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The climate of 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. The spatial differentiation and temporal variability, as evident from different climate proxy datasets, has remained notoriously difficult for models to reproduce. In light of this complexity, we examine the previously described evidence for (i) opposing northern and southern precipitation regimes during the Holocene across the Mediterranean basin, and (ii) an east-to-west precipitation gradient or dipole during the early Holocene, from a wet eastern Mediterranean to dry western Mediterranean. Using quantitative climate information from marine and terrestrial pollen archives, we focus on two key time intervals, the early to mid-Holocene (8000 to 6000 cal yrs BP) and the late Holocene (4000 to 2000 yrs BP), in order to test the above mentioned hypotheses on a Mediterranean-wide scale. Palynologically derived climate information is compared with the output of regional-scale climate-model simulations for the same time intervals.

Quantitative pollen-based precipitation estimates were generated along a longitudinal gradient from the Alboran (West) to the Aegean Sea (East); they are derived from terrestrial pollen records from Greece, Italy and Malta as well as from pollen records obtained from marine cores. Because seasonality represents a key parameter in Mediterranean climates, special attention was given to the reconstruction of season-specific climate information, notably summer and winter precipitation. The reconstructed climatic trends corroborate a previously described 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 reversed during the late Holocene, with a wetter northern Mediterranean region and drier conditions in the east and south. More sites from the northern part of the Mediterranean basin are needed to further substantiate these observations. With regard to the existence of a west-east precipitation dipole during the Holocene, our pollen-based climate data show that the strength of this dipole is strongly linked to the seasonal parameter reconstructed: Early Holocene summers show a clear east-to-west gradient, with summer precipitation having been highest in the central and eastern Mediterranean and lowest over the western Mediterranean. In contrast, winter precipitation signals are less spatially coherent. A general drying trend occurred from the early to the late Holocene; particularly in the central and eastern Mediterranean. However, summer precipitation in the east remained above modern values, even during the late Holocene interval.

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Pollen-inferred precipitation estimates were compared to regional-scale climate modelling simulations based on the HadAM3 GCM coupled to the dynamic HadSM3 and the high-resolution regional HadRM3 models. Climate model outputs and pollen-inferred precipitation estimates show remarkably good overall correspondence, although many simulated patterns are of marginal statistical significance. Nevertheless, models weakly support an east to west division in summer precipitation and there are suggestions that the eastern Mediterranean experienced wetter summer and winter conditions during the early Holocene and wetter summer conditions during the late Holocene. The extent to which summer monsoonal precipitation may have existed in the southern and eastern Mediterranean during the mid-Holocene remains an outstanding question; our model, consistent with other global models, does not suggest an extension of the African monsoon into the Mediterranean. Given the difficulty in modelling future climate change in Southern Europe, more simulations based on high resolution global models and very high resolution regional downscaling, perhaps even including transient simulations, are required to fully understand the patterns of change in winter and summer circulation patterns over the Mediterranean region.

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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) 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 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.

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. 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 (Peyron et al., 2013). 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 observed 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; Finne et al., 2011; Roberts et al., 2011, 2012; Luterbacher et al., 2012; Guiot and Kaniewski, 2015). A gradient of precipitation or an east-west division during the Holocene is suggested by marine pollen records (Dormoy et al., 2009), lake-level reconstructions (Magny et al., 2013) and speleothem isotopes

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(Roberts et al. 2011); the east-west pattern of change has also been corroborated through a Bayesian inverse modelling approach (Guiot and Kaniewski, 2015)

