Clim. Past Discuss., 6, 1655–1683, 2010
www.clim-past-discuss.net/6/1655/2010/
doi:10.5194/cpd-6-1655-2010

Climate of the Past Discussions

Late Holocene climate variability in the southwestern Mediterranean region: an integrated marine and terrestrial geochemical approach

C. Martín-Puertas[1], **F. Jiménez-Espejo**[2], **F. Martínez-Ruiz**[2], **V. Nieto-Moreno**[2], **M. Rodrigo**[2], **M. P. Mata**[3], **and B. L. Valero-Garcés**[4]

[1]German Research Center for Geosciences (GFZ), Telegrafenberg, 14473 Potsdam, Germany
[2]Facultad de Ciencias, Instituto Andaluz de Ciencias de la Tierra, Campus Fuentenueva, 18002 Granada, Spain
[3]Instituto Geológico y Minero de España, Área de cambio global. C/La Calera, 28760, Tres Cantos, Madrid, Spain
[4]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (CSIC), Apdo 13034, 50080, Zaragoza, Spain

Received: 20 August 2010 – Accepted: 26 August 2010 – Published: 6 September 2010

Correspondence to: C. Martín-Puertas (celia@gfz-potsdam.de)

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

Abstract

A combination of marine (Alboran Sea cores, ODP 976 and TTR 300 G) and terrestrial (Zoñar Lake, Andalucia, Spain) paleoclimate information using geochemical proxies provides a high resolution reconstruction of climate variability and human influence in southwestern Mediterranean region for the last 4000 years at inter-centennial resolution. Proxies respond to changes in precipitation rather than temperature alone. Our archive documents a succession of dry and wet periods coherent with the North Atlantic climate signal. Drier stages occurred prior to 2.7 cal ka BP, well-correlated with the global aridity crisis of the third-millennium BC, and during the Medieval Warm Period (1.4–0.7 cal ka BP). Wetter conditions prevailed from 2.7 to 1.4 cal ka BP and after the Medieval Warm Period and the onset of the Little Ice Age. Hydrological signatures during the Little Ice Age are highly variable but consistent with more humidity that the period before. Additionally, Pb anomalies in sediments at the end of Bronze Age suggest anthropogenic pollution earlier than the Roman Empire development in the Iberian Peninsula. The evolution of the climate in the study area during the Late Holocene confirms the see-saw pattern previously shown between eastern and western Mediterranean regions and suggests a higher influence of the North Atlantic dynamics in the western Mediterranean.

1 Introduction

The southwestern Mediterranean region is an area of great interest for paleoclimate research, characterized by the interaction of the northern Africa subtropical and mid-latitude North Atlantic climate systems. Both have controlled climate variability since the onset of modern Mediterranean climate after the mid Holocene and helped to create the singular environmental conditions that determine the landscape, biota and human societies evolution in the area.

CPD
6, 1655–1683, 2010

Geochemical archives encoded in marine and lacustrine sediments offers clues for reconstructing the environmental processes and past climate changes. In paleoceanography, geochemical proxies describe most of the processes occurring in the ocean such as paleoproductivity (Ba/Al) (e.g., Martínez-Ruiz et al., 2003), deepwater ventilation (U/Th) (e.g., Mangini et al., 2001) and paleotemperatures (Mg/Ca) (e.g., Toyofuku et al., 2000). In lakes, the use of geochemical data has been focused on atmospheric pollution (e.g., Renberg et al., 2001; Ruiz-Fernández et al., 2007) but more recently also on paleoenvironmental (e.g., Koinig et al., 2003; Eusterhues et al., 2005; Selig et al., 2007) and paleoclimate reconstructions (e.g., Moreno et al., 2007; Tanaka et al., 2007; Brauer et al., 2008; Giralt et al., 2008; Czymzik et al., 2010; Martín-Puertas et al., 2009). Nevertheless, reconstructing environmental and climate proxies from geochemical composition should be done carefully since each lake is unique, controlled to some extent by its geographic and geological setting and the interactions among external chemical inputs and internal biogeochemical cycles may greatly affect our ability to reconstruct forcing variables (Cohen, 2003).

In the southwestern Mediterranean region, several paleoclimate studies have been carried out using geochemical proxies from marine sediments, focused on abrupt climate changes since the Last Glacial Maximum (Martínez-Ruiz et al., 2003; Moreno et al., 2005; Sierro et al., 2005; Cacho et al., 2006; Frigola et al., 2007; Jiménez-Espejo et al., 2008) and the Holocene (Dormoy et al., 2009). However the study of the Late Holocene is still relatively poor since it requires higher resolution records for reconstructing short-term variability and only few studies are available (Martín-Puertas et al., 2008, 2009). The rapid response of lakes to changes in the environmental conditions together with relatively high sedimentation rates favor the preservation of high-resolution geochemical signals (Battarbee, 2000).

In this article, we combine geochemical information from lower-resolution marine records in the southwestern Mediterranean Sea (Alboran Sea), which provides evidences of changes in the hydrographic conditions and sea surface temperature, and higher-resolution lacustrine record in the southwest of Iberian Peninsula, which shows

CPD
6, 1655–1683, 2010

hydrological fluctuations in the continent and human impact. The aim of this study is to understand the linkages between marine and terrestrial environments using geochemical proxies in order to obtain a more accurate reconstruction of the climate change dynamics in the southwestern Mediterranean region during the Late Holocene.

2 Regional setting

The southwestern Mediterranean region can be defined as the westernmost basin of the Mediterranean Sea, called the Alboran Sea, and southern Iberian Peninsula and northern Morocco (Fig. 1). The area is characterized by semi-humid Mediterranean climate with warm and dry summer and mild and wetter winter. The Alboran Sea receives terrigenous sediments from both, African and European continents as atmospheric dust and coastal/riverine inputs (e.g. Martínez-Ruiz et al., 2003); the thermohaline circulation is controlled by the exchange of different saline water masses through the Gibraltar Strait (Fig. 1) (e.g., Rogerson et al., 2008). Zoñar Lake is one of the few permanent lakes in southern Iberian Peninsula (37°29′00″ N, 4°41′22″ W, 300 m a.s.l.) (Fig. 1), highly sensitive to the precipitation regime (Valero-Garcés et al., 2006) and with a continuous and high-resolution record for the Late Holocene (Martín-Puertas et al., 2008).

3 Materials and methods

Two marine cores from Alboran Sea basin and a terrestrial core from Zoñar Lake (Fig. 1) have been selected for this study. The maximum distance between the marine and terrestrial sites is about 300 km. The marine records selected are: the ODP Site 976 in the West Alboran basin, located at 36°12′ N, 4°18′ W, 1108 m b.s.l.; and Site TTR 300 G at 36°52′55″ N, 2°17′25″ W drilled at 1860 m b.s.l in the East Alboran Sea basin (Fig. 1). Core ODP 976 was recovered during the ODP cruise, Leg 161 in 1995 and 300 G during the Training Through Research (TTR) cruise 14, Leg 2 in

