

# *Precipitation changes in the Mediterranean basin during the Holocene from terrestrial and marine pollen records: a model–data comparison*

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1 **The climate of the Mediterranean basin during the**  
2 **Holocene from terrestrial and marine pollen records: A**  
3 **model/data comparison**

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28 Abstract

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

41 Quantitative pollen-based precipitation estimates were generated along a longitudinal gradient  
42 from the Alboran (West) to the Aegean Sea (East); they are derived from terrestrial pollen  
43 records from Greece, Italy and Malta as well as from pollen records obtained from marine cores.  
44 Because seasonality represents a key parameter in Mediterranean climates, special attention  
45 was given to the reconstruction of season-specific climate information, notably summer and  
46 winter precipitation. The reconstructed climatic trends corroborate a previously described  
47 north-south partition of precipitation regimes during the Holocene. During the early Holocene,  
48 relatively wet conditions occurred in the south-central and eastern Mediterranean region, while  
49 drier conditions prevailed from 45°N northwards. These patterns reversed during the late  
50 Holocene, with a wetter northern Mediterranean region and drier conditions in the east and  
51 south. More sites from the northern part of the Mediterranean basin are needed to further  
52 substantiate these observations. With regard to the existence of a west-east precipitation dipole  
53 during the Holocene, our pollen-based climate data show that the strength of this dipole is  
54 strongly linked to the seasonal parameter reconstructed: Early Holocene summers show a clear  
55 east-to-west gradient, with summer precipitation having been highest in the central and eastern  
56 Mediterranean and lowest over the western Mediterranean. In contrast, winter precipitation  
57 signals are less spatially coherent. A general drying trend occurred from the early to the late  
58 Holocene; particularly in the central and eastern Mediterranean. However, summer  
59 precipitation in the east remained above modern values, even during the late Holocene interval.



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

75  
76



## 77 **1 Introduction**

78 The Mediterranean region is particularly sensitive to climate change due to its position within  
 79 the confluence of arid North African (i.e., subtropically influenced) and temperate/humid  
 80 European (i.e., mid-latitudinal) climates (Lionello, 2012). Palaeoclimatic proxies, including  
 81 stable isotopes, lipid biomarkers, palynological data and lake-levels, have shown that the  
 82 Mediterranean region experienced climatic conditions that varied spatially and temporally  
 83 throughout the Holocene (e.g. Bar-Matthews and Ayalon, 2011; Luterbacher et al., 2012;  
 84 Lionello, 2012; Triantaphyllou et al., 2014, 2016; Mauri et al., 2015; De Santis and Caldara  
 85 2015; Sadori et al., 2016a) and well before (eg. Sadori et al., 2016b). Clear spatial climate  
 86 patterns have been identified from east to west and from north to south within the basin (e.g.  
 87 Zanchetta et al., 2007; Magny et al., 2009b, 2011, 2013; Zhornyak et al., 2011; Sadori et al.,  
 88 2013; Fletcher et al., 2013). Lake-level reconstructions from Italy suggest contrasting patterns  
 89 of palaeohydrological changes for the central Mediterranean during the Holocene (Magny et  
 90 al., 2012, 2013). Specifically, lake level maxima occurred south of approximately 40°N in the  
 91 early to mid-Holocene, while lakes north of 40°N recorded minima. This pattern was reversed  
 92 at around 4500 cal yrs BP.

93 Quantitative pollen-based precipitation reconstructions from sites in northern Italy indicate  
 94 humid winters and dry summers during the early to mid-Holocene, whereas southern Italy was  
 95 characterised by humid winters and summers; the N-S pattern reverses in the late Holocene,  
 96 with drier conditions at southern sites and wet conditions at northern sites. These findings  
 97 support a North–South partition for the central Mediterranean with regards to precipitation, and  
 98 also confirm that precipitation seasonality is a key parameter in the evolution of Mediterranean  
 99 climates (Peyron et al., 2013). The pattern of shifting N-S precipitation regimes has also been  
 100 identified for the Aegean Sea (Peyron et al., 2013). Taken together, the evidence from pollen  
 101 data and from other proxies covering the Mediterranean region suggest a climate response that  
 102 can be linked to a combination of orbital, ice-sheet and solar forcings (Magny et al., 2013).

103 An east-west pattern of climatic change during the Holocene is also observed in the  
 104 Mediterranean region (e.g., Combourieu Nebout et al., 1998; Geraga et al., 2010; Colmenero-  
 105 Hildago et al., 2002; Kotthoff et al., 2008; Dormoy et al., 2009; Finne et al., 2011; Roberts et  
 106 al., 2011, 2012; Luterbacher et al., 2012; Guiot and Kaniewski, 2015). A gradient of  
 107 precipitation or an east-west division during the Holocene is suggested by marine pollen records  
 108 (Dormoy et al., 2009), lake-level reconstructions (Magny et al., 2013) and speleothem isotopes



(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.

