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Holocene hydro-climatic variability in the Mediterranean: a synthetic multi-proxy reconstruction

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Abstract

Here we identify and analyze proxy data interpreted to reflect hydro-climatic variability over the last 10000 years from the Mediterranean region to: 1) outline millennial and multi-centennial scale trends and 2) identify regional patterns of hydro-climatic variability. A total of 47 lake, cave and marine records were transformed to z-scores to allow direct comparisons between sites, put on a common timescale and binned into 200-year time slices. Six different regions were identified based on numerical and spatial analyzes of z-scores: S Iberia and Maghreb, N Iberia, Italy, the Balkans, Turkey, and the Levant, and the overall hydro-climate history of each region was reconstructed. N Iberia is largely decoupled from the five other regions throughout the Holocene. Wetter conditions occur in the five other regions between 8500 to 6100 yrs BP. After 6000 yrs BP climate oscillated until around 3000±300 yrs BP, which seems to have been the overall driest period in the Eastern Mediterranean and North Africa. In contrast, Italy and N Iberia seem to have remained wetter during this period. In addition, non-metric multidimensional scaling (nMDS) was applied to 18 long, continuous climate z-score records that span the majority of the Holocene. nMDS axes 1 and 2 illustrate the main trends in the z-score data. The first axis captures a long-term development of drier condition in the Mediterranean from 7900 to 3700 yrs BP. Rapid shifts occur in nMDS axis 2 at 6700 to 6300 BP, 4500 to 4300 BP, and 3500 to 3300 BP indicating centennial-scale climate change. Our synthesis highlights a dominant south/east vs north/west Mediterranean hydro-climate dipole throughout the Holocene and therefore confirms that there was no single climate trajectory characterizing the whole Mediterranean basin during the last ten millennia.

Keywords

Mediterranean, Holocene, paleoclimate, hydro-climate, nMDS, proxy synthesis

1. Introduction

During the course of the Holocene the Mediterranean region has seen human societies flourish and decline, empires come and go but humans have always persisted. The development, longevity, and well-being of human societies in the Mediterranean have often been linked to the climate of the region (Andel et al., 1986; Cline, 2014; Drake, 2012; Kaniewski et al., 2015; Knapp and Manning, 2016; Labuhn et al., 2016; Middleton, 2017; Roberts et al., 2011b; Weiss et al., 1993). The Mediterranean is characterized by a wealth of archaeological studies as well as a relatively dense network of paleoclimatic archives that make it a perfect case study to investigate the potential influence of climate on human societies and civilizations. Climate and climate variability have, on many occasions, been used to interpret and explain profound and rapid social transformations in human societies both on long (millennial to multi-centennial) and short (centennial to decadal) time scales (Berger and Guilaine, 2009; Kaniewski et al., 2013, 2015; Roberts et al., 2011b; Rosen and Rivera-Collazo, 2012; Weiss et al., 1993).

Linking archaeological and historical evidence with paleoclimate information is challenging, not only because of the often complex causal relationships between them, but also because the reconstructed 'picture' of the past is temporally incomplete, spatially inconsistent and restricted by uncertainties (see for instance, Knapp and Manning, 2016). Archaeological studies document societal change related to settlements, migration, or agricultural practices. However, the causes of such changes are more difficult to deduce from the archaeological material alone, which often presents challenges in terms of representativity, interpretability and chronology. Historical documents may be more specific in many of these respects (e.g. Telelis, 2008), but can be incomplete, discontinuous or biased. Paleoclimate information is based on proxy measurements in natural climate archives, but any reconstruction of, or explanations about, the climate of the past are based on interpretations, or statistically based estimates of the climate state for the pre-instrumental period. In addition, there is uncertainty related to sampling, chronology, replication and calibration, which should be clearly communicated. These uncertainties are inherent to the material that archaeologists, historians and paleoclimatologists work with, but some may be overcome as new investigations add extra pieces to the puzzle. That is why the study of climate, archaeology and history requires an interdisciplinary approach (e.g. Caseldine and Turney, 2010; Haldon et al., 2014; Izdebski et al., 2016).

The Mediterranean region generally experiences a climate of summer drought and winter rain (Köppen type Cs) (Lionello et al., 2006b, 2012). It marks a transitional zone between the Maghreb-Arabian arid zone, dominated by subtropical high pressure, and central-northern Europe, affected by westerly circulation. Precipitation is largely cyclonic and local cyclogenesis is well developed and primarily occurs over the Mediterranean Sea principally south of Genoa and near Cyprus (Harding et al., 2009; Lionello et al., 2006a; Trigo et al., 1999). Most cyclones, however, ultimately originate from the North Atlantic via synoptic disturbances (Lionello et al., 2006a; Trigo et al., 1999, 2002). The present-day climate presents clear spatial patterns that differentiate various parts of the Mediterranean region. On a basin scale, the northern (European) borderlands are overall wetter than those to the south and east, in Maghreb and southwest Asia.

Inter-annual variability in precipitation in the Mediterranean is influenced by the synoptic conditions that also affect adjacent regions, such as Western Europe. Observational records of precipitation in the western Mediterranean show a strong negative correlation with the state of the North Atlantic Oscillation (NAO) index (Trigo et al., 2004; Xoplaki et al., 2004). Instrumental precipitation records for the north-eastern sector of the Mediterranean show a weaker positive correlation with the NAO, a link that may also be evident in river-discharge and tree ring records (Cullen and deMenocal, 2000). This part of the Mediterranean can also be strongly influenced by the western Russian and/or Scandinavian High Pressure System in winter (e.g. Corte-Real et al., 1995; Lionello et al., 2006b). The influence of the Saharo-Arabian arid zone to the south is felt primarily during summer, when anticyclonic conditions migrate north to create seasonal drought. There is no evidence that summer monsoonal rains ever reached as far north as the Mediterranean Sea during the Holocene, so that precipitation sources in the Maghreb and the Sahel are decoupled, and instrumental rainfall time-series show no historical correlation (Ward et al., 1999). There are, however, teleconnections between the South Asian monsoon and summer weather conditions in the eastern Mediterranean, for example, via the ‘meltem’ or Etesian winds (Ziv et al., 2004). In addition, indirect links between the African Monsoon and the Mediterranean have been demonstrated both in the past and the present (Gaetani and Fontaine, 2014; Milner et al., 2012; Regattieri et al., 2015; Toucanne et al., 2015; Tzedakis, 2007). Beyond the influence of atmospheric circulation, the climate in the Mediterranean is strongly affected by orography linked to large scale and local topography, land-sea interactions as well as the Mediterranean Sea itself (Lionello et al., 2006b; Trigo et al., 1999, 2002). Many areas of the Mediterranean are semi-arid and the strong seasonal nature of precipitation, in combination with a pronounced seasonal evaporation, means that hydrological resources in the region are sensitive to climate change (García-Ruiz et al., 2011; e.g. Lionello et al., 2006b). Water management and conservation is important for present-day Mediterranean societies, and was also likely to have been a key issue in the past, especially in relation to agricultural practices (Halstead, 1989; Staubwasser and Weiss, 2006). Understanding hydrological variability in the Mediterranean in the long term is key to a better understanding of societal development and longevity in the past as well as in the future.

The climate during the Holocene displays both long-term millennial variability and variation at higher frequencies that is linked to multiple controls (Mayewski et al., 2004; Wanner et al., 2008, 2011). Three natural forcings, orbital, solar and volcanic, are generally seen as having the strongest influence on global climate. Insolation changes in response to orbital changes present a significant difference between the early and late Holocene (Berger and Loutre, 1991). In general, a decline in the receipt of incoming solar radiation in the Northern Hemisphere summer was associated with a cooling trend over the northern continents and the Atlantic Ocean and reduced seasonal differences (Wanner et al., 2008 and references therein). In the Mediterranean region long-term trends and shorter term variability in hydro-climate during the Holocene has long been attested in multiple records derived from different types of natural archives.

The overall aim of this paper is to provide a comprehensive review of paleoclimate proxy data from the Mediterranean for the last 10000 years, covering most of the Holocene . Previous review type papers with a focus on Holocene climate in the Mediterranean have tended to focus on: 1) shorter time periods (e.g. Finné et al., 2011; Labuhn et al., 2016; Luterbacher et al., 2012; Moreno et al., 2012; Roberts et al., 2011b, 2012), 2) specific geographical areas (e.g. Finné et al., 2011; Moreno et al., 2012; Robinson et al., 2006) or 3) or a specific type of proxy (e.g. Roberts et al., 2008). This review, however, is based on a broad and comprehensive range of records derived from different natural archives distributed throughout the Mediterranean region. By analyzing well-distributed proxy data recording hydro-climatic variability we aim to 1) identify records of high resolution and dating quality, 2) outline millennial and multi-centennial scale trends in hydro-climate evolution during the Holocene in the region, and 3) identify regional patterns of hydro-climate variability around the Mediterranean Sea during the Holocene.

2. Data and methods

2.1 Proxy data

Proxy data preserved in a number of different natural archives, primarily speleothems, lake and marine sediments have been consulted and utilized for the analyses in this paper. Only proxy data interpreted to reflect hydro-climate, and hydro-climatic variability, have been considered in this study omitting, for example, proxies interpreted to record temperature variability and pollen-based reconstructions. Pollen data are being used to reconstruct Mediterranean land cover in other papers within this special issue, and hence cannot also be used as a paleoclimate proxy to examine the relationship between climate and vegetation in the past. Note that interpretation of the selected proxies in terms of hydro-climate conditions is not always straightforward, as the specific meaning of a proxy depends on the local context (including climate, geology and vegetation) and is usually more complex than just reflecting humidity or precipitation amount. Nevertheless, common trends in proxy records can point to a common influence of hydro-climate conditions. It is not the goal of this paper to discuss in detail uncertainties related to the climate signal in each record (readers are advised to consult the original publications for the more nuanced interpretation concerning e.g. seasonality, stability of the climate signal, and non-climatic noise).

