Modern Analogues Technique (MAT): annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation). Changes in climate are expressed as differences with respect to the modern values (anomalies, mm/day). The modern values are derived from the ombrothermic diagrams (cf Fig. 1). Two key intervals of the Holocene corresponding to the two time slice experiments (Fig. 3) have been chosen: 8000–6000 cal yrs BP (a) and 4000–2000 (b) cal yrs BP. The climate values available during these periods have been averaged (stars).

Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in anomaly compared to present-day (mm/day). Simulations are based on a regional model (Brayshaw et al., 2010): standard model HadAM3 coupled to HadSM3 (dynamical model) and HadRM3 (high-resolution regional model. The hatching representing statistical significance refers to the anomalies shown on the same plot – i.e., the difference between the experiment (either 8000–6000 or 4000–2000) and the Present day control run. The hatched areas indicate areas where the changes are not significant (significance level of 0.30). Pollen-inferred climate estimates (stars) are the same as in Fig. 2: annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation).

Figure 4: Model simulation showing Present day minus Preindustrial precipitation anomalies (hatching at 70%/statistical significance over the insignificant regions)

Table 1: Metadata for the terrestrial and marine pollen records evaluated.

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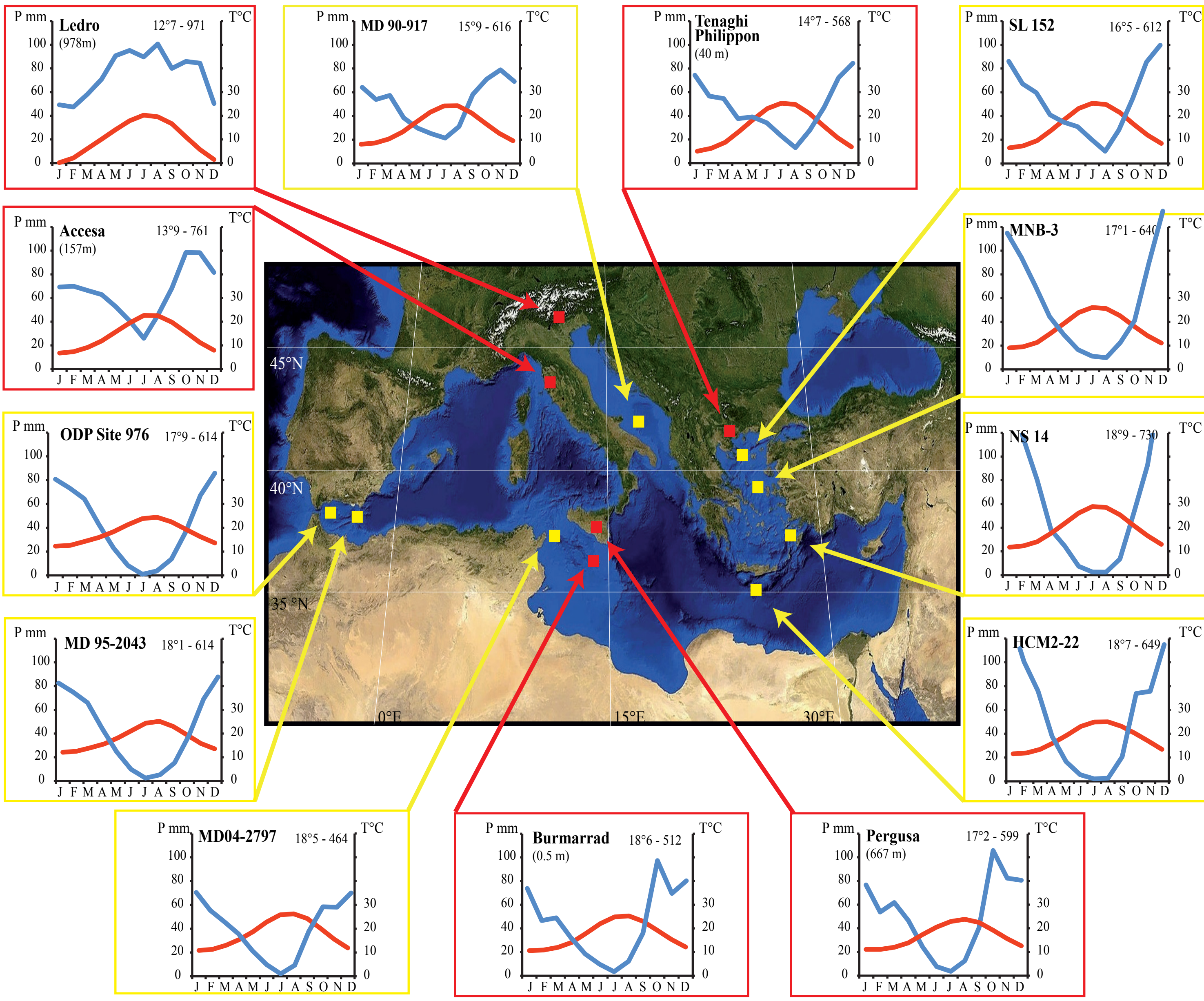