CPD
6, 1655–1683, 2010

2004. Zoñar Lake cores were recovered with a Kullenberg corer in 2004. The composite record was obtained from correlation of five cores in the deepest area (14 m depth, cores 1A, 1B, 1C and 1D, up to 6 m long) and one in the littoral zone (6 m depth, 2A, up to 3 m long) (see Martín-Puertas et al., 2008). Marine cores ODP 976 and 300 G and Zoñar core 1B were sampled continuously at 2, 1.5 and 10 cm intervals, respectively. Sediment samples were dried and homogenized in an agate mortar for subsequent geochemical analyses. Major elements (Al, Ti, Fe, Si, K, Ca, Mg and Mn) were measured using Atomic Absorption Spectrometry (AAS) (Perkin-Elmer 5100 spectrometer) with an analytical error of 2%. Analyses of trace elements (Li, Rb, Cs, Be, Sr, Ba, Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Y, Nb, Ta, Zr, Hf, Mo, Sn, Tl, Pb, U and Th) were performed using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) following HNO_3 + HF digestion. Measurements were taken in triplicates by spectrometry (Perkin-Elmer Sciex Elan 5000) using Re and Rh as internal standards. Variation coefficients determined by the dissolution of 10 replicates of powdered samples were higher than 3% and 8% for analyte concentrations of 50 ppm and 5 ppm, respectively (Bea, 1996). Additionally, stable oxygen isotope ratio of monospecific planktonic foraminifers (*G. bulloides*) from core 300 G were also obtained. Foraminifers were cleaned in an ultrasonic bath to remove fine-fraction contamination, rinsed with distilled water, and thoroughly washed in alcohol. Stable isotopes were measured using a Finnigan MAT 251 mass spectrometer (Isotope Laboratory, Marum, University of Bremen, Germany). $\delta^{18}O$ data are relative to the PDB standard. Analytical reproducibility of the method is approximately + 0.07% (see Jiménez-Espejo et al., 2008).

The age-depth model for the Alboran basin has already been performed for the Late Holocene using six radiocarbon data from *G. bulloides* for both cores, ODP 976 (the first 118 cm for the last 4.0 cal ka) (Combourieu-Nebout et al., 2009) and 300 G (the first 66 cm) (Jiménez-Espejo et al., 2008). The age model validation was further supported by comparison with close well-dated records in surrounding sites based in ^{210}Pb and radiocarbon dates (Nieto-Moreno, in preparation). For Zoñar Lake, the age-depth model for the last 4.0 cal ka is based on nine AMS^{14}C dates, ^{137}Cs dating and varve

CPD
6, 1655–1683, 2010
Late Holocene climate variability in the southwestern Mediterranean region
C. Martín-Puertas et al.

counting (Martín-Puertas et al., 2008). All radiocarbon ages for the marine core were calibrated to calendar years using Calib 5.1 software (Stuvier and Reimer, 1993) and the MARINE04 calibration curve including a standard marine correction of 400 years (Hughen et al., 2004). Continental data were calibrated using the INTCAL04 curve (Reimer et al., 2004).

4 Paleoenvironmental and paleoclimate proxies

4.1 Alboran Sea

Climate variability at global, regional and local scale modifies the hydrographic conditions of the Alboran Sea influencing the sedimentary dynamic (Sierro et al., 2005; Llave et al., 2006; Voelker et al., 2006). Terrigenous fraction of the Alboran sediments is the sum of atmospheric dust and eroded material transported by rivers from emerged areas. The first one is mainly related to the activity of Saharan dust air masses reaching the studied area (Weldeab et al., 2003; Moreno et al., 2005) and is responsible for an enrichment of heavy minerals in the sediments (rutile and zircon) (Guieu and Thomas, 1996). Based on mineralogical composition, Zr/Al ratio has been used as an indicator of Sahara dust deposition in the western Mediterranean basin (Moreno et al., 2005). The second one, the fluvial input from the emerged areas, comes mainly from the Iberian margin in northwestern Alboran Basin, whereas in southeastern Alboran Basin, the African and Iberian margins are both possible sources. Sediments are composed of clay minerals, quartz, and minor amounts of feldspar, dolomite and accessory minerals (Martínez-Ruiz et al., 2003). Mg-chlorite is especially abundant; therefore Mg enrichment (Mg/Al) has been suggested as a good detrital proxy (Jiménez-Espejo et al., 2008). Saharan winds increase during northern African and Mediterranean arid periods (Weldeab et al., 2003; Moreno et al., 2005) while contribution from the margin increases with precipitation, since it has been mainly associated to coastal/riverine process from the Last Glacial to 5.0 ka BP (Jiménez-Espejo et al., 2008). Nevertheless, during some periods of arid conditions (e.g. the Younger Dryas), increased erosion and

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD

6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

river incision is caused by a decrease of the vegetation cover rather than fluvial runoff (Jiménez-Espejo et al., 2008).

In order to discriminate the influence of riverine input on the Mg record, we have compared Mg/Al ratio with Zr/Al ratio (Saharan winds) (Fig. 2a). For more accurate record of both processes, we have chosen Mg/Al ratio from core ODP 976, since it is located closer to the Iberian margin and is significantly affected by fluvial discharges; and Zr/Al ratio from core 300 G, to be more pelagic and, therefore, more sensitive to aeolian inputs (Zuñiga et al., 2008). In general, the two proxies seem to have similar tendencies between 4000 and 2750 cal yr BP and they show opposite trends from 2750 cal yr BP to present day (Fig. 2a). Higher Saharan input and parallel profile of Zr/Al and Mg/Al ratios prior 2750 cal yr BP suggest more arid conditions and prevalence of wind eroding the Iberian and African margins. After 2750 cal yr BP, opposite profile of the proxies and lower values of Zr/Al ratio indicate humidity increase, weaker Saharan winds and fluvial runoff. Thus, Mg/Al ratio could be reflecting riverine input and indirectly precipitation for the last 2700 years (Table 1).

Another process affected by climate variability is the Mediterranean thermohaline circulation controlling the ventilation of the water column during the Holocene (Myers and Rohling, 2000). Oxygenation of the deep waters promotes low U-precipitation and, inversely, lower bottom water ventilation conditions cause U-enrichments (Anderson, 1982; Barnes and Cochran, 1990). Anomalies of U-concentration in sediments are estimated using the U/Th ratio and it is considered a good indicator of changes in the oxic bottom conditions in the Mediterranean basin (Jiménez-Espejo et al., 2007). Deepwater ventilation is induced by increased aridity and/or cooler temperatures during winter in the Gulf of Lion (Myers and Rohling, 2000; Pinardi and Masetti, 2000). So, variations of U/Th ratio would be related to both, precipitation and temperature. We compare the U/Th ratio with the δ^{18}O data, thought as sea surface temperature (SST) indicator during the Holocene; nevertheless, the influence of some combination of temperature-precipitation such as evapotranspiration cannot be totally discarded (Frigola et al., 2007; Jiménez-Espejo et al., 2008).

CPD
6, 1655–1683, 2010

C. Martín-Puertas et al.

4.2 Zoñar Lake

The major lacustrine response to climate change in Mediterranean areas is lake level fluctuations (Cohen, 2003). Water input to Zoñar Lake is the sum of rainfall, runoff, groundwater and springs, whereas the output is mostly by evaporation. Instrumental data for the last 20 years show that lake level fluctuation responds rapidly to changes in the precipitation (Valero-Garcés et al., 2006), thus, hydrology of the lake is directly related to the precipitation/evaporation balance (P/E). Ion water concentration increases during phases of higher evaporation, causing aragonite and gypsum precipitation in the lake and, consequently, Sr-enrichment in sediments. However Sr/Al ratio cannot be used as indicator of P/E variability trough the whole Late Holocene since aragonite precipitation only represents extreme periods of intensive evaporation. Beside lake level rise, higher precipitation also means more watershed erosion by runoff and increases in detrital input into the lake (clay minerals, quartz, feldspar and detrital calcite). Geochemically, the allochthonous component of the sediments is composed of Al, K, Fe, Si, Ca, Rb and other trace elements associated (Martín-Puertas et al., 2009). Based on the statistical treatment carried out by these authors, we propose Rb as possible proxy for watershed erosion. The first three components of the principal component analyses explain 64.61% of the total variance of the geochemical dataset: the first eigenvector (PC1) is tied at the negative end by the allochthonous component and at the positive end by the evaporite and endogenic carbonate components. PC2 is controlled by S at the positive end and by TOC, TIC, Mg and Ba at the negative end. And aragonite would be explained by this third component. Rb shows detrital behaviour (PC1$= -0.315$) and it is not influenced by the other processes occurring in the lake (PC2$= -0.04$), in comparison with other elements like Al (PC2$= -0.4$) or Fe (PC2$= 0.274$) (Martín-Puertas et al., 2009).