This study aims to reconstruct and evaluate N-S and W-E climate gradients for the Mediterranean basin, over two key periods in the Holocene, 8000-6000 cal yrs BP, and 4000-2000 cal yrs BP. We estimate the magnitude of precipitation changes and reconstruct climatic trends across the Mediterranean using both terrestrial and marine high-resolution pollen records. Precipitation is estimated using the Modern Analogue Technique (Guiot 1990) 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 Holocene climate (Hargreaves et al., 2013) for Europe (Mauri et al., 2014), and notably for Southern Europe (Davis and Brewer, 2009; Mauri et al., 2015). We aim to identify and quantify the spatio-temporal climate patterns in the Mediterranean Basin for two key intervals of the Holocene (8000–6000 and 4000–2000 cal yrs BP) based on terrestrial and marine high-resolution pollen records. Spatially, we focus on transects across the Mediterranean basin from north to south and from west to east. Because precipitation seasonality is a key parameter of Holocene climate change in the Mediterranean (Rohling et al., 2002; Peyron et al., 2011, Mauri et al., 2015), our quantitative climate estimates focus on summer and winter precipitation. Finally, we compare our pollen-inferred climate patterns with regional-scale climate model simulations (Brayshaw et al., 2011a) in order to critically assess the potential of the model set-up used to reproduce Holocene climate variability.

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 mostly dominated 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 (Figure 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, 3) inferred from the terrestrial sequences and marine pollen records were performed using the Modern Analogue Technique (MAT; Guiot, 1990). The MAT 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 use the distance structure of the data and essentially perform local fitting of the climate parameter (as the mean of *n*-closest sites) they 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 for the calibration of marine records using MAT.

Climate model simulations focused on regional-scale climate modelling simulations based on the HadAM3 GCM and the high-resolution regional HadRM3 models. Climate simulations are

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described fully in Brayshaw et al. (2010, 2011a, b). The HadAM3 global atmospheric model (resolution 2.5° latitude x 3.75° longitude, 19 vertical levels; Pope et al., 2000) is coupled to a slab ocean (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 "preindustrial", 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 (and there is no sea-level change) using values taken from a pre-industrial control run, 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.

To aid interpretability (and to increase the signal-to-noise ratio), time slice experiments are grouped into "late Holocene" (4000 BP and 2000 cal yrs BP) and "mid Holocene" (8000 BP and 6000 cal yrs BP) experiments. Changes in climate are expressed as differences with respect to the preindustrial control run and statistical significance is assessed with the Wilcoxon-Mann-Whitney significance test (Wilks, 1995).

3 Results and Discussion

A North-South precipitation pattern?

Proxy evidence shows contrasting patterns of palaeohydrological changes in the central Mediterranean. The early-to-mid-Holocene was characterized by lake-level and precipitation maxima south of around 40°N. At the same time, northern Italy experienced precipitation and lake-levels 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 across the Mediterranean (Magny et al., 2013). We focus on two key time periods, the early to mid-Holocene (8000-6000 cal yrs BP), and the late Holocene (4000-2000 cal yrs BP) 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 trends 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, with dry conditions in the North Aegean Sea and wet or near-modern conditions in the Southern Aegean Sea (Fig. 2a).

Precipitation reconstructions are particularly important for this region given that precipitation rather than temperature represents the dominant controlling factor on Mediterranean environmental system during the early to mid-Holocene (Renssen et al., 2012). Pollen and 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 (Bartlein et al., 2011; Mauri et al., 2014; Guiot and Kaniewski, 2015, Tarroso et al., 2016) and, even at local scales, pollen-inferred reconstructions of seasonal precipitation are very rare (Wu et al., 2007; Peyron et al., 2011, 2013; Combourieu-Nebout et al., 2013, Nourelbait et al., 2016). Several studies focused on the 6000 cal years BP period: 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

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reconstructions presented here. Compared to Davis et al. (2003), which focused on Holocene pollen-based temperature reconstructions for Europe, Mauri et al. (2015) have a broader set of sites and present reconstructed seasonal and annual precipitation. Mauri et al. (2015) results differ from the current study in using MAT with plant functional type scores and in producing gridded climate maps (Fig. 2b). Mauri et al. (2015) show wetter summers in Southern Europe (Greece and Italy) with a precipitation maximum between 8000 and 6000 cal yrs BP (Fig 2b), 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 (Fig 2b). Our reconstructions are in good agreement with Mauri et al. (2015), with summer (and annual) precipitation lower than modern over the northern Mediterranean region and wetter summer conditions over much of the south-central Mediterranean, 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 seems to corroborate the hypothesis of a north-south division in precipitation regimes during the Early to Mid-Holocene in central Mediterranean.