Figure 1: Locations of terrestrial (red) and marine (yellow) pollen records along a longitudinal gradient from west to east and along a latitudinal gradient from northern Italy to Malta.
Ombrothermic diagrams are shown for each site, calculated with the NewLoclim software program and database, which provides estimates of average climatic conditions at locations for which no observations are available (ex.: marine pollen cores).

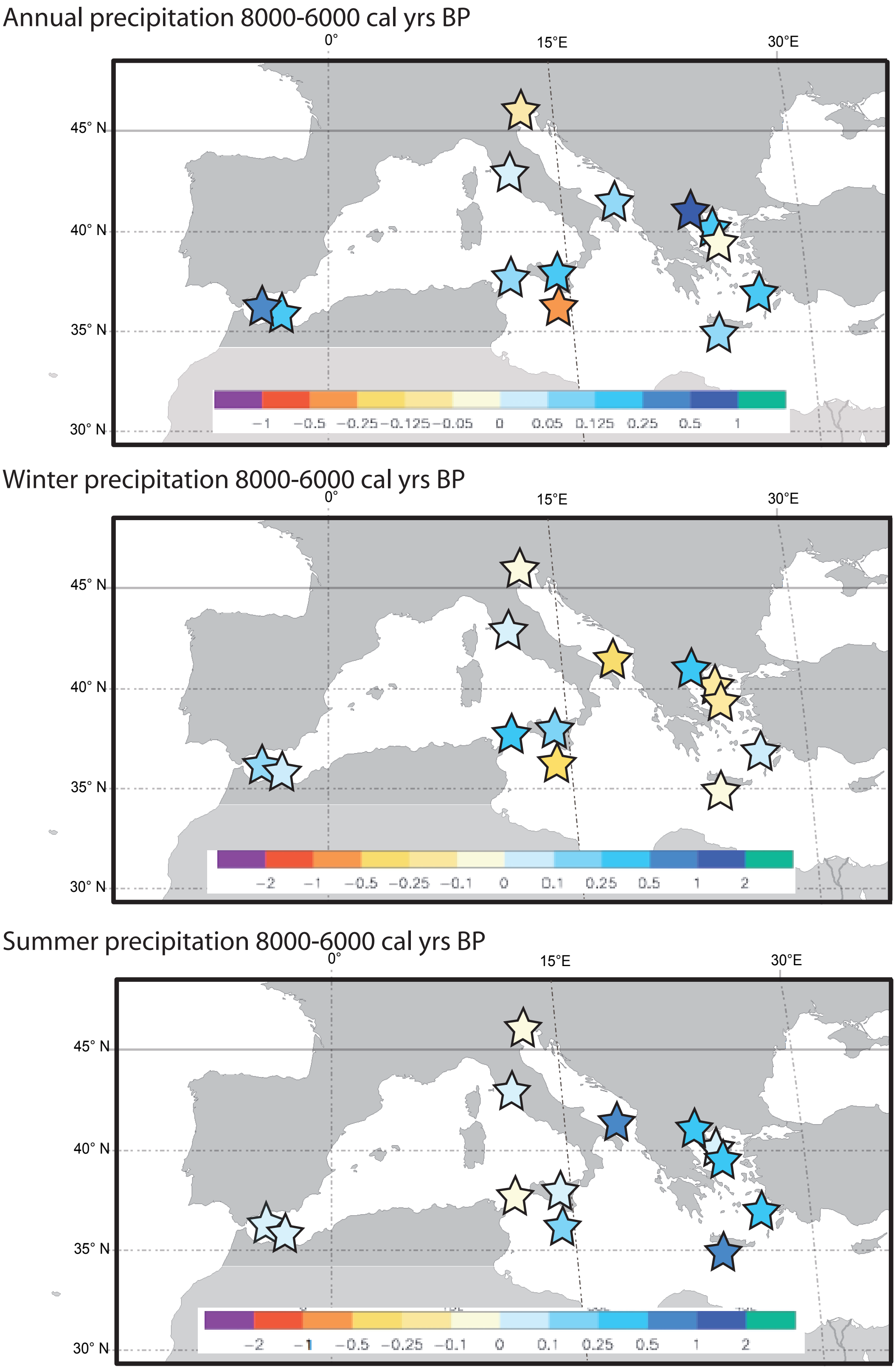
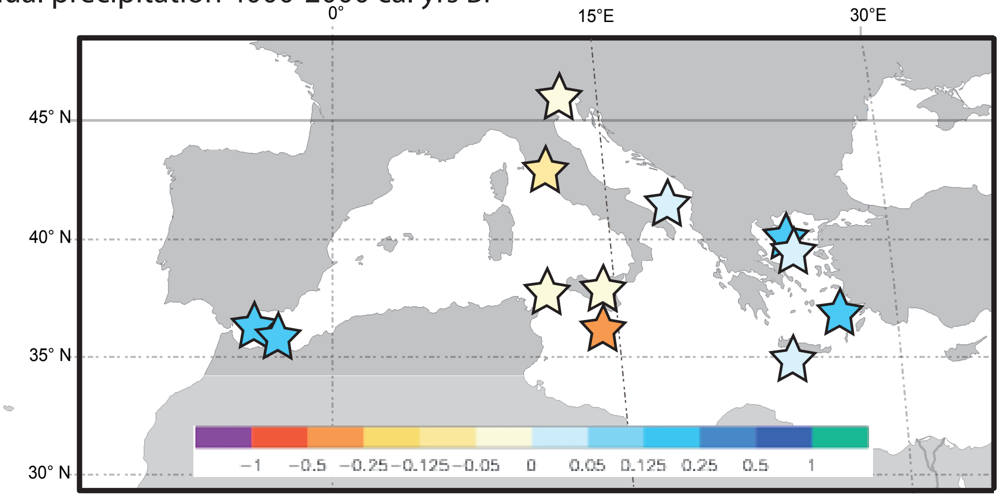


