



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

4
5 **Odile Peyron¹, Nathalie Combourieu-Nebout², David Brayshaw³, Simon**
6 **Goring⁴, Valérie Andrieu-Ponel⁵, Stéphanie Desprat^{6,7}, Will Fletcher⁸, Belinda**
7 **Gambin⁹, Chryssanthi Ioakim¹⁰, Sébastien Joannin¹, Ulrich Kotthoff¹¹, Katerina**
8 **Kouli¹², Vincent Montade¹, Jörg Pross¹³, Laura Sadori¹⁴, Michel Magny¹⁵**

- 9 [1] Institut des Sciences de l'Evolution (ISEM), Université de Montpellier, France
10 [2] UMR 7194 MNHN, Institut de Paléontologie Humaine 1, Paris, France
11 [3] University of Reading, Department of Meteorology, United Kingdom
12 [4] Department of Geography, Univ. of Wisconsin-Madison, Wisconsin, USA
13 [5] Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale (IMBE), Aix Marseille
14 Université, Aix-en-Provence, France
15 [6] EPHE, PSL Research University, Laboratoire Paléoclimatologie et Paléoenvironnements Marins,
16 Pessac, France
17 [7] Univ. Bordeaux, EPOC UMR 5805, Pessac, France
18 [8] Geography, School of Environment, Education and Development, University of Manchester, United
19 Kingdom
20 [9] Institute of Earth Systems, University of Malta, Malta
21 [10] Institute of Geology and Mineral Exploration, Athens, Greece
22 [11] Center for Natural History and Institute of Geology, Hamburg University, Hamburg, Germany
23 [12] Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece
24 [13] Paleoenvironmental Dynamics Group, Institute of Earth Sciences, Heidelberg University, Germany
25 [14] Dipartimento di Biologia Ambientale, Università di Roma "La Sapienza", Roma, Italy
26 [15] UMR 6249 Chrono-Environnement, Université de Franche-Comté, Besançon, France
27 Correspondence to: O. Peyron (odile.peyron@univ-montp2.fr)



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_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)



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

490 **Acknowledgements**

491 This study is a part of the LAMA ANR Project (MSHE Ledoux, USR 3124, CNRS)
492 financially supported by the French CNRS (National Centre for Scientific Research). Simon
493 Goring is currently supported by NSF Macrosystems grant 144-PRJ45LP. This is an ISEM
494 contribution n°XXXX.

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



529 References

- 530 Alpert, P., Baldi, M., Ilani, R., Krichak, S., Price, C., Rodó, X., Saaroni, H., Ziv, B., Kishcha,
 531 P., Barkan, J., Mariotti, A. and Xoplaki, E.: Relations between climate variability in the
 532 Mediterranean region and the Tropics: ENSO, South Asian and African monsoons, hurricanes
 533 and Saharan dust In: Lionello P, Malanotte-Rizzoli P, Boscolo R (eds) Mediterranean
 534 Climate Variability, Amsterdam, Elsevier 149-177, 2006.
- 535 Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A. and Hawkesworth, C.J.: Sea-land
 536 oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern
 537 Mediterranean region and their implication for paleorainfall during interglacial intervals.
 538 *Geochimica et Cosmochimica Acta* 67, 3181-3199, 2003.
- 539 Bar-Matthews, M. and Ayalon, A.: Mid-Holocene climate variations revealed by high-
 540 resolution speleothem records from Soreq Cave, Israel and their correlations with cultural
 541 changes, *Holocene*, 21, 163–172, 2011.
- 542 Bartlein, P.J., Harrison, S.P., Brewer, S., Connor, S., Davis, B.A.S., Gajewski, K., Guiot, J.,
 543 Harrison-Prentice, T.I., Henderson, A., Peyron, O., Prentice, I.C., Scholze, M., Seppä, H.,
 544 Shuman, B., Sugita, S., Thompson, R.S., Vau, A.E, Williams, J., and Wu H.: Pollen-based
 545 continental climate reconstructions at 6 and 21 ka: a global synthesis, *Climate Dynamics* 37,
 546 775-802, 2011.
- 547 Bosmans, J.H.C., Drijfhout, S.S., Tuenter, E., Hilgen, F.J., Lourens, L.J. and Rohling, E.J.:
 548 Precession and obliquity forcing of the freshwater budget over the Mediterranean, *Quaternary*
 549 *Science Reviews*, 123, 16-30, 2015.
- 550 Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi,
 551 A., Crucifix, M., Driesschaert, E., Fichet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A.,
 552 Laine, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu,
 553 Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last
 554 Glacial Maximum –Part 1: experiments and large-scale features, *Clim. Past*, 3, 261–277,
 555 2007a.
- 556 Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi,
 557 A., Crucifix, M., Driesschaert, E., Fichet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A.,
 558 Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, L., Yu, Y., and Zhao,
 559 Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum



- 560 – Part 2: feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes
561 heat budget, *Clim. Past*, 3, 279–296, 2007b.
- 562 Braconnot, P., Harrison, S., Kageyama, M., Bartlein, J., Masson, V., Abe-Ouchi, A., Otto-
563 Bliesner, B., and Zhao, Y.: Evaluation of climate models using palaeoclimatic data, *Nat.*
564 *Clim. Change*, 2, 417–424, 2012.
- 565 Brayshaw, D.J., Hoskins, B. and Black, E.: Some physical drivers of changes in the winter
566 storm tracks over the North Atlantic and Mediterranean during the Holocene. *Philosophical*
567 *Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 368,
568 5185–5223, 2010.
- 569 Brayshaw, D.J., Rambeau, C.M.C., and Smith, S.J.: Changes in the Mediterranean climate
570 during the Holocene: insights from global and regional climate modelling, *Holocene* 21, 15-
571 31, 2011a.
- 572 Brayshaw, D.J., Black, E., Hoskins, B. and Slingo, J.: Past climates of the Middle East. In:
573 Mithen, S. and Black, E. (eds.) *Water, Life and Civilisation: Climate, Environment and*
574 *Society in the Jordan Valley*. International Hydrology Series. Cambridge University Press,
575 Cambridge, pp. 25–50, 2011b
- 576 Carrión, J.S., Fernández, S., Jiménez-Moreno, G., Fauquette, S., Gil-Romera, G., González-
577 Sampériz, P. and Finlayson, C.: The historical origins of aridity and vegetation degradation in
578 southeastern Spain, *Journal of arid environments*, 74, 731–736, 2010.
- 579 Cheddadi, R., Yu, G., Guiot, J., Harrison, S.P., and Prentice, I.C.: The climate of Europe 6000
580 years ago, *Climate Dynamics* 13, 1–9, 1997.
- 581 Colmenero-Hidalgo, E., Flores, J.-A., and Sierro, F.J. Biometry of *Emiliana huxleyi* and its
582 biostratigraphic significance in the eastern north Atlantic Ocean and Western Mediterranean
583 Sea in the last 20,000 years, *Marine Micropaleontology*, 46, 247–263, 2002.
- 584 Colombaroli, D., Vannière, B., Chapron, E., Magny, M., and Tinner, W. Fire–vegetation
585 interactions during the Mesolithic–Neolithic transition at Lago dell’Accesa, Tuscany, Italy,
586 *The Holocene*, 18, 679–692, 2008.
- 587 Combourieu-Nebout, N., Paterne, M., Turon, J.-L., and Siani, G.: A high-resolution record of
588 the Last Deglaciation in the Central Mediterranean sea: palaeovegetation and
589 palaeohydrological evolution, *Quaternary Sci. Rev.*, 17, 303–332, 1998.