Terrigenous inputs can be by runoff, associated to more humid conditions, but also by wind erosion during arid stages. In order to test the reliability of the Rb as runoff proxy, we compare Rb/Al ratio with Sr/Al ratio (intensive evaporation phases) and the semi-quantitative lake level curve reconstructed for this lake based on multiproxy-analyses (Martín-Puertas et al., 2008) (Fig. 2b). Prior 2900 cal yr BP, Zoñar Lake dried out and palesoil developed even in the deepest basin. The onset of lacustrine deposition started at 2900–2600 cal yr BP with evaporitic facies (gypsum) and aragonite precipitation corresponding to ephemeral lake (Martín-Puertas et al., 2008, 2009). After that, Zoñar was a permanent lake until present day. Phases of intensive evaporation (Sr/Al peaks) correspond with lower values of Rb/Al (lower detrital input) and, additionally, the general tendencies of this ratio reflect the most important lake level changes interpreted from the multiproxy analyses (Fig. 2b). So, we propose Rb/Al variability responds mostly to changes in runoff-precipitation during the last 2600 years (Table 1).

5 Chronological marker and human influence

To compare the marine and continental records at high-resolution scales we should demonstrate the compatibility of both chronological model. As chronological markers, we have used the signatures of atmospheric lead pollution during Roman Empire (2050–1750 cal yr BP) and Medieval Times (950–750 cal yr BP) defined for the North Atlantic region (Renberg et al., 2001). Figure 3 shows Pb-enrichment in sediments (Pb/Al ratio) of Alboran Sea and Zoñar Lake: roman lead pollution is recorded in both, but medieval signal only occurs in the Alboran Sea. The radiocarbon data close to the Pb-enrichment in Alboran sediments supports the timing of lead pollution signature during Medieval Ages. The absence of that in the Zoñar Lake record could be explained by the type of sediments – gypsum and aragonite (up to 80%) from 1350 to 730 cal yr BP (^{14}C data, Fig. 3) (Martín-Puertas et al., 2008). In any case, synchronous Pb peak at Roman period would validate the comparison between both records.

CPD
6, 1655–1683, 2010

On the other hand, human influence can compromise the use of geochemical data as paleoclimate proxy, especially in continental records (Vannière et al., 2008). The watershed and the hydrological balance of Zoñar Lake have been directly affected by changes of the land uses and water management since the Bronze Age and particularly during the last 150 years (Valero-Garcés et al., 2006; Martín-Puertas et al., 2008). Pb/Al peak in Zoñar Lake at 2300–2100 cal yr BP (350–150 BC) (Fig. 3), but not in Alboran Sea, could indicate early lead contamination by runoff coinciding with Rb/Al peak at 2200 cal yr BP (Fig. 2b). It was a time of enhanced mining and smelting activity by Iberian culture and increased trading with Greek and Phoenician (Rothenberg et al., 1989). During the Roman period (100BC–AD300), human activities could have amplified the lake response to climate forcing (Martín-Puertas et al., 2009) and drier conditions during 2100–1700 cal yr BP and spring water derivation for human consumption would have been responsible for decrease lake level, increased chemical concentration and precipitation of gypsum. Sedimentological profiles show deposition of massive facies indicative of some soil erosion during Medieval Ages (Valero-Garcés et al., 2006); however, only from the onset of the industrial revolution, anthropogenic activities cause a significant increase of the soil erosion around Zoñar Lake (Valero-Garcés et al., 2006) (Fig. 3).

6 Climate variability for the South Iberian Mediterranean region

Once we know our records can be compared chronologically and the environmental proxies are not perturbed by human influence, the marine and continental records can be used for reconstructing natural climate variability over the South Iberian Mediterranean region during the Late Holocene. Precipitation proxies (Mg/Al and Rb/Al) are well-correlated at centennial to decadal scale (Fig. 4). U/Th ratio seems to be controlled by precipitation for the most part of the Late Holocene (Fig. 4), except at 1200–850 cal yr BP and before 2700 cal yr BP, when changes in the deep-water ventilation seem to be enhanced by colder winters. Increase of U/Th ratio at 1200 cal yr BP could

CPD
6, 1655–1683, 2010

be favored by sea surface warming since precipitation is lower. On the contrary, the change toward ventilated waters at 3400 cal yr BP would respond to a cooling during an interval of persistent drier conditions (Fig. 4). In any case, the correlation between most of the environmental proxies suggests a better response to changes in precipitation than temperature alone. So, moisture variability in the South Iberian region can be reconstructed on base of Mg/Al and Rb/Al ratios and supported by Zr/Al and U/Th ratios. From 4000 to 2700 cal yr BP, precipitation proxies do not work because very dry conditions prevailing in the western Mediterranean region (Fig. 2). This episode is according with the global aridity crisis in the third millennium BC (Weiss et al., 1993). General trend of Mg/Al, Rb/Al and Zr/Al ratios suggest a progressive humidity recovery from 2700 to 2500 cal yr BP. The most humid episode occurs at ~2500–1700 cal yr BP, characterized by an abrupt precipitation increase and weaker winds from Africa (Fig. 4). After that, proxies indicate gradual tendency toward aridity until present day, although with some fluctuations. Precipitation decreases reaching lower values from 1400 to 700 cal yr BP coinciding with the Medieval Climate Anomaly (MCA). The end of MCA is marked by increase of the precipitation at 700–550 cal yr BP (AD 1250–1400) and more ventilated deep-water, likely enhanced by cooling during the LIA (Fig. 4). After 500 cal yr BP (AD 1400) there are discrepancies between marine and continental hydrological signal. In Alboran Sea, there is a clear decrease of coastal/riverine input, even reaching lower values than during the MCA; however, in Zoñar Lake, although runoff also slightly decreases the LIA is wetter than the MCA. Paleoclimates records for the Iberian Peninsula (Moreno et al., 2008; Benito et al., 2010; Morellón et al., 2009) and Morocco (Esper et al., 2007) show that the LIA was wetter than the MCA, in agreement with Zoñar record. So, we conclude the record of the last 500 years in the core ODP976 could have been upset since it is the top of the core.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD

