Quaternary Science Reviews (2010)

doi:10.1016/j.quascirev.2010.05.014

Soil moisture fluctuations recorded in Saharan dust deposits on Lanzarote (Canary Islands) over the last 180 ka

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abstract

Aeolian sediments trapped in volcanically dammed valleys on Lanzarote, Canary Islands, were investigated in order to reveal environmental changes over the last 180 ka. Clay content and frequency dependent magnetic susceptibility were used as proxies for pedogenesis and palaeo-soil moisture. During the last 180 ka, these proxies showed a general pattern of enhanced soil moisture during glacials and stadials and more arid conditions during interglacials and interstadials. Comparisons of these results with proxies from regional palaeoclimate studies identified a positive correlation with proxies of trade wind strength off northwest Africa and inverse correlations with both sea surface temperatures in the northeast Atlantic and the extent of Mediterranean vegetation. Possible causes for the observed pattern include a glacial enhancement of precipitation from westerly cyclones, a change in relative humidity due to fluctuating air temperatures and an occasional influence of the African summer monsoon. Although it is not yet possible to clearly differentiate among these factors, it is clear that the first two factors must have been primarily dominant. These results represent the first quasi-continuous terrestrial data testifying to environmental changes in the northwest African coastal area for the last 180 ka and complement the abundant data derived from marine cores of the region. High latitude dynamics had a major influence in this area and were intermediated by North Atlantic sea surface temperatures. A possible negative correlation can also be observed with the orbital obliquity cycle with a 10 ka time lag, which is similar to the lag recorded from North Atlantic sea surface temperatures.

1. Introduction

In light of the human-triggered climate change predicted in the coming decades (Intergovernmental Panel on Climate Change, 2007), an increasing number of palaeoclimate studies have been conducted in order to understand the global climate system and its feedback relationships with terrestrial and oceanic ecosystems (e.g., Farrera et al., 1999; Thompson et al., 2000; Maslin et al., 2001; Battarbee et al., 2004). Special attention has been given to naturally unstable and vulnerable environments such as those in semiarid and arid regions (e.g., desert-margins), which often have a high population density (cf. Mabbutt, 1989; Mountney, 2003; Lioubimtseva, 2004). However, past climate and ecological conditions are not always well understood in these regions. This lack of understanding strongly complicates local climate prognoses and especially holds true for the arid and semiarid regions of northwest Africa that stretch from the Saharan desert to the Mediterranean Sea. Today, the climate of this region is influenced by three different wind systems: Atlantic westerlies, the Hadley circulation and the African summer monsoon system. Atlantic westerlies and monsoon circulation advect precipitation into the Mediterranean area during winter and into the Sahel during summer, respectively, the Hadley circulation is responsible for the northeast trade winds that cause dry conditions in the Saharan region (Nicholson, 2000).

Some aspects of the Late Quaternary palaeoclimate of northwest Africa are well known from marine studies carried out in the Northeast Atlantic and the Alborean Sea (e.g., Hooghiemstra, 1988; Dupont, 1993; Moreno et al., 2001; Bozzano et al., 2002; Freudenthal et al., 2002; Kuhlmann, 2003; Bout-Roumazeilles et al., 2007; Holz et al., 2007). Most of these investigations focused on reconstructing palaeowind systems for the past 250 ka (Moreno et al., 2001; Bozzano et al., 2002; Bout-Roumazeilles et al., 2007; Freudenthal et al., 2002) but, apart from some pollen records (Hooghiemstra, 1988; Dupont, 1993), found it difficult to derive terrestrial palaeohumidity and precipitation regimes from marine archives. More recently, some studies tried to infer Holocene fluvial activity from marine cores (e.g., Kuhlmann, 2003; Holz et al., 2007). Although palaeohumidity and precipitation are generally better recorded in terrestrial than in marine archives, to our knowledge, no terrestrial study from the Northwest African region has yet presented continuous records of precipitation regimes or landscape geomorphic reactions to precipitation changes. Instead, most terrestrial archives only record events limited to the Holocene or latest Pleistocene (e.g., Rohdenburg, 1977; Gasse et al., 1987; Petit-Maire et al., 1994; Cheddadi et al., 1998; Lancaster et al., 2002). The next archives that continuously cover at least the last glacial cycle are only found in the northern Mediterranean area (e.g., Pons and Reille, 1988; Allen et al., 1999; Narcisi, 2001). Due to this lack of data, no regional climate model can yet be validated for the northwest African region (e.g., Cheddadi et al., 1998).

The Canary Islands are located at the southernmost margin of the westerly-influenced Mediterranean climate zone and are strongly influenced by Saharan air from northwest Africa. Therefore, they are regarded as a key location for understanding climate changes in the transitional area between the Mediterranean climate zone with winter precipitation and the climate of the year round hyperarid Sahara (Meco et al., 1992; Kuhlmann, 2003). Furthermore, given that numerous palaeoclimate studies have indicated that monsoonal summer precipitation penetrated far into the Sahara during certain periods of the Quaternary (e.g., Lézine and Casanova, 1991; Petit-Maire et al., 1994; Kuper and Kröpelin, 2006), a monsoonal influence may have temporarily reached the latitude of the Canary Islands in the past.

Terrestrial palaeoenvironmental studies from the Canary Islands (dune-palaeosol sequences, marine terraces with underlying palaeosols, cave sediments), such as those on the nearby African continent, are typically discontinuous and are mostly restricted to the period from approximately 40 ka to the Holocene, likely due to the limits of ^{14}C-dating (e.g., Meco and Pomel, 1985; Petit-Maire et al., 1986; Rognon and Coudé-Gaussen, 1987; Rognon et al., 1989; Damnati et al., 1996; Meco et al., 1997; Coello et al., 1999). Furthermore, according to Meco et al. (2002), Late Pleistocene ^{14}C ages obtained from these islands have generally been equivocal, and therefore, Pleistocene palaeoclimate reconstructions based on ^{14}C-dating should be considered with care. In difference, U/Th and luminescence dating are regarded as more reliable than ^{14}C-dating. However, only a small number of palaeoenvironmental studies have used age models based on these methods (e.g. Pomel et al., 1985; Hillaire-Marcel et al., 1995; Rognon and Coudé-Gaussen, 1996a; Meco et al., 2002). In other words, due to these problems the Late Pleistocene palaeoenvironmental history of the islands remains largely unknown. In contrast with the other islands of the Canarian archipelago, the northeasternmost island of Lanzarote hosts several Miocene to Pliocene valleys that are dammed by Quaternary lava flows. Locally, these valleys are called vegas (Carracedo et al., 1998; Zöller et al., 2003). After damming, the valleys filled with several meters of sediment consisting of Saharan dust and local volcanic material. Luminescence dating and supporting correlations with nearby marine proxies showed that this material yields the first almost continuous record of terrestrial palaeohumidity from the northwest African area. The record stretches from at least early Marine Isotope Stage (MIS) 6 tothe Holocene (Suchodoletz et al., 2008). Quantitative estimates of palaeo-soil moisture were derived from the intensity of pedogenesis (Suchodoletz et al., 2009a). Similarly to the present study, former palaeoenvironmental studies from other regions deduced palaeo-soil moisture from clay content and/or frequency dependent magnetic susceptibility (e.g., Forster et al., 1994; Chlachula et al., 1998; Dearing et al., 2001; Sun et al., 2006; Zech et al., 2008). These methods exploit the facts that weathering processes lead to the production of clay minerals (e.g., Bronger et al., 1998; Sródon, 1999; Gillot et al., 2000) and that so-called superparamagnetic particles are proxy parameters for the intensity of pedogenesis. Superparamagnetic particles can be detected by environmental magnetic methods, especially the method called frequency-dependent magnetic susceptibility. Details of our environmental magnetic approach, a description of the data and discussion are found in Suchodoletz et al. (2009a). Our published interpretation is summarised as follows: Superparamagnetic magnetite/maghemite particles were produced either by low temperature oxidation of coarser magnetic particles with different origins (e.g., bacterial or detrital) (Maher, 1998; Van Velzen and Dekkers, 1999) or by neoformation of extremely fine and therefore superparamagnetic particles through the microbe-induced precipitation of magnetite or the transformation of poorly crystalline ferric Fe-(oxy)hydroxides by Fe-reducing bacteria. Superparamagnetic particles composed of maghemite nano-crystals are thought to be the main carriers of magnetic susceptibility in loess, loess-like sediments and paleosols (e.g., Chen et al., 2005). As proven by the clear negative correlation in all sections between a remanence controlled parameter and the frequency-dependent magnetic susceptibility, a non-remanence-carrying but highly susceptible mineral fraction plays an important role in variations of magnetic mineralogy. This fraction is most likely composed of superparamagnetic particles that derived from weathering of the primarily detrital ferrimagnetic minerals (Suchodoletz et al., 2009a). Time resolution of the archives is limited and restricted to the time scale of Marine Isotope Stages (MIS), at least for large parts of the Pleistocene sequences. This is due to the fact that the chronological pattern is blurred due to the close interfingering of material that was directly deposited as aeolian fallout with material that was originally deposited in the catchment area and subsequently derived as colluvial input from the slopes, although the time lag was not more than some ka (Suchodoletz et al., 2009b).