- 590 Combourieu-Nebout, N., Londeix, L., Baudin, F., and Turon, J.L.: Quaternary marine and
 591 continental palaeoenvironments in the Western Mediterranean Sea (Leg 161, Site 976,
 592 Alboran Sea): Palynological evidences, Proceeding of the Ocean Drilling Project, scientific
 593 results, 161, 457-468, 1999.
- 594 Combourieu-Nebout, N., Turon, J.L., Zahn, R., Capotondi, L., Londeix, L., and Pahnke, K.:
 595 Enhanced aridity and atmospheric high pressure stability over the western Mediterranean
 596 during North Atlantic cold events of the past 50 000 years, *Geology*, 30, 863-866, 2002.
- 597 Combourieu-Nebout, N., Peyron, O., Dormoy, I., Desprat, S., Beaudouin, C., Kotthoff, U.,
 598 and Marret, F.: Rapid climatic variability in the west Mediterranean during the last 25 000
 599 years from high resolution pollen data, *Clim. Past*, 5, 503-521, 2009.
- 600 Combourieu-Nebout, N., Peyron, O., Bout-Roumazeilles, V., Goring, S., Dormoy, I.,
 601 Joannin, S., Sadori, L., Siani, G., and Magny, M.: Holocene vegetation and climate
 602 changes in central Mediterranean inferred from a high-resolution marine pollen record
 603 (Adriatic Sea), *Clim. Past* 9, 2023-2042, 2013.
- 604 Davis, B. A. S., Brewer, S., Stevenson, A. C., and Guiot, J.: The temperature of Europe
 605 during the Holocene reconstructed from pollen data, *Quaternary Sci. Rev.*, 22, 1701–1716,
 606 2003.
- 607 Davis, B. A. S. and Brewer, S.: Orbital forcing and role of the latitudinal insolation/
 608 temperature gradient, *Clim. Dynam.*, 32, 143-165, 2009.
- 609 De Santis V. and Caldara M. The 5.5–4.5 kyr climatic transition as recorded by the
 610 sedimentation pattern of coastal deposits of the Apulia region, southern Italy, Holocene, 2015
- 611 Desprat, S., Combourieu-Nebout, N., Essallami, L., Sicre, M. A., Dormoy, I., Peyron, O.,
 612 Siani, G., Bout Roumazeilles, V., and Turon, J. L.: Deglacial and Holocene vegetation
 613 and climatic changes in the southern Central Mediterranean from a direct land-sea
 614 correlation, *Clim. Past*, 9, 767–787, 2013.
- 615 Djamali, M., Gambin, B., Marriner, N., Andrieu-Ponel, V., Gambin, T., Gandouin, E.,
 616 Médail, F., Pavon, D., Ponel, P., and Morhange, C.: Vegetation dynamics during the early to
 617 mid-Holocene transition in NW Malta, human impact versus climatic forcing. *Vegetation*
 618 *History and Archaeobotany* 22, 367-380, 2013.
- 619 Dormoy, I., Peyron, O., Combourieu Nebout, N., Goring, S., Kotthoff, U., Magny, M. and
 620 Pross, J.: Terrestrial climate variability and seasonality changes in the Mediterranean region



- 621 between 15,000 and 4,000 years B.P. deduced from marine pollen records, *Clim. Past*, 5, 615-
622 632, 2009.
- 623 Drescher-Schneider, R., de Beaulieu, J.L., Magny, M., Walter-Simonnet, A.V., Bossuet, G.,
624 Millet, L. Brugiapaglia, E., and Drescher A.: Vegetation history, climate and human impact
625 over the last 15 000 years at Lago dell'Accesa, *Veg. Hist. Archaeobot.*, 16, 279–299, 2007.
- 626 Eastwood, WJ., Leng, M., Roberts, N. and Davis B.: Holocene climate change in the eastern
627 Mediterranean region: a comparison of stable isotope and pollen data from Lake Gölhisar,
628 southwest Turkey, *J. Quaternary Science* 22, 327–341, 2007.
- 629 Finné, M., Holmgren, K., Sundqvist, H.S., Weiberg, E., and Lindblom, M.: Climate in the
630 eastern Mediterranean, and adjacent regions, during the past 6000 years, *J. Archaeol. Sci.*, 38,
631 3153-3173, 2011.
- 632 Fischer N., and Jungclaus, J. H.: Evolution of the seasonal temperature cycle in a transient
633 Holocene simulation: orbital forcing and sea-ice, *Clim. Past*, 7, 1139-1148, 2011.
- 634 Fletcher, W.J., and Sánchez Goñi, M.F.: Orbital- and sub-orbital-scale climate impacts on
635 vegetation of the western Mediterranean basin over the last 48,000 yr, *Quat. Res.* 70, 451-464,
636 2008.
- 637 Fletcher, W.J., Sanchez Goñi, M.F., Peyron, O., and Dormoy, I.: Abrupt climate changes of
638 the last deglaciation detected in a western Mediterranean forest record. *Clim. Past* 6, 245-264,
639 2010.
- 640 Fletcher, W.J., Debret, M., and Sanchez Goñi, M.F., Mid-Holocene emergence of a low-
641 frequency millennial oscillation in western Mediterranean climate: Implications for past
642 dynamics of the North Atlantic atmospheric westerlies. *The Holocene*, 23, 153-166, 2013.
- 643 Gambin B., Andrieu-Ponel V., Médail F., Marriner N., Peyron O., Montade V., Gambin T.,
644 Morhange C., Belkacem D., and Djamali M.: 7300 years of vegetation history and
645 quantitative climate reconstruction for NW Malta: a Holocene perspective. *Clim. Past* 12,
646 273-297, 2016
- 647 Geraga, M., Ioakim, C., Lykousis, V., Tsaila-Monopolis, S., and Mylona, G.: The high-
648 resolution palaeoclimatic and palaeoceanographic history of the last 24,000 years in the
649 central Aegean Sea, Greece, *Palaeogeogr. Palaeoclimatol.*, 287, 101–115, 2010.
- 650 Giorgi, F. and Lionello, P.: Climate change projections for the Mediterranean region, *Global*
651 *Planet. Change*, 63, 90–104, 2008.