The point of departure for our review of available proxy data are the previously published studies by Roberts et al. (2008), Finné et al. (2011) and Labuhn et al. (2018). Data from these compilations/reviews of paleoclimate archives were complemented by a further screening of published hydro-climate proxy records from within, or directly adjacent to, the Mediterranean basin. The selection of records has been based on a set of criteria that can be summarized as follows: robust dating and age-depth modeling, unambiguous proxy interpretation and a minimum mean sampling interval of 200 years, and a multi-millennial time duration, especially records that cover the full Holocene epoch.

The chronological information in the original publication of each record (or other relevant publications in cases when the chronological information is published separately) have been individually assessed for: relevant corrections and calibrations, sufficient dating density as well as stratigraphical order of age results. We have not re-calibrated any radiometric ages or re-calculated any age-depth models for this study, rather we used a qualitative assessment to ensure sufficient chronological control for the included records. . For details regarding the dating of each individual record included in this study we refer the reader to the original publications (**Table 1**).

The temporal resolution of any record depends on the rate of sedimentation of the archive that preserves the proxy signal together with the amount of material needed for analyses and the sampling technique. More highly resolved records have the ability to reflect climate variability at a fine temporal scale and to provide precise information about rates of change. These are both crucial factors when trying to understand the impact of climate change on past human societies (Finné and Weiberg, 2018; Kintigh and Ingram, 2018; Knapp and Manning, 2016; Labuhn et al., 2016). The temporal resolution of individual data series also determines the possible temporal resolution of any synthetic analysis. This means that the highest attainable temporal resolution in the present study is determined by the lowest temporal resolution of any of the included records. In order to maintain a temporal resolution that is meaningful for comparisons with other types of data, e.g. archaeological information or vegetation cover based on pollen, careful consideration was taken to balance the number of included records against the temporal resolution. Our selection criterion of a minimum sampling interval of 200 years allow us to work in two century-long time steps and to perform our analyses and between site comparisons at centennial scale resolution.

2.2. Climate z-scores

All records have been transformed to z-scores, i.e. the record mean was subtracted from each proxy value, and the difference was divided by the record's standard deviation. Z-scores were calculated for those parts of the records that are younger than 10000 years before present (where 'present' is defined to AD1950, from now we will only use yrs BP). This cut-off at 10000 yrs BP avoids the influence of large shifts in proxy values at the glacial-interglacial transition on z-scores, which may mask the more subtle Holocene proxy variability. Some of the z-score time series were multiplied by -1, so that within all time-series positive values correspond to wetter conditions and negative values correspond to relatively dry conditions. The records were then re-sampled at an annual time step by linear interpolation between measured proxy values. Based on the new time series of annual resolution, average z-scores were calculated for each 200-year interval (i.e. from 10000 to 9801 yrs BP, 9800 to 9601 yrs BP etc.; the youngest time slice includes 200 BP to present (-63 BP)). The same time intervals have been used for pollen data analysis (Fyfe et al., 2018; Woodbridge et al., 2018). Calculations were performed using R (R Core Team, 2016). From here on, time slices are referred to by their mid-point, for example, 400-201 yrs BP is described as 300 yrs BP.

This data manipulation creates time series which could slightly differ from the original records, e.g. some information is lost, for example, climate events shorter than 200 years may not fully be recorded in our re-analysis. However, the common 'time window' of 200 years and the common scale of the records as z-scores enables a quantitative comparison between records that would otherwise not be possible. This way, we can compare hydro-climate variability from a variety of different records and identify spatial patterns.

2.3 Non-metric multidimensional scaling nMDS

nMDS was selected as a versatile method that does not make assumptions about the data and allows all variation within the data to be captured within the axes, unlike other methods, such as Principal Components Analysis (PCA). nMDS scores are calculated based on pairwise distances among samples with a distance measure, such as Euclidean distance, (Holland, 2008). The axes illustrate variation within the data and are not interpreted as representing any particular variables. Non-metric multidimensional scaling (nMDS) with Bray-Curtis dissimilarity measure was applied to the climate z-scores using the R 'vegan' package (Oksanen et al., 2016) to summarize major variation within and between the paleoclimate datasets. Five dimensions were selected to summarize the datasets as this gave a stress value <0.05 (0.044), which confirms that the five axes provide excellent representation of the variability in the data.

nMDS is a rank-based indirect gradient analysis approach that produces an ordination based on a dissimilarity matrix (Buttigieg and Ramette, 2014) and maximizes the pairwise dissimilarity between samples. nMDS has the advantage that it can tolerate missing pairwise distances and can be used with mixed variables (Buttigieg and Ramette, 2014), it maps ranked samples non-linearly in ordination space, and can handle the non-linear responses of variables (Oksanen et al., 2016). The presence of zero values in the proxy datasets covering shorter periods of time (e.g. the early or late Holocene only) influences the plotting of samples in ordination space, therefore nMDS was applied to a sub-set of 18 complete and continuous records covering the time period from 9000 to 1200 yrs BP.

[Insert Figure 1.]

3. Results

In total 47 paleoclimate records from 44 sites have been included in this study (**Table 1**). To allow for a better temporal coverage of the Holocene different records from the same locations have been spliced together following the z-score transformation to create composite sequences for three sites (Grotte de Piste (#4a,b), Lago di Pergusa (#18a,b) and Nar Gölü (#26a,b)). Proxy data from terrestrial and lacustrine records are most common in our compilation. The most common hydro-climate proxy is $\delta^{18}O$, but the compilation of records also includes other stable isotopes such as $\delta^{13}C$ and δD, as well as elemental ratios, lake levels, or lamina thickness (**Table 1**). All of these were identified by the original investigators as responding primarily to hydro-climate.

3.1 Spatial and temporal coverage of records

The records cover an expansive spatial area of the Mediterranean region. A majority of records are located within the area classified as having a Mediterranean climate (Köppen type Cs) at present (Kottek et al., 2006). Generally, records are evenly distributed in the northern borderlands whereas the southern borderlands, other than Morocco, are nearly void of data (**Fig. 1**). The spatial coverage displays clusters of records that are located in the southern Levant, central Balkans and northern Iberia (**Fig. 1**). The number of records from the marine realm included in this study is very small (n=6) (**Table 1**). This is mainly a reflection of: the often relatively poor temporal and sampling resolution of these records owing primarily to the low sedimentation rates in many areas of the Mediterranean. Few marine cores present unambiguous hydro-climate proxies, and there are also problems associated with accurately dating marine records due to reservoir effects, for example (Reimer and McCormac, 2002; Siani et al., 2000).

Of the records we have included, 23 cover the complete, or nearly the complete, study period and an additional 7 records cover at least half the study period (**Fig. 2**). The remaining records cover different shorter periods throughout the Holocene (**Fig. 2**). The temporal distribution of records is lowest in the oldest and the most recent ends of the study period (i.e. early and late Holocene). There are 20 available z-scores for the oldest time slice 9900 yrs BP, and 26 for the youngest time slice at 100 yrs BP. The time slices between 3500 and 2700 have the highest number of available records (37-38) in the study period (**Fig. 2**).

[Insert Figure 2.]

3.2 Regional patterns of hydro-climate variability in climate z-scores

The identification of regional climate patterns based on available proxy evidence remains challenging because of chronological uncertainties, the low resolution of some records, seasonal biases in proxy responses and meanings, and regional discrepancies in the density of available proxy data. From the numerical analyses of hydro-climate proxy records, using the average z-scores per 200-year period, we can observe the following. Mapped z-scores for individual sites reveal that many of the records from the same region generally show common patterns (**Fig. 3 and Supp_Fig. 1**).

[Insert Figure 3.]

Based on the above results and in combination with previous research and the present-day geography of the Mediterranean, we have used the following six regions for outlining and discussing the Holocene climate evolution: South Iberian Peninsula and Maghreb, North Iberian Peninsula, Italy (Northern, the Apennine Peninsula and Sicily), the Balkans (including Greece), Turkey (the Anatolian Peninsula) and the Levant (**Fig. 1**). These overlap with regions used in a selection of Mediterranean case studies comparing pollen-inferred land cover change and archaeologically-derived demographic trends (Bevan et al., Roberts et al., this volume). For all regions the mean z-score value and the standard deviation were calculated (**Fig. 4 and Supp_Fig. 2**).

3.2.1. South Iberian Peninsula and Maghreb

From the calculated z-score mean the climate in the South Iberian Peninsula and Maghreb region seems to have been generally wetter from 9700 to 5700 yrs BP (**Fig. 3a,b**). From 7100 yrs BP there is trend towards drier conditions, however, this is interrupted between 5400 and 4500 by wetter conditions (**Fig. 4**). A period of drier conditions is inferred from 3300 to 1900 yrs BP. In this drier interval, however, the record from Laguna de Medina (Reed et al., 2001) suggests that conditions were wetter (**Fig. 4**). An overall trend toward wetter conditions starts at 2300 yrs BP and at 1300 yrs BP there is a strong signal of wetter conditions. This is again followed by drier conditions, while from 300 yrs BP conditions seem to be wetter (**Fig. 4**).

Although located closely together, and close to the Atlantic Ocean, the z-scores from lakes Sidi Ali (Zielhofer et al., 2017) and Tigalmamine (Lamb et al., 1989), and Laguna de Medina (Reed et al., 2001) and Grotte de Piste (Wassenburg et al., 2013, 2016) seem to portray some differences. While Sidi Ali and Tigalmamine clearly show wetter conditions in the interval from 10000 until 5800 yrs BP, Laguna de Medina and Grotte de Piste indicate a more subdued signal of wetter conditions interspersed with intervals of drier conditions. From around 5800 yrs BP Sidi Ali and Tigalmamine display a trend toward drier conditions while Laguna de Medina and Grotte de Piste show an opposite pattern. (**Fig. 4**). The standard deviation of the individual z-scores included in this region is relatively uniform throughout the Holocene and comparable to the standard deviation in the Balkans and Turkey. During three shorter intervals 4500-4100, 3300-3100 and 1300-1100 yrs BP the individual z-scores plot close the calculated mean (**Fig. 4**).