In this article, we compare the soil moisture proxies from Lanzarote with other palaeoclimate data from the Canary Islands, the northwest African margin and the Mediterranean area. We propose possible scenarios that help to explain the observed soil moisture pattern by considering the influences of western cyclones, the North African summer monsoon and changes in sea surface temperatures. Furthermore, we suggest a tentative correlation of our results with the orbital obliquity signal.

2. Study area

Lanzarote is the northeasternmost member of the volcanic Canary Island, and is located130 km off the coast of northwest Africa between 28°50’ to 29°13’N and 13°25’ to 13°52’W (Fig. 1). Basic volcanism started during the Miocene, about 15.5Ma ago (Carracedo et al., 1998; Geldmacher et al., 2001), and the latest eruptions occurred in 1730 - 1736 and 1824 (Rothe, 1996). Both the northern and the southern parts of the island are dominated by volcanic massifs of Miocene to Pliocene age, which have smoothed concave slopes due to strong erosion under subtropic summer-humid conditions during the Neogene (Höllermann, 2006). Several phases of pedogenesis caused the polygenetic calcretes that have been exposed along the slopes by erosional processes. The central part of the island between the volcanic complexes in the north and south exhibits a smoother topography, whereas the massifs are dissected by numerous U-shaped valleys and smaller gullies. Some of the large valleys were dammed by lava flows and pyroclastica during the Lower and Middle Pleistocene and thus served as sediment traps for Saharan dust and locally reworked volcanic material (Romero, 2003).

The climate of Lanzarote is maritime-semiarid. The mean annual temperature at sea level is 19.9° ± 3°C with only minor fluctuations caused by the influence of the cold marine Canary Current (Jahn, 1988). Year-round, the island climate is dominated by northeasterly marine trade winds (Fig. 1). During winter, these winds are occasionally interrupted by northwesterly winds caused by boreal cyclones and easterly Saharan air flow (Calima winds). Precipitation values range from 100 to 250 mm/a and decrease from high to low altitudes. In contrast to the western Canary Islands, Lanzarote receives no precipitation from orographically raised rade winds due to its low elevation (max. 670m). Precipitation originates from boreal winter cyclones that follow extremely southern tracks (Fig.1). Vegetation is very sparse and disperse, and the current vegetation cover is strongly disturbed by anthropogenic activity (Jahn, 1988; Kunkel, 1993). Shrubs are dominated by xerophytic and halophytic species.

Saharan dust is brought to Lanzarote mainly during two different synoptic situations. During winter, Calima events advect dust at low altitudes (0 -1500 m) to the archipelago. Calima-winds are continental African trade winds (Harmattan) that are deflected towards the west by Atlantic cyclones near the Canary Islands (cf. Criado and Dorta, 2003). During summer, dust is transported to latitudes north of the Canary Islands by the northern branch of the Saharan Air Layer originating from the Sahel region, which is active within an altitude of about 1500 to 5500 m a.s.l. There, the material sinks into the lowermost troposphere and is finally transported towards the island by the marine northeast trade wind (cf. Koopmann, 1981; Bozzano et al., 2002). Finally, dust sedimentation occurs either by dry or wet deposition (Criado and Dorta, 2003; Menéndez et al., 2007).

3. Material and methods

3.1. Studied sites

We studied sediment sequences from three vegas, which were formed by volcanic damming during the Lower and Middle Pleistocene (Fig. 1). The studied sections in the valley floors were located far from geomorphically active slopes. Polygenetic calcretes indicated that the smooth valley slopes underwent long-term alteration with several soil-forming periods. Valley floor sediments were characterised by alternating layers of reddish, clayey material and loess-like, yellowish, silty material. They contained a mixture of in-situ and colluvially reworked fluvioaeolian material consisting of both allochthonous Saharan dust and autochthonous volcanic material (Suchodoletz et al., 2009b). Both the reddish, clayey layers and the yellowish, loess-like layers had high quartz contents (Jahn, 1988; Suchodoletz et al., 2009b), demonstrating the steady accumulation of Saharan dust. The variability of pH-values between the different layers was low (between 7.6. and 8.2, with one exception of 6.6), although partially carbonate-free layers demonstrate that the originally carbonate-rich Saharan dust material must have been decalcified in the past (Jahn, 1995; Menéndez et al., 2007). The loess-like layers in particular were characterised by secondary carbonate nodules with diameters up to 2 cm, calcified root channels and vertical cracks, which were hardened in places into calcrete horizons. Ferromanganese concretions of up to 2 cm in diameter were also preferentially found in the loess-like layers. These features probably developed after sedimentation in the valley floors. Palaeosol sediments displayed greater amounts of clays with moderately strong vertic properties as well as clay illuviation. Although clay illuviation was detected by clay cutans during micromorphological investigations, this observation did not complicate the interpretation of clay contents because most cutans were broken and thus indicated that clay illuviation occurred on the slopes prior to redeposition of the material into the valley floors. Furthermore, environmental magnetic and sedimentologic proxies showed smooth patterns, suggesting no more than a minor bias from clay illuviation (see Suchodoletz et al., 2009a). General features of the loess-like and palaeosol sediments are listed in Table 1. In the upper parts of the profiles, we observed anthropogenically-influenced colluvial deposits of various thicknesses, some of which contained ovicaprid bones (Zöller et al., 2003; Suchodoletz et al., 2008) (Fig. 2).