- 652 Gogou, A., Bouloubassi, I., Lykousis, V., Arnaboldi, M., Gaitani, P., and Meyers, P.A.:
 653 Organic geochemical evidence of abrupt late glacial- Holocene climate changes in the North
 654 Aegean Sea, *Palaeogeogr. Palaeoclimatol.*, 256, 1 – 20, 2007.
- 655 Gogou, A., Triantaphyllou, M., Xoplaki, E., Izdebski, A., Parinos, C., Dimiza, M.,
 656 Bouloubassi, I., Luterbacher, J., Kouli, K., Martrat, B., Toreti, A., Fleitmann, D., Rousakis,
 657 G., Kaberi, H., Athanasiou, M., and Lykousis, V.: Climate variability and socio-
 658 environmental changes in the northern Aegean (NE Mediterranean) during the last 1500
 659 years, *Quaternary Science Reviews*, 136, 209-228, 2016.
- 660 Guiot J.: Methodology of the last climatic cycle reconstruction in France from pollen data,
 661 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 80, 49–69, 1990.
- 662 Guiot, J. and Kaniewski, D.: The Mediterranean Basin and Southern Europe in a warmer
 663 world: what can we learn from the past? *Front. Earth Sci.*, 18, 2015.
- 664 Hargreaves, J.C., Annan, J.D., Ohgaito, R., Paul, A., and Abe-Ouchi, A.: Skill and reliability
 665 of climate model ensembles at the Last Glacial Maximum and mid-Holocene, *Clim. Past*, 9,
 666 811-823, 2013.
- 667 Heiri, O., Brooks, S.J., Renssen, H., and 26 authors: Validation of climate model-inferred
 668 regional temperature change for late-glacial Europe. *Nature Communications* 5, 4914, 2014.
- 669 Heusser, L.E., and Balsam W.L.: Pollen distribution in the N.E. Pacific ocean, *Quaternary*
 670 *Research*, 7, 45-62, 1977.
- 671 Hewitt, C.D., Senior, C.A., and Mitchell, J.F.B. :The impact of dynamic sea-ice on the
 672 climatology and sensitivity of a GCM: A study of past, present and future climates, *Climate*
 673 *Dynamics* 17: 655–668, 2001.
- 674 Holmgren, K., Gogou, A., Izdebski, A., Luterbacher, J., Sicre, M.A., and Xoplaki, A.:
 675 Mediterranean Holocene Climate, Environment and Human Societies, *Quaternary Science*
 676 *Reviews*, 136, 1-4, 2016.
- 677 Ioakim, Chr., Triantaphyllou, M., Tsaila-Monopolis, S., and Lykousis, V.: New
 678 micropalaeontological records of Eastern Mediterranean marine sequences recovered offshore
 679 of Crete, during HERMES cruise and their palaeoclimatic paleoceanographic significance.
 680 *Acta Naturalia de “L’Ateneo Parmense”*, 45(1/4): p. 152. In: *Earth System Evolution and the*
 681 *Mediterranean Area from 23 Ma to the Present*”, 2009.



- 682 Jimenez-Moreno, G., Rodriguez-Ramirez, A., Perez-Asensio, J.N., Carrion, J.S., Lopez-
683 Saez, J.A., Villarías-Robles J., Celestino-Perez, S., Cerrillo-Cuenca, E., Leon, A., and
684 Contreras, C.: Impact of late-Holocene aridification trend, climate variability and geodynamic
685 control on the environment from a coastal area in SW Spain, *The Holocene*, 1-11, 2015
- 686 Joannin, S., Vannière, B., Galop, D., Peyron, O., Haas, J.N., Gilli, A., Chapron, E., Wirth, S.,
687 Anselmetti, F., Desmet, M., and Magny, M.: Climate and vegetation changes during the
688 Lateglacial and Early-Mid Holocene at Lake Ledro (southern Alps, Italy), *Clim. Past* 9, 913-
689 933, 2013.
- 690 Joannin, S., Brugiapaglia, E., de Beaulieu, J.L, Bernardo, L., Magny, M., Peyron, O., Goring,
691 S., and Vannière, B.: Pollen-based reconstruction of Holocene vegetation and climate in
692 southern Italy: the case of Lago Trifoglietti., *Clim. Past*, 8, 1973-1996, 2012.
- 693 Kotthoff, U., Pross, J., Müller, U.C., Peyron, O., Schmiedl, G., and Schulz, H. Climate
694 dynamics in the borderlands of the Aegean Sea during formation of Sapropel S1 deduced
695 from a marine pollen record, *Quaternary Sci. Rev.*, 27, 832–845, 2008.
- 696 Kotthoff, U., Koutsodendris, A., Pross, J., Schmiedl, G., Bornemann, A., Kaul, C., Marino,
697 G., Peyron, O., and Schiebel, R. Impact of late glacial cold events on the Northern Aegean
698 region reconstructed from marine and terrestrial proxy data, *J. Quat. Sci.*, 26, 86-96, 2011.
- 699 Kouli, K., Gogou, A., Bouloubassi, I., Triantaphyllou, M.V., Ioakim, Chr, Katsouras, G.,
700 Roussakis, G., and Lykousis, V.: Late postglacial paleoenvironmental change in the
701 northeastern Mediterranean region: Combined palynological and molecular biomarker
702 evidence, *Quatern. Int.*, 261, 118-127, 2012.
- 703 Kuhnt, T., Schmiedl, G., Ehrmann, W., Hamann, Y., and Andersen, N.: Stable isotopic
704 composition of Holocene benthic foraminifers from the eastern Mediterranean sea: past
705 changes in productivity and deep water oxygenation. *Palaeogeography, Palaeoclimatology,*
706 *Palaeoecology* 268, 106-115, 2008.
- 707 Lionello, P, Malanotte-Rizzoli, P, Boscolo, R, Alpert, P, Artale, V, Li, L. et al., The
708 Mediterranean climate: An overview of the main characteristics and issues. In: Lionello P,
709 Malanotte-Rizzoli P and Boscolo R (eds) *Mediterranean Climate Variability. Developments*
710 *in Earth & Environmental Sciences* 4, Elsevier, 1–26, 2006.
- 711 Lionello, P. (Ed.): *The climate of the Mediterranean region, From the past to the future,*
712 Elsevier, ISBN: 9780124160422, 2012.