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 higher precipitation in northern Italy and lower precipitation in southern Italy and Malta (Fig. 2a). Annual precipitation reconstructions suggest drying relative to the early Holocene, with modern conditions in northern Italy, and drier than modern conditions in central and southern Italy during most of the Late Holocene. Reconstructions for the Aegean Sea indicate higher summer and annual precipitation (Fig. 2b). Winter conditions reverse the early to mid-Holocene trend, with wetter conditions in the northern Aegean Sea and drier conditions in the southern Aegean Sea (Fig. 2b). Our reconstructions from all sites show a good fit with Mauri et al. (2015), except for the Alboran Sea where we reconstruct relatively wet conditions, whereas Mauri et al. (2015) reconstruct dry conditions (Fig. 2b). Our reconstruction of summer precipitation is very similar to Mauri et al. (2015) for Greece and the Aegean Sea where wet conditions are reported (Fig. 2b).

An East-West precipitation pattern?

An East to West precipitation gradient, or an East-West division during the Holocene has been suggested for the Mediterranean from pollen data and lakes isotopes (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 annual precipitation and seasonal precipitation signals appear to conflict in the early Holocene (Fig. 2a). The pollen-inferred annual precipitation indicates unambiguously wetter than today conditions south of 45°N in the western, central and eastern Mediterranean, except for Malta (Fig. 2a). Winter conditions show less spatial coherence, although the western basin appears to have experienced higher precipitation than modern, while drier conditions exist in the east (Fig. 2a). A prominent feature of the summer precipitation signal is an East to West signature of increasing summer precipitation.

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. As 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 gradient 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 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 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 suggests a humid early Holocene (9000-7300 cal BP) in southern Iberia, with equitable rainfall throughout the year (Walczak et al., 2015). Our reconstructions for the Alboran Sea which clearly shows an amplified precipitation seasonality (with higher annual/winter and lower than present 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 and Malta (Fig. 2b). In contrast, the Alboran and Aegean seas remain wetter. Winter and summer precipitation produce opposing patterns: a clear east-west division 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 maximum in the western Mediterranean and a minimum in the central and eastern Mediterranean (Fig. 2b). 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 (Fig. 2b). 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

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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 precipitation, which varies based on the seasonal parameter reconstructed: summers were overall dry or near-modern in the central and western Mediterranean and wetter in the eastern Mediterranean, while winters were wet in the western Mediterranean and drier in the central and eastern Mediterranean.

Data-model comparison

Figure 3 shows the data-model comparisons for the early to mid-Holocene (a) and late Holocene (b) compared to present values (in anomalies). 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 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, winter and summer conditions in the Eastern Mediterranean. There are indications of an east to west division in summer precipitation simulated by the climate model (the magnitude of the increase in the eastern side of the basin is, however, extremely small). 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 helps 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

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climate model suggests wetter winter and annual conditions in the far western Mediterranean (i.e., western Iberia and the NW coast of Africa) – similar to pollen-based reconstructions – and near-modern summer conditions during summers.

Model and pollen-based reconstructions for the late Holocene indicate declining winter precipitation in the eastern Mediterranean and southern Italy (Sicily and Malta), although model-based changes are not statistically significant. In contrast, late Holocene summer precipitation is higher than today in the eastern Mediterranean (though only marginally so in the climate model). The east-west division in summer precipitation is strongest during the late Holocene and there are suggestions that it appears to be consistently simulated in the climate model but again, the signal – particularly in the Eastern Mediterranean – is not statistically significant.

Our findings are consistent with previous data-model comparisons based on the same regional model. Previous comparisons suggested that the winter precipitation signal was strongest in the northeastern Mediterranean (near Turkey) during the early Holocene (Brayshaw et al., 2011a; Roberts et al., 2011) and that there was a drying trend in the Mediterranean from the early Holocene to the late Holocene, particularly in the east. This is coupled with a gradually weakening seasonal cycle of surface air temperatures towards the present.