135

## 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



141 originating over the Atlantic. In the western Mediterranean, precipitation is predominantly  
 142 affected by the North Atlantic Oscillation (NAO), while several systems interact to control  
 143 precipitation over the northern and eastern Mediterranean (Giorgi and Lionello, 2008).  
 144 Mediterranean summer climates are dominated by descending high pressure systems that lead  
 145 to dry/hot conditions, particularly over the southern Mediterranean where climate variability is  
 146 strongly influenced by African and Asian monsoons (Alpert et al., 2006) with strong  
 147 geopotential blocking anomalies over central Europe (Giorgi and Lionello, 2008; Trigo et al.,  
 148 2006).

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

159 Climate reconstructions for summer and winter precipitation (Figs. 2, 3) inferred from the  
 160 terrestrial sequences and marine pollen records were performed using the Modern Analogue  
 161 Technique (MAT; Guiot, 1990). The MAT compares fossil pollen assemblages to modern  
 162 pollen assemblages with known climate parameters. The MAT is calibrated using an expanded  
 163 surface pollen dataset with more than 3600 surface pollen samples from various European  
 164 ecosystems (Peyron et al., 2013). In this dataset, 2200 samples are from the Mediterranean  
 165 region, and the results shows that the analogues selected here are limited to the Mediterranean  
 166 basin. Since the MAT use the distance structure of the data and essentially perform local fitting  
 167 of the climate parameter (as the mean of  $n$ -closest sites) they may be less susceptible to  
 168 increased noise in the data set, and less likely to report spurious values than others methods (for  
 169 more details on the method, see Peyron et al., 2011). *Pinus* is overrepresented in marine pollen  
 170 samples (Heusser and Balsam, 1977; Naughton et al., 2007), and as such *Pinus* pollen was  
 171 removed from the assemblages for the calibration of marine records using MAT.

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



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<sub>2</sub> and CH<sub>4</sub> 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)



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

217 Precipitation reconstructions are particularly important for this region given that precipitation  
 218 rather than temperature represents the dominant controlling factor on Mediterranean  
 219 environmental system during the early to mid-Holocene (Renssen et al., 2012). Pollen and non-  
 220 pollen proxies, including marine and terrestrial biomarkers (terrestrial n-alkanes), indicate  
 221 humid mid-Holocene conditions in the Aegean Sea (Triantaphyllou et al., 2014, 2016). Results  
 222 within the Aegean support the pollen-based reconstructions, but non-pollen proxy data are still  
 223 lacking at the basin scale in the Mediterranean, limiting our ability to undertake independent  
 224 evaluation of precipitation reconstructions.

225 Very few large-scale climate reconstruction of precipitation exist for the whole Holocene  
 226 (Bartlein et al., 2011; Mauri et al., 2014; Guiot and Kaniewski, 2015; Tarroso et al., 2016) and,  
 227 even at local scales, pollen-inferred reconstructions of seasonal precipitation are very rare (Wu  
 228 et al., 2007; Peyron et al., 2011, 2013; Combourieu-Nebout et al., 2013, Nourelbait et al., 2016).  
 229 Several studies focused on the 6000 cal years BP period: Wu et al. (2007) reconstruct regional  
 230 seasonal and annual precipitation and suggest that precipitation did not differ significantly from  
 231 modern conditions across the Mediterranean; however, scaling issues render it difficult to  
 232 compare their results with the reconstructions presented here. Cheddadi et al. (1997) reconstruct  
 233 wetter-than-modern conditions at 6000 yrs cal BP in southern Europe; however, their study uses  
 234 only one record from Italy and measures the moisture availability index which is not directly  
 235 comparable to precipitation *sensu stricto* since it integrates temperature and precipitation. At  
 236 6000 yrs cal BP, Bartlein et al. (2011) reconstruct Mediterranean precipitation at values between  
 237 100 and 500 mm higher than modern. Mauri et al. (2015), in an updated version of Davis et al.  
 238 (2003), provide a quantitative climate reconstructions comparable to the seasonal precipitation



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.

254

#### 255 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).

269



## 270 *An East-West precipitation pattern?*

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

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

278 The annual precipitation and seasonal precipitation signals appear to conflict in the early  
 279 Holocene (Fig. 2a). The pollen-inferred annual precipitation indicates unambiguously wetter  
 280 than today conditions south of 45°N in the western, central and eastern Mediterranean, except  
 281 for Malta (Fig. 2a). Winter conditions show less spatial coherence, although the western basin  
 282 appears to have experienced higher precipitation than modern, while drier conditions exist in  
 283 the east (Fig. 2a). A prominent feature of the summer precipitation signal is an East to West  
 284 signature of increasing summer precipitation.

