Clim. Past Discuss., 7, 2355–2389, 2011
www.clim-past-discuss.net/7/2355/2011/
doi:10.5194/cpd-7-2355-2011

Climate
of the Past
Discussions

Revisiting the humid Roman hypothesis: novel analyses depict oscillating patterns

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Received: 17 June 2011 – Accepted: 28 June 2011 – Published: 14 July 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Previous studies have proposed that potential vegetation in the Mediterranean maintained a wetter climate during the Roman Period until the initiation of large scale deforestation. The reduction in evapotranspirative fluxes associated with deforestation is suggested to have caused climatic aridification leading to the establishment of the present-day Mediterranean climate. There is also evidence to indicate that during the Roman Period Mediterranean climate was influenced by low frequency fluctuations in sea level pressure over the North Atlantic, termed here: the Centennial North Atlantic Oscillation (CNAO). In order to understand the importance of each of these mechanisms and disentangle their respective signals in the proxy record, we have employed an interdisciplinary approach that exploits a range of tools and data sources. An analysis of archaeological site distribution and historical texts demonstrate that climate did not increase in aridity since the Roman Period. Using an Earth system model of intermediate complexity prescribed with a reconstruction of ancient deforestation, we find that Mediterranean climate was insensitive to deforestation in the Late Holocene. A novel analysis of a composite of proxy indicators of climatic humidity depicts spatial and temporal patterns consistent with the CNAO. The link between the CNAO during the Roman Period and climatic humidity signals manifest in our composite analysis are demonstrated using a modelling approach. Finally, we present evidence indicating that fluctuations in the CNAO contributed to triggering a societal tipping point in the Eastern Mediterranean at the end of the Roman Period.

1 Introduction

It is proposed that a wetter climate during the Roman Period was maintained by greater forest cover prior to the initiation of large scale deforestation coinciding with the expansion of Roman territory (Dümenil Gates and Ließ, 2001; Reale and Dirmeyer, 2000; Reale and Shukla, 2000). Here, we define the RP as beginning with the foundation

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of the Roman Republic (ca. 2400 yr. BP) and ending with the fall of the Western Roman Empire (ca. 500 yr. BP). The decrease in evapotranspirative fluxes and increase in albedo coinciding with an intensification of deforestation is hypothesised to have initiated a positive feedback whereby the humid climate maintained by the biosphere became increasingly arid until it shifted to the present climate-vegetation equilibrium (Brovkin et al., 1998; Charney et al., 1975; Dekker et al., 2010).The idea that the Roman Period (RP) was more humid compared with present has been supported, and was likely inspired, by a number of classical writings that give details of large agricultural yields imported to Rome from Northern Africa and present-day Middle-East, the so-called "*granary of Rome*" (Davis, 2007). As Rome expanded these imports from the Southern Mediterranean became critical *"The sustenance of the Roman people is day by day being tossed about at the caprice of wave and storm"* (Emperor Tiberius, 14 AD–37 AD in Wrench, 1946) owing to land degradation and population pressures in the Northern Mediterranean *"What now remains compared with what existed is like the skeleton of a sick man, all the fat and soft earth having been wasted away and only the bare framework of the land being left"* (Plato, ca. 400 BC in Williams, 2000). Cities such as Palmyra and Petra that were populous and prosperous during the RP but are now located in desert regions reinforce the idea that climate was wetter in Roman times around the Mediterranean compared with present (Huntington, 1911; Reale and Dirmeyer, 2000).

The influence of deforestation on climate cannot be understood without also analysing larger-scale climatic processes overprinting anthropogenic signals in the proxy record. There is evidence to indicate that climate in the Mediterranean during the RP was influenced by low frequency fluctuations in sea level pressure (SLP) over the North Atlantic, similar to the how the North Atlantic Oscillation (NAO) modifies climate today (Jones et al., 2006; Martin-Puertas et al., 2008; Rimbu et al., 2003). We set out to understand the impact of deforestation and SLP modifications on climate in the Mediterranean during the RP and disentangle their respective contribution to signals in the proxy record. The RP provides novel opportunities in this regard with historical data providing a supplement to conventional proxy records. In light of this we have designed an interdisciplinary approach to understand the respective impact of deforestation and SLP oscillations on climate in the Mediterranean during the time of the Romans.

The motivation for revisiting the hypothesis that deforestation caused climatic aridification in the Mediterranean arises from recently published palynological and charcoal based reconstructions of mid to late Holocene forest cover. These studies indicate that large-scale deforestation took place prior to the RP. For example, Yasuda et al. (2000) present evidence of large-scale deforestation in Syria as early as 9000 yr. BP. Tinner et al. (2009) also demonstrate large-scale Neolithic forest clearance near Gorgo Basso Lake in Western Sicily. A new semi-quantitative method for determining land cover from pollen percentages known as REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) has shown that the largest anthropogenic changes in land cover in the Czech Republic took place between 3200–2700 yr. BP (Mazier et al., 2010). In addition to empirical reconstructions, a number of models of human induced land cover change (see Gaillard et al. (2010) for an overview) all indicate that extensive land clearance had occurred prior to the RP. These land cover reconstructions are supported with explicit evidence of early Iron Age land clearance in Israel from the Old Testament Book of Joshua. The text describes how members of the house of Joseph were sent by Joshua to the Judean hills to "*go up to the forest, and clear there ground for yourselves...the hill country shall be yours, for though it is forest, you shall clear it and possess it to the farthest borders*" (Jos 17, 14–18 in Borowski, 1987).

In addition, we consider that the picture of the ancient Mediterranean landscape is open to misinterpretation. For example large yields from North Africa and the Middle-East that are interpreted as evidence of a more humid climate ignore that the Fertile Crescent (Syria, Lebanon, Israel, Palestine, Iraq and Nile catchment) and the northern coast of Africa remain highly productive, producing sufficient to support a population that in Roman times was a fraction of present day (Davis, 2007). Also, the city of Palmyra in modern Syria is given as evidence for climatic aridification because this once flourishing city is now surrounded by desert (Huntington, 1911; Reale and

Dirmeyer, 2000). However, Palmyra was established at an oasis (still present today) on an important trade route between the Western Levant and civilisations along the Tigris and Euphrates rivers. It was because of Palmyra's strategic location as a focal point of trade between kingdoms that it became such a large and prosperous city. Equally, Reale and Dirmeyer (2000) propose that the coincidence of the southern border of Roman Libya with the northern extent of the Sahara is evidence for a wetter climate in the RP. However, the southern border of Roman Libya (i.e. within ca. 100 km of the coast) still coincides with the northern extent of the desert and ancient North African cities such as Alexandria, Carthage, Berenice, Ghadamis, Djemila, and Thamugadi all remain important population centres today, indicating that climate has not changed significantly since the RP.