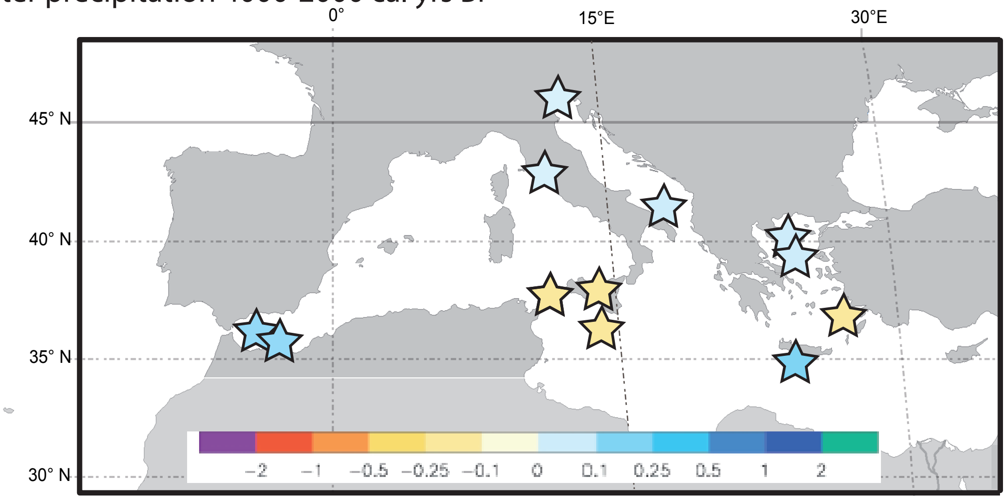
Figure 2a: 8000-6000 cal years BP

Pollen-inferred climate estimates as performed with the Modern Analogues Technique: annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation). Changes in climate are expressed as differences with respect to the modern values (anomalies, mm/day), which are derived from the ombrothermic diagrams (cf Fig. 1). Climate values reconstructed during the time slice 8000-6000 cal yrs BP have been averaged (stars).

Annual precipitation 4000-2000 cal yrs BP



Winter precipitation 4000-2000 cal yrs BP



Summer precipitation 4000-2000 cal yrs BP

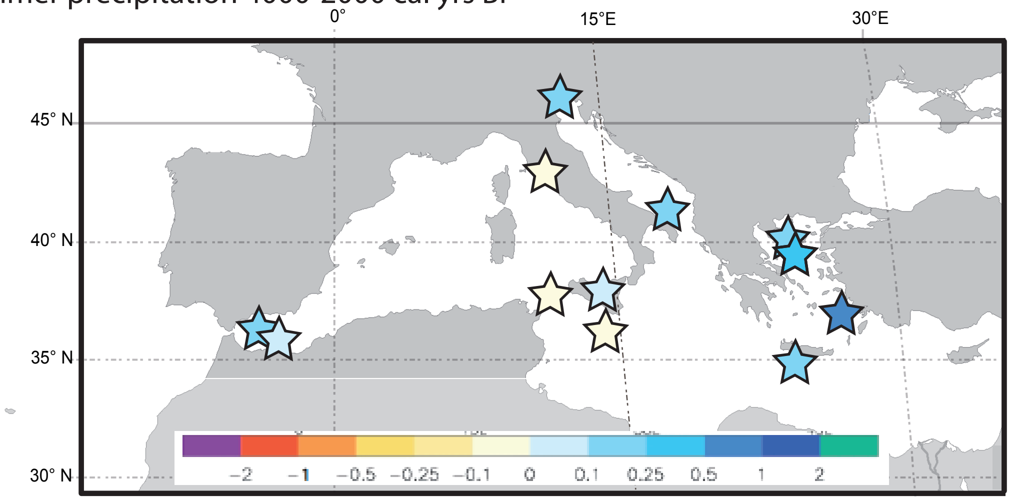


Figure 2b: 4000-2000 cal yrs BP

Pollen-inferred climate estimates as performed with the Modern Analogues Technique: annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation). Changes in climate are expressed as differences with respect to the modern values (anomalies, mm/day), which are derived from the ombrothermic diagrams (cf Fig. 1). Climate values reconstructed during the time slice 4000-2000 cal yrs BP have been averaged (stars).