285 Our reconstruction shows a good match to Guiot and Kaniewski (2015) who have also discussed  
 286 a possible east-to-west division in the Mediterranean with regard to precipitation (summer and  
 287 annual) during the Holocene. They report wet centennial-scale spells in the eastern  
 288 Mediterranean during the Early Holocene (until 6000 years BP), with dry spells in the western  
 289 Mediterranean. Mid-Holocene reconstructions show continued wet conditions, with drying  
 290 through the late Holocene (Guiot and Kaniewski, 2015). This pattern indicates a see-saw effect  
 291 over the last 10,000 years, particularly during dry episodes in the Near and Middle East. As in  
 292 our findings, Mauri et al. (2015) also reconstruct high annual precipitation values over much of  
 293 the southern Mediterranean, and a weak winter precipitation signal. Mauri et al. (2015) confirm  
 294 an east-west gradient for summer precipitation, with conditions drier or close to present in  
 295 south-western Europe and wetter in the central and eastern Mediterranean (Fig 2b). These  
 296 studies corroborate the hypothesis of an east-to-west division in precipitation during the early  
 297 to mid-Holocene in the Mediterranean as proposed by Roberts et al. (2011). Roberts et al.  
 298 (2011) suggest the eastern Mediterranean (mainly Turkey and more eastern regions)  
 299 experienced higher winter precipitation during the early Holocene, followed by an oscillatory  
 300 decline after 6000 yrs BP. Our findings reveal wetter annual and summer conditions in the  
 301 eastern Mediterranean, although the winter precipitation signal is less clear. However, the



302 highest precipitation values reported by Roberts et al. (2011) were from sites located in western-  
 303 central Turkey; these sites are absent in the current study. Climate variability in the eastern  
 304 Mediterranean during the last 6000 years is documented in a number of studies based on  
 305 multiple proxies (Finné et al., 2011). Most palaeoclimate proxies indicate wet mid-Holocene  
 306 conditions (Bar-Matthews et al., 2003; Stevens et al., 2006; Eastwood et al., 2007; Kuhnt et al.,  
 307 2008; Verheyden et al., 2008) which agree well with our results; however most proxies are not  
 308 seasonally resolved.

309 Roberts et al. (2011) and Guiot and Kaniewski (2015) suggest that changes in precipitation in  
 310 the western Mediterranean were smaller in magnitude during the early Holocene, while the  
 311 largest increases occurred during the mid-Holocene, around 6000-3000 cal BP, before declining  
 312 to modern values. Speleothems from southern Iberia suggests a humid early Holocene (9000-  
 313 7300 cal BP) in southern Iberia, with equitable rainfall throughout the year (Walczak et al.,  
 314 2015). Our reconstructions for the Alboran Sea which clearly shows an amplified precipitation  
 315 seasonality (with higher annual/winter and lower than present summer rainfall) for the Alboran  
 316 sites. It is likely that seasonal patterns defining the Mediterranean climate must have been even  
 317 stronger in the early Holocene to support the wider development of sclerophyll forests than  
 318 present in south Spain (Fletcher et al., 2013).

319

320 Late Holocene (4000 to 2000 cal yrs BP)

321 Annual precipitation reconstructions suggest drier or near-modern conditions in central Italy  
 322 and Malta (Fig. 2b). In contrast, the Alboran and Aegean seas remain wetter. Winter and  
 323 summer precipitation produce opposing patterns: a clear east-west division exists for summer  
 324 precipitation, with a maximum in the eastern and a minimum over the western and central  
 325 Mediterranean (Fig. 2b). Winter precipitation shows the opposite trend, with a maximum in the  
 326 western Mediterranean and a minimum in the central and eastern Mediterranean (Fig. 2b). Our  
 327 results are also in agreement with lakes and speleothem isotope records over the Mediterranean  
 328 for the late Holocene (Roberts et al., 2011), and the Finné et al. (2011) palaeoclimate synthesis  
 329 for the eastern Mediterranean. There is a good overall correspondence between trends and  
 330 patterns in our reconstruction and that of Mauri et al. (2015), except for the Alboran Sea (Fig.  
 331 2b). High-resolution speleothem data from southern Iberia show Mediterranean climate  
 332 conditions in southern Iberia between 4800 and 3000 cal BP (Walczak et al., 2015) which is in  
 333 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 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