In order to determine whether the timing and extent of deforestation during the Late Holocene could have caused climatic aridification in the Mediterranean, we incorporate the latest data on ancient land use change into simulations using an earth system model of intermediate complexity (EMIC). The outcomes of the simulations are interpreted in conjunction with a detailed analysis of the archaeological and historical record to understand the change in climatic humidity between the RP and present. Changes in climatic humidity are inferred based on the distribution of archaeological sites in the Fertile Crescent in relation to present-day precipitation and land use. The analysis of ancient habitation distribution as a proxy of climate change is a novel approach that potentially allows for local scale changes in rainfall distribution to be resolved. Indeed, the 4.2 KA aridification event, which has been linked to solar radiation variability (Staubwasser et al., 2003) and a southward movement of the Intertropical Convergence Zone (Marchant and Hooghiemstra, 2004), was captured in the archaeological record at Tell Leilan in the Northern Fertile Crescent. The city of Tell Leilan, which currently receives 450 mm yr^{-1} precipitation, underwent such extreme aridification that it was almost entirely abandoned (Weiss et al., 1993). This suggests that habitation distribution in The Fertile Crescent is highly sensitive to changes in climatic humidity and thus represents and appropriate proxy to capture climatic aridification.

To determine the impact of SLP oscillations on climate during the RP we consult proxy records of climatic humidity. We use the term climatic humidity rather than precipitation because certain proxies are indicators of evaporation and precipitation ratios rather than precipitation only. A number of proxy records provide evidence of an increase in climatic humidity in the Mediterranean coinciding with the RP. In Israel an anomalous wet period is apparent during the RP in a speleothem record from the Soreq cave (Bar-Matthews et al., 1997; Orland et al., 2009) and reconstructed levels of the Dead Sea (Bookman et al., 2004; Migowski et al., 2006). An isotopic analysis of trees used to construct a Roman siege ramp against Jewish rebels at the Fortress of Masada above the Dead Sea also indicate a humid climate during the RP in Israel (Issar and Yakir, 1997). However, there is contrasting evidence to suggest that the RP was more arid than the period that preceded it. For instance, a continuous pollen sequence from 10 000 yr. BP to present for Lake Tigalmamine in the Middle Atlas Mountains of Morocco demonstrates that the period 3500 BP–2500 BP was considerably wetter than the RP that followed (Cheddadi et al., 1998). Equally, a study of a composite of lake levels in the Jura Mountains indicates that the period 2750–2350 yr. BP was more humid than the RP (Magny, 2004). Such signals in the proxy record of a seesaw in climatic humidity between the East and West Mediterranean are consistent with modern teleconnections between Mediterranean climate and the NAO (Cullen and deMenocal, 2000).

Under present-day conditions oscillations in sea level pressure (SLP) gradients over the North Atlantic have been shown to have an important impact on Mediterranean winter precipitation at yearly and decadal timescales (Cullen and deMenocal, 2000; Hurrell, 1995). Under NAO^+ (NAO^-) a strengthening (weakening) of the pressure gradient between a high pressure region over the Atlantic subtropics and a low near Iceland causes the track of westerly winds to move northwards (southwards) making Northern (Southern) European winters wetter and milder whilst Southern (Northern) Europe becomes drier and cooler (Cullen and deMenocal, 2000; Hurrell, 1995). Within the Mediterranean a seesaw pattern in relation to NAO phase is exhibited whereby the

South-Eastern Mediterranean becomes wetter (drier) under NAO$^+$ (NAO$^-$) compared the remainder which becomes drier (wetter) (Cullen and deMenocal, 2000). Decadal fluctuation of the pressure gradient is linked to changes in sea surface temperature (SST) between the subtropics and the North Atlantic (Marullo et al., 2011; Robertson et al., 2000). Coincident warming (cooling) in the North Atlantic and cooling (warming) in the subtropics modify SLP in these regions and cause a strengthening (weakening) of the gradient (Robertson et al., 2000; Marullo et al., 2011). Centennial-scale changes in the NAO are proposed based on a negative temperature trend of SST in the North Atlantic and a positive SST trend in the subtropics (Rimbu et al., 2003). The cooling of SST in the North Atlantic and warming in the subtropics in the period 6000 yr. BP to 2000 yr. BP is proposed to have caused a weakening of the NAO, followed by a slight reversal to positive phase during the RP (Rimbu et al., 2003). The mechanism forcing changes in North Atlantic SLP are likely different for differing timescales as atmospheric processes have a major forcing on SST at shorter timescales, whereas centennial changes in SST are likely driven to a greater extent by external forcings and changes in meridional overturning circulation. The separate forcing of the NAO mode at different timescales means that opposite NAO modes can coexist depending on the temporal resolution under investigation. For this reason we chose to term centennial scale changes in North Atlantic pressure gradients the Centennial North Atlantic Oscillation (CNAO) to distinguish it from the NAO.

To understand the impact of the CNAO on Mediterranean climate during the RP we have developed a composite of proxy indicators of climatic humidity. A composite analysis of modern precipitation indices at Southern European weather stations was used to demonstrate an anti-correlation in precipitation between the South-Eastern Mediterranean compared with the remainder in relation to the phase of the NAO (Cullen and deMenocal, 2000). Our composite analysis covers the period 3000 yr. BP–1000 yr. BP and is presented so that spatial and temporal changes in climatic humidity are apparent. Cullen and deMenocal (2000) restricted their analysis to indices of winter precipitation to identify links to the NAO. However, the majority of rainfall in the Mediterranean falls in winter months (Peel et al., 2007), making less seasonally specific proxy indicators of climatic humidity appropriate for picking up changes linked to the CNAO. Whereas archaeological analysis facilitates a detailed understanding of a trend in climatic humidity for a particular region; the composite analysis illustrates the spatial and temporal patterns in climatic humidity throughout the Mediterranean during the RP. Thus, we can use this analysis to identify whether the climate exhibited seesaw patterns consistent with the CNAO. Of course the composite analysis also facilitates the identification of aridification trends arising from deforestation should they be present in the composite data. To understand if the patterns depicted in the composite analysis are consistent with changes in the CNAO forced by Atlantic SST, we have prescribed SSTs consistent with a strong and weak CNAO in an EMIC and compared the precipitation signal in the Mediterranean with that of the composite analysis.

2 Methodology

The RP in the Mediterranean is one that provides both exceptional opportunities and exceptional challenges in terms of paleoreconstructions. In terms of opportunities, Late Holocene archaeological and historical data record a history of human interaction with the environment that are extremely useful as a supplement to conventional proxy-based climate reconstructions. However, the high intensity of anthropogenic activity during this period means that conventional methods of land cover reconstructions are fraught with uncertainty (Gaillard et al., 2010). In light of this we have designed a methodology that draws on a range of data sources and tools to understand the impact of deforestation and the CNAO on climate during the RP. We begin in Sect. 2.1.1 with an analysis of archaeological site distribution to understand if climate in the Mediterranean has undergone a trend towards aridification since the RP as indicated by previous studies (Dümenil Gates and Ließ, 2001; Reale and Dirmeyer, 2000; Reale and Shukla, 2000). Section 2.1.2 presents details of simulations designed to uncover if large-scale deforestation is a plausible mechanism for climatic aridification in the Mediterranean. In

Sect. 2.2.1 we present the composite analysis of proxy indicators of climatic humidity. The composite analysis facilitates the identification of more complex climatic patterns compared with the archaeological analysis and is applied to investigating the influence of CNAO on climate in the Mediterranean during the RP. In Sect. 2.2.2 we again apply EMIC simulations to understand the link between SST and the climatic patterns manifest in the composite analysis.