6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

7 South Iberian Mediterranean Archive and its connection with the Northern Hemisphere climate changes

As we have shown above, our environmental proxies are mostly driven by changes in precipitation; nevertheless humid conditions have been related to cooling phases in northern-central Europe and the Mediterranean region during the last three millennia (Magny, 2004; Mauquoy et al., 2008). The occurrence of lower SST in Alboran Sea are synchronous with cool pulses in the western Mediterranean (Frigola et al., 2007) and global polar cooling described by Mayewski et al. (2004) (Fig. 4); however there are some disagreements, which could be induced by the influence of other climate factors on the isotopic signal. Attending to global and regional cool episodes, it can be observed that the association cool/wet and warm/dry conditions do not occur always in this region. The most humid period recorded during the Late Holocene (2.5–1.7 cal ka BP) coincides with two cool pulses for the western Mediterranean – M2 and M1 – (Frigola et al., 2007) and also lower SST for Alboran Sea (Fig. 4). This period has been recognized as a cool and wet episode in the North Atlantic region associated to solar forcing, which started at 2.8 cal ka BP (Bond et al., 2001; van Geel et al., 1999), e.g.: northern Europe (Bond and Lotti, 1995), Greendland (Stuvier et al., 1995) western-central Europe (Magny, 2004), Denmark (Mauquoy et al., 2008), The Netherlands (van Geel et al., 1996) and NW Iberia (Bernárdez et al., 2008). On the other hand, cool and dry periods have been reconstructed for 3.4–2.7 cal ka BP and 1.2–1.0 cal ka BP (Mayewski et al., 2004). Pollen data from the Iberian Peninsula (Jalut et al., 2000) and marine core ODP 976 (Combourien Nebout et al., 2009) suggest arid conditions prior 3000 cal yr BP and during the MCA coinciding with lower precipitation reconstructed (Fig. 4). Arid conditions in southwestern Mediterranean region are in concordance with central Europe (Magny, 2004) (Fig. 5b). The onset of the last cool episode – the LIA – (600–200 cal yr BP) is characterized in both Alboran and Zoñar records by a sharply increase in precipitation, but it is followed by a slight decrease in precipitation, also recorded in central Europe (Magny, 2004) and in NE Spain (Morellón et al., 2009). However, more humid condition are also recorded in central-western Europe (high lake level, Magny et al., 2007) (Fig. 5b, green bars) and northernwestern Europe (peat bog developments, Mauquoy et al., 2008; and glacial advances, Nesje et al., 2008) showing hydrological discrepancies in the western part of Europe.

The most recent precipitation reconstruction for the Late Holocene in west-central Africa is based on the record of Sahara dust flux (Mulitza et al., 2010). These authors reconstruct weaker Sahara dust emissions, more fluvial deposits and humid conditions ($^{18}\delta O_{carbonates}$) during 3150–1750 cal yr BP in response to more continental precipitation; a gradual Sahara dust strengthening until 1000 cal yr BP together with higher values of $^{18}\delta O$ indicating tendency toward aridity. For the last 700 cal yr BP, isotope composition suggests humidity recovery; however, Saharan dust influx also increased because of changes in land uses (Mulitza et al., 2010). Increasing Saharan dust is also recorded in Alboran basin during the last 700 years (Fig. 5c).

The Late Holocene climate variability over the eastern Mediterranean shows opposite humidity conditions (Fig. 5d): a wet period from 3500 to 3000 cal yr BP and 1700–1000 cal yr BP and aridity for 3000–1700 cal yr BP and 800–270 cal yr BP. The MCA was humid in the eastern Mediterranean (Schilman et al., 2001; Wick et al., 2003; Jones et al., 2005, 2006; Neumann et al., 2007) and the LIA show some fluctuations and regional variability since it is recorded as humid (Issar, 1998; Dragoni, 1998) but also dry (Bar-Matthews et al., 1998).

Comparison among southwestern Mediterranean, north-central Europe, West Africa and eastern Mediterranean regions suggests that moisture variability in the study area is more similar to west-central Europe and West Africa rather than eastern Mediterranean region during the Late Holocene. Opposite temperature and precipitation pattern between western and eastern Mediterranean, has already been evidenced by several authors during the Holocene (Rimbu et al., 2004; Felis and Rimbu, 2010; Touchan et al., 2010). At regional scale, climate evidences suggest meridional modes of variability differencing western and eastern regions in Mediterranean. Additionally, the influence of a zonal mode (westerlies) differentiating mid-latitude and tropical climate

CPD
6, 1655–1683, 2010

regions is also recorded over the study area: humid conditions after the maximum solar output at 2.8 cal ka BP start 300 years later in southern Europe and West Africa respect to central Europe (this study; Mulitza et al., 2010); and the MCA signature is synchronous in our record and central Europe whereas it is less pronounced in West Africa.

8 Conclusions

Changes in geochemical composition of sediments from the Alboran Sea and Zoñar Lake records are used to reconstruct environmental changes in response to humidity conditions in the South Iberian Mediterranean region during the Late Holocene. The robust chronological control of marine and continental proxies allows a comparison and integration of both records at centennial to decadal scales. Since 2700 cal yr BP, changes in precipitation have controlled the detrital sedimentation in both depositional environments allowing the reconstruction of moisture variability based on geochemical proxies. The two archives record four main stages for the Late Holocene: i) an arid period prior 2.7 cal ka BP, ii) moisture recovery and wettest conditions for 2.5–1.7 cal ka BP, iii) a gradual decrease in precipitation and driest conditions during the MCA (1.4–0.7 cal ka BP) and iv) more humid conditions and hydrological instability during the last 700 years. The southwestern Mediterranean region climate evolution correlates better with the climate variability in western-central Europe and West tropical Africa rather than eastern Mediterranean supporting a seesaw pattern for the Mediterranean region during the Holocene. Additionally, evidences of Pb-enrichment in sediments from the terrestrial record during the Late Bronze Age suggest early anthropogenic pollution.

Acknowledgements. Projects LIMNOCLIBER REN 2003-09130-C02-02, CALIBRE CGL 2006-13327-c04/CLI, CGL-2006-2956-BOS, CGL2009-07603 (MICINN), 200800050084447 (MARM) and RNM 05212 (Junta de Andalucía), we also thanks Projects GRACCIE (CSD2007-00067) and CTM2009-07715(MICINN), Research Group 0179 (Junta de Andalucía) and the

Training-Through-Research Programme. We are grateful to the LRC (Minnesota, USA) to Doug Schnuremberger, Mark Shapley and Anders Noren for making possible the 2004 Zoñar expedition. Celia Martín-Puertas is grateful to Alexander von Humboldt Foundation.

References

Anderson, R. F.: Concentration, vertical flux, and remineralization of particulate uranium in seawater, Geochim. Cosmochim. Ac., 46, 1293–1299, 1982.

Barnes, C. E. and Cochran, J. K .: Uranium removal in oceanic sediments and the oceanic U-balance, Earth Planet. Sc. Lett., 97, 94–101, 1990.

Bar-Matthews, M., Ayalon, A., and Kaufman, A.: Middle to late Holocene (6500 years period) paleoclimate in the eastern Mediterranean region from stable isotopic composition of speleothems from Soreq Cave, Israel, in: Water, Environments and Society in times of Climate Change, edited by: Issar, A. S. and Brown, N., Kluwer Academic Publisher, 203–214, 1998.

Battarbee, R. W.: Paleolimnological approaches to climate change, with special regard to the biological record, Quaternary Sci. Rev., 19, 107–124, 2000.

Bea, F.: Residence of REE, Y, Th and U in granites and crustal protoliths: implications for the chemistry of crustal melts, J. Petrol., 37, 521–552, 1996.

Benito, G., Rico, M., Sánchez-Moya, Y., Sopeña, A., Thorndycraft, V. R., and Barriendos, M.: The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentín River, southeast Spain, Global Planet. Change., 70, 53–63, 2010.

Bernárdez, P., González-Álvarez, R., Francés, G., Prego, R., Bárcena, M. A., and Romero, O. E.: Late Holocene history of the rainfall in the NW Iberian peninsula-Evidence from a marine record, J. Mar. Syst., 72, 366–382, 2008.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130–2136, 2001.

Bond, G. and Lotti, R.: Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation, Science, 267, 1005–1010, 1995.

Brauer, A., Haug, G. H., Dulski, P., Sigman, M., and Negendank, J. F. W.: An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period, Nat. Geosci., 1(8), 520–523, doi:10.1038/ngeo263, 2008.