[Insert Figure 4.]

3.2.2. North Iberian Peninsula

The overall climate picture of the North Iberian Peninsula region from 10000 to 4700 yrs BP is one of alternating periods of dry and wet conditions. Throughout the Holocene dry intervals occur regularly at 9300, 8500, 7700, 6700, 5700, 4700, 2700 and 1700 and 500 yrs BP suggesting a cyclic pattern of 800-1000 years (**Fig. 4**). At 3700 yrs BP no short period of dry conditions is recorded and instead a longer period of wetter conditions is evident from 4200 to 3000 yrs BP. From 2600 yrs BP the regional mean suggests wetter conditions again, primarily driven by the strong signal from Lake Montcortes (Corella et al., 2011) (**Fig. 4**). These overall wetter conditions remain in place until 1700 yrs BP. From 1300 yrs BP, when conditions are wetter again following the dry interval at 1700 yrs BP, there is a trend towards drier conditions until the present (**Fig. 4**).

The standard deviation of the individual z-scores included in this region is generally small suggesting that there was a homogenous climate driver, and that the response to climate shifts in the records is similar. From 2500 yrs BP, however, the standard deviation increases suggesting that the climate or the climate response in the records became less homogenous (**Fig. 4**). It is primarily the addition of the high amplitude signal from Lake Montcortes (Corella et al., 2011) after 3500 yrs BP that increases the standard deviation in the region (**Fig. 4**).

3.2.3. Italy

The mean z-score value from the sites located in Italy suggests that the climate in this region was drier from 10000 until 8700 yrs BP (**Fig. 3a**) when there was a rapid switch toward wetter conditions (**Fig. 4**). Wetter conditions remain in place until 6900 yrs BP. From 6900 yrs BP and onwards the z-score mean is close to zero with little variability. From 4000 yrs BP the standard deviation gradually increases. This gradual increase is partly a result of a separation between the z-scores from northern and southern Italy. The northern records suggest that the climate became gradually drier here from 4000 yrs BP until present whereas the z-score results from the south suggest the climate here became gradually wetter at the same time (**Fig. 4**). The standard deviation compares well to the other regions but between 8700 and 7100 yrs BP it increases strongly (**Fig. 4**). In this interval, the stable oxygen isotope records from Lake Pergusa (Sadori et al., 2008, 2016; Zanchetta et al., 2007a), Grotta di Carburangeli (Frisia et al., 2006) and Corchia Cave (Zanchetta et al., 2007b) indicate an almost opposite climate picture to that provided by the lake level record from Lake Preola (Magny et al., 2011) and the Ca/Ti elemental record derived from sediment core DP30 from the Gulf of Taranto (Goudeau et al., 2014) (**Fig. 3b; Fig. 4**).

3.2.4. The Balkans

The mean z-score calculated from the records from the Balkans suggests that the climate in the period from 9900 to 8900 yrs BP was dry (**Fig. 4**). From 8700 yrs BP, however, there is a clear and rapid trend toward wetter conditions. Wet conditions dominate from 8700 to 6300 yrs BP (**Fig. 3b**). The wettest conditions are recorded at 8100 yrs BP and although wetter conditions seem to be largely sustained for another 1800 years a trend toward drier conditions is evident from this point in time (**Fig. 4**). At 4900 yrs BP the driest conditions in the Balkans are recorded (**Fig. 3c**). The drier conditions continue until 2500 yrs BP, but are interrupted between 4500 and 4100 yrs BP by wetter conditions (**Fig. 4**). Slightly wetter conditions from 2500 to 1900 yrs BP are replaced by a clear trend toward drier conditions that continues until the present.

Throughout the Holocene the standard deviation is rather uniform, from 4500 until 2300 yrs BP, however, it is reduced even though the number of records included increases. In this region the records from Lake Prespa (Leng et al., 2010) and Lake Dojran (Francke et al., 2013) account for a large part of the standard deviation (**Fig. 4**). These two records, however, have similar trends that closely follow the calculated z-score mean for this region, albeit showing different individual z-scores. The standard deviation between the individual z-scores is similar to that of S Iberia and the Maghreb, and to Turkey (**Fig. 4**).

3.2.5. Turkey

In Turkey the mean z-score suggests that the climate was wetter from 10000 to 4500 yrs BP. The mean z-score displays a clear trend between 10000 and 3000 yrs BP, from these overall wetter conditions to a generally drier situation (**Fig. 4**). From 4500 yrs BP drier conditions dominate. Aridity is most pronounced from 3000 to 1900 yrs BP, followed by a trend toward wetter conditions (**Fig. 3d**). From 900 yrs BP conditions again move toward increased aridity.

The individual records from Turkey provide a generally coherent picture of the climate evolution of this region from 10000 until 5200 yrs BP and again between 3000 and 2300 yrs BP and after 1500 yrs BP (**Fig. 4**). In-between these periods the standard deviation is larger but still on par with the other regions. The record from Lake Van (Wick et al., 2003), which lies at the eastern extremity of Turkey deviates from the majority of records between 9600 and 8600 yrs BP and 5300 and 3900 yrs BP (**Fig. 3c; Fig. 4**).

3.2.6. The Levant

From 9900 to 8700 the records from the Levant show a coherent picture of a wetter climate (**Fig. 4**). From 7500 yrs BP a trend toward dry conditions is recorded but the z-score mean suggests that overall wetter conditions remain in place in the Levant until 6100 yrs BP. However, the lake level reconstruction from the Dead Sea (Migowski et al., 2006) suggests a drier climate for the period from 8600 to 5700 yrs BP (**Fig. 4**). These opposing signals means that the standard deviation is large in this interval (**Fig. 4**). The three available records from the Levant display a rare period of coherency between 5900 and 5700 yrs BP when they all indicate dry conditions. At this point the trend toward more arid conditions is broken and two periods of wetter conditions are evident centered at 4700 and 3700 yrs BP. From 5300 to 4500 yrs BP the records from Soreq Cave (Bar-Matthews et al., 2003; Bar-Matthews and Ayalon, 2011) and Jeita Cave (Cheng et al., 2015) show opposing climate signals (**Fig. 3c**) and from 4500 to 3500 yrs BP the lake level record from the Dead Sea again is opposite to the two caves, that now agree (**Fig. 4**). This means that the interval from 5300 to 3500 yrs BP also is one of large standard deviation (**Fig. 4**). After 3500 yrs BP the picture is more coherent again and the mean z-score suggests that conditions were generally drier. From 3100 to 2900 yrs BP again all records from the region suggest dry conditions (**Fig. 3d**). A less coherent picture of drier conditions remains in place until 1700 yrs BP when a trend toward wetter conditions starts.

The inconsistency between the records, in combination with the low number of available records, mainly before 3000 yrs BP, means that the standard deviation is generally large in this region during the early and mid-Holocene.

3.3 General results of nMDS

The five nMDS axes are expected to reflect the majority of the variation in the datasets (stress value <0.05) and the strong positive relationship between the actual dissimilarities between objects and the ordination distances demonstrates that that ordination visualization of the data is reliable, as demonstrated in the stress plot (**Supp_Fig. 3**). The site score results from the nMDS analysis provide some insights into regional similarities between paleoclimate records within the Mediterranean (**Fig. 5**). However, this is an incomplete data set (based on 18 sites only) and does not cover the whole of the last 10000 years due to the low number of sites included as a result of the need to exclude zero values from the nMDS analysis. Even though the number of sites was reduced the spatial coverage of the Mediterranean region is still good.

[Insert Figure 5.]

3.4 nMDS analysis of Holocene climate change in the Mediterranean

Patterns of temporal change within the paleoclimate datasets are summarized into the five nMDS axes (**Fig. 4; see Supp_Fig. 4 for all 5 nMDS axes**). The major trend of increasing z-score values between 9000 and 8000 BP is reflected in the nMDS scores until ~7900 BP, which is then followed by declining z-score values, as demonstrated in nMDS axis 1, while other variability in the datasets is summarized in axes 2 to 5. Clear changes are demonstrated in axis 2 between 8000-7000 BP and 3000-2000 yrs BP. Axes 1 and 2 appear to illustrate the major trends in the datasets while axes 3-5 appear to provide a signal that is also reflective of site specific variability. Time intervals clustered together in nMDS ordination space appear to represent periods of relative climatic stability (**Fig. 6**), whereas intervals where samples are spread further apart may represent periods of more rapid climate change (e.g. 6700 to 6300 BP, 4500 to 4300 BP, and 3500 to 3300 BP). The mapped nMDS scores for sites (**Fig. 5**) does not demonstrate any clear grouping of sites by region (symbol sizes represent the nMDS scores for axis 1 and 2), although most Eastern Mediterranean seem to show positive nMDS scores. The most negative nMDS site scores are in southern Italy and Iberia. The lack of clearer regional patterns in the nMDS site scores is partly due to the limited number of sites that were suitable for including in this analysis.

The similarity between nMDS axis 1 and the z-scores implies that this axis represents a trend from wetter conditions in the earlier Holocene and drier conditions in the later Holocene across a majority of records (**Fig. 4**). This pattern is positive for all regions apart from N Iberia; it is especially clearly marked in the S Iberia/Maghreb, the Balkans, Turkey and the Levant. However, the general advice when applying nMDS is not to relate environmental variables to the distances in an nMDS ordination (Legendre et al., 2005), therefore the general trend may be relevant, but the magnitude of change is not possible to interpret.

[Insert Figure 6.]