3.2. Methods

3.2.1. Chronostratigraphy

Chronostratigraphies were developed for the vegas based on optically stimulated luminescence (OSL) dating of fine (4 - 11 µm) and coarse (63 - 200 µm) quartz grains and infrared stimulated luminescence (IRSL) dating of fine-grained polymineral samples. Samples were prepared under subdued red light (wavelength 640 ± 20 nm) in the Bayreuth luminescence laboratory (Germany). Standard preparation methods were used, including etching with HCl and H_2O_2 to remove carbonate and organic matter and sieving and sedimentation in settling tubes to separate fine and coarse grains. In order to obtain coarse quartz grains, density separation was conducted with a lithium heteropolytungstate solution and by etching with HF. Fine-grained quartz was obtained by etching with hexafluorosilicic acid (Fuchs et al., 2005). Luminescence measurements were carried out with two Risø-Readers TL/OSL-DA-15 by applying the single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) for coarse- and fine-grained quartz OSL; the multiple aliquot additive protocol of Lang et al. (1996) was used for fine-grained IRSL. Dose rates were determined by thick source α–counting at the University of Bayreuth (Germany), inductively coupled plasma source mass spectrometry (ICP-MS) at the Bayreuth Centre for Ecology and Environmental Research (BAYCEER, Germany), and atomic adsorption spectrometry (AAS) at the University of Marburg (Germany). Chronostratigraphies were further corroborated based on interprofile correlations as well as correlations between kaolinite contents from the vegas and proxies from nearby marine cores (Suchodoletz et al., 2008).

3.2.2. Frequency-dependent magnetic susceptibility

Dry sediment aliquots were collected from all vegas at 5-cm intervals and filled into plastic boxes. The frequency dependence of magnetic susceptibility (k_{fd}) was determined using a MAGNON Susceptibility Bridge (MAGNON, Dassel, Germany) at AC-fields of 80 A/m at 1 and 8 kHz (k_{fd} = (k@1kHz - k@8kHz)/k@1kHz * 100 in %) with a noise-level of about 1%.

3.2.3. Grain size analyses

In order to evaluate grain sizes, sediment samples (10 g each) were collected from all three vegas at 5-cm intervals. The material was treated with 10% and 30% HCl at 65°C to remove Ca-carbonate and dolomite. Subsequently, organic carbon was destroyed using 32% H_2O_2. Sand was removed by wet sieving, and the fraction < 63 µm was treated for several hours in an ultrasonic bath in order to disintegrate the abundant aggregates of clay and ferromanganese oxides and hydroxides, which would have strongly biased the grain size results (cf. Suchodoletz et al., 2009a). After 0.1 M sodium pyrophosphate was added and the material was shaken for 24 h in order to disperse clay, the sample was analysed with a Malvern 2600C Laser Analyser at GFZ Potsdam/ Germany. To facilitate the interpretation of results, the means of three successive measurements were taken for 32 grain size classes. Following the method of Konert and Vandenberghe (1997), we used a conspicuous inflection point of the grain size distributions to separate the first dominant grain size peak from the following peaks and thus obtained a limit clay/silt of 6.18 µm. In order to clarify the pedogenetic signal, we removed the signal of the coarse silt fraction by using the clay ratio for the < 42 µm fraction. Coarse silt and fine sand showed a similar distribution over the studied depth interval and, due to their smaller specific surface area, are believed to make only a minor contribution to weathering, far smaller than the contribution by fine/middle silt (cf. Helgeson et al., 1984).

4. Results

4.1. Chronostratigraphy

Aggregation and iron staining have often been reported for Saharan dust grains (e.g., Koopmann, 1981; Evans et al., 2004), which has caused ages to be overestimated by several ka for fine grains (4 - 11 µm) of quartz and feldspar due to insufficient bleaching of the luminescence signal during aeolian transport. In contrast, quartz coarse grains (63 - 200 µm) were mostly transported as single grains and were thus most likely only slightly affected by age overestimations due to aggregation. Furthermore, as a result of strong anomalous fading (an unpredictable loss of the luminescence signal with time), IRSL ages for fine grains are often strongly underestimated and must be regarded with caution. Finally, the effects on coarse-grained quartz OSL ages of insufficient bleaching during fluvial transport into the valley bottoms after aeolian deposition was largely corrected using the statistical technique of Juyal et al. (2006), as modified by Fuchs et al. (2007). Thus, the coarse-grained quartz OSL technique, which showed an average error of 13.8% in the vegas, was selected. Unfortunately, quartz OSL ages only extend back to 125 ka, whereas feldspar IRSL ages stretch into the Middle Pleistocene. However, due to the low reliability of the IRSL ages, the age model beyond the range of the coarse-grained quartz OSL ages (beyond 125 ka) was established by correlating the kaolinite contents measured in the vegas with those measured in nearby marine cores (see Suchodoletz et al., 2008).

Sediment ages of the investigated vega sections ranged between Middle Pleistocene and Holocene in Femés and Teguise and between Upper Pleistocene and Holocene in Guatiza III. The highest average sedimentation rates were identified at Guatiza III, followed by Femés and Teguise. All vegas showed a hiatus between about 15 ka and 30 ka, concurrent with a “geomorphological crisis” on Fuerteventura and in NW-Morocco that was characterised by strong erosion and described by Rognon and Coudé-Gaussen (1987). Chronostratigraphy was described in detail in Suchodoletz et al. (2008) (Fig. 4).

Because the sediments are complex mixtures of in-situ aeolian and reworked colluvial material from the slopes, there is a small discrepancy between the time when sediment properties were obtained and the time measured by dating methods. This effect, in combination with the complex chronostratigraphic information collected from luminescence dating, interprofile correlation and correlations with nearby marine proxies, means that no exact error of the age model can be given. Therefore, some parts of the Pleistocene sequences have time resolutions in the range of several ka and can only be used to identify Marine Isotope Stages (MIS) and substages.

4.2. Clay content and magnetic susceptibility

Although samples were given extensive ultrasonic treatment before laser analysis, a clear and continuous clay signal was recognisable throughout the sequences and was comparable to the results of parallel pipette analysis for samples that were not treated in an ultrasonic bath (cf. Suchodoletz et al., 2009a). Clay contents and k_{fd} values also exhibited nearly parallel behaviour over time among the vegas, indicating a common climatic impact on the island (Figs. 2 - 4). Minor differences among the vega profiles probably resulted from different time resolutions and colluvial perturbation of the chronological pattern (cf. Suchodoletz et al., 2008). Glacials and stadials (parts of MIS 2, 3, 4 and 6) generally showed enhanced clay contents and k_{fd} values; the highest values were found for the periods between 145 and 125 ka and between 75 and 45 ka. Cold periods were therefore characterised by higher soil moisture. By contrast, the proxies showed that warmer interglacials and interstadials (most parts of MIS 1, 3, and 5 as well as the period between 170 and 145 ka in MIS 6) experienced conditions that were at least as dry as the present. Apart from a possible hiatus between 15 and 25 ka, the profile of Femés showed an almost complete sequence for the last 180 ka (Figs. 3, 4). Due to both its completeness and its consistently intermediate temporal resolution, the Femés sequence was identified as the most appropriate profile for palaeoclimatic interpretation in this study.

5. Discussion

5.1. Comparing soil moisture proxies with palaeoclimate studies from the Canary Islands, Northwest Africa and the Mediterranean

Palaeoclimatic studies from the Eastern Canary Islands (Meco and Pomel, 1985; Petit-Maire et al., 1986; Rognon and Coudé-Gaussen, 1987; Rognon et al., 1989; Damnati et al., 1996;

Meco et al., 1997; Coello et al., 1999) (Fig. 3) have used various archives mostly based on ^{14}C-dating methods to identify several palaeosols between 40 and 25 ka. However, no consistent pattern exists among palaeosols from different archives, which may be due to the general problems with ^{14}C-dating reported by Meco et al. (2002). Furthermore, palaeosols dated to 40 ka may be somewhat older than reported due to the large uncertainty at the upper limit of ^{14}Cdating. In general, the climate of the period between >40 and 25 ka appears to have been generally wetter than in the present day and characterised by unstable climate conditions. Investigations based on U/Th and especially TL dating (Rognon and Coudé-Gaussen, 1996a; Pomel et al., 1985; Hillaire-Marcel et al., 1995) are regarded as relatively reliable. These studies interpreted the period between 50 ka and the Last Glacial Maximum (LGM, ca. 21 ka) as a time of a generally wetter but unstable climate, whereas the period prior to 50 ka was characterised by increased humidity and a stable climate. Soil moisture proxies from the vegas also indicated that the period between 75 and 25 ka was generally wetter than the Holocene. Furthermore, the shift from wet to somewhat drier and instable conditions (which were nevertheless wetter than the Holocene) around 50 ka was manifested in the soil moisture proxies from the Guatiza III and Femés vegas as a decrease in k_{fd} and clay content; particularly low values were found for the period between 40 and 30 ka (Fig. 3). Thus, although we encountered problems with ^{14}C-dating and somewhat masked by inconsistent time resolutions between the different studies, our findings were generally consistent with previous studies from the eastern Canary Islands.