2.1 Deforestation

2.1.1 Archaeological and historical data analysis

The application of archaeological data as a proxy of climate has precedent (Weiss et al., 1993), however rather than focusing on one site we aim to understand changes in water availability in a wider context by analysing the distribution of archaeological sites over the entire Fertile Crescent. The Fertile Crescent was chosen owing to the wealth of historical information related to it and because previous studies indicate that precipitation reduced by half in the region owing to deforestation since the RP (Reale and Shukla, 2000). There is also extensive modern empirical evidence, supported by modelling studies, to indicate that the Fertile Crescent is one of the most climatically sensitive regions in the Mediterranean to changes in land cover (Alpert and Mandel, 1986; De Ridder and Gallée, 1998). Given that the region is in a marginal climatic zone with steep gradients in precipitation over relatively short distances, it represents an ecotone between arable land and desert. Therefore significant decreases in climatic humidity associated with deforestation would cause the border of the ecotone to move leaving previously occupied archaeological sites abandoned in desert regions as occurred during the 4.2 ka aridification event (Weiss et al., 1993). It is important to note that archaeological site distribution is only used to infer a trend towards climatic aridification following the RP and that oscillation between humid and dry periods cannot be picked up with this type analysis. Site distribution alone can only capture the movement in the ecotone in one direction, whereas stratigraphic dating would be required to identify the waxing and waning of the ecotone as Weiss et al. (1993) demonstrated at Tell Leilan.

Archaeological site data was provided from a geo-referenced database of sites (Pedersen, 2010) dating from the Bronze Age until present. We used a gridded dataset of average yearly precipitation interpolated from rain gauge stations at 0.25 degree resolution for the period 1951–2007 (Yatagai et al., 2008) to determine present-day precipitation isohyets. Using ArcGIS 9, a 2 km buffer was placed around each site and a spatial analysis was done to determine whether a site coincided with agricultural or inhabited land (Tateishi et al., 2008). Ground-truthing was carried out using Google Earth imagery and the Arc2Earth extension for ArcGIS.

2.1.2 Deforestation simulation

All simulations in this study were carried out using the Planet Simulator: an EMIC with dynamic vegetation and mixed layer ocean capabilities (Fraedrich et al., 2005a, b). The Planet Simulator has the advantage that it is relatively computationally inexpensive and therefore facilitates long term simulations required to achieve a potential biosphere at equilibrium with prescribed boundary conditions (Dekker et al., 2010). All simulations were carried out at T42 spectral triangular resolution (~2.8 × 2.8 degrees latitude-longitude) with 10 vertical layers.

Ancient deforestation was prescribed as a forested fraction of potential vegetation from 27.5° N to 55° N and 15° W to 50° E using a reconstruction based on population estimates and the contribution of technological advances (Kaplan et al., 2009). The potential vegetation for each time slice was derived from initialising the model with a map of modern day above ground biomass (AGB) (Olson, 1983). Simulations were run for 300 yr with dynamic vegetation until the biosphere had achieved equilibrium state (Dekker et al., 2010). Using model-derived AGB was deemed the best method for an independent derivation of AGB for the Mediterranean. This is because, although forest composition is known at different time periods at given sites, accurately estimating AGB for the entire Mediterranean from such records is difficult (Gaillard et al., 2010). More so since many of the regions of interest are too arid to preserve a palynological record. Experiments were prescribed with climatologically derived, monthly SST averages for the period 1981–2002 (Reynolds et al., 2002). Each experiment lasted 30 yr, with the final 20 yr used in analysis to ensure the system was at equilibrium with prescribed boundary conditions. To calculate the regional average and standard deviation in evapotranspiration (the contribution of vegetative evapotranspiration and other sources of evaporation) we took the yearly average from our 20 yr simulations and adjusted the averaging of the flux at each cell to account for change in cell size at different latitudes. The spatially weighted values were averaged over all land cells to provide the regional average and standard deviation. To understand how deforestation affected climate we compared 5 simulations: one of potential vegetation and 4 prescribed with a forested fraction of potential vegetation for time slices of 2500 yr. BP, 2000 yr. BP, 1500 yr. BP and 100 yr. BP (Kaplan et al., 2009).

2.2 Centennial North Atlantic Oscillation

2.2.1 Composite proxy analysis

Given that no database exists where raw data from proxy reconstructions of Mediterranean climate are systematically compiled; a search of the literature was carried out and each corresponding author contacted in order to access raw proxy data for analysis. In instances where authors were not contactable we digitised figures from the original papers using GetData software. The proxy records used in the composite proxy analysis are presented in Table 1. The geographic distribution of proxy records used in the analysis is illustrated in Fig. 1. For each record we calculated the mean of the climatic humidity indicator for the period 3000 yr. BP–1000 yr. BP and used this to determine whether a certain 100 yr period was relatively wet or dry in the context of that particular proxy. In cases where there was more than 1 data point in a 100 yr time slice, we took the average of all data points in that time slice. In cases where there were none, we performed linear interpolation between data points. The composite analysis is presented in Fig. 5 in results and the data from which it is derived is supplied in the online supplementary material.

2.2.2 Centennial North Atlantic Oscillation simulation

Given that the CNAO is driven by SST changes, we applied climatological SSTs (Smith and Reynolds, 2003) to force the Planet Simulator with strong and weak CNAO to understand the impact of changes in CNAO on climate in the Mediterranean. It has been demonstrated that the Planet Simulator is capable of simulating atmospheric response to SST forcing comparable to the more complex ECHAM4 (Donders et al., 2009; Grosfeld et al. 2008; Romanova et al. 2006). To achieve a SST anomaly of appropriate magnitude for centennial SST changes (Rimbu et al., 2003) we calculated the Monthly 10 yr average SST anomaly for 1904–1914 and 1984–1994: the coldest and warmest periods in the Northern hemisphere 20th century climatological SST record respectively. The resultant temperature anomaly was added to and subtracted from the monthly SST fields used in the deforestation simulations. Simulations were carried out for each land cover scenario but no discernable interaction between land cover and CNAO was detected.

3 Results

3.1 Archaeological and historical analysis

Archaeological site distribution in the Fertile Crescent in relation to present-day precipitation and cultivated land is presented in Fig. 2. The sites in green are those that coincide with currently inhabited or arable land. The sites in black are located neither on arable or inhabited land. In total 2345 sites were used in the analysis. Of these 129 (5.5 %) are now located in abandoned regions. The majority of abandoned sites are located along the north-east of the Jazira (A) and in lower Southern Mesopotamia

(B). It can be seen that areas of arable land extend into regions that receive less than 250 mm y^{-1} precipitation, which is considered the minimum requirement for dry-land farming (Bowden, 1979). In these regions, cultivation is possible owing to the supplementation of precipitation in dry periods with irrigation from rainwater harvesting, wadi's (ephemeral streams), rivers and groundwater extraction, practices that were employed in ancient times as they are today (Huntington, 1911)

3.2 Deforestation and Mediterranean climate

The regionally averaged yearly evapotranspiration meaned over 20 yr of simulations for land cells prescribed with potential vegetation and vegetation at 2500 yr. BP, 2000 yr. BP, 1500 yr. BP and 100 yr. BP is presented in Fig. 3 (Kaplan et al., 2009). It can be seen that a decrease in evapotranspirative fluxes in the order of 20 % occurred prior to the RP as a result of deforestation. Between the RP and present there is a reduction in evapotranspirative fluxes in the order of 10 %, indicating that the greatest anthropogenic perturbation to climate arising from deforestation occurred prior to the RP.