Cacho, I., Shackleton, N., Elderfield, H., Sierro, F. J., and Grimalt, J. O.: Glacial rapid variability in deep-water temperature and δ^{18}O from the western Mediterranean Sea, Quaternary Sci. Rev., 25, 3294–3311, 2006.

Cohen, A. S.: Paleolimnology, The history and evolution of lake systems, Oxford University Press, New York, 2003.

Combourieu-Nebout, N., Peyron, O., Dormoy, I., Desprat, S., Beaudouin, C., Kotthoff, U., and Marret, F.: Rapid climatic variability in the west Mediterranean during the last 25 000 years from high resolution pollen data, Clim. Past, 5, 503–521, doi:10.5194/cp-5-503-2009, 2009.

Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Nanmann, R., and Brauer, A.: A 450-years record of spring/summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany), Water Resour. Res., 1–50, doi:10.1029/2009WR008360, in press, 2010.

Dormoy, I., Peyron, O., Combourieu-Nebout, N., Goring, S., Kotthoff, U., Magny, M., and Pross, J.: Terrestrial climate variability and seasonality changes in the Mediterranean region between 15 000 and 4000 years BP deduced from marine pollen records, Clim. Past, 5, 615–632, doi:10.5194/cp-5-615-2009, 2009.

Dragoni, W.: Some considerations on climatic changes, water resources and water needs in the Italian region south of 43° N, in: Water, Environment and Society in Times of Climate Change, edited by: Issar, A. S. and Brown, N., Kluwer Academic Publishers, 241–271, 1998.

Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E.: Long-term drought severity variations in Morocco, Geophys. Res. Lett., 27, L17702, doi:10.1029/2007GL030844, 2007.

Eusterhues, K., Heinrichs, H., and Schneider, J.: Geochemical response on redox fluctuations in Holocene lake sediments, Lake Steisslingen, southern Germany, Chem. Geol., 222, 1–22, 2005.

Felis, T. and Rimbu, N.: Mediterranean climate variability documented in oxygen isotope records from northern Red Sea corals – A review, Global Planet. Change., 71, 232–241, 2010.

Frigola, J., Moreno, A., Cacho, I., Canals, M., Sierro, F. J., Flores, J. A., Grimalt, J. O., Hodell, D. A., and Curtis, J. H.: Holocene climate variability in the western Mediterranean region from a deepwater sediment record, Paleoceanography, 22, PA2209, doi:10.1029/2006PA001307,

2007.
Giralt, S., Moreno, A., Bao, R., Sáez, A., Prego, R., Valero-Garcés, B. L., Pueyo, J. J., González-Sampériz, P., and Taberner, C.: A statistical approach to disentagle environmental forcing in a lacustrine record: the Lago Chungará case (Chilean Altiplano), J. Paleolimnol., 40, 195–215, 2008.
Guieu, C. and Thomas, A.: Saharan aerosol: from the soil to the Ocean, in: The impact of desert dust across the Mediterranean, edited by: Guerzoni, S. and Chester, R., Kluwer Academy Publishers, 207–216, 1996.
Hughen, K. A., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, P. J., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E.: Marine04 Marine Radiocarbon Age Calibration, 0–26 ka cal BP, Radiocarbon, 46, 1059–1086, 2004.
Issar, A. S.: Climate change and history during the Holocene in the eastern Mediterranean region, in: Water, Environment Society in Times of Climate Change, edited by: Issar, A. S. and Brown, N., Kluwer Academic Publishers, 113–128, 1998.
Jalut, G., Esteban Amat, A., Bonnet, L., Gauquelin, T., and Fontugne, M.: Holocene climatic changes in the western Mediterranean, from southeast France to southeast Spain, Palaeogeogr. Palaeocl., 160, 255–290, 2000.
Jiménez-Espejo, F. J., Martínez-Ruiz, F., Sakamoto, T., Iijima, K., Gallego-Torres, D., and Harada, N.: Paleoenvironmental changes in the western Mediterranean since the last glacial maximum: high resolution multiproxy record from the Algero-Balearic basin, Palaeogeogr. Palaeocl., 246, 292–306, 2007.
Jiménez-Espejo, F. J., Martínez-Ruiz, F., Rogerson, M., González-Donoso, J. M., Romero, O., Linares, D., Sakamoto, T., Gallego-Torres, D., Rueda Ruiz, J. L., Ortega-Huertas, M., and Perez Claros, J. A.: Detrital input, productivity fluctuations, and water mass circulation in the westernmost Mediterranean Sea since the Last Glacial Maximum, Geochem. Geophy. Geosy., 9, Q11U02, doi:10.1029/2008GC002096, 2008.
Jones, M. D., Leng, M. J., Roberts, N., Türkeş, M., and Moyeed, R.: A coupled calibration and modelling approach to the understanding of dry-land lake oxygen isotope records, J. Paleolimnol., 34, 391–411, 2005.
Jones, M. D., Roberts, N., Leng, M. J., and Türkeş, M.: A high-resolution late Holocene lake

CPD
6, 1655–1683, 2010
Late Holocene climate variability in the southwestern Mediterranean region
C. Martín-Puertas et al.

isotope record from Turkey and links to North Atlantic and monsoon climate, Geology, 34, 361–364, 2006.
Koinig, K. A., Shotyk, W., Lotter, A. F., Ohlendorf, C., and Strum, M.: 9000 years of geochemical evolution of lithogenic major and trace elements in the sediment of an alpine lake-the role of climate, vegetation, and land-use history, J. Paleolimnol., 30, 307–320, 2003.
Llave, E., Schönfeld, J., Hernández-Molina, F. J., Mulder, T., Somoza, L., Díaz Del Río, V., and Sánchez-Almazo, I.: High-resolution stratigraphy of the Mediterranean outflow contourite system in the Gulf of Cadiz during the late Pleistocene: The impact of Heinrich events, Mar. Geol., 227, 241–262, 2006.
Magny, M.: Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements, Quatern. Int., 113, 65–79, 2004.
Magny, M., de Beaulieu, J.-L., Drescher-Schneider, R., Vannière, B., Walter-Simonnet, A.-V., Miras, Y., Millet, L., Bossuet, G., Peyron, O., Brugiapaglia, E., and Leroux, A.: Holocene climate changes in the central Mediterranean as recorded by lake-level fluctuations at Lake Accesa (Tuscany, Italy), Quaternary Sci. Rev., 26, 1736–1758, 2007.
Mangini, A., Jung, M., and Laukenmann, S.: What do we learn from peaks of uranium and of manganese in deep sea sediments?, Mar. Geol., 177, 63–78, 2001.
Martín-Puertas, C., Valero-Garcés, B. L., Mata, M. P., González-Sampériz, P., Bao, R., Moreno, A., and Stefanova, V.: Arid and humid phases in southern Spain during the last 4000 years: The Zoñar Lake record, Córdoba, Holocene, 18, 907–921, 2008.
Martín-Puertas, C., Valero-Garcés, B. L., Mata, M. P., Moreno, A., Giralt, S., Martínez-Ruiz, F., and Jiménez-Espejo, F.: Geochemical processes in a Mediterranean Lake: a high resolution study of the last 4000 years in Zoñar Lake, southern Spain, J. Paleolimnol., 1–17, doi:10.1007/s10933-009-9373-0, in press, 2009.
Martínez-Ruiz, F., Paytan, A., Kastner, M., González-Donoso, J. M., Linares, D., Bernasconi, S. M., and Jiménez-Espejo,F. J.: A comparative study of the geochemical and mineralogical characteristics of the S1 sapropel in the western and eastern Mediterranean, Palaeogeogr. Palaeocl., 190, 23–37, 2003.
Mauquoy, D., Yeloff, D., van Geel, B., Charman, D. J., and Blundell, A.: Two decadally resolved records from north-west European peat bolgs show rapid climate changes associated with solar variability during the mid-late Holocene, J. Quaternary. Sci., 23, 745–763, 2008.
Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F.,