In contrast to Holocene winter precipitation changes in the Mediterranean (which are consistent with simulated changes in Mediterranean storm tracks; Brayshaw et al 2010), 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 north-eastern extension of the west African monsoon to reach the southeastern Mediterranean, even in the early-to-mid-Holocene (Brayshaw et al., 2011a). Even though the regional climate model simulates a small change in precipitation compared to the proxy results, it cannot 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 about summer precipitation in the Eastern Mediterranean during the Holocene remain. Climate dynamics 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. Based on the high-resolution coupled climate model EC-Earth, Bosmans et al.

(2015) shows 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.

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).

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 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. So, it will not be 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 openly 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 as the severity/length of bioclimatic drought is determined by both temperature and precipitation. Also, we are dealing with a season which 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

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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. All of these points may seem very picky on the ecology side, but they may have a real influence leading to problems and mismatches between different reconstruction approaches and 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 increasingly being investigated (eg. 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 ky 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. 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.

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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 the central and eastern Mediterranean and a minimum over the western Mediterranean, while the signal for winter precipitation is less spatially consistent. 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.

The regional climate model outputs show a remarkable qualitative agreement with our pollen-based reconstructions, though it must be emphasised that the changes simulated are typically very small and 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 wetter conditions both in winter and in summer during the early and late Holocene and marginally wetter conditions in summer during the late Holocene (both consistent with the paleo-records). It is therefore noted that the use of higher-resolution climate models (both regional and global) may offer benefits for data-model comparison: both due to the inherently "patchy" nature of climate signals and palaeo-records, and through the better representation of the underlying atmospheric dynamics. It is therefore argued that more model simulations – ideally with higher resolution atmospheric dynamics – are required to fully understand the changes in the winter and summer circulation patterns over the Mediterranean region.

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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:

(a) 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 and 4000–2000 cal yrs BP. The climate values available during these periods have been averaged (stars).

(b) Comparison of our pollen-based climate reconstructions for the Mediterranean region with the pollen-inferred climate reconstruction at the European scale of Mauri et al (2015), expressed in anomaly (mm/month). These authors used the MAT with a modern analogue selection based on PFT (plant functional type) scores (and not pollen assemblages like the method used in this paper) and a 4D interpolation technique to produce gridded paleoclimate maps (for more details, see Mauri et al., 2015).

Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in anomaly (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 plots are hatched where it passes a significance test (threshold used here 70%). Pollen-inferred climate estimates (stars) are the same as in Figure 2: annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation).