- 713 Luterbacher, J., García-Herrera, R., Akcer-On, S., Allan R., Alvarez-Castro M.C, and 41
714 authors: A review of 2000 years of paleoclimatic evidence in the Mediterranean. In: Lionello,
715 P. (Ed.), The Climate of the Mediterranean region: from the past to the future. Elsevier,
716 Amsterdam, The Netherlands, 2012.
- 717 Magny, M., de Beaulieu, J.L., Drescher-Schneider, R., Vannière, B., Walter-Simonnet, A.V.,
718 Miras, Y., Millet, L., Bossuet, G., Peyron, O., Brugiapaglia, E., and Leroux, A. : Holocene
719 climate changes in the central Mediterranean as recorded by lake-level fluctuations at Lake
720 Accessa (Tuscany, Italy), Quaternary Sci. Rev. 26, 1736–1758, 2007.
- 721 Magny, M., Vannière, B., Zanchetta, G., Fouache, E., Touchais, G., Petrika, L., Coussot, C.,
722 Walter-Simonnet, A.V., and Arnaud, F.: Possible complexity of the climatic event around
723 4300-3800 cal BP in the central and western Mediterranean, The Holocene, 19, 823-833,
724 2009.
- 725 Magny, M., Vannière, B., Calo, C., Millet, L., Leroux, A., Peyron, O., Zanchetta, G., La
726 Mantia, T. and Tinner, W.: Holocene hydrological changes in south-western Mediterranean as
727 recorded by lake-level fluctuations at Lago Preola, a coastal lake in southern Sicily, Italy,
728 Quaternary Sci. Rev., 30, 2459-2475, 2011.
- 729 Magny, M., Joannin, S., Galop, D., Vannière, B., Haas, J.N, Bassetti, M., Bellintani, P.,
730 Scandolari, R., and Desmet, M.: Holocene palaeohydrological changes in the northern
731 Mediterranean borderlands as reflected by the lake-level record of Lake Ledro, northeastern
732 Italy, Quaternary Res., 77, 382-396, 2012a.
- 733 Magny, M., Peyron, O., Sadori, L., Ortu, E., Zanchetta, G., Vannière, B., and Tinner, W.:
734 Contrasting patterns of precipitation seasonality during the Holocene in the south- and north-
735 central Mediterranean, J. Quaternary Sci., 27, 290–296, 2012b.
- 736 Magny, M. and 29 authors: North-south palaeohydrological contrasts in the central
737 Mediterranean during the Holocene: tentative synthesis and working hypotheses, Clim. Past 9,
738 2043-2071, 2013.
- 739 Mauri, A., Davis, B., Collins, P.M. and Kaplan, J.: The climate of Europe during the
740 Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation, Quat. Sc.
741 Rev. 112, 109-127, 2014.



- 742 Mauri, A., Davis, B., Collins, P.M. and Kaplan, J.: The influence of atmospheric circulation
743 on the mid-Holocene climate of Europe: a data–model comparison, *Clim. Past* 10, 1925-1938,
744 2015.
- 745 Morrill, C., Anderson, D.M, Bauer, B.A, Buckner, R.E., Gille, P., Gross, W.S., Hartman, M.,
746 and Shah, A.: Proxy benchmarks for intercomparison of 8.2 ka simulations, *Clim. Past* 9, 423-
747 432, 2013.
- 748 Naughton, F., Sanchez Goñi, M.F., Desprat, S., Turon, J.L., Duprat, J., Malaizé, B., Joli, C.,
749 Cortijo, E., Drago, T., and Freitas, M.C.: Present-day and past (last 25 000 years) marine
750 pollen signal off western Iberia, *Marine Micropaleontology* 62, 91-114, 2007.
- 751 Nourelbait, M., Rhoujjati, A., Benkaddour, A., Carré, M., Eynaud, F., Martinez, P. and
752 Cheddadi, R.: Climate change and ecosystems dynamics over the last 6000 years in the
753 Middle Atlas, Morocco, *Clim. Past* 12, 1029-1042, 2016.
- 754 Peyron, O., Goring, S., Dormoy, I., Kotthoff, U., Pross, J., de Beaulieu, J.L., Drescher-
755 Schneider, R., and Magny, M.: Holocene seasonality changes in the central Mediterranean
756 region reconstructed from the pollen sequences of Lake Accesa (Italy) and Tenaghi Philippon
757 (Greece), *The Holocene*, 21, 131-146, 2011.
- 758 Peyron, O., Magny, M., Goring, S., Joannin, S., de Beaulieu, J.-L., Brugiapaglia, E., Sadori,
759 L., Garfi, G., Kouli, K., Ioakim, C., and Combourieu-Nebout, N. Contrasting patterns of
760 climatic changes during the Holocene in the central Mediterranean (Italy) reconstructed from
761 pollen data, *Clim. Past* 9, 1233-2013, 2013.
- 762 Pope, V.D., Gallani, M.L., Rowntree, R.R. and Stratton, R.A.: The impact of new physical
763 parameterizations in the Hadley Centre climate model: HadAM3, *Climate Dynamics* 16, 123-
764 146, 2000.
- 765 Pross, J., Kotthoff, U., Müller, U.C., Peyron, O., Dormoy, I., Schmiedl, G., Kalaitzidis, S.,
766 and Smith, A.M.: Massive perturbation in terrestrial ecosystems of the Eastern Mediterranean
767 region associated with the 8.2 kyr climatic event, *Geology*, 37, 887-890, 2009.
- 768 Ramos-Román, M.J., Jiménez-Moreno, G., Anderson, R.S., García-Alix, A., Toney, J.L.,
769 Jiménez-Espejo, F.J. and Carrión, J.S.: Centennial-scale vegetation and North Atlantic
770 Oscillation changes during the Late Holocene in the southern Iberia, *Quaternary Science*
771 *Reviews*, 143, 84-98, 2016.