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

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

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

383 In contrast to Holocene winter precipitation changes in the Mediterranean (which are consistent  
 384 with simulated changes in Mediterranean storm tracks; Brayshaw et al 2010), it is clear that  
 385 most global climate models (PMIP2, PMIP3) simulate only very small changes in summer  
 386 precipitation in the Mediterranean during the Holocene (Braconnot et al., 2007a,b, 2012; Mauri  
 387 et al., 2014). The lack of a summer precipitation signal is consistent with the failure of the north-  
 388 eastern extension of the west African monsoon to reach the southeastern Mediterranean, even  
 389 in the early-to-mid-Holocene (Brayshaw et al., 2011a). Even though the regional climate model  
 390 simulates a small change in precipitation compared to the proxy results, it cannot be robustly  
 391 identified as statistically significant. This is to some extent unsurprising, insofar as the regional  
 392 climate simulations presented here are themselves “driven” by data derived from a coarse global  
 393 model (which, like its PMIP2/3 peers, does not simulate an extension of the African monsoon  
 394 into the Mediterranean during this time period). Therefore, questions about summer  
 395 precipitation in the Eastern Mediterranean during the Holocene remain. Climate dynamics need  
 396 to be better understood in order to confidently reconcile proxy data (which suggest increased  
 397 summer precipitation during the early Holocene in the Eastern Mediterranean) with climate  
 398 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 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



431 significant part of precipitation as snowfall, which is not directly available to plant life. This  
 432 may be important in the long run for improving the interpretation of long-term Holocene  
 433 changes and contrasts between different proxies, such as lake-levels and speleothems. All of  
 434 these points may seem very picky on the ecology side, but they may have a real influence  
 435 leading to problems and mismatches between different reconstruction approaches and different  
 436 proxies (e.g. Davis et al., 2003; Mauri et al., 2015).

437 Another important point is the question of human impact on the Mediterranean vegetation  
 438 during the Holocene. Since human activity has influenced natural vegetation, distinguishing  
 439 between vegetation change induced by humans and climatic change in the Mediterranean is a  
 440 challenge requiring independent proxies and approaches. Therefore links and processes behind  
 441 societal change, and climate change in the Mediterranean region increasingly being investigated  
 442 (eg. Holmgren et al., 2016; Gogou et al., 2016; Sadori et al., 2016a). Here, the behavior of the  
 443 reconstructed climatic variables between 4000 and 2000 cal yrs BP is likely to be influenced  
 444 by non-natural ecosystem changes due to human activities such as the forest degradation that  
 445 began in lowlands, progressing to mountainous areas (Carrión et al., 2010). These human  
 446 impacts add confounding effects for fossil pollen records and may lead to slightly biased  
 447 temperature reconstructions during the Late Holocene, likely biased towards warmer  
 448 temperatures and lower precipitation. However, if human activities become more marked at  
 449 3000 cal ky BP, they increase significantly over the last millennia (Sadori et al., 2016) which  
 450 is not within the time scale studied here. Moreover there is strong agreement between summer  
 451 precipitation and independently reconstructed lake-level curves (Magny et al., 2013). For the  
 452 marine pollen cores, human influence is much more difficult to interpret given that the source  
 453 area is so large, and that, in general, anthropic taxa are not found in marine pollen assemblages.

454

## 455 **Conclusions**

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



464 Climatic trends reconstructed in this study seem to corroborate the north-south division of  
465 precipitation regimes during the Holocene, with wet conditions in the south-central and eastern  
466 Mediterranean, and dry conditions above 45°N during the early Holocene, while the opposite  
467 pattern dominates during the late Holocene. This study also shows that a prominent feature of  
468 Holocene climate in the Mediterranean is the east-to-west division in precipitation, strongly  
469 linked to the seasonal parameter reconstructed. During the early Holocene, we observe an east-  
470 to-west division with high summer precipitation in the central and eastern Mediterranean and a  
471 minimum over the western Mediterranean, while the signal for winter precipitation is less  
472 spatially consistent. There was a drying trend in the Mediterranean from the early Holocene to  
473 the late Holocene, particularly in central and eastern regions but summers in the east remained  
474 wetter than today.

475 The regional climate model outputs show a remarkable qualitative agreement with our pollen-  
476 based reconstructions, though it must be emphasised that the changes simulated are typically  
477 very small and of questionable statistical significance. Nevertheless, there are indications that  
478 the east to west division in summer precipitation reconstructed from the pollen records do  
479 appear to be simulated by the climate model. The model results also suggest that parts of the  
480 eastern Mediterranean experienced wetter conditions both in winter and in summer during the  
481 early and late Holocene and marginally wetter conditions in summer during the late Holocene  
482 (both consistent with the paleo-records). It is therefore noted that the use of higher-resolution  
483 climate models (both regional and global) may offer benefits for data-model comparison: both  
484 due to the inherently “patchy” nature of climate signals and palaeo-records, and through the  
485 better representation of the underlying atmospheric dynamics. It is therefore argued that more  
486 model simulations – ideally with higher resolution atmospheric dynamics – are required to fully  
487 understand the changes in the winter and summer circulation patterns over the Mediterranean  
488 region.