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

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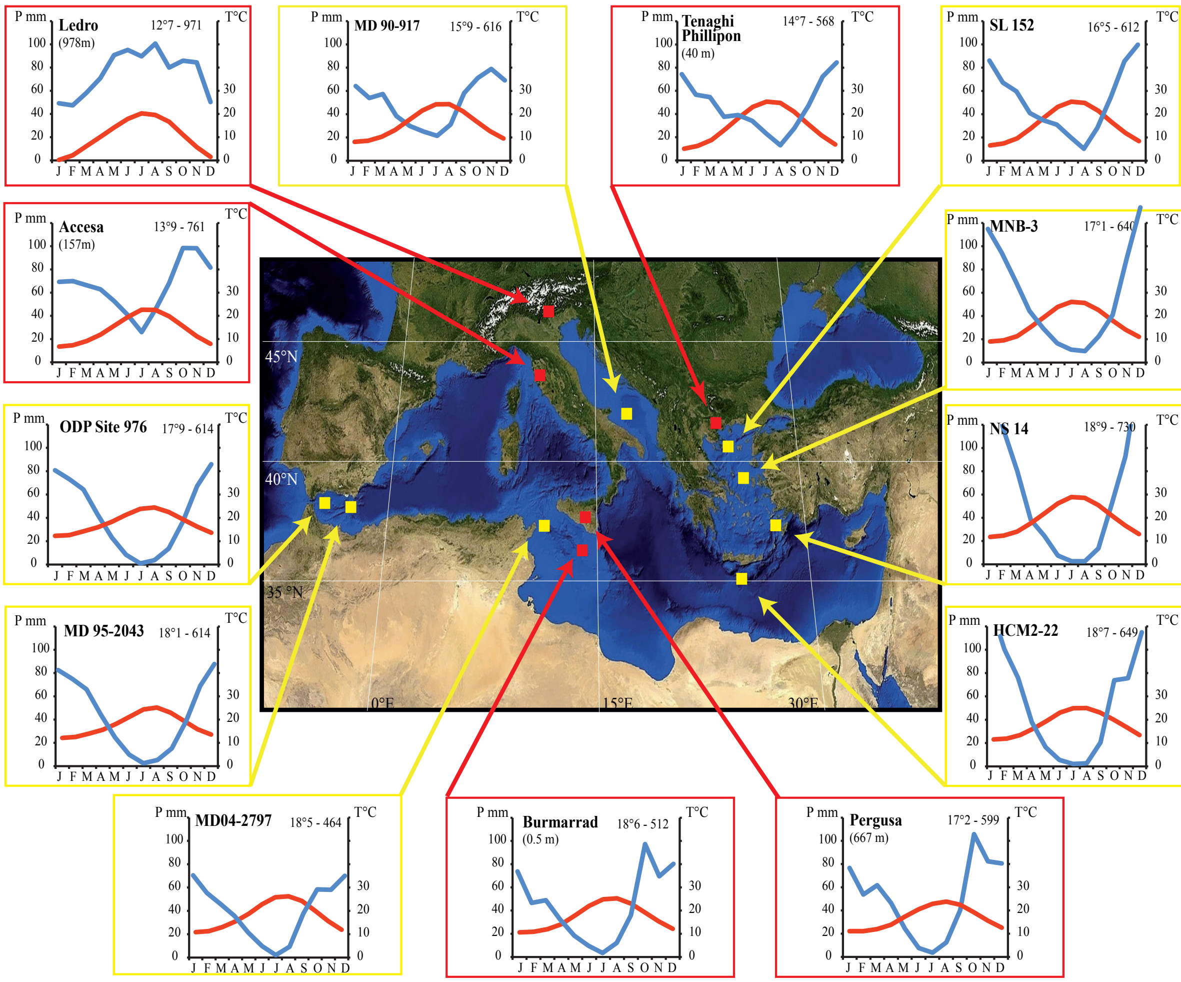

Figure 1: Locations of terrestrial (red) and marine (yellow) pollen records. Ombrothermic diagrams are calculated with the NewLoclim software, which provides estimates of average climatic conditions at locations for which no observations are available (ex.: marine pollen cores).