Staubwasser, M., Schneider, R. R., and Steig, E. J.: Holocene climate variability, Quaternary. Res., 62, 243–55, 2004.
Morellón, M., Valero-Garces, B. L., González-Samperiz, P., Vegas-Villarúbia, T., Rubio, E., Rieradevall, M., Delgado-Huertas, A., Mata, P., Romero, O., Engstrom, D.R., López-Vicente, M., Navas, A., and Soto, J.: Climate changes and human impact recorded in the sediments of Lake Estanya (NE Spain) during the Medieval Warm Period and Little Ice Age, J. Paleolimnol., 1–30, doi:10.1007/s10933-009-9346-3, in press, 2009.
Moreno, A., Cacho, I., Canals, M., Grimalt, J. O., Sánchez-Goñi, M. F., Shackleton, N., and Sierro, F. J.: Links between marine and atmospheric processes oscillating on a millennial time-scale, A multi-proxy study of the last 50 000 yr from the Alboran Sea (western Mediterranean Sea), Quaternary land-ocean correlation, Quaternary. Sci. Rev., 24, 1623–1636, 2005.
Moreno, A., Giralt, S., Valero-Garces, B. L., Saéz, A., Bao, R., Prego, R., Pueyo, J. J., and Taberner, C.: A 14 ka record of the tropical Andes: The Lago Chungara sequence (18° S, northern Chilean Altiplano), Quatern. Int., 161, 4–21, 2007.
Moreno, A., Valero-Garcés, B. L., González-Sampériz, P., and Rico, M.: Flood response to rainfall variability during the last 2000 years inferred from the Taravilla Lake record (Central Iberian Range, Spain), J. Paleolimnol., 40, 943–961, 2008.
Mulitza, S., Heslop, D., Pittauerova, D., Fischer, H. W., Meyer, I., Stuut, J. B., Zabe, M., Mollenhauser, G., Collins, J. A., Kuhnert, H., and Schulz, M.: Increase in African dust flux at the onset of commercial agriculture in the Sahel region, Nature, 466, 226–228, doi:10.1038/nature09213, 2010.
Myers, P. G. and Rohling, E. J.: Modeling a 200 yr interruption of the Holocene sapropel S1, Quaternary Res., 53, 98–104, 2000.
Nesje, A., Dahl, S. O., Thun, T., and Nordli, Ø.: The "Little Ice Age" glacial expansion in western Scandinavia: summer temperature or winter precipitation?, Clim Dynam, 30, 789–801, 2008.
Neumann, F. H., Kagan, E. J., Schwab, M. J., and Stein, M.: Palynology, sedimentology and palaeoecology of the late Holocene Dead Sea, Quaternary Sci. Rev., 26, 1476–1498, 2007.
Pinardi, N. and Masetti, E.: Variability of the large scale general circulation of the Mediterranean Sea from observations and modeling: A review, Palaegeogr. Palaeocl., 158, 153–174, 2000.
Reimer, P. J., Baillie, M. G., Bard, E., Beck, J. W., Buck, C. E., Blackwell, P. G., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T.

CPD
6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver,M., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E.: IntCal04: A New Consensus Radiocarbon Calibration Dataset from 0–26 ka BP, Radiocarbon, 46, 1029–1058, 2004.
Renberg, I., Bindler, R., and Brännvall, M. L.: Using the historical atmospheric lead-deposition record as a chronological marker in sediment deposits in Europe, Holocene, 11, 511–516, 2001.
Rimbu, N., Dima, M., Lohmann, G., and Stefan, S.: Impacts of the North Atlantic Oscillation and the El Niño-Southern Oscillation on Danube river flow variability, Geophys. Res. Lett., 31, 1–4, 2004.
Rogerson, M., Cacho, I., Jiménez-Espejo, F. J., Reguera, M. I., Sierro, F. J., Martínez-Ruiz, F., Frigola, J., and Canals, M.: A dynamic explanation for the origin of the western Mediterranean organic-rich layers, Geochem. Geophy. Geosy., 9, Q07U01, doi:10.1029/2007GC001936, 2008.
Rothenberg, B., Garcia Palomero, F., Bachmann, H. G., and Goethe, J. W.: Mineria y metalurgia en las antiquas civilizaciones mediterraneas y europeas, edited by: Domergue, I. C., Madrid, Tomo, 1, 57–70, 1989.
Ruiz-Fernández, A. C., Páez-Osuna, F., Urrutia-Fucugauchi, J., and Preda, M.: ^{210}Pb geochronology of sediment accumulation rates in Mexico City Metropolitan Zone as recorded at Espejo de los Lirios lake sediments, Catena, 61, 31–48, 2007.
Selig, U., Leipe, T., and Dörfler, W.: Paleolimnological Record of nutrient and metal profile in prehistoric, historic and modern sediments of three lakes in north-eastern Germany, Water Air Soil Poll., 184, 183–194, 2007.
Sierro, F. J., Hodell, D. A., Curtis, J. H., Flores, J. A., Reguera, I., Colmenero-Hidalgo, E., Bárcena, M. A., Grimalt, J. O., Cacho, I., Frigola, J., and Canals, M.: Impact of iceberg melting on Mediterranean thermohaline circulation during Heinrich events, Paleoceanography, 20, 1–13, 2005.
Schilman, B., Bar-Matthews, M., Almogi-Labin, A., and Luz., B.: Global climate instability reflected by Eastern Mediterranean marine records during the Late Holocene, Palaeogeog. Palaeocl., 176, 157–176, 2001.
Stuvier, M. and Reimer, P. J.: Extended ^{14}C data base and revised CALIB 3.0. ^{14}C Age calibration program, Radiocarbon, 35, 215–230, 1993.
Stuvier, M., Grottes, P. M., and Braziunas, T. F.: The GISP2 16O climate record of the past

CPD
6, 1655–1683, 2010

16 500 years and the role of the sun, ocean, and volcanoes, Quaternary Res., 44, 341–354, 1995.
Tanaka, K., Akagawa, F., Yamamote, K., Tani, Y., Kawabe, I., and Kawai, T.: Rare Earth Elements geochemistry of Lake Baikal sediment: its implication for geochemical response to climate change during the Last Glacial/Interglacial transition, Quaternary Sci. Rev., 26, 1362–1368, 2007.
Toyofuku, T., Kitazato, H., Kawahata, H., Tsuchiya, M., and Nohara, M.: Evaluation of Mg/Ca thermometry in foraminifera: Comparison of experimental results and measurements in nature, Paleoceanography, 15, 456–464, 2000.
Touchan, R., Anchukaitis, K. J., Meko, D. M., Sabir, M., Attalah, S., and Aloui, A.: Spatiotemporal drought variability in northwestern Africa over the last nine centuries, Clim. Dynam., 1–16, doi:10.1007/s00382-010-0804-4, 2010.
Valero-Garcés, B. L., González-Sampériz, P., Navas, A., Machín, J., Mata, P., Delgado-Huertas, A., Bao, R., Moreno, A., Carrión, J. S., Schwalb, A., and González-Barrios, A.: Human impact since medieval times and recent ecological restoration in a Mediterranean lake: The Laguna Zoñar, southern Spain, J. Paleolimnol., 35, 441–465, 2006.
Vannière, B., Colombaroli, D., Chapron, E., Leroux, A., Tinner, W., and Magny, M.: Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy), Quaternary Sci. Rev., 27, 1181–1196, 2008.
van Geel, B., Buurman, J., and Waterbolk, H. T.: Archaelogical and palaeoecological indications of an abrupt climate change in the Netherlands, and evidence for climatological teleconnections around 2650 BP, J. Quaternary Sci., 11, 451–460, 1996.
van Geel, B., Raspopov, O. M., Renssen, H., van der Plicht, J., Dergachev, V. A., and Meijer, H. A. J.: The role of solar forcing upon climate change, Quaternary Sci. Rev., 18, 331–338, 1999.
Voelker, A. H. L., Lebreiro, S. M., Schönfeld, J., Cacho, I., Erlenkeuser, H., and Abrantes, F.: Mediterranean outflow strengthening during Northern Hemisphere coolings: A salt source for the glacial Atlantic?, Earth Planet Sc. Lett., 245, 39–55, 2006.
Weiss, H., Courty, M.-A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., and Curnow, A.: The genesis and collapse of third millennium north mesopotamian civilization, Science 261, 995–1004, 1993.
Weldeab, S., Siebel, W., Wehausen, R., Emeis, K.-C., Schmiedl, G., and Hemleben, C.: Late Pleistocene sedimentation in the Western Mediterranean Sea: implications for productivity