489

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495



## 496 **Figure captions**

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

502 Figure 2:

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

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

518 Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in  
 519 anomaly (mm/day). Simulations are based on a regional model (Brayshaw et al., 2010):  
 520 standard model HadAM3 coupled to HadSM3 (dynamical model) and HadRM3 (high-  
 521 resolution regional model). The plots are hatched where it passes a significance test (threshold  
 522 used here 70%). Pollen-inferred climate estimates (stars) are the same as in Figure 2: annual  
 523 precipitation, winter precipitation (winter = sum of December, January and February  
 524 precipitation) and summer precipitation (summer = sum of June, July and August  
 525 precipitation).

526

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

528



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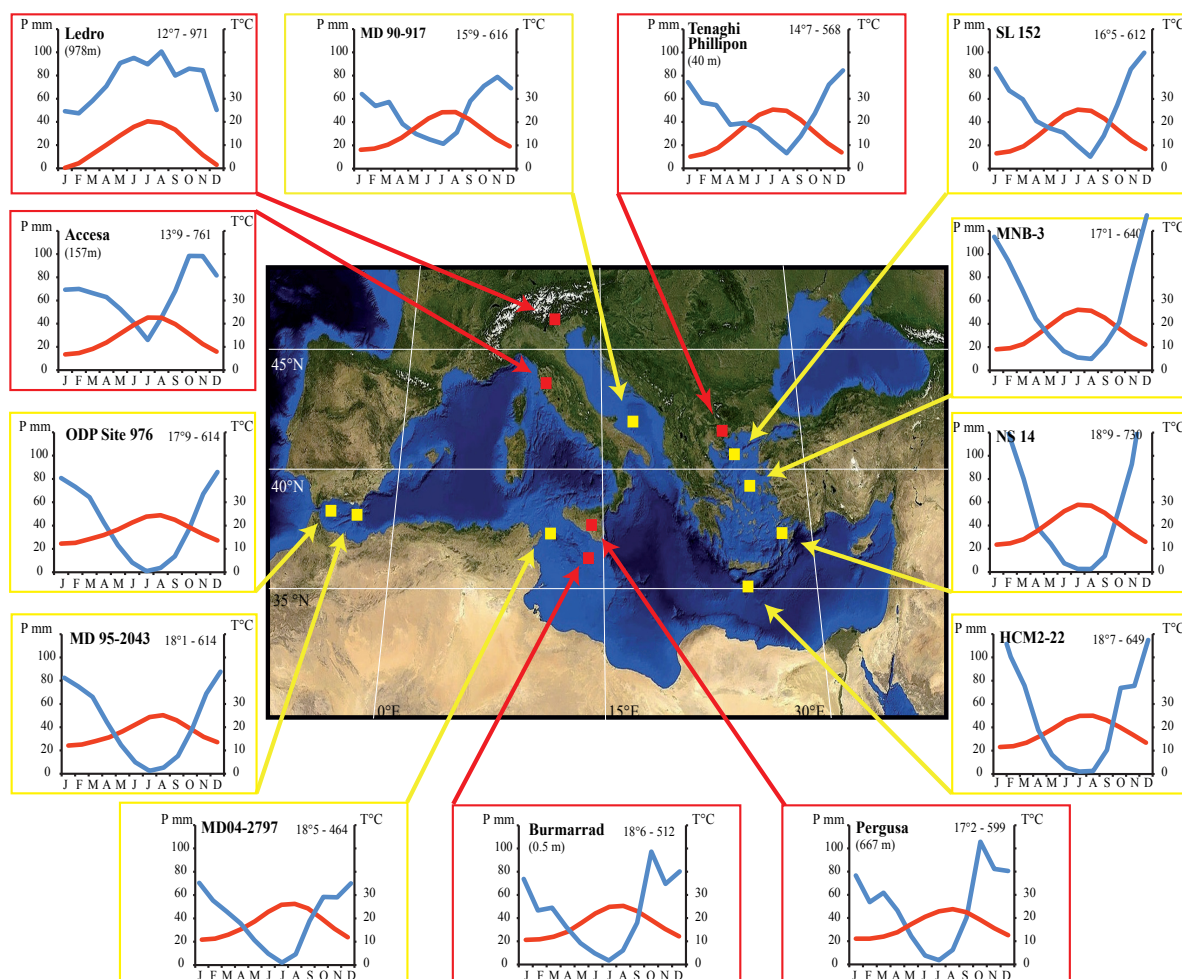


Figure 1: Locations of terrestrial (red) and marine (yellow) pollen records. Ombrothermic diagrams are calculated with the NewLoclim software, which provides estimates of average climatic conditions at locations for which no observations are available (ex.: marine pollen cores).