The spatial expression of the statistically significant ($t(38) = 2.024$, $p = 0.05$) anomaly in yearly average evapotranspiration between forest cover at 100 yr. BP – potential forest cover is presented in Fig. 4. It should be noted that the anomaly in terms of biomass between potential vegetation and the deforested scenario at 100 yr. BP is considerably less in the Mediterranean compared with Northern and Central Europe. This is owing to low potential biomass of Mediterranean vegetation simulated by the Planet Simulator compared with AGB at northern latitudes. Given such small anomalies in biomass in the Mediterranean, the climatic feedback caused by deforestation in terms of evapotranspiration is statistically insignificant. Northern and Western Europe exhibit significant climatic feedbacks in relation to deforestation owing to much greater potential biomass and hence greater changes to fluxes arising from deforestation (see non-shaded areas in Fig. 4). Therefore, our simulations indicate that the Mediterranean climate is insensitive to deforestation not just between the RP and present but during the entire anthropogenic period.

3.3 Composite proxy analysis

The composite analysis is presented in Fig. 5 along with a map indicating the spatial distribution and relative state of each record at 2700 yr. BP and 1500 yr. BP. In the composite analysis we have presented the proxies arranged in ascending order from west to east and divided into 100 yr time steps so that spatial and temporal patterns are identifiable. Each time step is colour coded blue or yellow to distinguish whether it was relatively humid or arid in the context of that particular proxy. White indicates no data is available. The composite of proxies exhibit a seesaw pattern in precipitation between the East and West Mediterranean during the period of the analysis. The Western Mediterranean exhibits a relatively humid signal in the early part (before 2300 yr. BP) of the analysis compared with the Eastern Mediterranean which is relatively arid during the same period. A switch to a more humid climatic regime is exhibited in the Eastern Mediterranean around 2100 yr. BP coincident with increased aridity in the Western Mediterranean. After 1500vyr. BP there is a return to arid conditions in the east, whilst a coincident increase in climatic humidity is evident in the Western Mediterranean. There is no aridification trend, in opposition to the theory of climate aridification arising from deforestation beginning in the RP (Dümenil Gates and Ließ, 2001; Reale and Dirmeyer, 2000; Reale and Shukla, 2000).

3.4 CNAO and Mediterranean climate

The statistically significant ($t(38) = 2.024$, $p = 0.05$) anomaly in SLP between a CNAO$^-$ – CNAO$^+$ are presented in Fig. 6a. There is an increase in pressure over the Icelandic low and a decrease in pressure over the sub-tropics in accordance with cooling in the North Atlantic and warming in the sub-tropics (Fig. 6b). The associated weakening of the CNAO causes an increase in westerly storm tracks over the Mediterranean

(Fig. 6c). Interestingly, there is also a statistically significant increase in the sub-tropical high over the Arabian Peninsula and Eastern Mediterranean (Fig. 6a). The anomaly in SLP and associated statistically significant relative anomaly in precipitation is presented in Fig. 6d. The strengthening of the high pressure system over the Middle-East has the effect of blocking the intrusion of moist, westerly airflows and decreasing winter (DJFM) rainfall as seen by a reduction in rainfall over Egypt and Southern Israel.

4 Discussion

4.1 Ancient deforestation and Mediterranean climate

Previous studies have indicated that deforestation in the Mediterranean beginning in the RP caused climate to become increasingly arid leading to the establishment of the present climate-vegetation equilibrium (Dümenil Gates and Ließ, 2001; Reale and Dirmeyer, 2000; Reale and Shukla, 2000). It is proposed that precipitation may have reduced by half over North-East Africa and the Middle-East as a result of deforestation (Reale and Shukla, 2000). However, the large numbers of vegetation reconstructions that have become available in the intervening years demonstrate that extensive land clearance had occurred well before the RP. When we prescribed land cover in an EMIC from one such reconstruction (Kaplan et al., 2009), we found a regionally averaged decrease in evapotranspiration in the order of 20 % between a potential vegetation scenario and land cover at 2500 yr. BP, whereas the decrease between the RP and present was in the order of 10 % (Fig. 3). An examination of the spatial expression of climate perturbations arising from anthropogenic deforestation (Fig. 4) indicates that Central and Northern Europe were the most sensitive to changes in forest cover owing to high AGB in these regions compared with the Mediterranean where AGB is comparatively low. Indeed, simulations of deforestation indicate that climate in the Mediterranean was insensitive to changes in forest cover not only between the RP and present but throughout the entire anthropogenic period.

To test whether the insensitivity of Mediterranean climate to land cover changes expressed by our simulations was appropriate, we carried out an analysis of archaeological site distribution to examine shifts in ecotones owing to changes in climatic humidity during the Late Holocene (Fig. 2). It was found that 5.5 % of sites are in regions currently abandoned or too arid for viable habitation. The abandoned sites are primarily located in the north-east of the Jazira and in lower Southern Mesopotamia. However, before assumptions on changes in water availability can be made; an understanding of the historical context of these sites is required. Detailed historical descriptions of the North-Eastern Jazira region exist from accounts of two Roman military campaigns in 177 AD and 363 AD. The site of Hatra, which is currently in a desert region, is described by Cassius Dion (177 AD in Stein, 1941) as a city with *"neither water (save a small amount and that poor in quality) nor timber nor fodder. These very disadvantages, however, afford it protection, making impossible a siege by a large multitude".* Hatra's location in an arid region was quite typical of fortified cities from this era but what such cities also had in common was that the groundwater table was high and could be exploited from wells within the city walls, thus making them almost impossible to besiege. A later account of the northward march of a Roman army from Hatra describes the crossing of an arid plain extending for 70 mille (110 km) which was void of potable water or edible vegetation as far as Ur (present-day Tell A'far) (Ammianus Marcellinus, 363 AD in Stein, 1941). Tell A'far today, as then, coincides with the northern border of the desert, indicating that the location of desert and arable ecotone has changed little since the RP in this region. The reason for a large number of abandoned sites between Hatra and Tell A'far is that this plain was an important trade route between kingdoms in lower Mesopotamia and those in the Northern Jazira plains: the route along the Tigris being too rugged for rapid movement (Ammianus Marcellinus, 363 AD in Stein, 1941). The abandoned sites along this route were located at springs (still present today) or where there was easy access to groundwater (Stein, 1941). Any site with even limited water supply in this arid plain could potentially profit as a focal point for trade on one of the busiest trade routes in the ancient world (Stein, 1941).