A comparison of the soil moisture proxies from Lanzarote with other palaeoclimatic proxies from the northwestern African and Mediterranean areas produced three notable observations (Fig. 4):

- Elevated soil moisture was inversely correlated with the extent of arboral vegetation in the Mediterranean area, which was reconstructed from marine and terrestrial pollen studies conducted off Iberia and northwest Africa (Hooghiemstra et al., 1992) and in a lake from northern Greece (Tzedakis et al., 2003).
- Elevated soil moisture generally correlated well with high organic carbon and pollen levels, which indicate stronger trade winds off northwest Africa, in marine cores that were collected near the coast of northwest Africa and the Canary Islands (deMenocal et al., 1993; Freudenthal et al., 2002). It was also correlated with lower sea surface temperature (SST), which was inferred from distributions of foraminifera in marine cores retrieved near Cap Blanc/Mauritania (Crowley, 1981).
- Periods of enhanced soil humidity on Lanzarote were coeval with most sapropels in the Eastern Mediterranean Sea (S1, S2, S4, S5, S6). The only exception is sapropel S3, which formed during a generally dry period on Lanzarote (Kallel et al., 2000). Although the northward advance of the African summer monsoon into the Sahara has not been well studied over the last 200 ka, the sapropels in the Eastern Mediterranean Sea reflect high Nile river discharge, which directly relates to the effect of the African monsoon on the upper catchment of the Nile. These results indicate that the occurrence of sapropels in the Eastern Mediterranean Sea can be used as a proxy for the northern migration of the monsoon front into the Sahara.

5.2. Palaeoclimatic scenarios for periods of enhanced soil moisture on Lanzarote

Based on a comparison with Mediterranean and northwest African palaeoclimatic proxies, three possible palaeoclimatic scenarios for periods of enhanced soil moisture on Lanzarote during the Late Quaternary are discussed below. Each scenario is based on a factor that could have triggered a more positive hydrologic budget for the vegas and thereby enhanced soil moisture.

Scenario I: higher precipitation due to more intensive North Atlantic winter cyclones. As in the Mediterranean region and southern Morocco, the amount of precipitation on the Canary

Islands is currently negatively correlated with the North Atlantic Oscillation (NAO) (Garcia-Herrera et al., 2001). During negative NAO phases, Atlantic cyclone tracks shift southward (Hurrell, 1995; Knippertz et al., 2003) and precipitation is enhanced (García-Herrera et al., 2001). Thus, actual precipitation on the Canary Islands similar to that in the Mediterranean region, is linked to the pressure distribution of the North Atlantic.

Although some palaeoclimatic studies reported generally dry glacial conditions in the Mediterranean and contrastingly wet interglacials (Dearing et al., 2001; Woodward, 1999), others assumed that the westerlies shifted southward during glacial periods and advected moist air into parts of the Mediterranean region and North Africa (Fig. 5a). High lake levels in Italy during the Last Glacial Maximum (LGM) were attributed to wetter winters (Narcisi et al., 1992; Narcisi, 2001), and contemporary high lake levels in the central Saharan Hoggar Massif were ascribed to a southward shift of the Subtropical Jet Stream (Maley, 2000). Accordingly, the recharge of groundwater aquifers in the Northern Sahara from 45 to 23.5 ka was attributed to southerly-shifted Atlantic westerlies (Edmunds et al., 2004). Rognon and Coudé-Gaussen (1996b) reported a large-scale eastward migration of dune sands in the eastern Canary Islands and coastal Morocco at about 18 ka, which they attributed to strong westerlies; sand mobilisation was ascribed to sand availability from the shelf rather than to aridity. Likewise, modelling studies showed a southward shift of winter westerlies under “glacial-like” boundary conditions in Europe (Ganopolski et al., 1998; Kageyama et al., 1999). Altogether, this work provides a strong case for increased westerly cyclonic activity connected with precipitation in some Mediterranean and North African regions, including the Canary Islands, during glacial periods. However, some pollen studies (Hooghiemstra et al., 1992; Tzedakis et al., 2003) (Fig. 5, columns 4, 5) reported that arboreal Mediterranean vegetation was limited in extent during the more humid glacial and stadial periods on Lanzarote. To evaluate these contrasting observations, we treated cold Heinrich events as extreme glacial periods. Pollen studies from the Mediterranean area showed that, during these events, steppic vegetation prevailed over arboreal vegetation (Sanchez-Goñi et al., 2000; Boessenkool, 2001; Turon et al., 2003). Although some authors assumed generally dry conditions during Heinrich events (Sanchez-Goñi et al., 2000; Turon et al., 2003), others suggested wet and very cold winter conditions with increased runoff and enhanced anticyclonic-driven summer aridity (e.g., Boessenkool, 2001). The latter scenario was supported by Ruddiman and McIntyre (1981), who proposed that a southward shift of the Arctic Front in the North Atlantic during these cold events pushed the trajectories of winter cyclones off Iberia southward to latitudes of about 40°N.

Extrapolating this scenario from extreme Heinrich events to glacial periods in general, the limited extent of thermophilous arboreal vegetation in the Mediterranean region was caused by lower winter temperatures, and contemporaneous humid conditions on Lanzarote were due to enhanced winter precipitation from southerly-shifted winter cyclones (Fig. 5a). The stronger trade winds observed off northwest Africa during cold periods (Freudenthal et al., 2002; deMenocal et al., 1993) (Fig. 4, columns 1, 2) could thus have been caused by enhanced anticyclonic circulation with stronger trade winds during summer; the trade winds were shifted to the south by North Atlantic cyclones during winter.