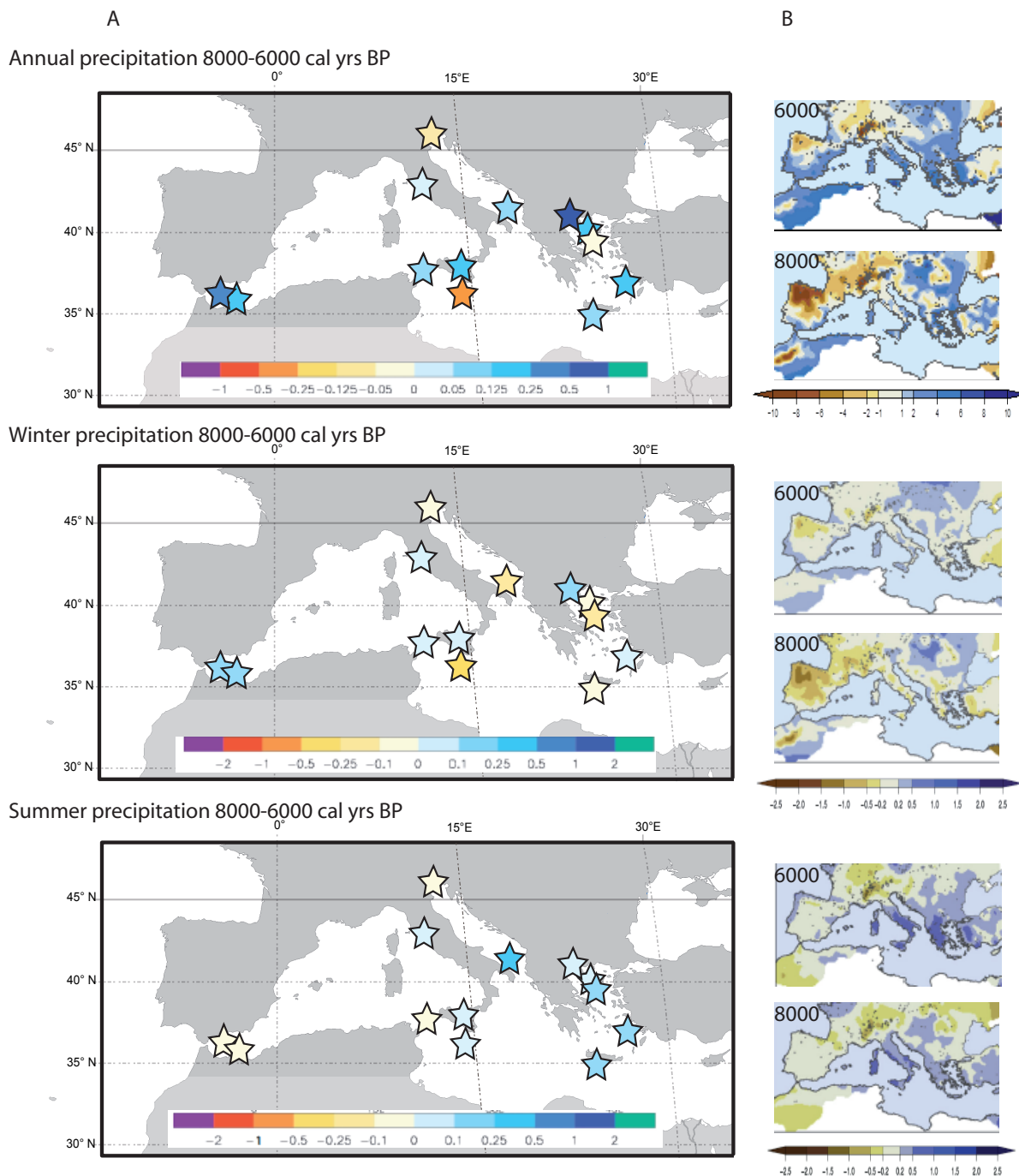


Figure 2: 8000-6000 cal years BP  
 (A) Pollen-inferred climate estimates as performed with the Modern Analogues Technique : annual precipitation, winter precipitation (winter = sum of December, January and February precipitation) and summer precipitation (summer = sum of June, July and August precipitation). 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).