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A similar scenario describes the rise and fall of Petra in Southern Jordan. Petra was established and became highly profitable as a trade city on the caravan routes between North Africa, the Arabian Peninsula, and the Fertile Crescent. The Nabataen civilisation used rainwater harvesting techniques and exploited local springs to ensure year round water supply that enabled them to control trade amongst some of the world's most developed civilisations (Ortloff, 2005). In opposition to the hypothesis that climate change was responsible for the abandonment of the city (Huntington, 1911; Reale and Dirmeyer, 2000); it is more likely that improvements in ship building technology caused overland trade routes in the region to fall into disuse (ca. 300 AD) as trade moved to the Mediterranean Sea, Red Sea and Arabian Gulf (Artzy, 1994).

Lower Southern Mesopotamia also exhibits a large number of abandoned sites. This region underwent dramatic changes during the Holocene owing to the inundation of the Arabian Gulf ending around 7500 yr. BP. It is hypothesised that this led to a mass migration of people northwards into Mesopotamia (Rose, 2010). Population pressure in association with increasing aridity initiated these early civilizations to develop extensive irrigation networks that allowed them to exploit the land between the Tigris and Euphrates rivers for agriculture (Adams, 1981). The extensive evidence for early irrigation in the Mesopotamian region suggests that in the past, as now, Mesopotamia received limited precipitation. Over time, irrigation canals became clogged with sediment owing to a breakdown in maintenance related to periods of political and social upheaval (Perry, 1986). Indeed many of the ancient, neglected irrigation canals in lower Mesopotamia are still visible from satellite imagery alongside abandoned archaeological sites in our dataset. In fact, much of the region has only been brought back under irrigated cultivation in the latter half of the twentieth century (FAO, 2009). Therefore, the abandoned sites in lower Mesopotamia are not representative of change in climatic humidity; rather they demonstrate changes in land management over millennia. It could be argued therefore, that the sites in Southern Mesopotamia are not appropriate proxies of changing climatic humidity as agriculture in this region was always dependent on irrigation from the Tigris and Euphrates rivers. However, the establishment of early irrigation is indication in itself of persistent aridity in lower Mesopotamia from the beginnings of human civilisation in the early-mid Holocene.

Our archaeological analysis supports interpretations based on our simulations that no dramatic reductions in climatic humidity occurred in the Fertile Crescent since the RP as a result of deforestation. Instead, social and economic developments changed how humans interact with the landscape and indeed changed the landscape itself. That is not to say that human habitation patterns in the region are insensitive to climatic shifts. For example, an aridification event at 4200 yr. BP led to the abandonment of cities in the Northern Jazira plains (Weiss et al., 1993). Of course, conditions in the Fertile Crescent cannot be indicative of the entire Mediterranean. However, the detailed analysis of the archaeological record in a region of distinct ecotones that exhibit high climatic sensitivity to land cover change is instructive of the upper level of climatic sensitivity to deforestation that can be expected for the entire Mediterranean region.

4.2 CNAO and Mediterranean climate

Our composite analysis of proxy-based reconstructions of climatic humidity depict a seesaw pattern between the Eastern and Western Mediterranean in the period 3000 yr. BP to 1000 yr. BP (Fig. 5) consistent with CNAO forcing. The cooling of SST in the North Atlantic and warming in the subtropics in the period 6000 yr. BP to 2000 yr. BP is proposed to have caused a weakening of the CNAO, followed by a slight reversal to positive phase during the RP (Rimbu et al., 2003). The early part of our composite analysis (before ca. 2300 yr. BP) exhibits a precipitation pattern consistent with the negative phase of the CNAO with relatively high climatic humidity in the Western Mediterranean and relatively arid conditions in the South-East. A reversal in this signal is exhibited ca. 2100 yr. BP whereby climatic humidity in the South-Eastern Mediterranean increases significantly and a drying trend is witnessed in the West. The timing of these shifts in climatic humidity between the Eastern and Western Mediterranean occur slightly earlier in our reconstruction compared with the climatic signal that could be expected in the Mediterranean based on reconstructions of CNAO mode

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by Rimbu et al. (2003). However, the Rimbu et al. (2003) reconstruction is a composite of a number of paleo-SST records spanning 10 000 yr smoothed to generate a CNAO index. Given limits in the geographic distribution of SST records, some key Atlantic regions responsible for forcing CNAO are missing in the final index. However, our composite analysis is geographically more complete to pick up oscillating patterns in climatic humidity between the East and West Mediterranean indicative of changes in CAO/AMO/NAO index. So although our composite analysis is not based on paleo-SSTs, the close link between Mediterranean precipitation variability and NAO phase (Cullen and deMenocal, 2000; Marullo et al., 2011), indicate that the CNAO underwent a trend from negative to positive at the beginning of the RP followed by a shift back to negative after 2500 yr. BP.

The link between changes in precipitation patterns in the Mediterranean associated with changes in North Atlantic SLP arising from the opposite trend in Northern and Southern Atlantic SST are demonstrated in Fig. 6a–d. The mechanism behind the increase in climatic humidity in the Western Mediterranean under CNAO$^-$ is owing to an increase in zonal storm tracks caused by a weakening of the CNAO (Fig. 6c) (Cullen and deMenocal, 2000; Hurrell, 1995). The cause of coincident drying in South-Eastern Mediterranean is less straightforward but appears to be related to a modification of Mediterranean SSTs driven by the CNAO. The large warming (cooling) of SST in the Western Mediterranean associated with CNAO$^-$ (CNAO$^+$) has little effect on SLP there. However, owing to changes in atmospheric pressure gradients it causes a significant increase (decrease) in SLP over the Eastern Mediterranean and blocks (facilitates) the intrusion of moist, westerly airflows (Fig. 6a–d) (Ben-Gai et al., 2001). Marullo et al. (2011) have demonstrated that decadal modification of Atlantic SSTs driven by the Atlantic Multi-decadal Oscillation (AMO) exhibit coherence with Mediterranean SST exceeding 99 % confidence limit for periods exceeding 100 yr. For winter, they find that the strongest correlations between Atlantic and Mediterranean SST occur between the Eastern Mediterranean and the Sub-Polar Gyre (SPG). In our composite proxy analysis the most distinct and consistent modifications in climatic humidity are also in the Eastern Mediterranean, indicating that it is the most sensitive region in the Mediterranean to longer-scale changes in CNAO mode. As mentioned, there is a close agreement in the spatial response of climatic humidity between our proxy analysis and modern precipitation patterns based on seasonal to decadal fluctuations in the NAO/AMO. This strongly indicates that modifications in SLP gradients over the North Atlantic impacted climate in the Mediterranean during the Late Holocene at seasonal, decadal and centennial frequencies.