4. Discussion

The number of paleoclimate studies from the Mediterranean region is relatively large and covers many aspects of climate variability. Hydro-climate variability inferred from proxy data has been linked, for instance, to changes in insolation during the Holocene and to a number of different atmospheric circulation regimes and large-scale teleconnection patterns (e.g. Cullen and deMenocal, 2000; Jones et al., 2006; Roberts et al., 2012; Rohling et al., 2002; Zielhofer et al., 2017) . Correlations between modern day precipitation and atmospheric teleconnection patterns can provide information and analogues of spatial patterns of precipitation in the past and how these may be related to large-scale dynamics. However, these will not take account of orbitally-induced changes in insolation which were significantly different between the early and late Holocene. It is beyond the scope of this study to go into detail regarding the effects that different atmospheric teleconnection patterns may have had on precipitation in the region during the Holocene. Recent advances in climate modeling, and the downscaling of global models to fit regions, have provided new possibilities to investigate how variations in hydro-climate have occurred in response to changes in insolation, ice-sheet configuration and greenhouse gas concentrations (Brayshaw et al., 2010, 2011). Insights into large-scale atmospheric processes provided by these modeling experiments seem to present a good framework for discussing the climate history of the relatively large Mediterranean region especially when considering long-term change (millennial to multi-centennial).

The z-score results from this study clearly shows an overall trend from a wetter early and mid-Holocene to a drier late-Holocene in all regions except N Iberia (**Fig. 4**). The results from the nMDS analysis suggest this trend started at 7900 yrs BP and continued until 3700 yrs BP (**Fig. 4**). Our data also show that there are periods of relative stability in the hydro-climate in the Mediterranean followed by more rapid (centennial-scale) change e.g. 6700 to 6300 BP, 4500 to 4300 BP, and 3500 to 3300 BP (**Fig. 6**). The z-score data from different regions within the Mediterranean analyzed in this paper also highlight the spatio-temporal variability of hydro-climate in this region during the Holocene (see **Fig. 3** for a selection of maps indicating the spatial variability in the Mediterranean). Our results demonstrate significant variability between regions in the Mediterranean but also that there is variability within the regions (**Fig. 4 and Supp_Fig 1**). This indicates that incoherencies in hydro-climate variability occurs at different levels of spatial scales and that a full understanding of the hydro-climate in the Mediterranean region requires an understanding of the variability at regional as well as local scales.

Many of the apparent incoherencies in hydro-climate variability result from uncertainty in the individual chronologies, which influence whether or not detected changes appear synchronous or not. The meaning of individual proxy records (e.g. reflecting runoff or precipitation), as well as the season they represent, is generalized in our analysis as average "hydro-climate conditions". Seasonality, not always discussed in original publications, or the season reflected by a certain proxy could change over time (e.g. Zielhofer et al., 2017). Nevertheless, the large number of records used in this study and the re-sampling of the time series to 200-year time steps allows meaningful conclusions on the temporal evolution and spatial patterns of hydro-climatic conditions.

Spatial inhomogeneity in hydro-climatic variability is a well-known feature of the Mediterranean climate. In a Mediterranean-wide perspective, differences between the western and the eastern parts of the Mediterranean have been identified at various temporal scales (Labuhn et al., 2016; Roberts et al., 2011a, 2012) but differences between different regions of the eastern Mediterranean have also been identified (Finné et al., 2011; Roberts et al., 2011c). The results from this study also suggest differences in hydro-climatic variability between the western and the eastern parts of the Mediterranean (along with sub-regional variability), and the addition of proxy data from central Mediterranean provide an opportunity to link the west with the east. Before returning to a discussion about regional variability in the Mediterranean, we will discuss the long-term trends in the hydro-climate history evident from our results and relate these to large-scale processes that can affect atmospheric circulation processes with a particular focus on the position of the North Atlantic storm track.

4.1 Millennial scale trends and long-term variability

The position and strength of the North Atlantic storm track plays an important role in controlling the amount of precipitation received in large parts of Europe (Hawcroft et al., 2012). Long-term changes in the strength and position of the North Atlantic storm track have been found on glacial and interglacial time scales as well as during the current interglacial, primarily relating to changes in the configuration of ice-sheets and insolation during the course of the Holocene (Brayshaw et al., 2010; Li and Battisti, 2008; Orme et al., 2016, 2017; Perșoiu et al., 2017).

The z-score data presented in this paper suggests that the Mediterranean region was generally wetter during the first half of the Holocene compared to the latter half (prior to 6000 yrs BP), notably in the southern and eastern regions (**Fig. 3a,b and Fig. 4**). In northern Iberia this pattern is not evident. This finding is broadly in line with previous results from individual records and climate modeling studies (see supplementary figure 3 for individual records; Brayshaw et al., 2011). Modeling suggests that the mean increase in precipitation in the early

Holocene was <7% whereas some site-specific reconstructions suggest >20% (Jones et al., 2007; Roberts et al., 2011a). The increase in precipitation in the early Holocene has been linked to the position and strength of the storm track over the North Atlantic and to the increased land-sea temperature contrast as well as a stronger air-sea temperature contrast that resulted from the stronger seasonality leading to more frequent formation of cyclones and increased convective winter rainfall (Bosmans et al., 2015; Brayshaw et al., 2010, 2011; Roberts et al., 2011a). It cannot be explained by an intrusion of summer monsoon rainfall into the Mediterranean even though it extended much further north in the early Holocene (e.g. Arz, 2003; Perez-Sanz et al., 2014). Modeling experiments suggest that in the early Holocene the Atlantic storm track was shifted south compared to the present, and that this in turn led to a strengthening of the storm track in the Mediterranean region (Brayshaw et al., 2010). Proxy data from Romania also suggest a south-ward displacement of Atlantic storm track and a strong zonal flow in the early and mid-Holocene until approx. 4700 yrs BP followed by a gradual shift to the north (Perşoiu et al., 2017). Similarly, proxy data from coastal sites in NW Scotland and Galicia (NW Spain) suggest a southerly position of the Atlantic storm track at 4000 yrs BP and that a gradual shift to the north took place from 3000 to 800 yrs BP leaving southern Europe drier (Orme et al., 2017). An additional forcing mechanism was provided by orbitally-induced strengthening of the South Asian monsoon circulation during the early Holocene. While this did not affect the Mediterranean directly, a stronger high pressure over Tibet would have altered the northeasterly air flow that descends over the eastern Mediterranean and southwest Asia in summer (Kutzbach and Otto-Bliesner, 1982).

Indirect links between the orbitally intensified African monsoon and increased winter precipitation during the early Holocene may also have played a role. Proxy evidence, pre-dating the Holocene, suggest that seasonality was more pronounced and that winter precipitation in the central and eastern Mediterranean increased during precession minima (Regattieri et al., 2015, Toucanne et al., 2015, Tzedakis et al., 2007). Higher summer sea surface temperatures in the Mediterranean Sea persisting into autumn have been invoked to explain the increase in rainfall (Tzedakis et al., 2007, Milner et al., 2012, Regattieri et al., 2015). The wetter climate conditions in the Levant and Turkey during the early Holocene are broadly coeval with the formation of marine sapropel 1 in the eastern Mediterranean Sea, that occurred between approximately 9500 and 6500 yrs BP (Ariztegui et al., 2000). The formation has been linked to increased freshwater input from the Nile river and from increased precipitation on the sea itself as well as over the northern borderlands (Roberts el al., 2008). Modeling also suggests that convective winter rainfall over local areas of the Mediterranean Sea, caused by increased air-sea temperature contrasts also contributed significant amounts of freshwater (Bosmans et al., 2015). Our data clearly support the idea that freshwater from the northern borderlands contributed to the formation of marine sapropel 1 especially after 8500 yrs BP and that the termination is linked to reduced precipitation around 6500 yrs BP in much of the eastern sector.

The overall aridification of the Mediterranean suggested by both global and regional climate models (Brayshaw et al., 2011) fits well with the gradual trend towards drier conditions visible in most regional z-score means from the early Holocene to the mid-late Holocene and with the results of the nMDS analysis (Axis 1) (**Fig. 4**). It seems as if the gradual northward displacement of the North Atlantic storm track and reduced land-sea temperature contrasts in response to orbitally driven changes in insolation in turn reduced the strength of the Mediterranean storm track which led to a gradual reduction of precipitation in the region (Brayshaw et al., 2010).

The hydro-climate proxy data in this paper do not provide any insights into the seasonality of precipitation or possible changes in this seasonality. Presently, cyclonic depressions are mainly active in winter and modeling results support the idea that precipitation was mainly higher in winter also during the Holocene, although the idea of more cyclonic precipitation in summer has been discussed for a long time (Peyron et al., 2017; Roberts et al., 2011a; Rohling and Hilgen, 1991; Tzedakis, 2007). It has been suggested that the strengthening of the Asian summer monsoon in the early Holocene meant that the descent of air over the eastern Mediterranean was enhanced effectively inhibiting cloud formation and precipitation, and hence leading to drier summers (Brayshaw et al., 2011). Drier summers in the early Holocene were also inferred by Tzedakis (2007) and proxy data from central Turkey suggest wet winters and dry summers during the early Holocene. However, the results from central Turkey also imply that wetter conditions may be related to reduced summer evaporation due to lower temperatures (Dean et al., 2018; Lewis et al., 2017). A comparison between regional hydro-climate data and regional pollen data from the Mediterranean may offer an opportunity to further investigate the spatio-temporal evolution of precipitation seasonality in the region.