Scenario II: higher precipitation due to a northern advance of the African summer monsoon. Apart from sapropel S 3, which formed about 80 ka ago during a dry period on Lanzarote, sapropels in the eastern Mediterranean Sea formed during periods of enhanced soil moisture on Lanzarote, indicating that strong monsoonal precipitation occurred in the Nile catchment (Fig. 5, column 6). Based on terrestrial inputs to the northwest African continental margin, Kuhlmann (2003) assumed that the African summer monsoon advanced to the Canary Island area for the Early Holocene and MIS 5e (Eemian) (Fig. 5b). Similarly, Tjallingi et al. (2008) applied a grain-size-based humidity index and modelling studies and found that most humid monsoonal conditions off Cape Blanc/Mauritania occurred during MIS 1 and, to a lesser degree, during warm substages 5a and 5c. This demonstrated that the African summer monsoon reached its northernmost advance off northwest Africa during warm periods, with maximal values during the Holocene. The African summer monsoon generally advanced and retreated from south to north and back again (e.g., Yan and Petit-Maire, 1994); it arrived later at and retreated earlier from its northernmost points. In the Early Holocene, Hoelzmann et al. (2004) demonstrated that the most humid conditions occurred in the Sahara/Sahel zone around 9.5 ka. Vega sediments from Lanzarote, potentially the northernmost point in the monsoonal area, indicated dryness from about 8.5 ka (Suchodoletz et al., 2010). Thus, the monsoonal influence could not have lasted longer than about 2 ka and was, if present at all, restricted to the interval between about 10.5 and 8.5 ka. Because the more humid periods on Lanzarote had much longer durations of up to 35 ka, it is clear that these periods cannot be exclusively explained by monsoonal influence. On the other hand, our results do not exclude the assumption of Kuhlmann (2003) that the African summer monsoon may have progressed to the latitude of the Canary Islands during some short periods of the Quaternary, where it could have contributed to the observed increase in soil moisture (Fig. 5b). If this is true, a monsoonal influence coeval with sapropel S 5 could possibly explain the intermediate soil moisture found on Lanzarote for at least early MIS 5e (between 126 and 115 ka) (Fig. 5, column 6), a period expected to be dry based on the general pattern of low soil moisture during the Upper and Middle Pleistocene (Fig. 4). In general, monsoonal influences seem to have been too brief to be well resolved in the vega sediments (Suchodoletz et al., 2008).

Scenario III: a decrease of air temperature causing a relative increase of soil moisture. Today, the Canary Current transports relatively cold water from High Northern Latitudes to the Canary Islands. In a core collected off Cap Blanc/Mauritania (around 650 km south of Lanzarote), Crowley (1981) showed that this current was also active during the Pleistocene (Fig. 5, column 3), when it experienced glacial sea surface temperatures (SST) 5 - 7°C lower than today. From a core off southern Iberia (1000 km north of Lanzarote), Cayre et al. (1999) reported a general decrease of glacial SST of about 4°C and a decrease of about 10°C during Heinrich events.

A low SST directly lowered overlying air temperature and probably caused the following effects for the vega sediments: (i) reduced evapotranspiration from soils (Hölting, 1996) and (ii) a lower altitude of condensation. Recently, the minimum altitude of trade wind clouds is about 1000 m, which affects the highest peaks of the Famara Massif (altitude 670 m) during only some days of the year (Kämmer, 1974). As reduced glacial air temperatures caused a parallel lowering of the condensation altitude and the trade wind inversion layer (T. Foken, oral communication; Schubert et al., 1995), trade wind clouds on Lanzarote may have experienced a moisturising effect similar to that recently observed on the northeastern slopes of the higher western Canary Islands (Fig. 6). Furthermore, increased glacial trade wind speeds (deMenocal et al., 1993; Freudenthal et al., 2002) (Fig. 5, columns 1, 2) should have increased the amount of trade wind cumulus clouds (Albrecht, 1981), although this effect was probably somewhat neutralised by the reducedwater vapour content of the atmosphere, which caused the trade wind clouds to have lower densities (e.g., Ganopolski et al., 1998; Clark et al., 1999). The lowered SST probably had a third effect on vega sediments: (iii) in combination with a relatively warm land surface during summer, a low SST would have fostered the formation of coastal fog such as that recently seen on the southern Moroccan coast (Kämmer, 1974).

None of the presented scenarios for enhanced Quaternary soil humidity on Lanzarote can be excluded at this time. It is not yet possible to discriminate among the effects of different scenarios for specific time periods, as shown in the following example from the Lower Holocene. Proxies from the vega sediments indicated humid conditions from about 15 to 8.5 ka, which were followed by continuous aridity. Verschuren et al. (2004) showed that most studies from the westerly-influenced Mediterranean area witnessed fairly humid conditions between ca.10 and 4 ka, and Cheddadi et al. (1998) reconstructed higher westerly precipitation in the Atlas Mountains from 7 to 2.5 ka. These observations exclude a scenario in which the shift at 8.5 ka ago towards lower soil moisture on Lanzarote was caused by reduced precipitation from westerly cyclones. Using wavelet-analyses, Kuhlmann (2003) reported a major change in the sedimentation pattern off the Canary Islands ca. 8.5 ka ago, which was ascribed to the end of monsoonal influence in this region. Consequently, humid conditions in the Lanzarote vegas during the Lower Holocene could have been caused by monsoonal precipitation. On the other hand, Boessenkool (2001) reported that SST in the Canary Current, about 1000 km north of the Canary Islands, increased steeply to recent values at about 8.7 ka. A parallel SST rise was seen by Zhao et al. (1995) about 900 km downstream off Cap Blanc between 10 and 7.5 ka, but Kim et al. (2007) were not able to confirm this rise close to the Canary Islands. Hence, either decreased SST and air temperatures or a northern expansion of the African summer monsoon could explain the humid conditions in the vegas until about 8.5 ka.

This example demonstrates that it is not yet possible to detail the different causes for enhanced soil humidity on Lanzarote during the Late Quaternary. However, some combination of increased precipitation from westerly cyclones and lowered SST and air temperature probably triggered the increased soil moisture on Lanzarote during most of the glacial periods. Precipitation from a northward-shifted African summer monsoon may have amplified this increase in soil humidity during several short periods or may have prolonged moist phases by several ka into warm stages such as MIS 5e or early MIS 1.

Due to the complex character of our age model, no exact error can be given (see Section 4). However, a periodic cyclicity of about 40 ka was suggested in the soil humidity pattern from Lanzarote, with minimum pedogenesis during the Middle/Late Holocene and during periods of 40, 80, 120 and 160 ka during the Upper Pleistocene (Fig. 4). This cyclicity was most clearly recognisable in Femés and in the lower parts of Teguise and in Guatiza (Figs. 3, 4) and was hardly recognisable at the upper part of the Teguise profile due to its low time resolution (cf. Fig. 2). The cyclicity was reminiscent of the 41 ka obliquity cycle (e.g., Zachos et al., 2001) and was obviously negatively correlated with this astronomic parameter when accounting for a time lag of about 10 ka between obliquity maxima and pedogenesis minima (Fig. 4, arrows). The correlation in the Upper Holocene was biased due to anthropogenic colluvia consisting of eroded soil material, which simulated strong pedogenesis in place of the expected minimum. The case for correlation is strengthened by the facts that the chronostratigraphy of the vegas was constructed independently of tuning to Milankovich parameters and that the cyclicity is present throughout the whole sequence. Due to the chronostratigraphic uncertainty, the roughly 10 ka time lag can only be approximated. However, because this phenomenon was present throughout the sequence, it appears to be a real phenomenon rather than an artefact. In northern North Atlantic cores, Ruddiman and McIntyre (1984) found a 41-ka cyclicity in SST that was positively correlated with the obliquity cycle with a lag of 9e13 ka, similar to the lag observed on Lanzarote. Thus, the assumed negative correlation between pedogenesis and obliquity was probably transmitted by SST, which was also negatively correlated with pedogenesis on Lanzarote (Fig. 4). Obliquity triggers changes of global ice volume, which in turn controls North Atlantic SST (e.g., Ruddiman and McIntyre, 1984; deMenocal et al., 1993). Ruddiman (2003) confirmed this observation with a model incorporating the main drivers of the climate system and found a time lag of 6.5 ± 1 ka between the obliquity cycle, ice sheet growth and SST. In spite of the uncertainties inherent in both this model and our vega chronostratigraphies, it appears that the obliquity signal was transferred to the vega sediments of Lanzarote by way of the Northern Hemisphere ice sheets and the related North Atlantic SST. The SST influenced the sediments either by changing the evaporation rate and thus indirectly enhancing soil moisture or by changing the track of the North Atlantic westerlies, which depend on the temperature of the

North Atlantic (Ruddiman and McIntyre, 1984). Consequently, we can confirm the hypothesis of Moreno et al. (2002), that most of the Late Quaternary climate variability in the northwest African region at the latitude of the Canary Islands was controlled by northern high latitude dynamics.