- 772 Renssen, H., Seppa, H., Crosta, X., Goosse, H., and Roche, D.M.: Global characterization of
 773 the Holocene Thermal Maximum, *Quat. Sci. Rev.*, 48, 7-19, 2012.
- 774 Roberts, N., Brayshaw, D., Kuzucuoğlu, C., Perez, R., and Sadori, L.: The mid-Holocene
 775 climatic transition in the Mediterranean: Causes and consequences, *The Holocene*, 21, 3-13,
 776 2011.
- 777 Roberts, N., Moreno, A., Valero-Garces, B. L., Corella, J. P., Jones, M., Allcock, S., et al.
 778 Palaeolimnological evidence for an east-west climate see-saw in the mediterranean since AD
 779 900, *Glob. Planet. Change*, 84-85, 23-34, 2012.
- 780 Rohling, E.J., Cane, T.R., Cooke, S., Sprovieri, M., Bouloubassi, I., Emeis, K.C. et al: African
 781 monsoon variability during the previous interglacial maximum, *Earth Planet. Sc. Lett.*, 202,
 782 61-75, 2002.
- 783 Sadori, L. and Narcisi, B.: The postglacial record of environmental history from Lago di
 784 Pergusa, Sicily, *The Holocene*, 11, 655-671, 2001.
- 785 Sadori, L. and Giardini, M.: Charcoal analysis, a method to study vegetation and climate of
 786 the Holocene: The case of Lago di Pergusa, Sicily (Italy), *Geobios-Lyon*, 40, 173-180, 2007.
- 787 Sadori, L., Zanchetta, G., and Giardini, M.: Last Glacial to Holocene palaeoenvironmental
 788 evolution at Lago di Pergusa (Sicily, Southern Italy) as inferred by pollen, microcharcoal, and
 789 stable isotopes, *Quatern. Int.*, 181, 4-14, 2008.
- 790 Sadori, L., Jahns, S., and Peyron, O.: Mid-Holocene vegetation history of the central
 791 Mediterranean, *The Holocene*, 21, 117-129, 2011.
- 792 Sadori, L., Ortu, E., Peyron, O., Zanchetta, G., Vannière, B., Desmet, M., and Magny, M.: The
 793 last 7 millennia of vegetation and climate changes at Lago di Pergusa (central Sicily, Italy),
 794 *Clim. Past*, 9, 1969-1984, 2013.
- 795 Sadori, L., Giraudi, C. Masi, A., Magny, M., Ortu, E., Zanchetta, G., and Izdebski, A.
 796 Climate, environment and society in southern Italy during the last 2000 years. A review of the
 797 environmental, historical and archaeological evidence, *Quaternary Science Reviews*, 136,
 798 173-188, 2016a.
- 799 Sadori, L., Koutsodendris, A., Masi, A., Bertini, A., Combourieu-Nebout, N., Francke, A.,
 800 Kouli, K., Joannin, S., Mercuri, A.M, Panagiotopoulos, K., Peyron, O., Torri, P., Wagner, B.,
 801 Zanchetta, G., and Donders, T.H.: Pollen-based paleoenvironmental and paleoclimatic



- 802 change at Lake Ohrid (SE Europe) during the past 500 ka, *Biogeosciences* 12, 15461-15493,
803 2016b.
- 804 Stevens, L.R., Ito, E., Schwalb, A., and Wright, H.E.: Timing of atmospheric precipitation in
805 the Zagros Mountains inferred from a multi-proxy record from Lake Mirabad, Iran. *Quat.*
806 *Res.* 66, 494-500, 2006.
- 807 Tarroso, P., Carrión, J., Dorado-Valiño, M., Queiroz, P., Santos, L., Valdeolmillos-Rodríguez,
808 A., Célio Alves, P., Brito, J. C., and Cheddadi, R.: Spatial climate dynamics in the Iberian
809 Peninsula since 15 000 yr BP, *Clim. Past*, 12, 1137-1149, 2016.
- 810 Triantaphyllou, V., Antonarakou, A., Kouli, K., Dimiza, M., Kontakiotis, G., Papanikolaou,
811 M.D. et al.: Late Glacial–Holocene ecostratigraphy of the south-eastern Aegean Sea, based on
812 plankton and pollen assemblages, *Geo-Mar. Lett.*, 29, 249-267, 2009a.
- 813 Triantaphyllou, M.V., Ziveri, P., Gogou, A., Marino, G., Lykousis, V., Bouloubassi, I.,
814 Emeis, K.-C., Kouli, K., Dimiza, M., Rosell-Mele, A., Papanikolaou, M., Katsouras, G., and
815 Nunez, N.: Late Glacial-Holocene climate variability at the south-eastern margin of the
816 Aegean Sea, *Mar. Geol.*, 266, 182-197, 2009b.
- 817 Triantaphyllou, M.V., Gogou, A., Bouloubassi, I., Dimiza, M., Kouli, K., Rousakis, A.G.,
818 Kothhoff, U., Emeis, K.C., Papanikolaou, M., Athanasiou, M., Parinos, C., Ioakim, C., V. and
819 Lykousis, V.: Evidence for a warm and humid Mid-Holocene episode in the Aegean and
820 northern Levantine Seas (Greece, NE Mediterranean), *Regional Environmental Change*, 14,
821 1697-1712, 2014.
- 822 Triantaphyllou, M.V., Gogou, A., Dimiza, M.D., Kostopoulou, S., Parinos, C., Roussakis, G.,
823 Geraga, M., Bouloubassi, I., Fleitmann, D., Zervakis, V., Velaoras, D., Diamantopoulou, A.,
824 Sampatakis, A. and Lykousis, V.: Holocene Climate Optimum centennial-scale
825 paleoceanography in the NE Aegean Sea (Mediterranean Sea). *Geo-Marine Letters*, 36, 51-66,
826 2016.
- 827 Trigo R.M. and 21 coauthors: Relations between variability in the Mediterranean region and
828 Mid-latitude variability. In: Lionello P, Malanotte-Rizzoli P, Boscolo R, Eds., *The*
829 *Mediterranean Climate: an overview of the main characteristics and issues*. Elsevier,
830 Amsterdam, 2006.
- 831 Tzedakis, P.C.: Seven ambiguities in the Mediterranean palaeoenvironmental narrative,
832 *Quaternary Sci. Rev.*, 26, 2042-2066, 2007.