4.2 Inter-regional variability and shorter term variability

The compilation and analysis of proxy data undertaken here show intra-regional coherence in the long-term trends of Holocene hydro-climatic variability that suggests these trends are driven by common large scale forcings. Furthermore, the z-scores presented in this paper suggest that the response to these large scale shifts varied throughout the Mediterranean on both regional and local scales (**Fig. 3**). Some of the differences between the regions and within the regions, i.e. between individual z-score time series, are a result of the inherent dating uncertainties, seasonal differences in proxy response, or different proxy sensitivity, i.e. to what extent a proxy is climate dependent (Labuhn et al., 2016). Differences may also occur due to spatiotemporal variability in climate patterns. This may be illustrated by the record from Lake Van (Wick et al., 2003) that between ~5300 and 3900 yrs BP is more similar to the records from Soreq Cave and the Dead Sea (Bar-Matthews and Ayalon, 2011; Migowski et al., 2006), belonging to the Levant, than the records from Turkey. At the same time Jeita Cave is decoupled from the records from southern Levant and instead resembles the records from central and western Turkey, something that has been noted for younger periods (Cheng et al., 2015; Labuhn et al., 2016). This indication of shifting large-scale patterns of climate in time and space is something that should be investigated further. From the individual z-scores as well as the regional means it is obvious that well-known shorter intervals of dry, and or cold, climate conditions, e.g. at 8200, 4200 and 3200 yrs BP are not well captured by our method indicating that it is not well-suited to address the issue of climate events or short term (decadal-centennial) variability.

The hydro-climatic history of the North Iberian region seems to be closely linked to that of the North Atlantic. The alternating periods of dry conditions that occur in this region seem to match closely in time episodes of ocean cooling and an increase in ice-rafted debris recorded in the North Atlantic, occurring in a cyclical pattern of around 1500 years, the so-called Bond events (Bond et al., 2001). The ocean-atmosphere link during these events is not fully understood but these events are associated with wetter conditions in NW Europe and drier conditions in N Iberia (Smith et al., 2016). A pattern that has been attributed to a short-term northward shift of the storm track during episodes of N Atlantic cooling (Di Rita et al., 2018; Fletcher et al., 2013). The homogenous response of proxies in N Iberia is probably one of the reasons why this pattern is clearly picked up in this region compared to other regions, although it may be noted that it has been detected in other individual records, for instance in Sidi Ali and Grotte de Piste from the Maghreb (see Wassenburg et al., 2016; Zielhofer et al., 2017 for details). Northern Iberia, which today receives precipitation in summer as well as winter, seems to be least affected by the northward displacement of the North Atlantic storm track during the course of the Holocene as there is no evidence of gradual change from this region. Regional as well as global climate models provide little information about the climate situation in North Iberia during the Holocene (Brayshaw et al., 2011).

In contrast, the five other regions seem to share a more common climate history, although with differences (**Fig. 4 and Supp_Fig. 1**). Adjacent regions generally show common trends; thus the record from Levant and Turkey resemble each other, as do Italy and the Balkans. More surprising is the lack of similarity between the South Iberia-Maghreb and northern Iberia, given the fact that these two-regions exhibit a good correlation in hydro-climate during the last millennium (Luterbacher et al., 2012; Moreno et al., 2012).

The z-score results clearly show wetter climate conditions in the Maghreb, Turkey and the Levant in the early and mid-Holocene (**Fig. 3a-c, Fig. 4**). The similarity in the response in the three regions suggest a coherence in the climate across these regions in the early Holocene. At the same time the z-score regional means suggest that the regions of Italy and the Balkans remained drier from 9900 until approximately 8500 yrs BP (**Fig. 3a**). From 8500 yrs BP all five regions show wetter conditions (**Fig. 3b**) indicating a strong regional coherency lasting until 6100 yrs BP when more arid conditions commence. Regional climate model experiments indicate that coastal areas especially in the NE Mediterranean, the Balkans and Turkey, and to some extent the Levant, received more precipitation at 8000 and 6000 yrs BP (Brayshaw et al., 2011). This precipitation increase has been linked to an east-west pressure di-pole that promotes a southerly airflow over the Eastern Mediterranean steering the path of cyclones toward the northeast. At present, a similar situation can occur in the Eastern Mediterranean when the local expression of the East Atlantic pattern promotes a southerly air flow increasing precipitation in the coastal areas of W and NE Greece and W Turkey (Dünkeloh and Jacobeit, 2003; Xoplaki et al., 2004). This southerly airflow is also connected to the strength of the Siberian high pressure system via the so-called North Sea-Caspian Pattern Index (a local expression of the East Atlantic/Western Russia pattern) occurring at a lower level (Kutiel et al., 2002; Kutiel and Benaroch, 2002).

After 6000 yrs BP wetter conditions persist in Turkey, which fits well with the outcome of the regional climate model. Similarly, the wetter conditions outlined for S Iberia and Maghreb after 6000 yrs BP also fits well with regional modeling results (Brayshaw et al., 2011). From 6000 yrs BP until approximately 3000 yrs BP, S Iberia and Maghreb, and Turkey share a trend from wetter to drier conditions whereas the other regions show little variability (**Fig. 4**). The whole of the East Mediterranean experienced arid conditions at 3000±300 BP (**Fig. 3d**), which may have been the driest time of the whole Holocene in this area. By contrast, Italy and parts of the northwest Mediterranean were relatively wet at this time (**Fig. 3d**). After ~3000 yrs BP there are somewhat different trends in the regions going toward the present. The trend towards wetter conditions evident in the Levant from ~1700 yrs BP is matched by similar trends in S Iberia-Maghreb and Turkey although these start somewhat earlier. Our synthesis thus highlights a dominant south/east vs north/west Mediterranean hydro-climate dipole through the Holocene. This partly corresponds to a similar pattern that is evident in data over shorter timescales, even if forcing mechanisms may not have been the same. A similar dry/wet pattern has been inferred from tree ring widths (Cook et al., 2016), lakes (Roberts et al., 2012) and multi-proxy data (Luterbacher et al., 2012). In this pattern, the northwest was dry during the Medieval Climate Anomaly and wet during the Little Ice Age, and vice-versa in the south and east.

5. Conclusions

The data presented in this paper indicate that there was long-term and shorter-term climate variability in the Mediterranean region during the Holocene. Mapping of paleoclimate z-scores from sites spanning the Mediterranean clearly indicates both regional differences and dissimilarities within regions. This highlights the importance of exploring regional and local scales when trying to understand past hydro-climate variability in the Mediterranean. More research is needed on shifting large-scale patterns of climate in time and space, indicated by the similarities and contrasts between records from different regions, which may yield further insights into changes into teleconnection patterns.

The analysis of z-scores indicates that the hydro-climate in N Iberia has been largely decoupled from the other five regions in the Mediterranean studied here. N Iberia seems to be characterized by a strong direct link to the N Atlantic and short-term (e.g. NAO-type) shifts in storm tracks. The hydro-climate history in the five other regions is more coherent, especially adjacent regions which share common trends. There is a long-term trend in the z-score data from the remaining five regions indicating a shift from a generally wetter early-mid Holocene to a drier mid-late Holocene. This period of wetter conditions is longer in the south and the east compared to the northern and central parts of the Mediterranean. Before 8700 yrs BP climate was wetter in the Maghreb, Turkey and the Levant but drier in Italy and the Balkans. From 8500 to 6100 yrs BP there is a coherent picture of a wetter climate in most Mediterranean regions, other than the northwest. After 6000 yrs BP the detailed picture is less homogenous until around 3000±300 yrs BP which seems to have been the overall driest period in the Eastern Mediterranean and in S Iberia and Maghreb. In contrast Italy and N Iberia seems to have remained wetter during this period. Our synthesis thus highlights a dominant south/east vs north/west Mediterranean hydro-climate dipole throughout the Holocene, which corresponds to similar patterns seen on shorter timescales (e.g. last millennium), even if the causal mechanisms were not identical.

Higher nMDS values appear to reflect wetter climate and lower nMDS scores drier climate, based on comparisons with the climate z-score patterns. The results from the nMDS analysis on a reduced, yet spatially well-distributed, set of records suggest that after 9000 yrs BP the climate in most of the Mediterranean was wetter, gradually becoming drier until 3700 yrs BP. Relative stability in the hydro-climate in the Mediterranean, interspersed with more rapid (centennial-scale) change e.g. 6700 to 6300 BP, 4500 to 4300 BP, and 3500 to 3300 BP, is indicated by nMDS axis 2.

This study provides a readily available source of information about hydro-climatic variability for different regions within the Mediterranean, which facilitates comparisons with information about vegetation cover based on pollen and data about anthropogenic activity based on archaeological data.

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Declaration of conflicting interests

The authors declare no conflict of interests.

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Figures and tables:

Table 1: List of paleoclimate records compiled and analyzed for this study, sorted by location from West (1) to East (44). ID numbers correspond to locations in Figures 1 and 3. Bold numbers indicate records used in nMDS analysis. Information in 'Proxy' column lists proxies identified by the original investigators as responding primarily to hydro-climatic variability and thus used in this study. Mean sampling intervals calculated for the period 10000 to present (or for as long as applicable within this period) from original data files. All ^{14}C records are AMS except, [1] which was dated with conventional radiocarbon dating. [2]For additional information about U-Th dating of this record please consult McDermott et al., 1999. [3]For additional information about the dating of this record please consult Wagner et al., 2012.

Figure. 1: Location of compiled and analyzed hydro-climate proxy records and the outline of the six identified regions in the Mediterranean. ID numbers correspond to information in Table 1. Bold numbers indicate records used in nMDS analysis.

Figure. 2: Top panel: Number of analyzed records. Bottom panel: Temporal coverage of individual binned z-score time series. Please note that some records continue further back in time than what is shown on this graph. ID numbers correspond to information in Table 1. Note that TIC record #10 (Corella et al., 2011) was cut off at approximately 3500 yrs BP due ambiguity in proxy interpretation.

Figure 3. Selection of maps showing the calculated z-score values for four different 200-year time slices in the Mediterranean region. The selected time slices are representative of longer-term trends and provide an example of the spatial variability in climate data. Positive (negative) z-score values indicate wetter (drier) climate conditions. ID numbers correspond to information in Table 1. Map a) shows wetter conditions in Maghreb, Levant and Turkey, but dry in Italy and the Balkans in the early Holocene. Map b) shows the wettest recorded interval during the Holocene. Conditions were wet everywhere in the region except in the northwestern part in this early Holocene interval. Map c) this mid-Holocene interval shows drying in the eastern part of the Mediterranean and maximum wetness in N Iberia). Map d) shows one of the driest recorded intervals in the eastern Mediterranean, conditions however, are wetter in Italy in this late Holocene time slice. All 200-year time slice z-score maps are available in the supplementary information, see **Supp_Fig. 1**.