6. Conclusions

Investigations of soil moisture in sediments derived from Saharan dust and local volcanic material in volcanically dammed valleys of Lanzarote demonstrate that this unique terrestrial archive documents changes in environmental conditions in the northwest African region. The sediments can be used to trace the influences of sea surface temperatures and westerly cyclones on this island during the last 180 ka. In agreement with former studies, the results showed that environmental conditions in this area were controlled primarily by northern high latitude rather than low-latitude dynamics, with the obliquity cycle as a possible trigger. However, our findings did not exclude an occasional influence of the low-latitude African summer monsoon as previously assumed by Kuhlmann (2003), although the duration of this influence was barely resolvable in our archives.

Although it was not possible to sufficiently discriminate among the factors influencing soil moisture on Lanzarote, our results represent the first detailed description of the environmental conditions of the coastal area of northwest Africa during the last 180 ka. Recent arid/semiarid conditions on Lanzarote were the exception rather than the rule during the Late Quaternary, when most glacials and stadials had a positive hydrologic landscape budget than today. Nevertheless, our conclusions are tentative and further investigations are needed in order to understand the climate system of the northwest African area.

Acknowledgments

The work of the first author was funded for two years by a postgraduate grant from the Free State of Bavaria, Germany, supplied by the University of Bayreuth. Further financial support was given by Deutsche Forschungsgemeinschaft (project no. Zo 51/29-1).

We also thank Christian Zeeden (University of Utrecht, Netherlands) and the participants in the annual meeting of the “Research group desert margins Germany” that was held in February 2008 in Gießen/Germany for very fruitful discussions.

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Table

Table 1
General features of loess-like and palaeosol sediment layers from the Lanzarote vegas. Data taken from Suchodoletz et al. (2009b).

general properties	**loess-like layers**	**palaeosol sediments**
colour	reddish	yellowish-brownish
clay content (%)*	23-41	59-80
pH	7.6-8.2	6.6-8.2
vertic properties	-	+/++
iron-manganese concretions	+/++	-/+
secondary calcification	+/++	-/+
clay illuviation	-/+	+/++

-, No occurrence; +, slight/medium occurrence; ++, strong occurrence.
* Data only from Femés.

Figures

Figure 1

Overview of North Africa and surrounding areas. The position of Lanzarote is marked with a blank circle. Main atmospheric circulation systems (westerly winter cyclones, trade winds and African summer monsoon) are indicated by arrows with a continuous line, and the marine Canary Current is indicated by an arrow with a dashed line. The locations of palaeoclimatic studies that were compared with soil moisture proxies from Lanzarote are represented by filled circles with numbers. Round inset: Lanzarote, showing the locations of the studied sections: Femés, Teguise and Guatiza III.

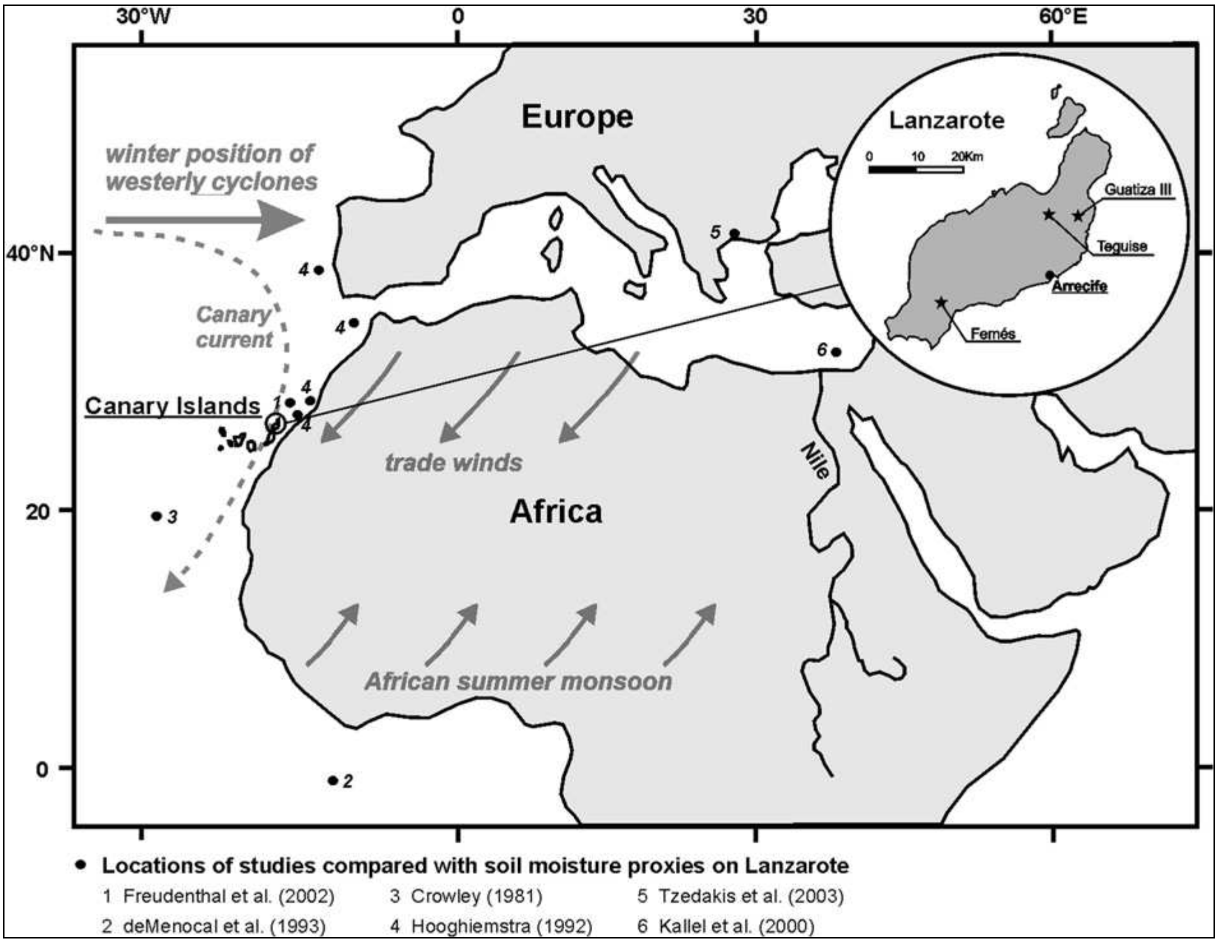

Figure 2

Correlation of Guatiza III, Femés and Teguise profiles with humidity proxies for clay content (a), magnetic frequency-dependent magnetic susceptibility (k_{fd}) (b), and luminescence dating. Clay content is given as the ratio (fraction< 6.18 µm)/(whole fraction < 42 µm) in arbitrary units, and frequency-dependent magnetic susceptibility is given in %.