4.3 Impact of CNAO on Roman Civilisation

Although the archaeological analysis demonstrates that no aridification trend took place in the Fertile Crescent since ancient times, the waxing and waning of humid and arid periods associated with the CNAO likely contributed to societal changes in the region throughout the Late Holocene. For instance, the period from 2100 yr. BP–1500 yr. BP was one of relatively high climatic humidity and coincided with a surge in population in the Western Fertile Crescent (Foss, 1997). Increasing population pressure necessitated an intensification of settlements in marginal and upland regions which brought about increased erosion and land degradation during the mid-late RP (Casana, 2008; Leroy, 2010). Population continued to grow until ca. 500 AD when large scale land abandonment took place throughout the region (Casana, 2008; Foss, 1997; Wilkinson, 1999) coincident with a shift to arid conditions in our composite analysis. Wishing to avoid putting forth a case for environmental determinism, this period gives tantalising clues in understanding the complex nature of societal tipping points (Scheffer, 2009). Of course there is a multitude of contributing factors, but it seems likely that population increase and associated land degradation in operation with CNAO fluctuations contributed to diminish societal resilience during the late RP. The shift to arid conditions ca. 2400 yr. BP was the trigger for the widespread social upheaval and land abandonment that followed. These events eventually led to the migration into the region by Arab tribes from the south and an end to centuries of Classical influence in the Fertile Crescent (Foss, 1997).

5 Summary

Our interdisciplinary study provides a novel proxy dataset based on archaeological site distribution and a novel method to interpret a composite of existing proxy records of climatic humidity. The signals manifest in these proxy analyses are consistent with climatic response simulated using an EMIC prescribed with independent reconstructions of deforestation and SST in the Late Holocene. Our methodology indicates that Holocene deforestation had little impact on climate in the Mediterranean but potentially led to climatic aridification in Central and Northern Europe. Climatic aridification in Northern Europe warrants further investigation as it would represent possibly the earliest occurrence of anthropogenic climate change where it also to be found in the Northern European proxy record. The primary driver for changes in climatic humidity in the Mediterranean during the RP was found to be related to SST change in the North Atlantic and associated oscillations in SLP gradients there. We refer to these SLP oscillations as the Centennial North Atlantic Oscillation (CNAO) and it is manifest in the Mediterranean by a seesaw pattern in climatic humidity between the East and West. The Eastern Mediterranean underwent a relatively humid phase during the RP owing to a positive phase of the CNAO at this time. Given that this region is in a marginal climatic zone that receives the majority of its rainfall in winter, changes in CNAO phase likely had an important impact and contributed to an increase in population in the region whilst under Roman occupation. The link between fluctuations in CNAO phase and societal change in the Eastern Mediterranean should not be overstated. Nonetheless, the CNAO was likely a contributing factor determining societal resilience in the Middle East in the past and doubtless will be in the future.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/7/2355/2011/cpd-7-2355-2011-supplement.zip.

Acknowledgements. The authors wish to thank Jed Kaplan et al. for providing the digital data from their reconstruction of ancient deforestation. Thanks also go to Olof Pedersén who maintains an open-access database of archaeological sites in the Near East that was used in this project. We would also like to thank all the people who provided their proxy data for use in the composite proxy analysis.

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Table 1. List of proxy datasets used in the composite analysis of proxy indicators of climatic humidity. The geographical distribution of each record is illustrated in Fig. 1. Pann, Pwin, Pspr, Paut indicate annual, winter and autumn precipitation respectively.

	Site	Lat	Lon	Proxy	Indicator	Reference
1	Zonar lake, Spain	37.48	−4.41	lake varve	Pann	Martín-Puertas et al. (2009)
2	Sierra Nevada Spain	37.07	−3.35	Solifluction landforms	Pwin	Oliva et al. (2009)
3	Lake Tigalmamime, Morocco	32.92	5.35	Pollen from lake sediments	Pann	Cheddadi et al. (1998)
4	Lake Tigalmamime, Morocco	32.91	5.36	Pollen from lake sediments	Pwin	Lamb et al. (1995)
5	Jura Mountains, France	46.86	6.01	Composite of lake levels	Pann	Magny (2004)
6	Northern Tunisia	33.41	10.85	Tephrochronology	Pwin	Marquer et al. (2008)
7	Lake Accesa, Italy	43	10.9	Lake level	Pann	Magny et al. (2007)
8	Lake Mezzano, Italy	42.61	11.76	Lake level	Pann	Giraudi (2004)
9	Lake Fucino, Italy	42	13.54	Lake level	Pann	Giraudi (1998)
10	Lake Pamvotis, Greece	39.6	20.8	Pollen, Fossil ostracod taxonomy and isotope analysis	Pann	Bottema (1974); Frogley et al. (2001) in Eastwood et al. (2007)
11	Lake Pamvotis, Greece	39.6	20.8	Fossil ostracod taxonmy and isotope analysis	Pann	Frogley et al. (2001)
12	Lake Xinias, Greece	39	22.2	Pollen and lithostratigraphy	Pann	Digerfeldt et al. (2007)
13	Lake Golishar, Turkey	37.1	29.6	Stable isotope and pollen	Pann	Eastwood et al. (2007)
14	Lake Nar, Turkey	38.34	34.46	Oxygen isotopes	Pann	Jones et al. (2006)
15	Eski Acigol, Turkey	38.55	34.54	Pollen and distom isotope analysis	Pann	Roberts et al. (2001)
16	Soreq cave, Israel	31.73	35.18	Speleothem growth	Paut	Orland et al. (2009)
17	Soreq cave, Israel	31.73	35.18	Speleotherm growth	Paut	Bar-Matthews et al. (1997)
18	Dead Sea, Israel	31.5	35.5	Lithologic analysis and carbon dating	Pann	Migowski et al. (2006)
19	Dead Sea, Israel	31.5	35.5	Lithologic analysis and carbon dating	Pann	Bookman et al. (2004)
20	Lake Van, Turkey	38.44	42.71	Pollen, charcoal, isotope and geochemical analysis	Pann	van Zeist and Woldring (1978); Lemcke and Sturm (1997); Wick et al. (2003) in Eastwood et al. (2007)
21	Lake Van, Turkey	38.44	42.71	Pollen, charcoal, isotope and geochemical analysis	Pann	Wick et al. (2003)

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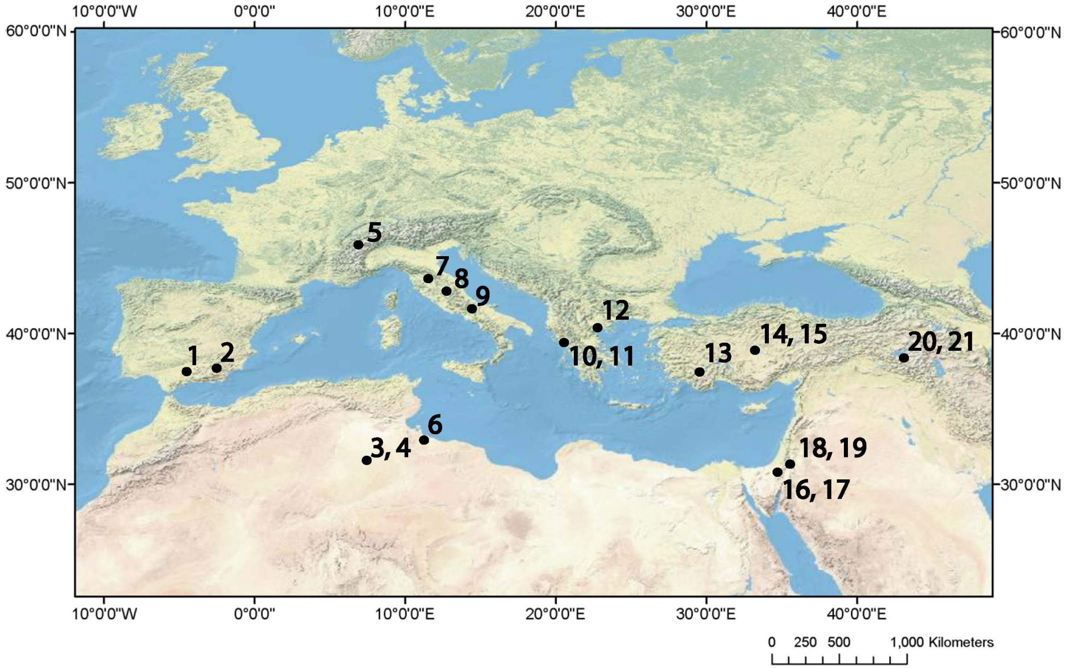