Figure 4. Individual z-score records and the calculated regional mean z-scores for identified regions in the Mediterranean (see Fig 1 for spatial coverage) plotted against time. Grey shading shows one standard deviation from the mean. Positive (negative) z-score values indicate wetter (drier) climate conditions. ID numbers correspond to information in Table 1. The two graphs to the right show nMDS axis 1 and axis 2 plotted against time. The blue line excludes record #18 (Sadori et al., 2008, 2016) to improve the temporal coverage of the analysis. Super-imposed red line shows the results from the analysis for a slightly shorter time period when record #18 is included.

Figure 5. Map showing the spatial pattern of nMDS scores for axis 1 (upper) and axis 2 (lower). ID numbers correspond to information in Table 1 and Fig. 1. Symbol sizes suggest some regional grouping particularly between the western (NW) and the eastern parts of the Mediterranean.

Figure 6. nMDS axis 1 (plotted on the x-axis) vs axis 2 (plotted on the y-axis) scores for each 200-year time slices used in this study. The position of samples plotted in ordination space reflects their similarity (greater distance between points indicates greater dissimilarity). The black lines show the samples plotted through time. Three periods of relative stability (closer plotting of samples in ordination space) in hydro-climate are separated by rapid change e.g. at 6700 to 6300 yrs BP, 4500 to 4300 yrs BP, and 3500 to 3300 yrs BP indicated by longer black lines (i.e. samples plotted further apart).

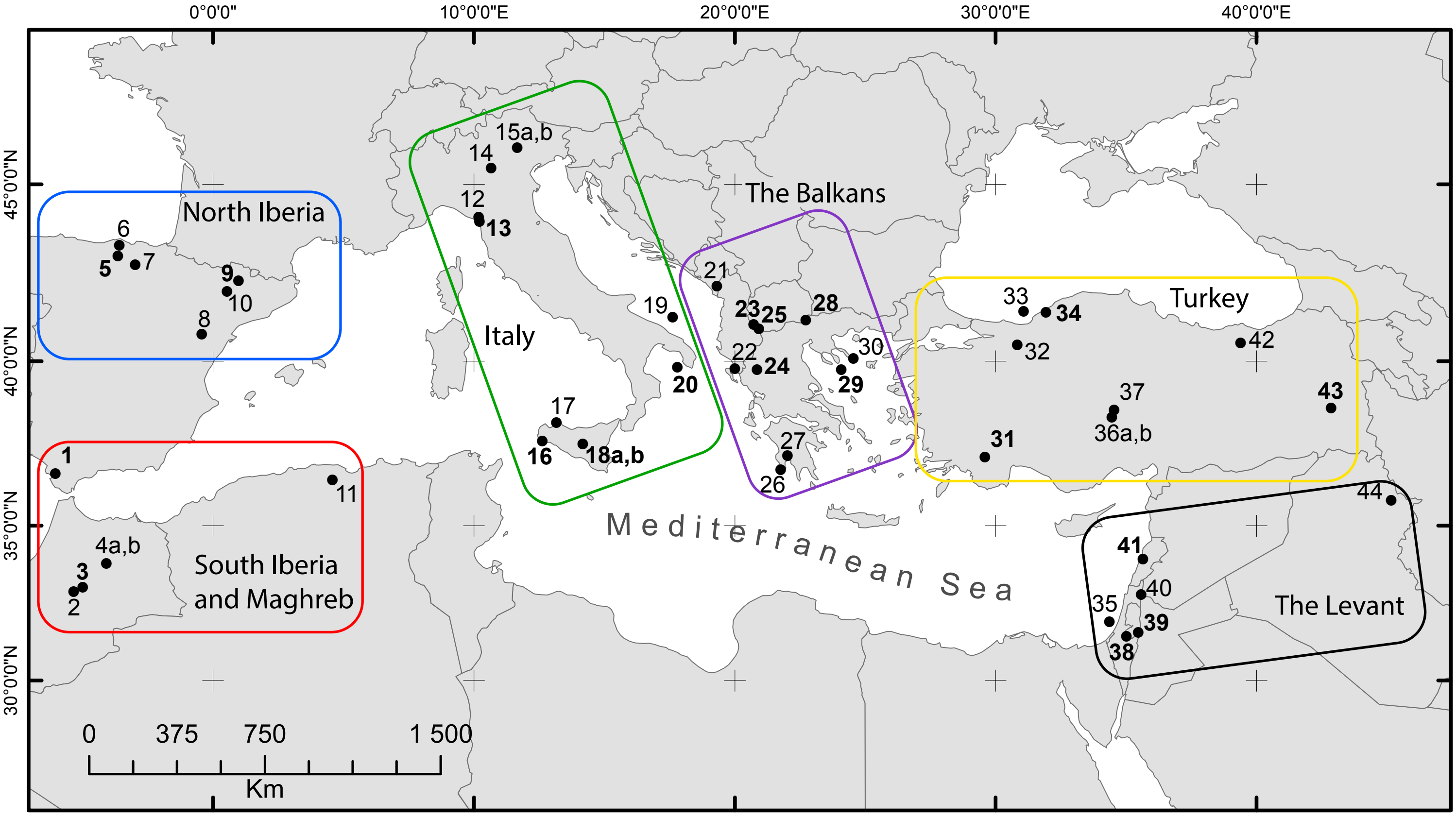
Supplementing figures

Supp_Fig 1. Maps for each 200-year time slice from 9900 to 100 yrs BP showing the calculated z-score for each individual record included in this study. Positive (negative) z-score values indicate wetter (drier) climate conditions. ID numbers correspond to information in Table 1.

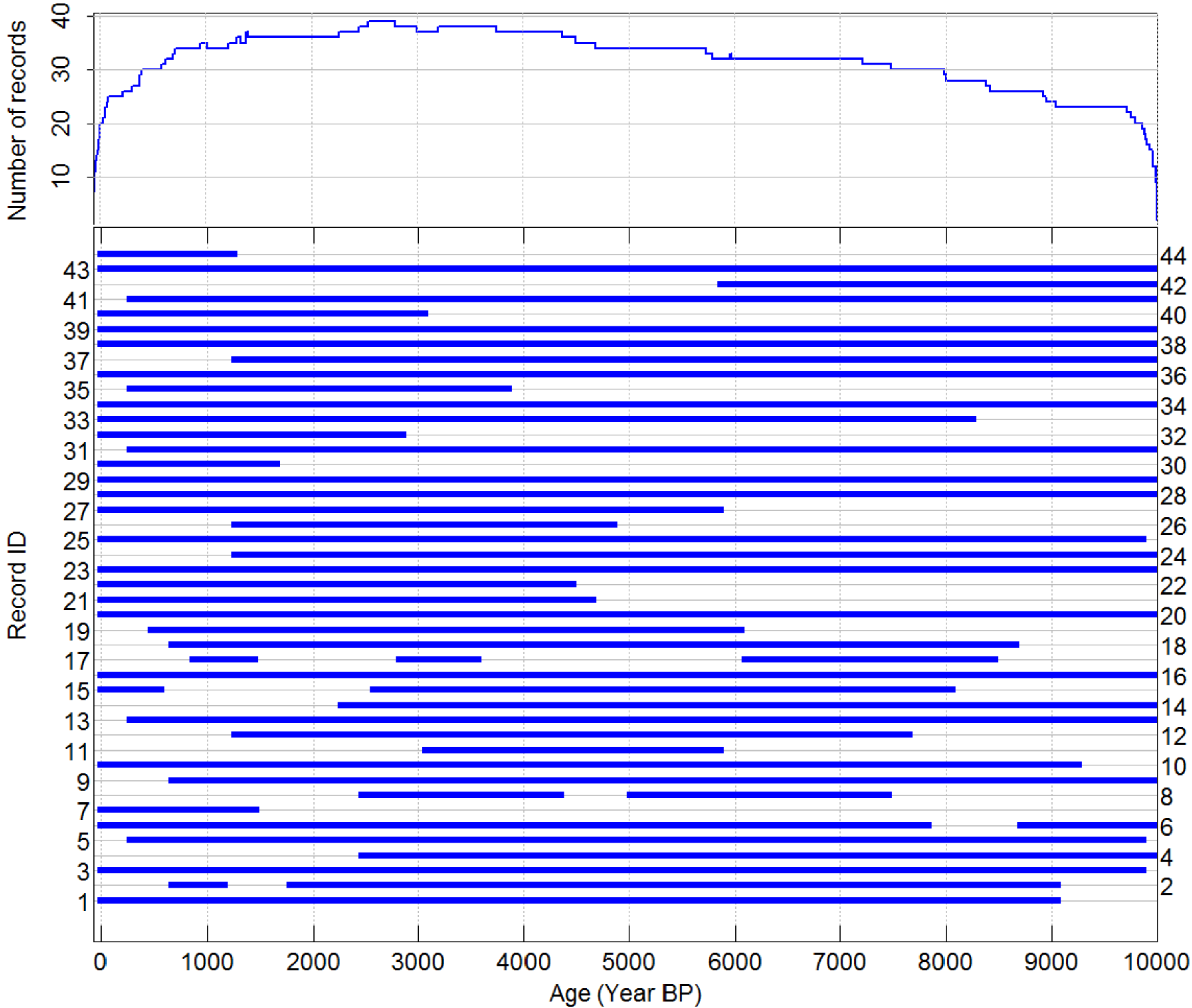
Supp_Fig 2. Same as Figure 4 but z-score axes are homogenous. Individual z-score records and the calculated regional mean z-scores for identified regions in the Mediterranean (see Fig 1 for spatial coverage) plotted against time. Grey shading shows one standard deviation from the mean. Positive (negative) z-score values indicate wetter (drier) climate conditions. ID numbers correspond to information in Table 1. The two graphs to the right show nMDS axis 1 and axis 2 plotted against time. The blue line excludes record #18 (Sadori et al., 2008, 2016) to improve the temporal coverage of the analysis. Super-imposed red line shows the results from the analysis for a slightly shorter time period when record #18 is included.