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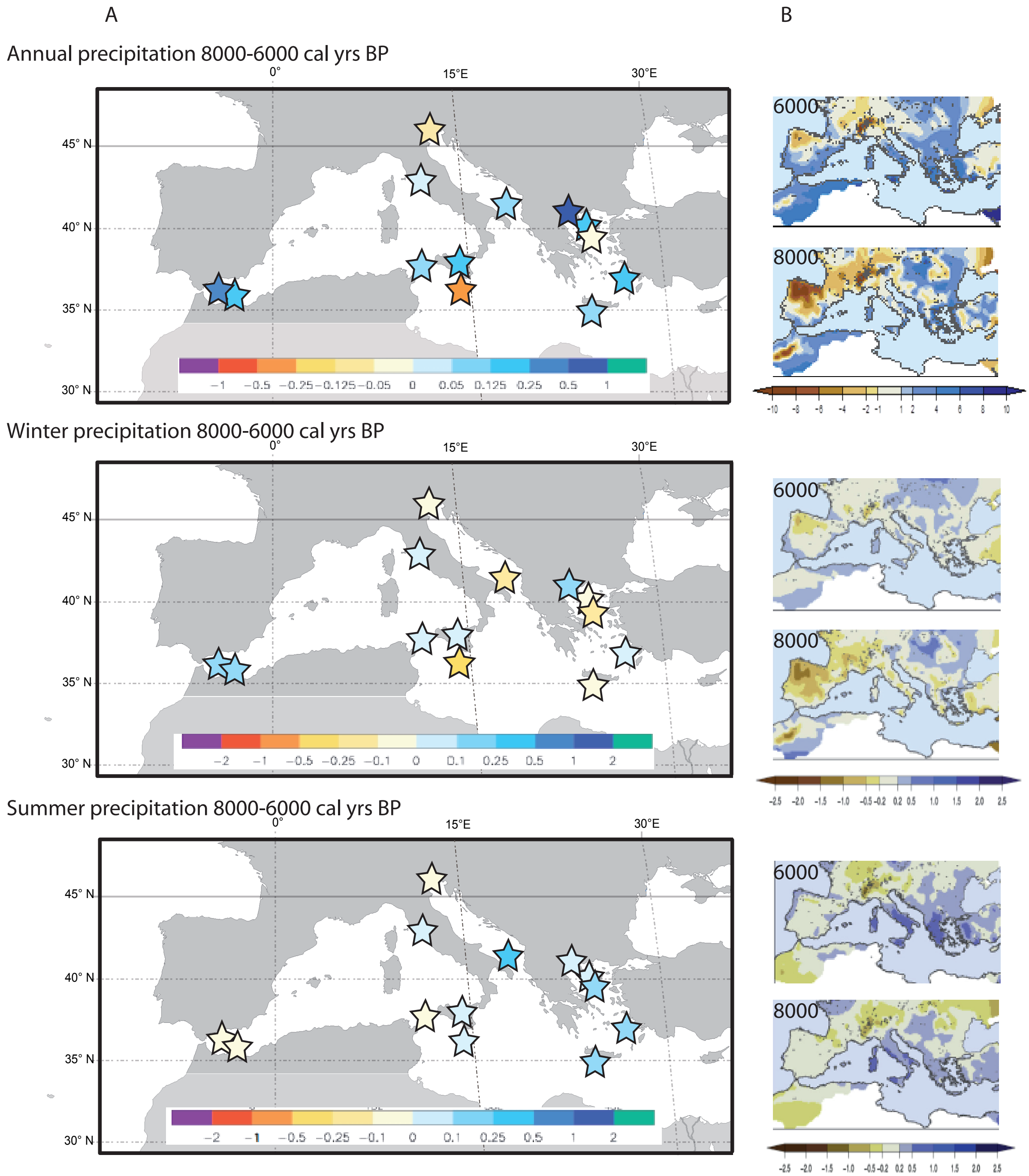

Figure 2: 8000-6000 cal years BP
(A) Pollen-inferred climate estimates as performed with the Modern Analogues Technique : annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation). 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 8000-6000 cal yrs BP have been averaged (stars).
(B) Pollen-inferred climate reconstruction at the European scale of Mauri et al (2015), expressed in anomaly (mm/month). These authors used a modern analogue selection based on PFT (plant functional type) scores (and not pollen assemblages like the method used in A) and a 4D interpolation technique to produce gridded paleoclimate maps (for more details, see Mauri et al., 2015).