Fig. 1. Geographic distribution of proxy records used in composite analysis. The numbering coincides with the first column in Table 1.

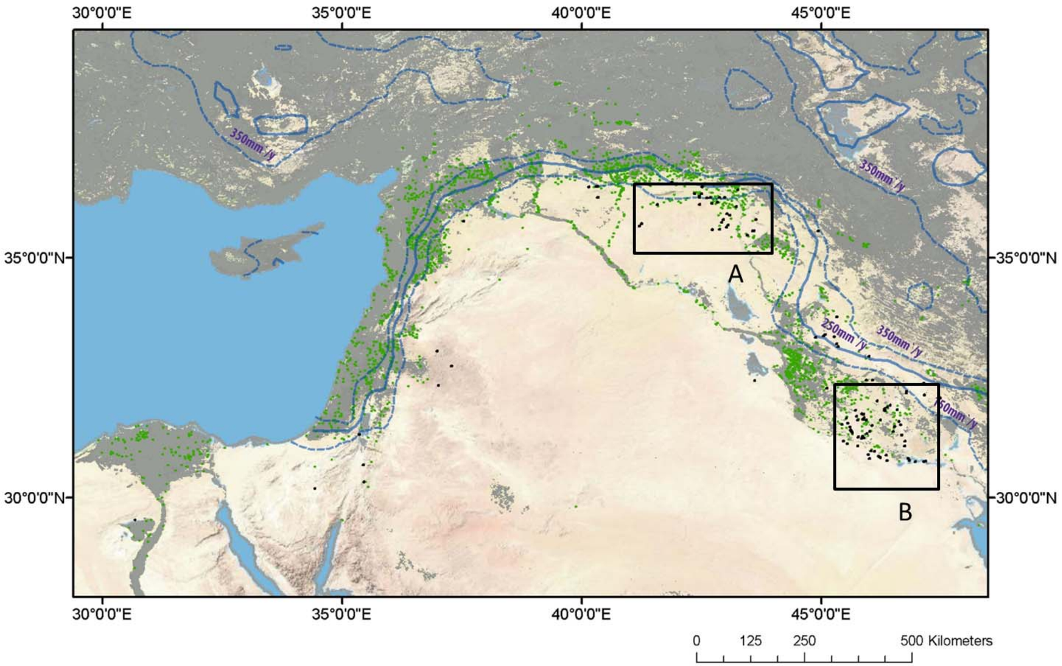

Fig. 2. Archaeological site distribution overlaid with present-day precipitation and land cover. Green points are sites coinciding with land currently under cultivation or habitation, black points are sites in presently abandoned regions. Present-day precipitation is represented in isohyets and grey regions are currently arable or inhabited land. The regions marked **(A)** and **(B)**, where most of the abandoned sites are located, are the north-east of the Jazira and lower Southern Mesopotamia respectively.

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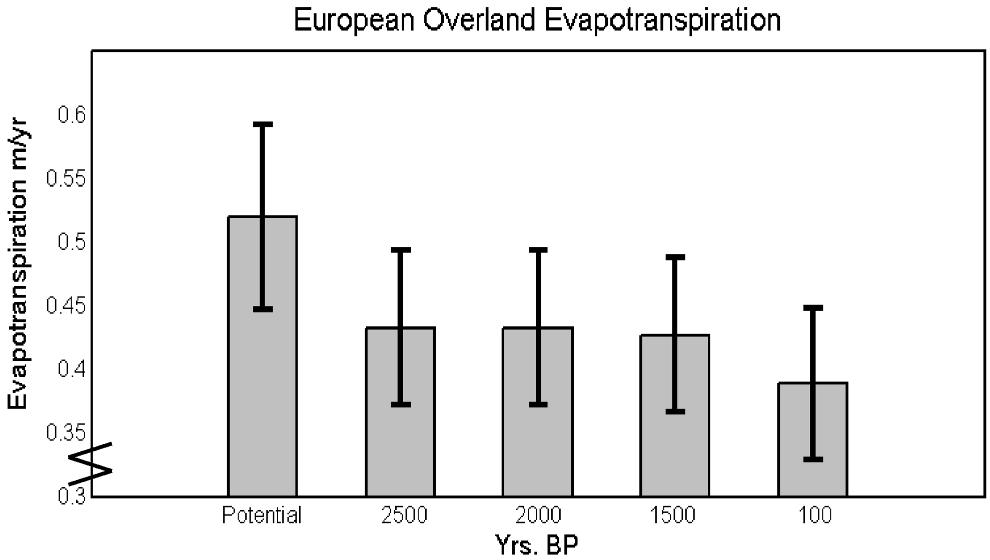

Fig. 3. European average overland evapotranspiration ($\mathrm{m\,yr^{-1}}$). The change in evapotranspirative fluxes is shown in relation to land cover changes prescribed from Kaplan et al. (2009). Standard deviation is illustrated by error bars.

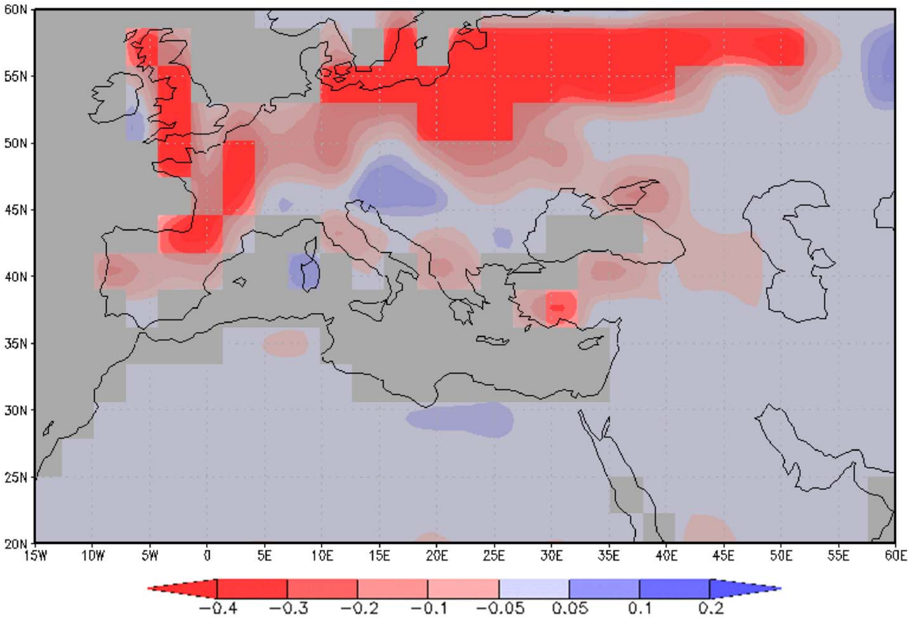

Fig. 4. Yearly average anomaly in evapotranspiration (m yr^{-1}): forest cover 100 yr. BP – potential forest cover. The largest changes in evapotranspirative fluxes between potential forest cover and forest cover at 100 yr. BP are in Northern and Central Europe. The shaded areas are regions where the changes in fluxes are statistically insignificant (t(38) = 2.024, $p = 0.05$).