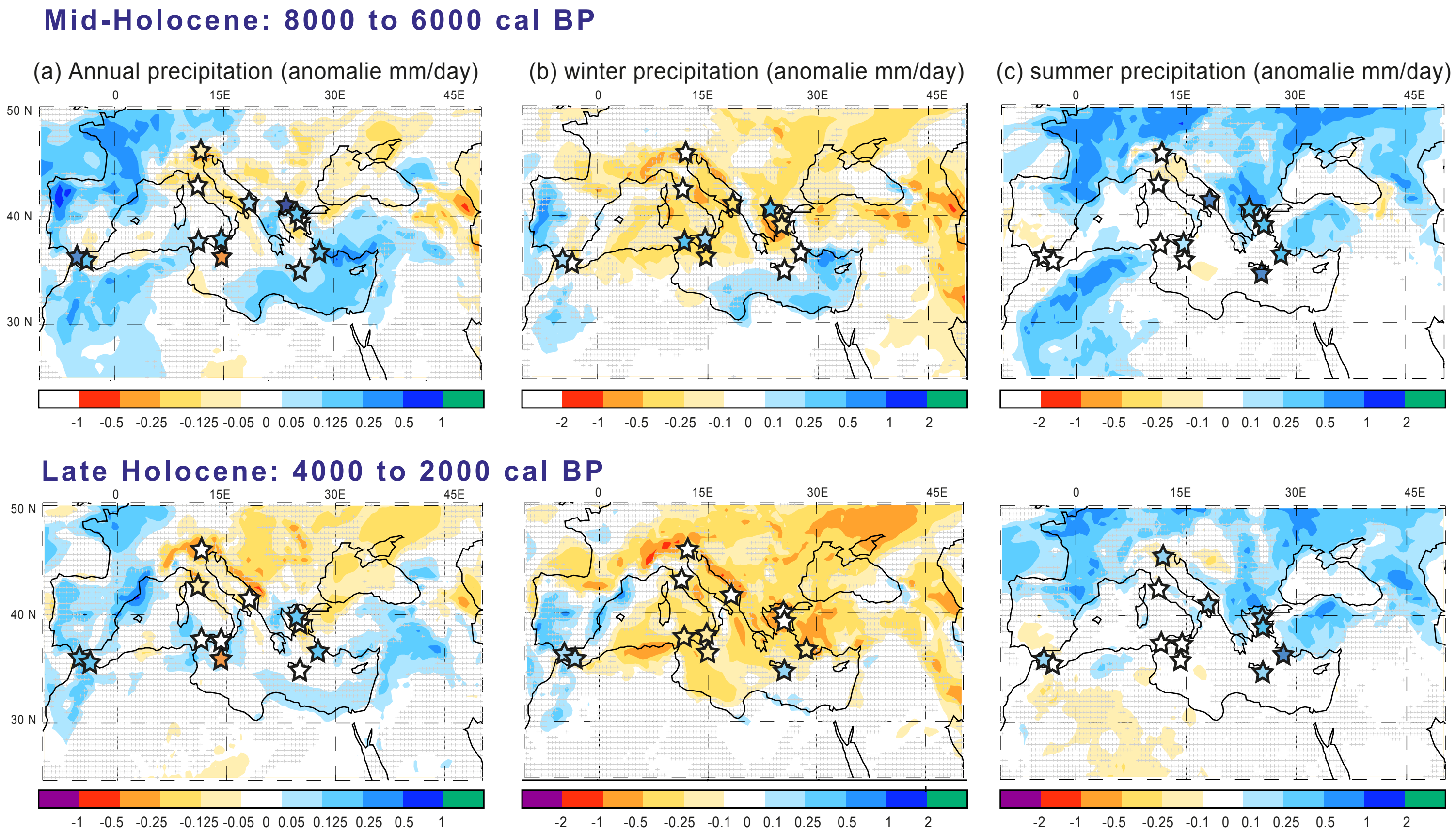


Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in anomaly compared to present-day (mm/day)

Simulations are based on a regional model (Brayshaw et al., 2010): standard model HadAM3 coupled to HadSM3 (dynamical model) and HadRM3 (high-resolution regional model. The hatching representing statistical significance refers to the anomalies shown on the same plot – i.e., the difference between the experiment (either 8000–6000 or 4000–2000) and the Present day control run. The hatched areas indicate areas where the changes are not significant (significance level of 0.30). Pollen-inferred climate estimates (stars) are the same as in Fig. 2: annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation).