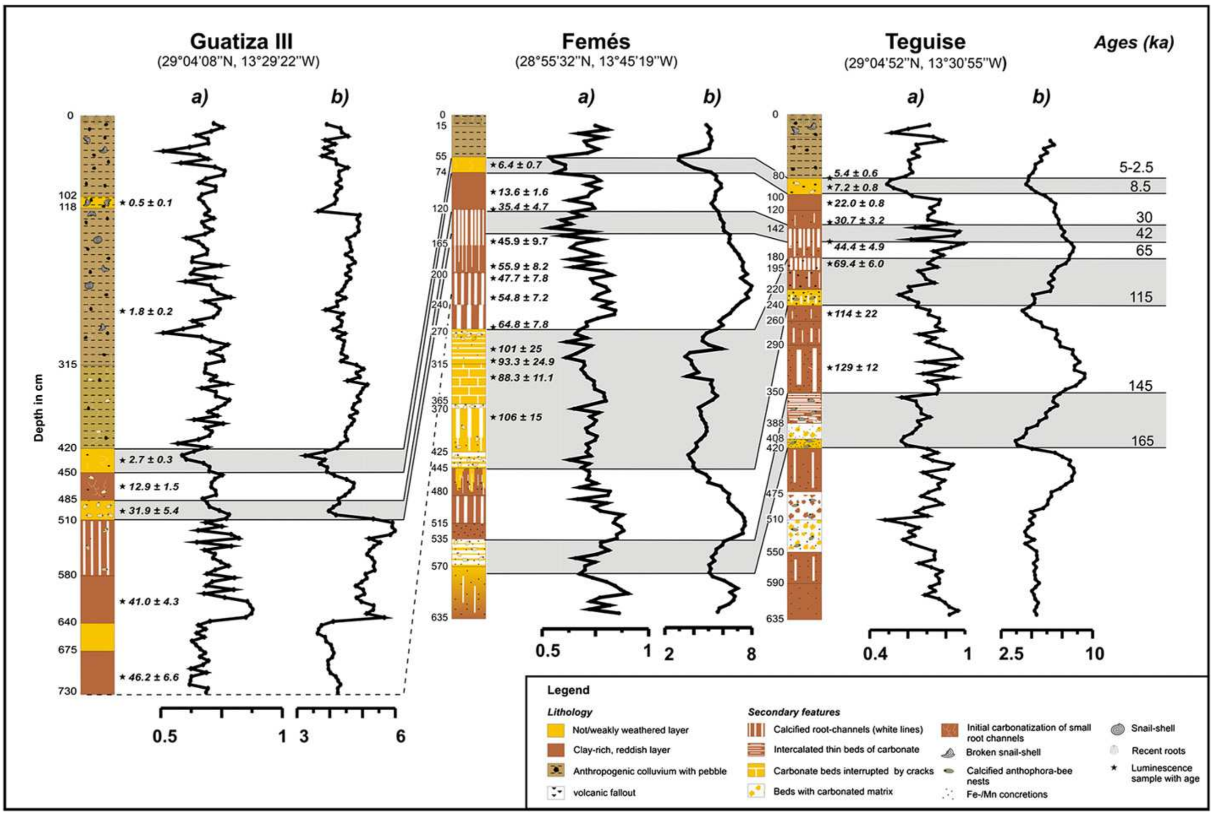

Figure 3

Proxies for soil moisture on Lanzarote, adapted to an absolute time scale and compared with the results of former palaeoclimatic studies from the Eastern Canary Islands. ^{14}C ages were calibrated using calpal-online. Dark grey layers indicate periods of enhanced soil moisture, middle grey layers indicate medium soil moisture and light layers indicate arid soil moisture regimes. MIS means marine isotope stage. 1) Meco and Pomel (1985); 2) Meco et al. (1997) + Damnati et al. (1996); 3) Coello et al. (1999); 4) Petit-Maire et al. (1994); 5) Rognon and Coudé-Gaussen (1987); 6) Rognon et al. (1989); 7) Rognon and Coudé-Gaussen (1996a); 8) Pomel et al. (1985); 9) Meco et al. (2002); 10) Hillaire-Marcel et al. (1995).

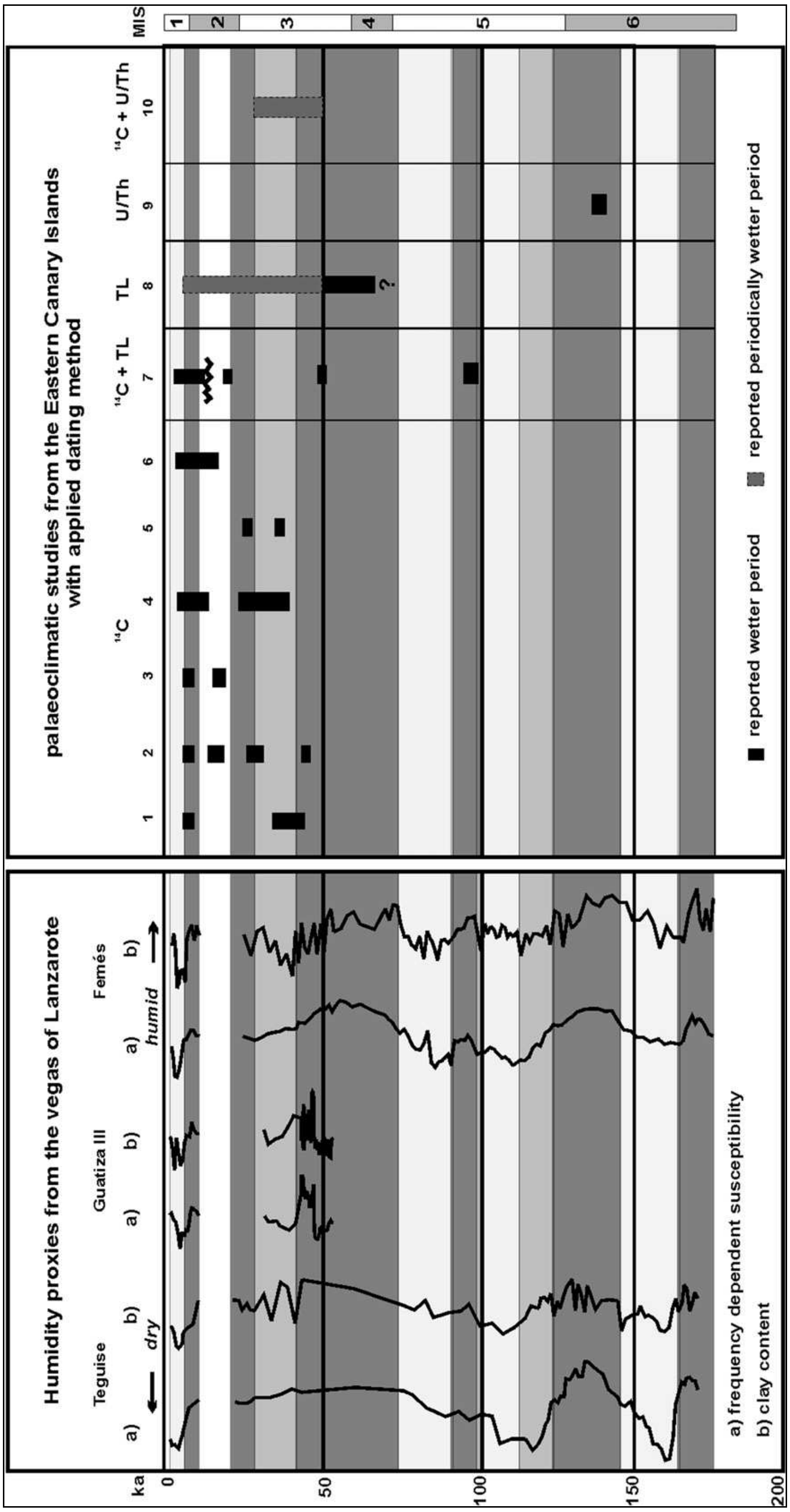

Figure 4

Proxies for soil moisture on Lanzarote, adapted to an absolute time scale and compared with the obliquity cycle and proxies from other palaeoclimate studies in the Mediterranean and northwest African areas. Note the inverse scale for the winter SST in the northeast Atlantic, which shows high values to the left. Dark grey layers indicate periods of enhanced soil moisture, middle grey layers indicate medium soil moisture and light layers indicate arid soil moisture regimes. MIS means marine isotope stage. 1) Zachos et al. (2001); 2) Freudenthal et al. (2002); 3) deMenocal et al. (1993); 4) Crowley (1981); 5) Hooghiemstra et al. (1992); 6) Tzedakis et al. (2003); 7) Kallel et al. (2000).