Supp_Fig 3. The nMDS stress plot shows a strong positive relationship between the actual dissimilarities between objects and the ordination distances which demonstrates that that ordination visualization of the data is reliable. Using five dimensions to summarize the datasets gave a stress value <0.05 (0.044), confirming that the five axes provide an excellent representation of the variability in the data.

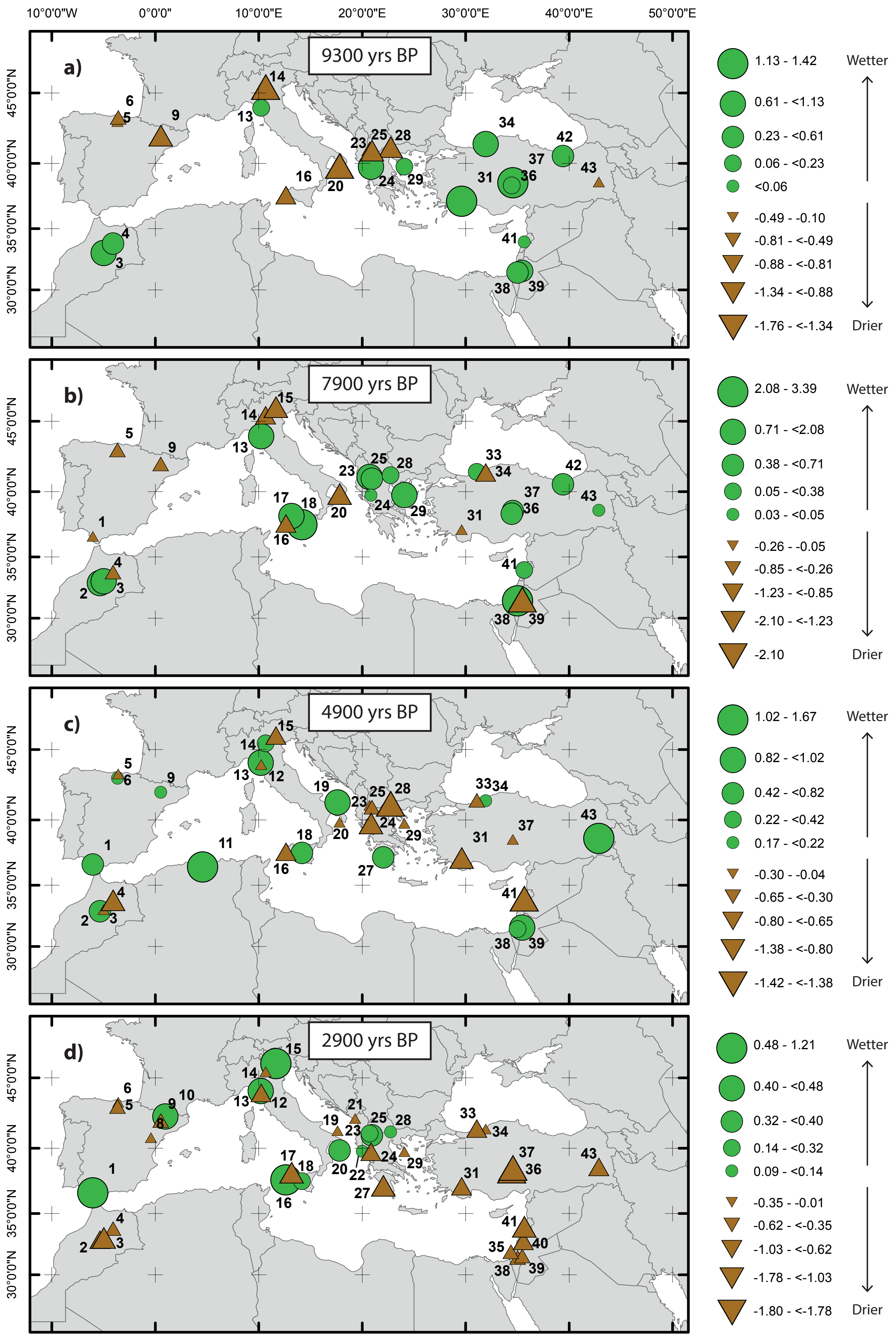
Supp_Fig 4. The results for all 5 nMDS axes plotted against time. nMDS axes 1 and 2 illustrate the main trends in the z-score data whereas the remaining axes seem to also reflect site specific variability.



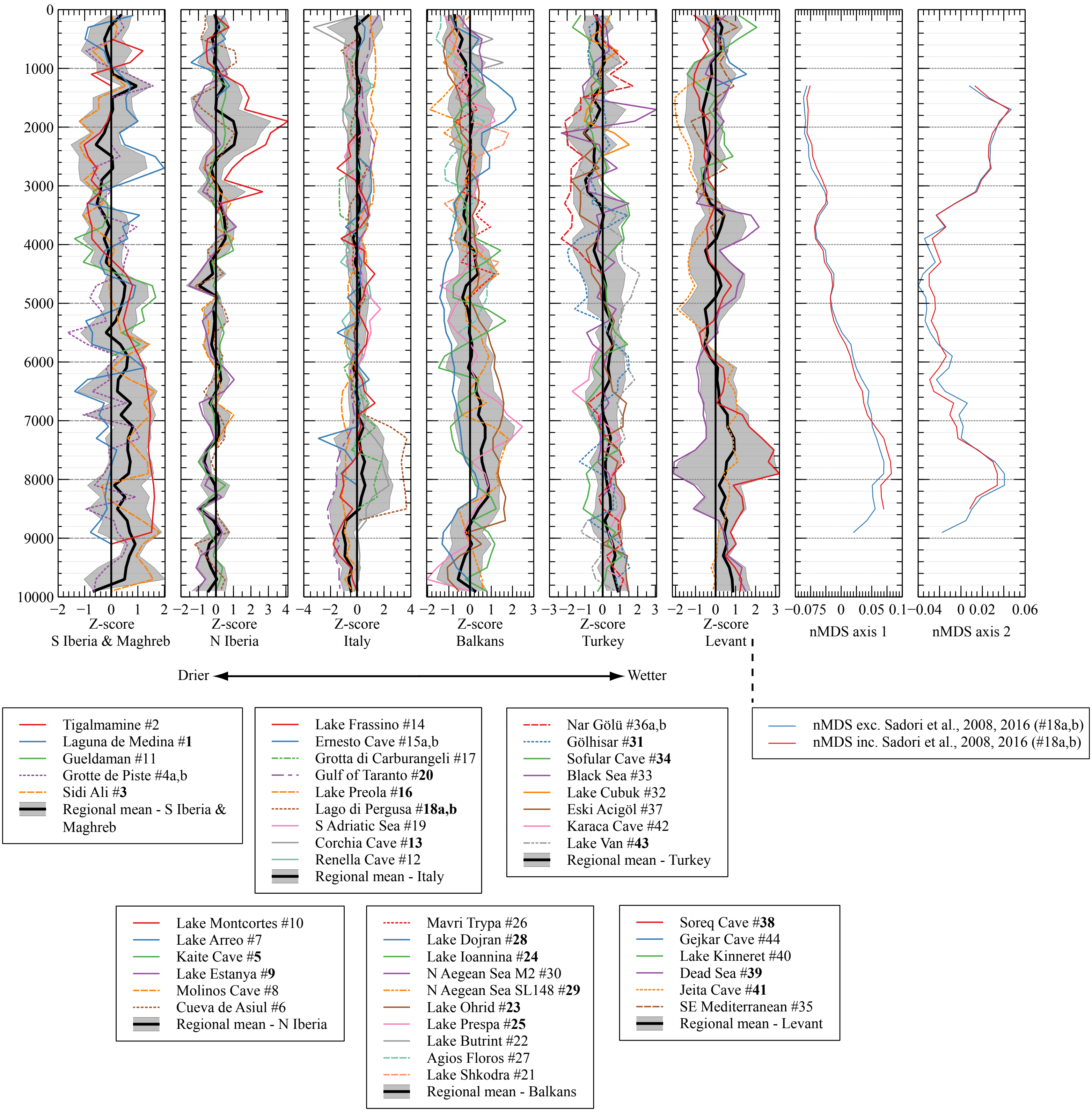
0°0'0"
10°0'0"E
20°0'0"E
30°0'0"E
40°0'0"E
45°0'0"N
40°0'0"N
35°0'0"N
30°0'0"N
North Iberia
South Iberia and Maghreb
Italy
The Balkans
Turkey
The Levant
Mediterranean Sea
1
2
3
4a,b
5
6
7
8
9
10
11
12
13
14
15a,b
16
17
18a,b
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36a,b
37
38
39
40
41
42
43
44
0
375
750
1 500
Km