- 833 Vanni re, B., Power, M.J., Roberts, N., Tinner, W., Carrion, J., Magny, M., Bartlein, P., and
834 Contributors Data: Circum-Mediterranean fire activity and climate changes during the mid
835 Holocene environmental transition (8500-2500 cal yr BP), *The Holocene*, 21, 53-73, 2011.
- 836 Vanni re, B., Magny, M., Joannin, S., Simonneau, A., Wirth, S.B., Hamann, Y., Chapron,
837 E., Gilli, A., Desmet, M., and Anselmetti, F.S.: Orbital changes, variation in solar activity and
838 increased anthropogenic activities: controls on the Holocene flood frequency in the Lake
839 Ledro area, Northern Italy, *Clim. Past*, 9, 1193-1209, 2013.
- 840 Verheyden S., Nader F.H., Cheng H.J., Edwards L.R. and Swennen R.: Paleoclimate
841 reconstruction in the Levant region from the geochemistry of a Holocene stalagmite from the
842 Jeita cave, Lebanon. *Quaternary Research*, 70, 368-381, 2008.
- 843 Walczak, I.W., Baldini, J.U.L., Baldini, L.M., Mcdermott, F., Marsden, S., Standish, C.D,
844 Richards, D.A., Andreo, B and Slater J.: Reconstructing high-resolution climate using CT
845 scanning of unsectioned stalagmites: A case study identifying the mid-Holocene onset of the
846 Mediterranean climate in southern Iberia, *Quaternary Science Reviews* 127, 117-128, 2015.
- 847 Wilks D. S.: *Statistical methods in the atmospheric sciences* (Academic Press, San Diego,
848 CA), 1995.
- 849 Wood, S.N. Fast stable restricted maximum likelihood and marginal likelihood estimation of
850 semiparametric generalized linear models. *Journal of the Royal Statistical Society (B)* 73(1),
851 3-36, 2011.
- 852 Wu, H., Guiot, J., Brewer, S., and Guo, Z.: Climatic changes in Eurasia and Africa
853 at the Last Glacial Maximum and mid-Holocene: reconstruction from pollen data using
854 inverse vegetation modelling, *Clim. Dyn.*, 29, 211-229, 2007.
- 855 Zanchetta, G., Borghini, A., Fallick, A.E., Bonadonna, F.P., and Leone, G.: Late Quaternary
856 palaeohydrology of Lake Pergusa (Sicily, southern Italy) as inferred by stable isotopes of
857 lacustrine carbonates, *J. Paleolimnol.*, 38, 227-239, 2007.
- 858 Zhorniyak, L.V., Zanchetta, G., Drysdale, R.N., Hellstrom, J.C., Isola, I., Regattieri, E.,
859 Piccini, L., Baneschi, I., and Couchoud, I.: Stratigraphic evidence for a “pluvial phase”
860 between ca. 8200-7100 ka from Renella cave (Central Italy), *Quat. Sci. Rev.*, 30, 409-417,
861 2011.