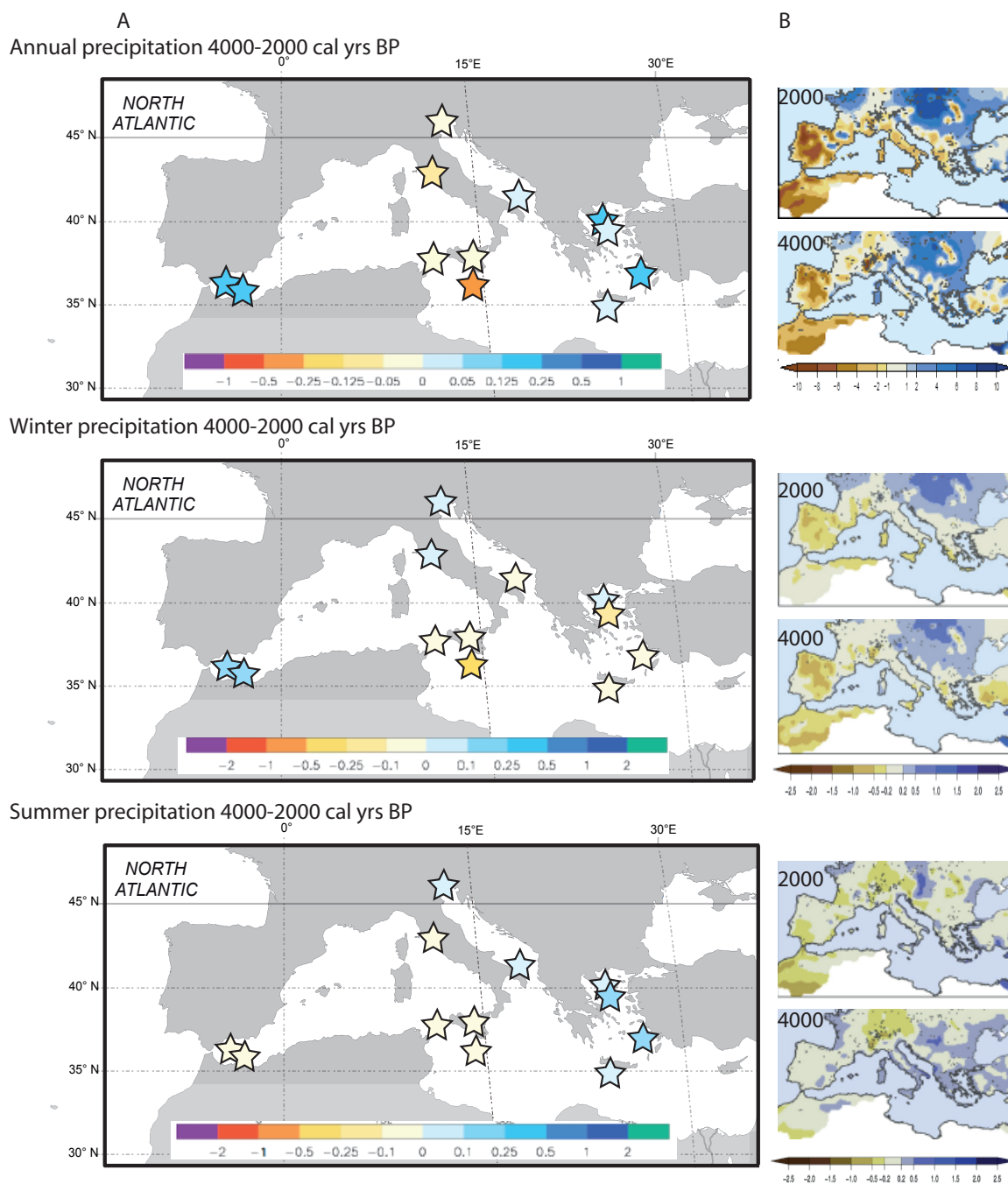
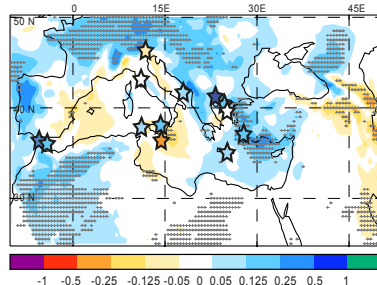