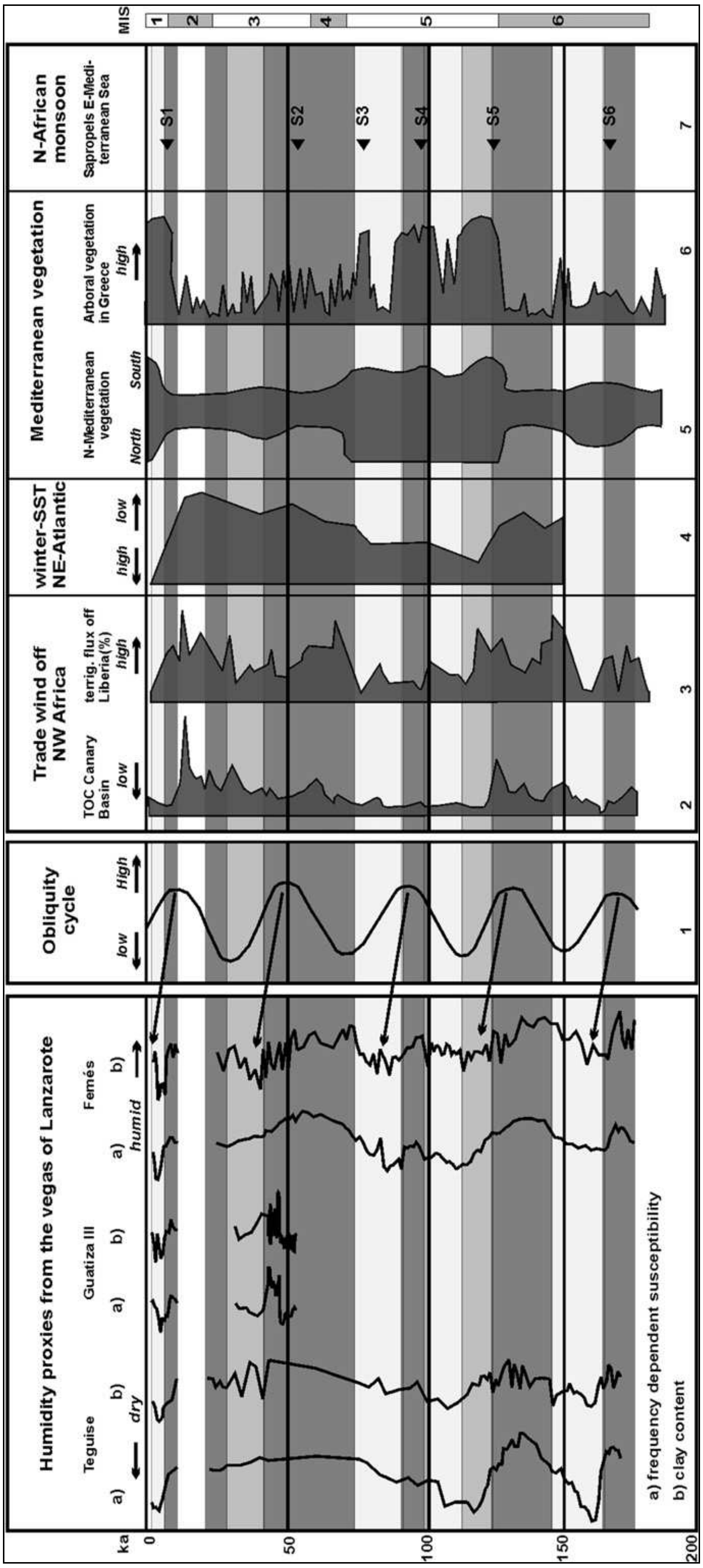

Figure 5

(a) Assumed shift of westerly cyclones during glacial periods as compared to the recent situation. (b) Two possible positions for the maximal northern influence of the African summer monsoon during warmer periods as compared to the recent situation.

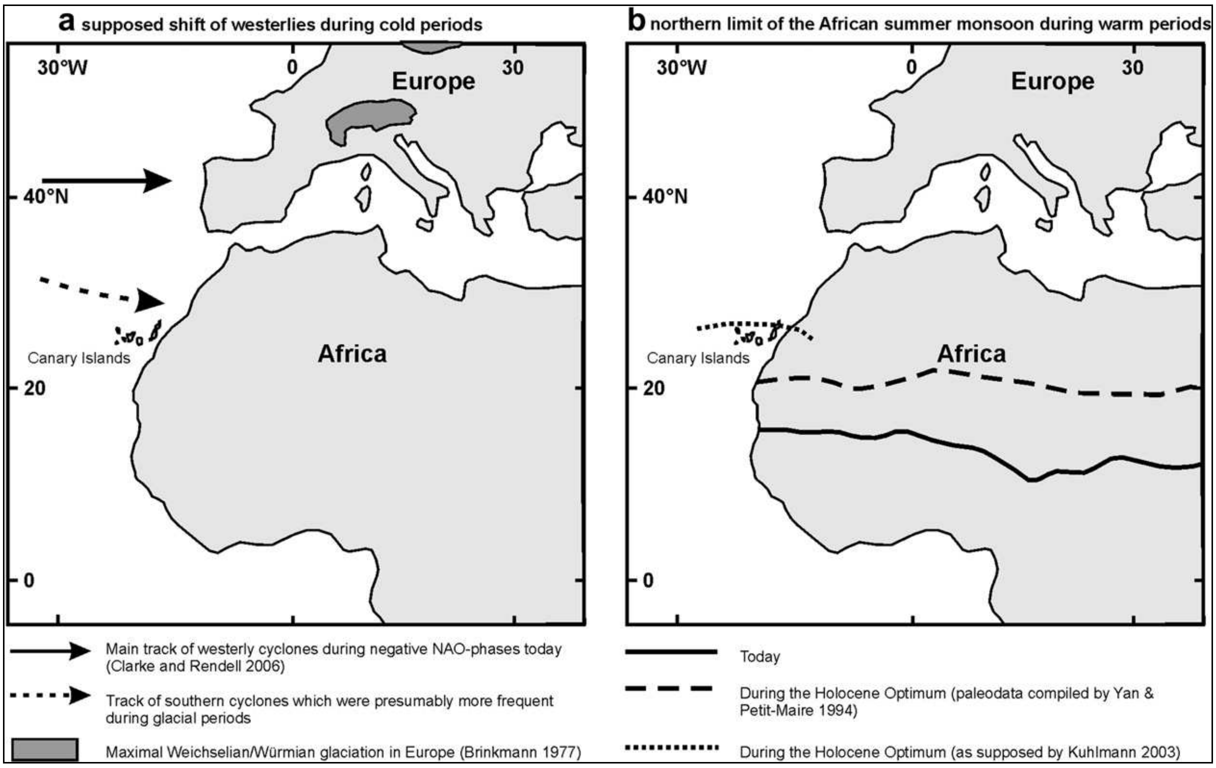

Figure 6

Above: Modern situation in the Lanzarote area, showing warmer SST and air temperature than glacial periods (below).