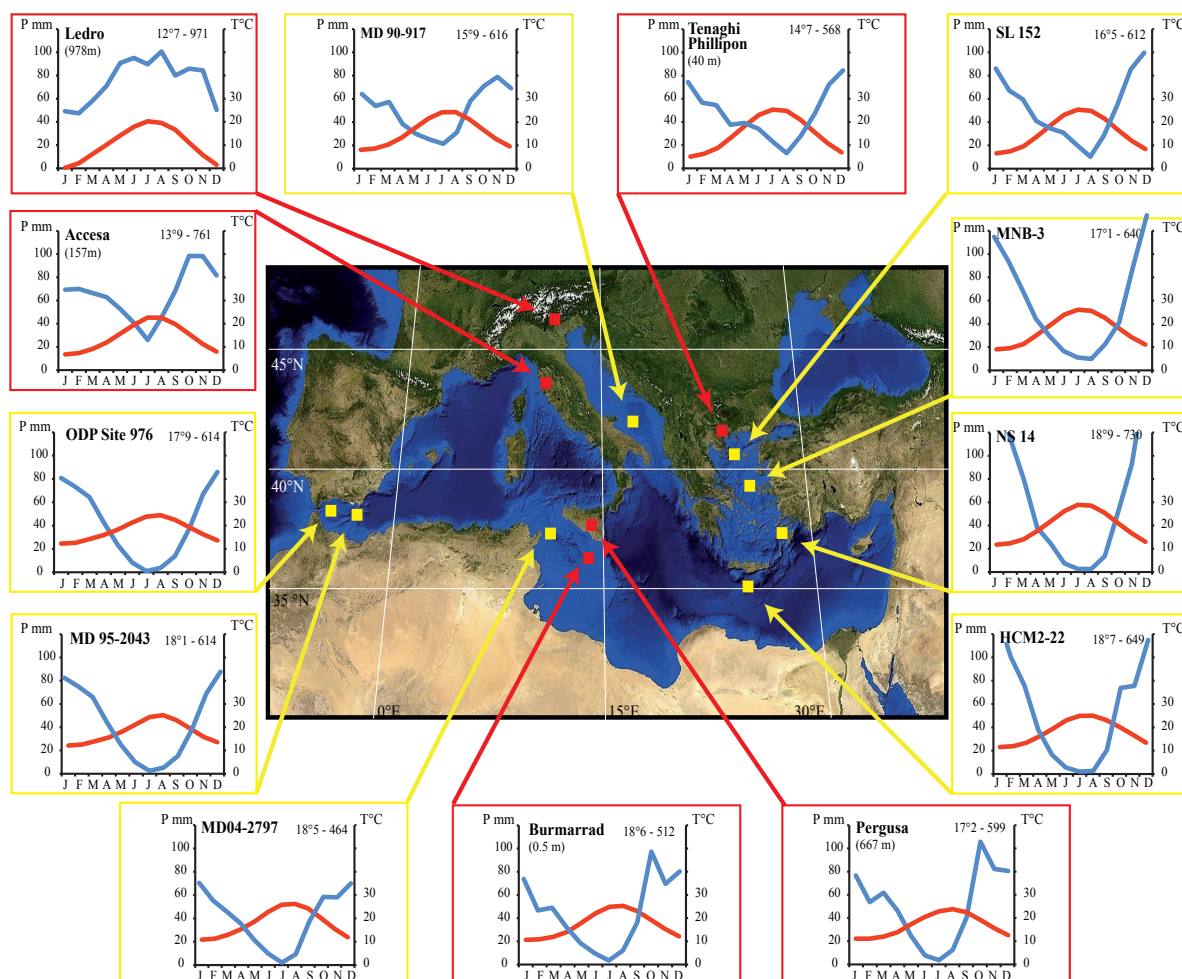


Figure 1: Locations of terrestrial (red) and marine (yellow) pollen records. Ombrothermic diagrams are calculated with the NewLoclim software, which provides estimates of average climatic conditions at locations for which no observations are available (ex.: marine pollen cores).

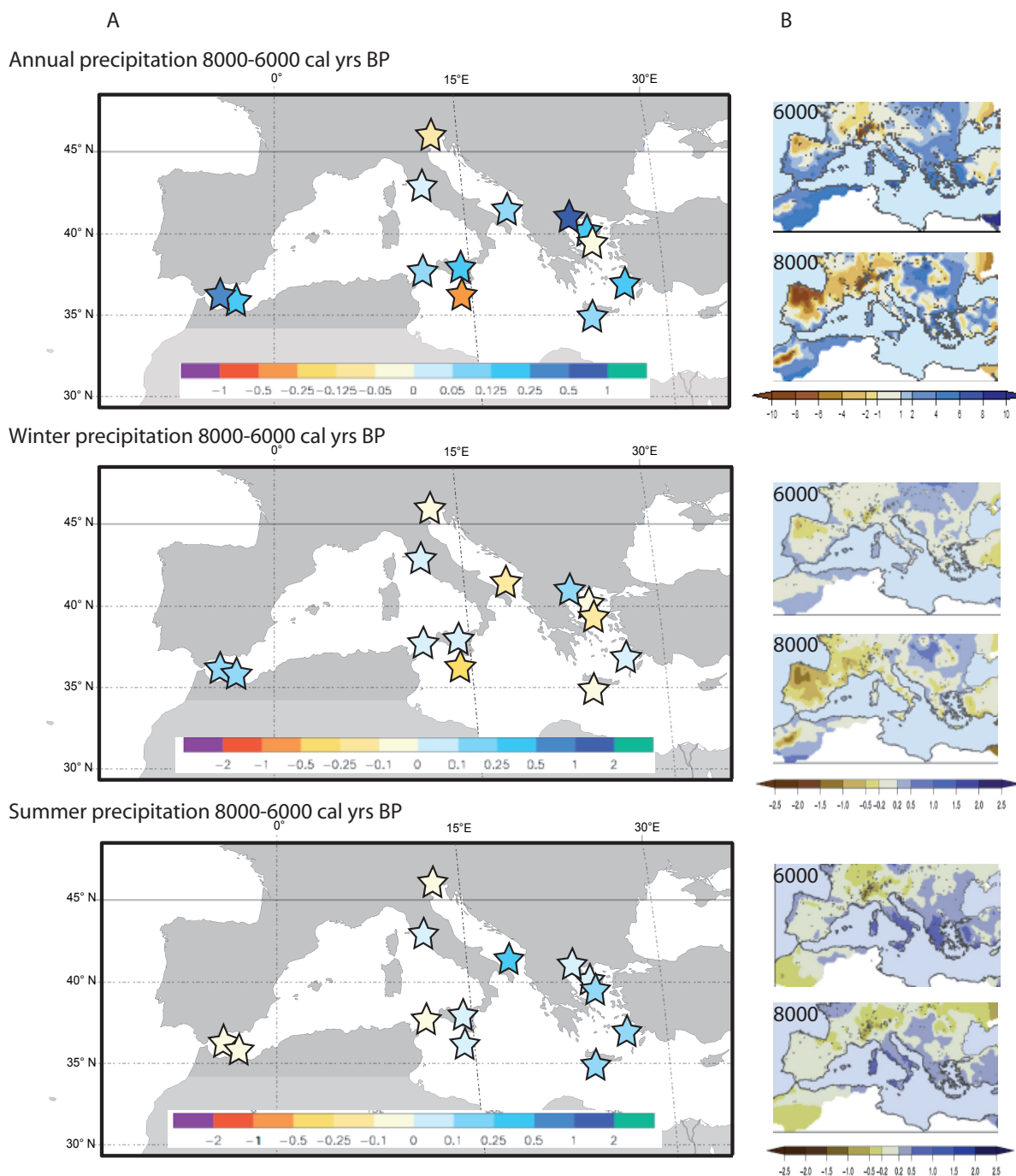


Figure 2: 8000-6000 cal years BP

(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).