Figure 2: 4000-2000 cal yrs BP

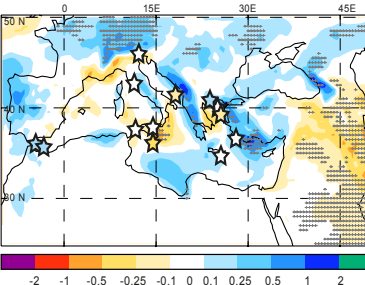


### Mid-Holocene: 8000 to 6000 cal BP

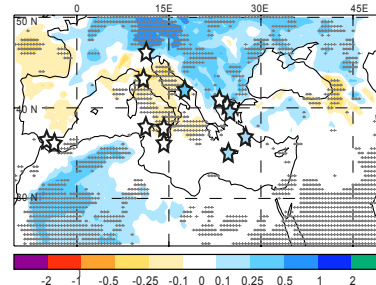
(a) Annual precipitation (anomalie mm/day)



(b) winter precipitation (anomalie mm/day)



(c) summer precipitation (anomalie mm/day)



### Late Holocene: 4000 to 2000 cal BP

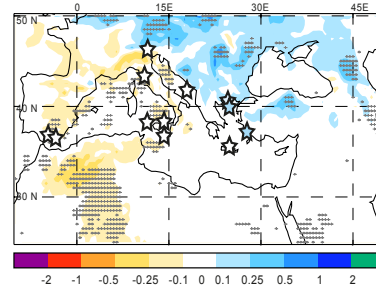
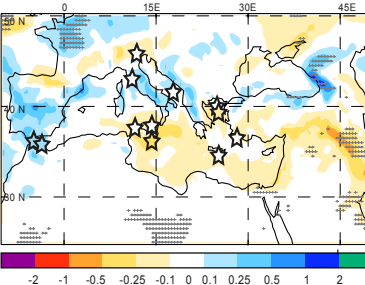
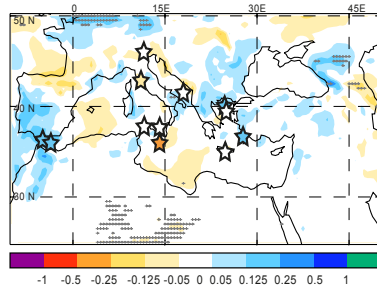


Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in anomaly (mm/day).

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 and summer precipitation.



| <b>Terrestrial pollen records</b>         |                  |                 |                                 |                                                                                                                                                                  |
|-------------------------------------------|------------------|-----------------|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                           | <b>Longitude</b> | <b>Latitude</b> | <b>Elevation<br/>(m a.s.l.)</b> | <b>References</b>                                                                                                                                                |
| <b>Lago di Ledro</b> (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)                                                                  |
| <b>Accesa</b> (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) |
| <b>Trifoglietti</b> (southern Italy)      | 16°01'E          | 39°33'N         | 1048                            | Joannin et al., (2012) ;<br>Peyron et al. (2013)                                                                                                                 |
| <b>Pergusa</b> (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)                                        |
| <b>Tenaghi Philippon</b> (Greece)         | 24°13.4'E        | 40°58.4'N       | 40                              | Pross et al., (2009, 2015); Peyron et al. (2011); Schemmel et al., (2016)                                                                                        |
| <b>Burmarrad</b> (Malta)                  | 14°25'E          | 35°56'N         | 0.5                             | Djamali et al., (2013); Gambin et al., (2016)                                                                                                                    |
| <b>Marine pollen records</b>              |                  |                 |                                 |                                                                                                                                                                  |
|                                           | <b>Longitude</b> | <b>Latitude</b> | <b>Water-<br/>depth</b>         | <b>References</b>                                                                                                                                                |
| <b>ODP 976</b> (Alboran Sea)              | 4°18'W           | 36°12' N        | 1108                            | Combourieu-Nebout et al., (1999, 2002, 2009) ; Dormoy et al., (2009)                                                                                             |
| <b>MD95-2043</b> (Alboran Sea)            | 2°37'W           | 36°9'N          | 1841                            | Fletcher and Sánchez Goñi( 2008); Fletcher et al., (2010)                                                                                                        |
| <b>MD90-917</b> (Adriatic Sea)            | 17°37'E          | 41°97'N         | 845                             | Combourieu-Nebout et al., (2013)                                                                                                                                 |
| <b>MD04-2797</b> (Siculo-Tunisian strait) | 11°40'E          | 36°57'N         | 771                             | Desprat et al., (2013)                                                                                                                                           |
| <b>SL152</b> (North Aegean Sea)           | 24°36' E         | 40°19' N        | 978                             | Kotthoff et al., (2008, 2011), Dormoy et al., (2009).                                                                                                            |
| <b>NS14</b> (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)                                                                                   |
| <b>HCM2/22</b> (south Crete)              | 24°53'E          | 34°34 N         | 2211                            | Kouli et al., (2012) ; Triantaphyllou et al., (2014)                                                                                                             |
| <b>MNB-3</b> (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.