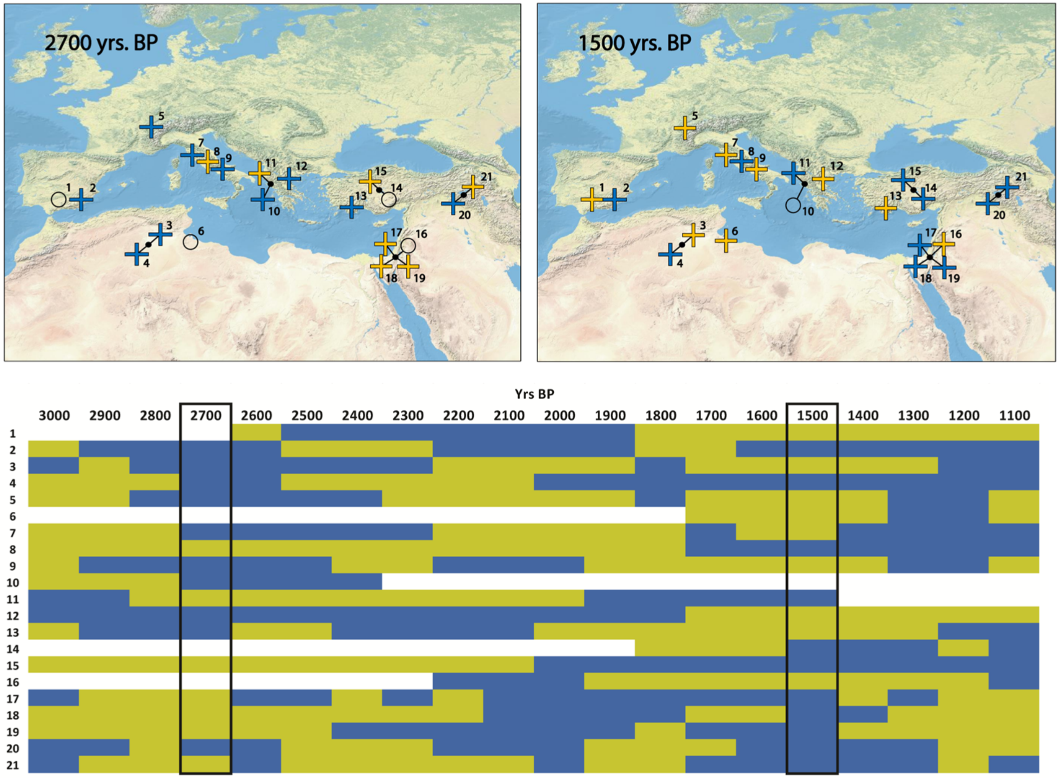

Fig. 5. Composite of proxy indicators of climatic humidity. The composite analysis displays changes in climatic humidity in the Mediterranean region for the period 3000 yr. BP–1000 yr. BP. The maps above show the spatial distribution and relative state of each proxy for the time slices indicated. Blue indicates that the time slice in question was relatively humid, yellow relatively arid and white or a hollow circle that no data is available.

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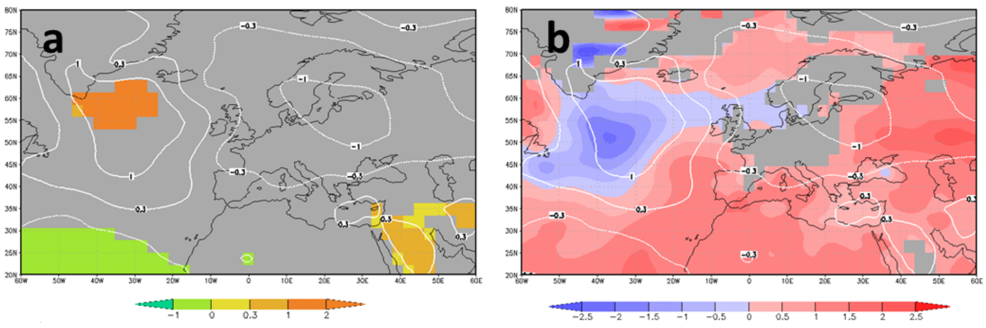
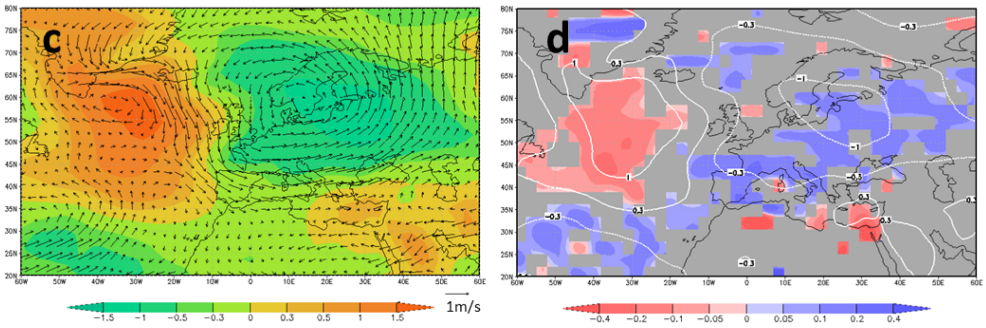


Statistically significant SLP (Pa) and SLP (Pa)

Statistically significant 2m temperature (K) and SLP (Pa)



800 hPa wind (m/s) and SLP (Pa)

Statistically significant relative precipitation and SLP (Pa)

Fig. 6. Climatic anomaly CNAO$^-$ – CNAO$^+$. In each panel the grey shaded areas show regions where the climatic response to changing SST are statistically insignificant ($t(38) = 2.024$, $p = 0.05$). The SLP contours are displayed in each panel so that climatic responses to SLP changes are apparent. The non-grey shaded regions in panel **(a)** show the statistically significant change in SLP associated with a change in SST **(b)**. The weakening in the CNAO over the North Atlantic facilitates the intrusion of moist westerly airflows into the Mediterranean **(c)**. The progress of these airflows is blocked by a high pressure system over the Eastern Mediterranean, causing climate to become more arid there under CNAO$^-$ **(d)**.