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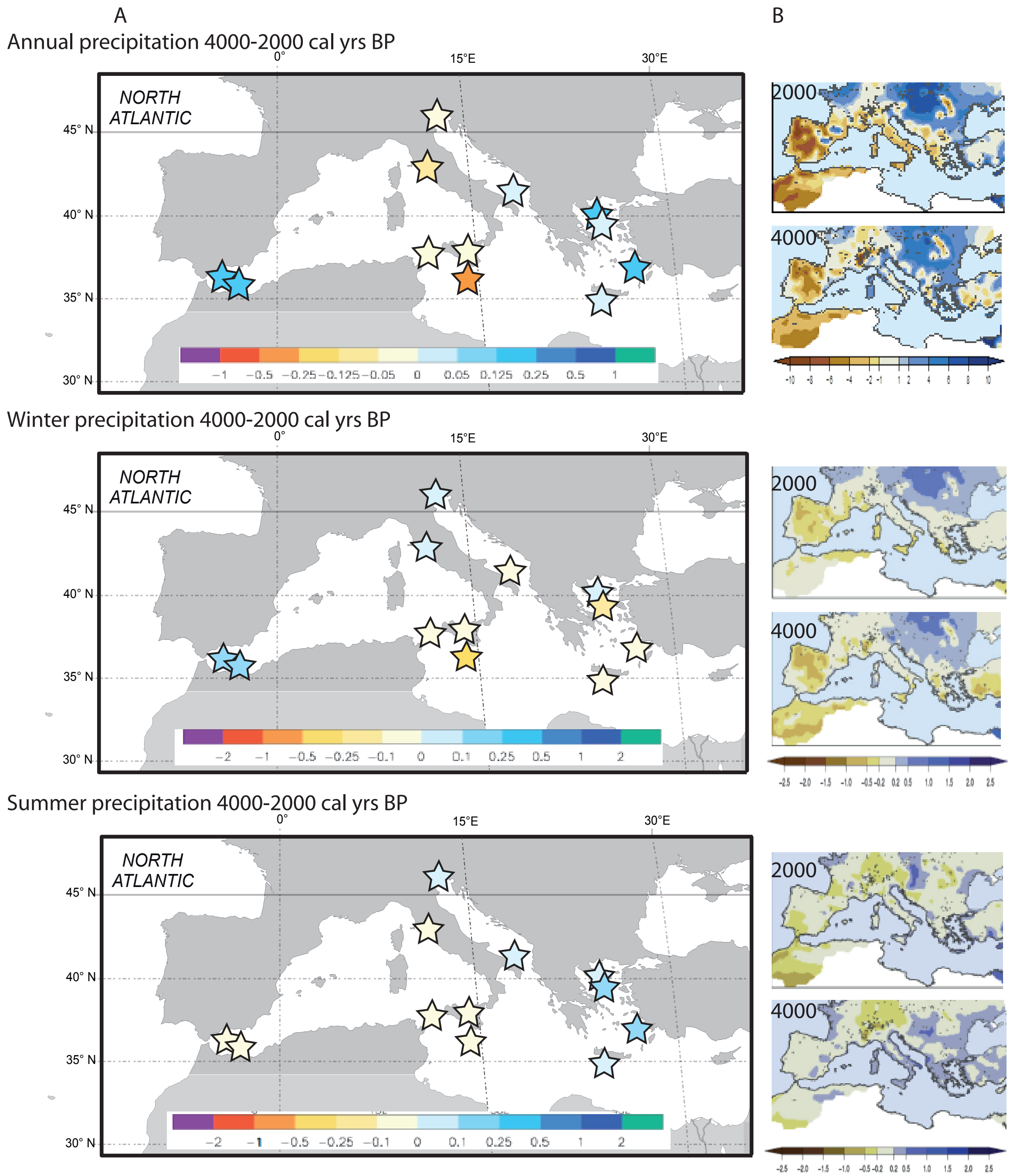