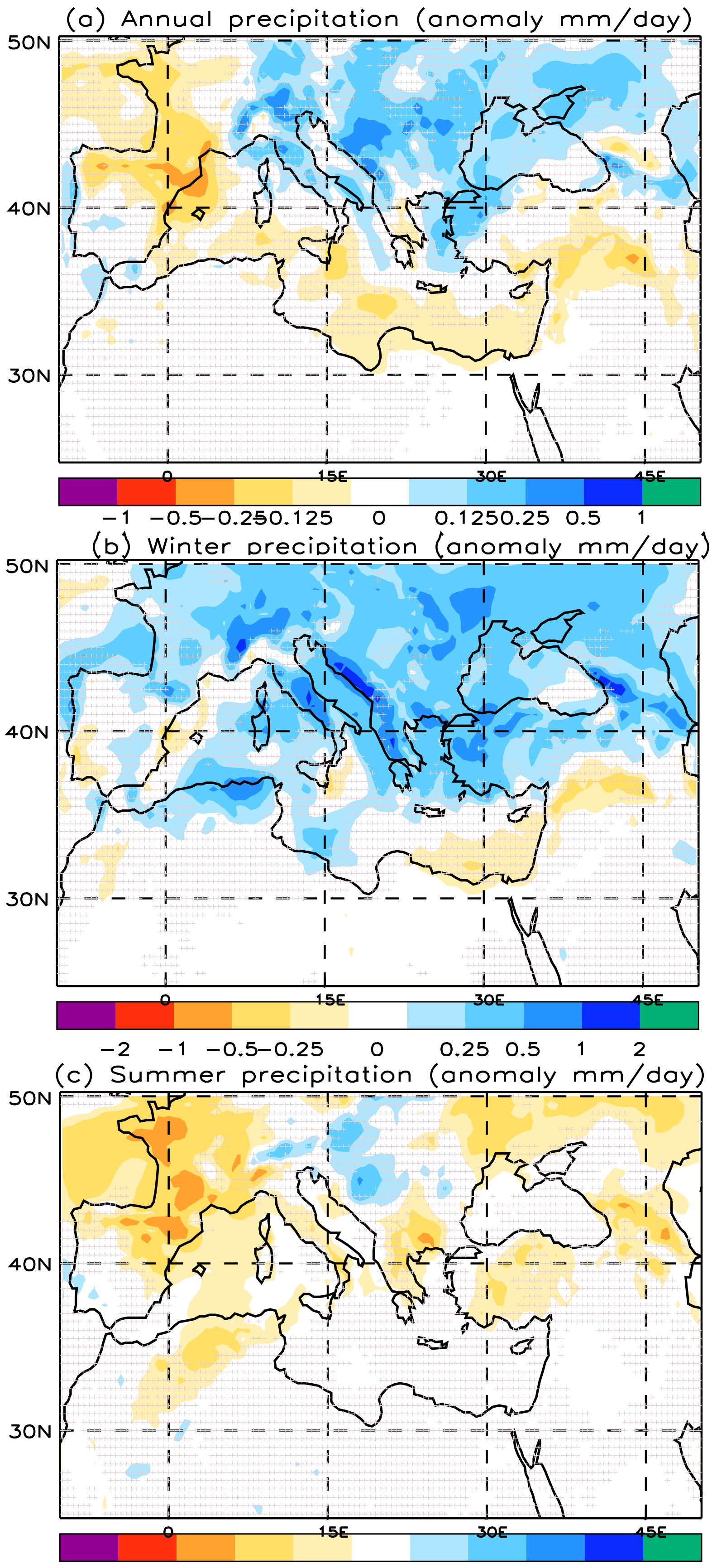


Figure 4: Model simulation showing Present day minus Preindustrial precipitation anomalies
(hatching at 70%/statistical significance over the insignificant regions)