CPD
6, 1655–1683, 2010

changes and climatic conditions in the catchment areas, Palaeogeogr. Palaeocl., 190, 121–137, 2003.

Wick, L., Lemcke, G., and Sturm, M.: Evidence of Lateglacial and Holocene climatic change and human impact in eastern Anatolia: high-resolution pollen, charcoal, isotopic and geochemical records from the laminated sediments of Lake Van, Turkey, Holocene, 13, 665–675, 2003.

Zúñiga, D., Calafat, A., Heussner, S., Miserocchi, S., Sanchez-Vidal, A., Garcia-Orellana, J., Canals, M., Sánchez-Cabeza, J.A., Carbonne, J., Delsaut, N., and Saragoni, G.: Compositional and temporal evolution of particle fluxes in the open Algero-Balearic basin (western Mediterranean), J. Marine. Syst., 70, 196–214, 2008.

CPD

6, 1655–1683, 2010

Table 1. Geochemical proxies applied for this study from Alboran Sea and Zoñar Lake sediments.

Proxy	Source	Environmental process	Forcing variable	Validity (cal yr BP)
Mg/Al ratio	Alboran ODP976	Fluvial runoff	Precipitation	2700 to present
Zr/Al ratio	Alboran 300 G	Saharan winds	Precipitation*	4000 to present
U/Th ratio	Alboran 300 G	Deep water ventilation*	Precipitation Temperature	4000 to present
$\delta^{18}O$	Alboran 300 G	Sea Surface Temperature	Temperature	4000 to present
Rb/Al ratio	Zoñar Lake	Runoff	Precipitation	2600 to present
Pb/Al ratio	Alboran 300 G Zoñar Lake	Lead pollution	Human impact	4000 to present

* Inverse relationship between the proxy and the variable.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD

6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

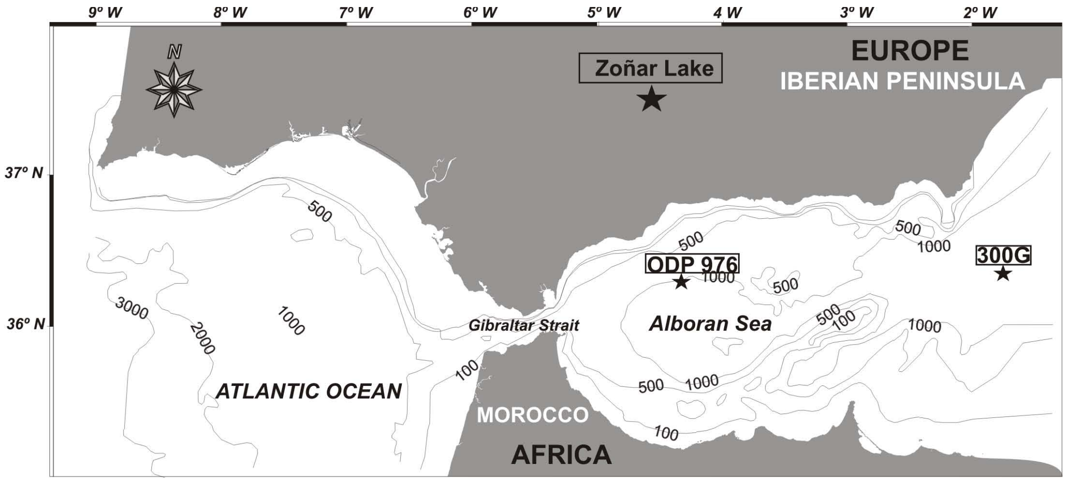

Fig. 1. Map of continental and marine core sites.

CPD
6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

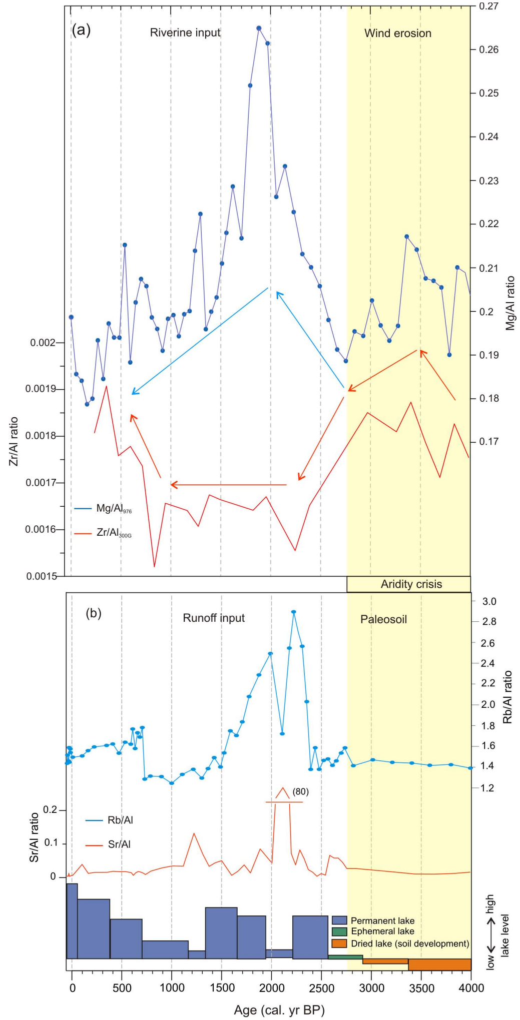

Fig. 2. Caption on next page.

CPD
6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Fig. 2. **(a)** Alboran paleoenvironmental proxies: in blue, Mg/Al ratio from core ODP976 sediments as indicator of Iberian riverine inputs into Alboran basin; in red, Zr/Al ratio from core 300 G as Saharan dust inflow. **(b)** Zoñar paleoenvironmental proxies: in blue, Rb/Al ratio as detrital input into the lake; in red, Sr/Al ratio as ion water concentration (Martín-Puertas et al., 2010); and lake level reconstruction from multiproxy analyses published in Martín-Puertas et al. (2008).