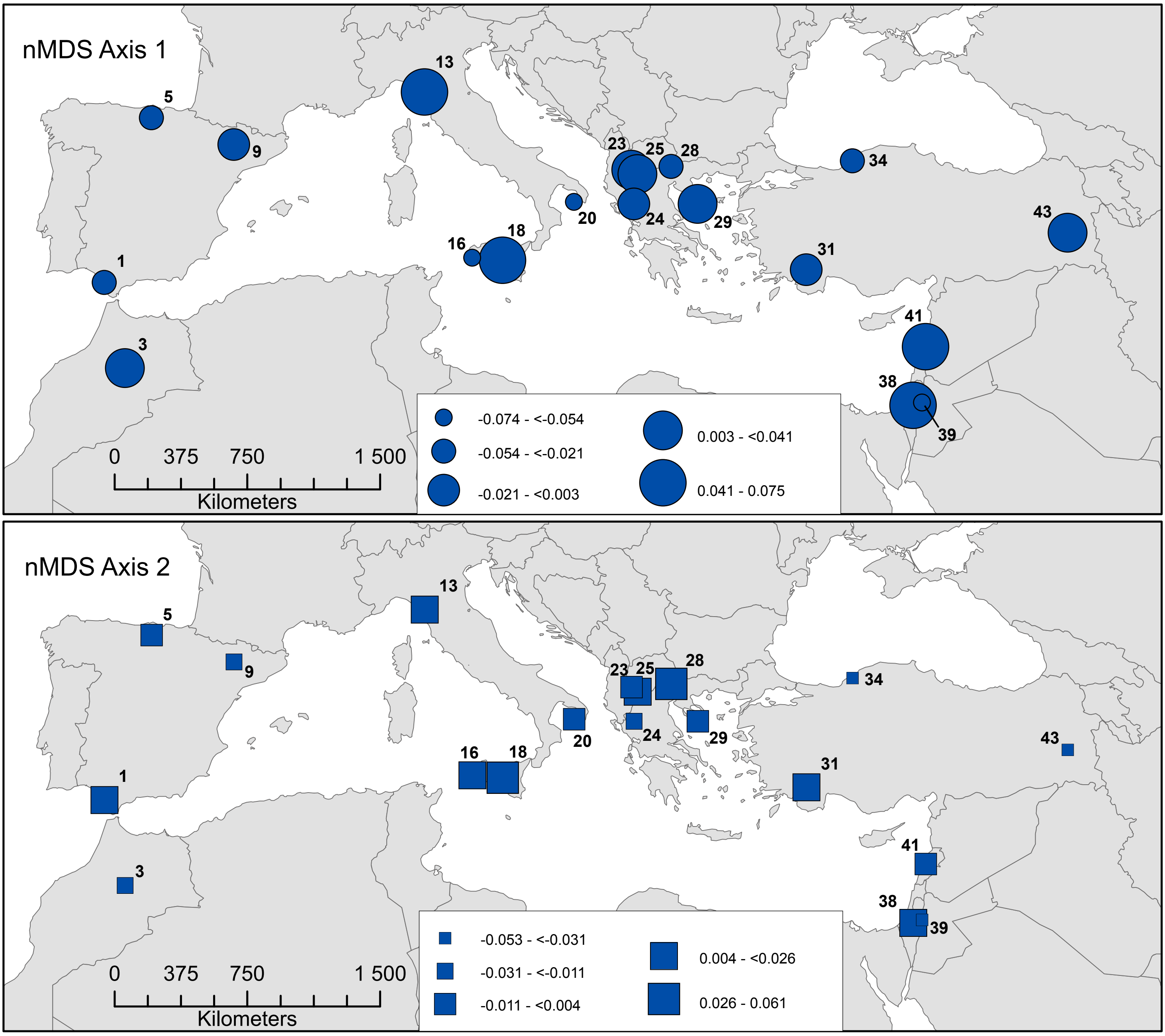
Number of records
10
20
30
40
Record ID
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Age (Year BP)



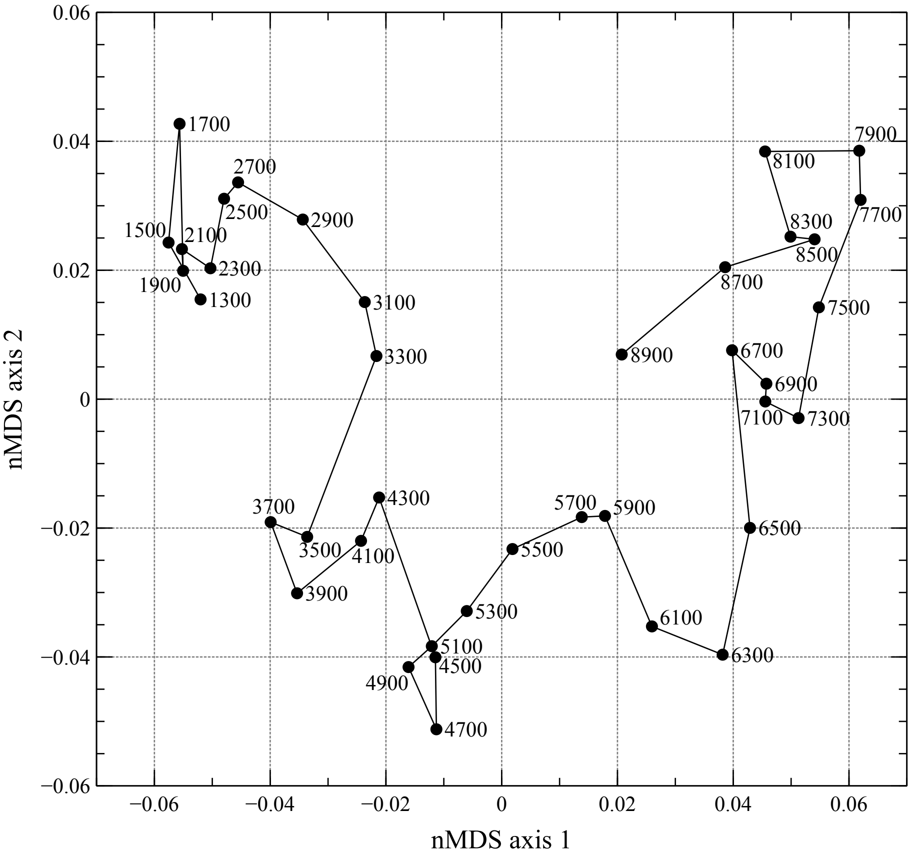
10°0'0"W
0°0'0"
10°0'0"E
20°0'0"E
30°0'0"E
40°0'0"E
50°0'0"E
45°0'0"N
40°0'0"N
35°0'0"N
30°0'0"N
a)
9300 yrs BP
1.13 - 1.42
0.61 - <1.13
0.23 - <0.61
0.06 - <0.23
<0.06
-0.49 - -0.10
-0.81 - <-0.49
-0.88 - <-0.81
-1.34 - <-0.88
-1.76 - <-1.34
Wetter
Drier
b)
7900 yrs BP
2.08 - 3.39
0.71 - <2.08
0.38 - <0.71
0.05 - <0.38
0.03 - <0.05
-0.26 - -0.05
-0.85 - <-0.26
-1.23 - <-0.85
-2.10 - <-1.23
-2.10
Wetter
Drier
c)
4900 yrs BP
1.02 - 1.67
0.82 - <1.02
0.42 - <0.82
0.22 - <0.42
0.17 - <0.22
-0.30 - -0.04
-0.65 - <-0.30
-0.80 - <-0.65
-1.38 - <-0.80
-1.42 - <-1.38
Wetter
Drier
d)
2900 yrs BP
0.48 - 1.21
0.40 - <0.48
0.32 - <0.40
0.14 - <0.32
0.09 - <0.14
-0.35 - -0.01
-0.62 - <-0.35
-1.03 - <-0.62
-1.78 - <-1.03
-1.80 - <-1.78
Wetter
Drier



0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Z-score
S Iberia & Maghreb
Z-score
N Iberia
Z-score
Italy
Z-score
Balkans
Z-score
Turkey
Z-score
Levant
nMDS axis 1
nMDS axis 2
Drier
Wetter
Tigalmamine #2
Laguna de Medina #1
Gueldaman #11
Grotte de Piste #4a,b
Sidi Ali #3
Regional mean - S Iberia & Maghreb
Lake Frassino #14
Ernesto Cave #15a,b
Grotta di Carburangeli #17
Gulf of Taranto #20
Lake Preola #16
Lago di Pergusa #18a,b
S Adriatic Sea #19
Corchia Cave #13
Renella Cave #12
Regional mean - Italy
Nar Gölü #36a,b
Gölhisar #31
Sofular Cave #34
Black Sea #33
Lake Cubuk #32
Eski Acigöl #37
Karaca Cave #42
Lake Van #43
Regional mean - Turkey
nMDS exc. Sadori et al., 2008, 2016 (#18a,b)
nMDS inc. Sadori et al., 2008, 2016 (#18a,b)
Lake Montcortes #10
Lake Arreo #7
Kaite Cave #5
Lake Estanya #9
Molinos Cave #8
Cueva de Asiul #6
Regional mean - N Iberia
Mavri Trypa #26
Lake Dojran #28
Lake Ioannina #24
N Aegean Sea M2 #30
N Aegean Sea SL148 #29
Lake Ohrid #23
Lake Prespa #25
Lake Butrint #22
Agios Floros #27
Lake Shkodra #21
Regional mean - Balkans
Soreq Cave #38
Gejkar Cave #44
Lake Kinneret #40
Dead Sea #39
Jeita Cave #41
SE Mediterranean #35
Regional mean - Levant



nMDS Axis 1
13
5
9
23
25
28
34
20
24
29
43
18
16
31
1
3
41
38
39
-0.074 - <-0.054
-0.054 - <-0.021
-0.021 - <0.003
0.003 - <0.041
0.041 - 0.075
0
375
750
1 500
Kilometers
nMDS Axis 2
13
5
9
23
25
28
34
20
24
29
43
16
18
31
1
3
41
38
39
-0.053 - <-0.031
-0.031 - <-0.011
-0.011 - <0.004
0.004 - <0.026
0.026 - 0.061
0
375
750
1 500
Kilometers



nMDS axis 2
nMDS axis 1
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.06
−0.04
−0.02
0
0.02
0.04
0.06
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
5500
5700
5900
6100
6300
6500
6700
6900
7100
7300
7500
7700
7900
8100
8300
8500
8700
8900