Terrestrial pollen records					
	Longit.	**Latitude**	**Elev. (m a.s.l)**	**Temporal resolution**	**References (non- exhaustive)**
Ledro (North Italy)	10°76'E	45°87'N	652	8000-6000: 71 4000-2000: 60 10966-10: 66	Joannin et al. (2013), Magny et al. (2009, 2012a), Vannière et al. (2013), Peyron et al. (2013)
Accesa (Central Italy)	10°53'E	42°59'N	157	8000-6000: 90 4000-2000 : 133 11029-100: 97	Drescher-Schneider et al. (2007), Magny et al. (2007, 2013), Colombaroli et al. (2008), Sadori et al. (2011), Vannière et al. (2011), Peyron et al. (2011, 2013)
Trifoglietti (Southern Italy)	16°01'E	39°33'N	1048	8000-6000: 95 4000-2000: 86 9967-14: 73	Joannin et al. (2012), Peyron et al. (2013)
Pergusa (Sicily)	14°18'E	37°31'N	667	8000-6000: 166 4000-2000: 90 12749-53: 154	Sadori and Narcisi (2001); Sadori et al. (2008, 2011, 2013, 2016b); Magny et al. (2011, 2013)
Tenaghi Philippon (Greece)	24°13.4' E	40°58.4'N	40	8000-6000: 64 4000-2000: no 10369-6371:53	Pross et al. (2009, 2015), Peyron et al. (2011), Schemmel et al., (2016)
Burmarrad (Malta)	14°25'E	35°56'N	0.5	8000-6000: 400 4000-2000: 285 6904-1730: 110	Djamali et al. (2013), Gambin et al., (2016)

Marine pollen records					
	Longit.	**Latitude**	**Water-depth**	**Temporal resolution**	**References**
ODP 976 (Alboran Sea)	4°18'W	36°12' N	1108	8000-6000: 142 4000-2000: 181 10903-132: 129	Combourieu-Nebout et al. (1999, 2002, 2009) ; Dormoy et al., (2009)
MD95-2043 (Alboran Sea)	2°37'W	36°9'N	1841	8000-6000: 111 4000-2000: 142 10952-1279: 106	Fletcher and Sánchez Goñi (2008); Fletcher et al., (2010)
MD90-917 (Adriatic Sea)	17°37'E	41°97'N	845	8000-6000: 90 4000-2000: 333 10495-2641: 122	Combourieu-Nebout et al. (2013)
MD04-2797 (Siculo-Tunisian strait)	11°40'E	36°57'N	771	8000-6000: 111 4000-2000: 666 10985-2215: 127	Desprat et al. (2013)
SL152 (North Aegean Sea)	24°36' E	40°19' N	978	8000-6000: 60 4000-2000: 95 9999-0: 76	Kotthoff et al. (2008, 2011), Dormoy et al. (2009).
NS14 (South Aegean Sea)	27°02'E	36°38'N	505	8000-6000: 80 4000-2000: 333 9988-2570: 107	Kouli et al. (2012) ; Gogou et al. (2007); Triantaphyllou et al. (2009a, b)
HCM2/22 (South Crete)	24°53'E	34°34 N	2211	8000-6000: 181 4000-2000: 333 8091-2390: 247	Ioakim et.al. (2009) ; Kouli et al, (2012) ; Triantaphyllou et al. (2014)

MNB-3 (North Aegean Sea)	25°00’E	39°15’N	800	8000-6000: 153 4000-2000: 166 8209-2273: 138	Geraga et al. (2010) ; Kouli et al., (2012) ; Triantaphyllou et al, (2014)

Table 1: Metadata for the terrestrial and marine pollen records evaluated. The temporal resolution is calculated for the two periods (8000-6000 and 4000-2000) and for the entire record.