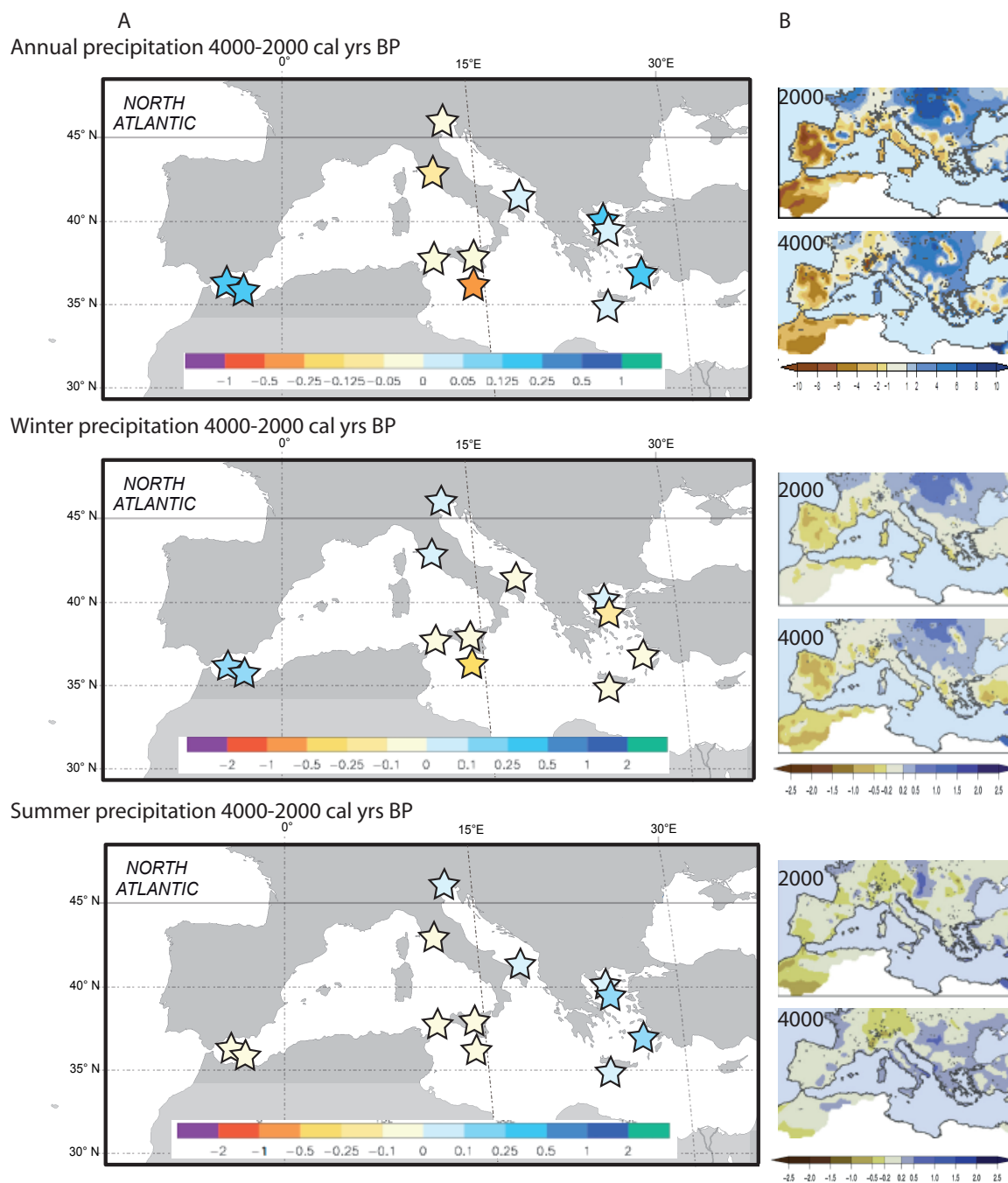
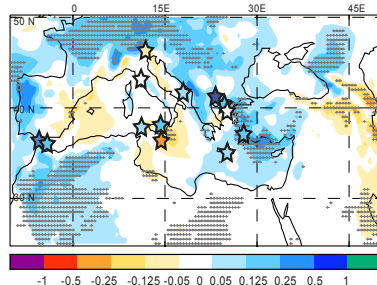


Figure 2: 4000-2000 cal yrs BP

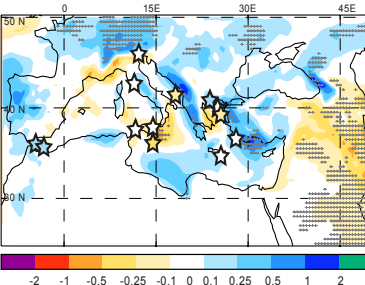


Mid-Holocene: 8000 to 6000 cal BP

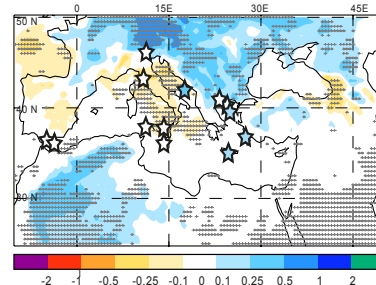
(a) Annual precipitation (anomalie mm/day)



(b) winter precipitation (anomalie mm/day)



(c) summer precipitation (anomalie mm/day)



Late Holocene: 4000 to 2000 cal BP

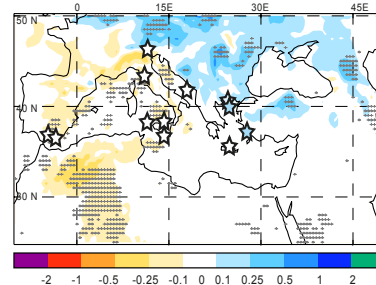
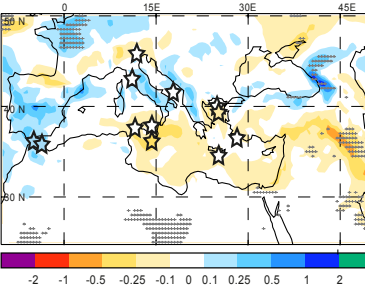
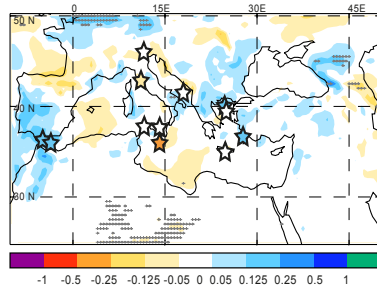


Figure 3: Data-model comparison for mid and late Holocene precipitation, expressed in anomaly (mm/day).

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.



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.