Figure 2: 4000-2000 cal yrs BP

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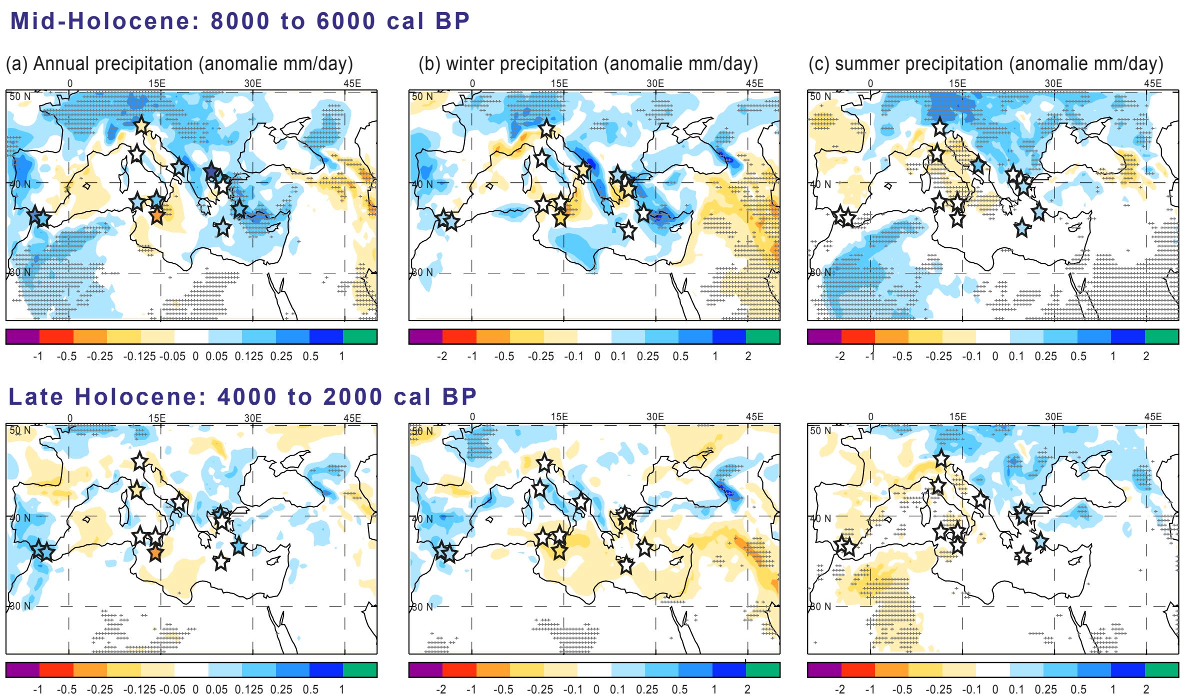

Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in anomaly (mm/day). Simulations are based on a regional model (Brayshaw et al., 2010): standard model HadAM3 coupled to HadSM3 (dynamical model) and HadRM3 (high-resolution regional model). The plots arehatched where it passes a significance test (threshold used here 70%).
Pollen-inferred climate estimates (stars) are the same as in Figure 2: annual precipitation, winter precipitation and summer precipitation .

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Terrestrial pollen records				
	Longitude	**Latitude**	**Elevation (m a.s.l)**	**References**
Lago di Ledro (Northern Italy)	10°76'E	45°87'N	652	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	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	Joannin et al., (2012) ; Peyron et al. (2013)
Pergusa (Sicily)	14°18'E	37°31'N	667	Sadori and Narcisi (2001); Sadori and Giardini (2007); Sadori et al. (2008, 2011, 2013, 2016b); Magny et al. (2011, 2013)
Tenaghi Philippon (Greece)	24°13.4'E	40°58.4'N	40	Pross et al., (2009, 2015); Peyron et al. (2011); Schemmel et al., (2016)
Burmarrad (Malta)	14°25'E	35°56'N	0.5	Djamali et al., (2013); Gambin et al., (2016)

Marine pollen records				
	Longitude	**Latitude**	**Water-depth**	**References**
ODP 976 (Alboran Sea)	4°18'W	36°12' N	1108	Combourieu-Nebout et al., (1999, 2002, 2009) ; Dormoy et al., (2009)
MD95-2043 (Alboran Sea)	2°37'W	36°9'N	1841	Fletcher and Sánchez Goñi(2008); Fletcher et al., (2010)
MD90-917 (Adriatic Sea)	17°37'E	41°97'N	845	Combourieu-Nebout et al., (2013)
MD04-2797 (Siculo-Tunisian strait)	11°40'E	36°57'N	771	Desprat et al., (2013)
SL152 (North Aegean Sea)	24°36' E	40°19' N	978	Kotthoff et al., (2008, 2011), Dormoy et al., (2009).
NS14 (South Aegean Sea)	27°02.87'E	36°38.9'N	505	Kouli et al., (2012) ; Gogou et al., (2007); Triantaphyllou et al., (2009a, b)
HCM2/22 (south Crete)	24°53'E	34°34 N	2211	Kouli et al., (2012) ; Triantaphyllou et al,(2014)
MNB-3 (North Aegean Sea)	25°00'E	39°15.43'N	800	Kouli et al., (2012) ; Triantaphyllou et al, (2014)

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