CPD
6, 1655–1683, 2010

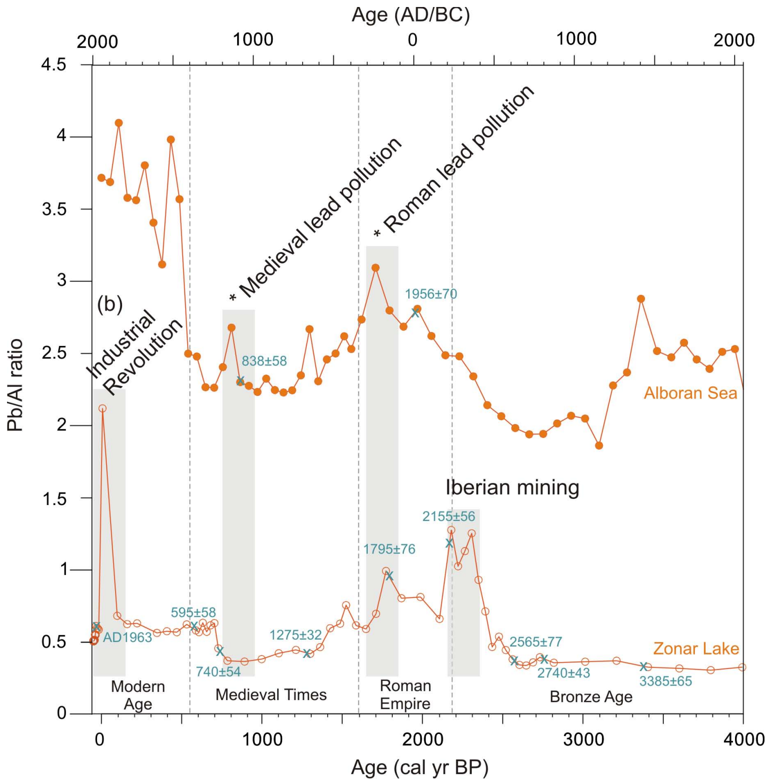

Fig. 3. Pb/Al ratios from Alboran (core ODP976) and Zoñar Lake. ^{14}C data and ^{137}Cs signal for AD 1963 are included. Gray bars indicate the lead pollution peaks.

CPD
6, 1655–1683, 2010

Late Holocene climate variability in the southwestern Mediterranean region

C. Martín-Puertas et al.

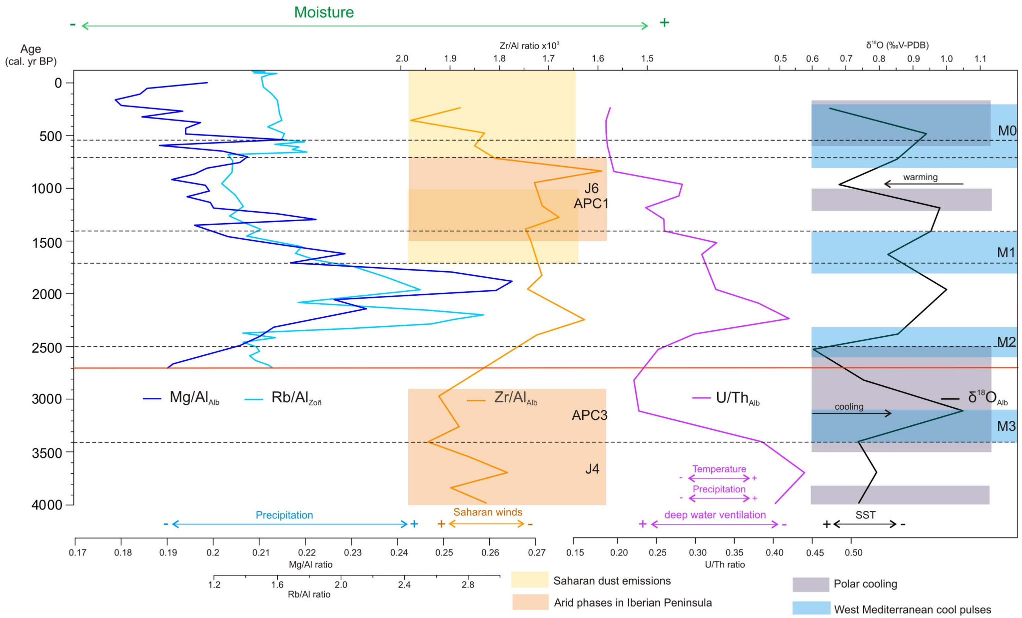

Fig. 4. Marine and continental approach based on geochemical proxies for the climate variability: Rb/Al ratio from Zoñar Lake sediments and Mg/Al ratio from Alboran Sea sediments represent precipitation; Zr/Al ratio indicates Saharan winds; U/Th ratio shows changes in deep water ventilation and $\delta^{18}O$ as indicator of Sea Surface Temperature (SST). Climatic events defined for western Mediterranean region are included for comparison: Alboran Sea pollen events from core ODP 976 (APC1 and APC3) (Combourieu-Nebout et al., 2009), aridification phases in the western Mediterranean (J4 and J6) (Jalut et al., 2000), polar cooling (Mawyesky et al., 2004) and central Mediterranean cold pulses (M0 to 3) (Frigola et al., 2007) during Late Holocene.

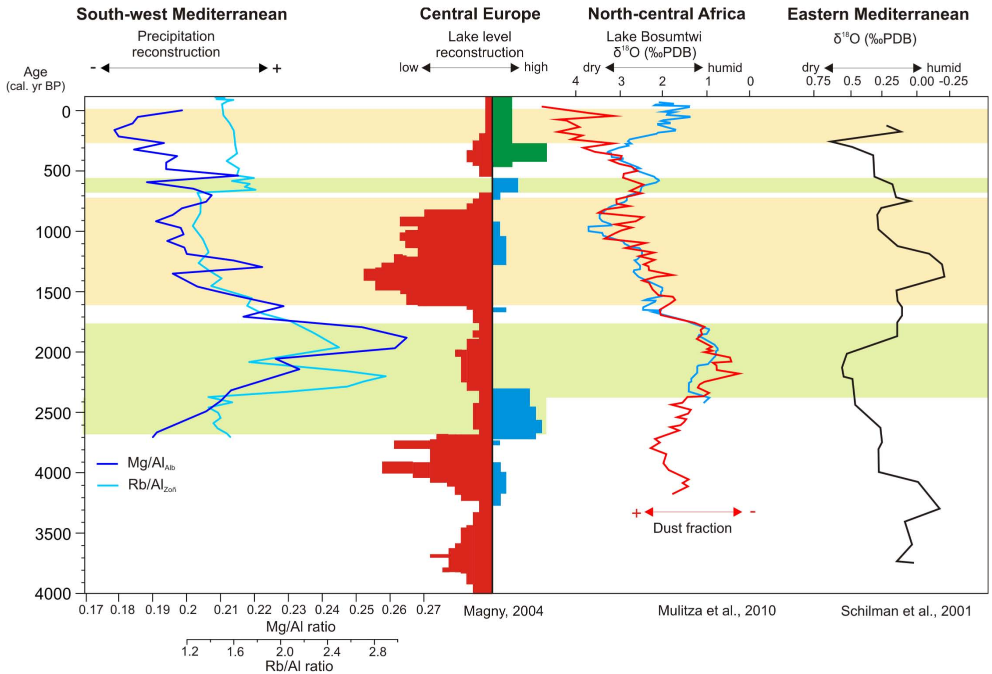

Fig. 5. Precipitation proxies (Rb/Al and Mg/Al ratios) compared with lake level reconstruction for central Europe (Magny, 2004, in blue and red; Magny et al., 2007, in green), δ^{18}O composition from Lake Bosumtwi (Mulitza et al., 2010) and South East Mediterranean Sea (Schilman et al., 2001) as indicators of humid conditions in north-central Africa and eastern Mediterranean, respectively.

CPD
6, 1655–1683, 2010

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion