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ScienceDirect
Sedimentary Geology 202 (2007) 499–508
Sedimentary Geology
www.elsevier.com/locate/sedgeo

Variability in terrigenous sedimentation processes off northwest Africa and its relation to climate changes: Inferences from grain-size distributions of a Holocene marine sediment record

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Abstract

Variations in deposition of terrigenous fine sediments and their grain-size distributions from a high-resolution marine sediment record offshore northwest Africa (30°51.0′N; 10°16.1′W) document climate changes on the African continent during the Holocene. End-member grain-size distributions of the terrigenous silt fraction, which are related to fluvial and aeolian dust transport, indicate millennial-scale variability in the dominant transport processes at the investigation site off northwest Africa as well as recurring periods of dry conditions in northwest Africa during the Holocene. The terrigenous record from the subtropical North Atlantic reflects generally humid conditions before the Younger Dryas, during the early to mid-Holocene, as well as after 1.3 kyr BP. By contrast, continental runoff was reduced and arid conditions were prevalent at the beginning of the Younger Dryas and during the mid- and late Holocene. A comparison with high- and low-latitude Holocene climate records reveals a strong link between northwest African climate and Northern Hemisphere atmospheric circulation throughout the Holocene. Due to its proximal position, close to an ephemeral river system draining the Atlas Mountains as well as the adjacent Saharan desert, this detailed marine sediment record, which has a temporal resolution between 15 and 120 years, is ideally suited to enhance our understanding of ocean–continent–atmosphere interactions in African climates and the hydrological cycle of northern Africa after the last deglaciation.

Keywords: Aeolian dust; Climate; End-member model; Grain size; Holocene; Northwest Africa

1. Introduction

Hemipelagic sediments deposited on continental margins are important archives monitoring land–ocean interactions and their variability related to climate oscillations on various temporal and spatial scales. The terrigenous fraction of marine sediment records reflects the input of material produced on and discharged from continents, which is directly related to climate conditions in the hinterland.

For a long time, the Holocene climatic period was considered as a rather stable period in Earth history. However, many investigations provide evidence that the Holocene climate of the North Atlantic region exhibits variability on (sub-)millennial timescales (e.g. Bond et al., 1997). In addition, marine, terrestrial and limnological studies show evidence of large-amplitude changes in the hydrological cycle, particularly in the African tropics and subtropics but also in the Mediterranean realm during the last deglaciation (e.g. Roberts et al., 1993; Gasse, 2000;

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0037-0738/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.sedgeo.2007.03.015

deMenocal et al., 2000a; Stein, 2001; Swezey, 2001; Arz et al., 2003). Palaeohydrological changes in Africa, over the period for which radiocarbon dating is possible, appear to have been a complex alternation of wet and dry episodes with abrupt transitions (e.g. Gasse, 2000; deMenocal et al., 2000a). From about 10,000 to 4000 years ago, Neolithic civilizations flourished in a relatively humid and green Sahara, and land-locked lakes in northern East Africa extended tens or even hundreds of metres above their present level (Gasse, 2000).

Today, the Sahara Desert, one of the world's most important source regions for mineral dust formation (e.g. Harrison et al., 2001), represents a major source of terrigenous sediments. However, next to aeolian dust, there is another important source of terrigenous sediments deposited along the northwest African continental margin. A number of permanent and ephemeral rivers transport sediments derived from the hinterland of the Atlas Mountain range to the continental shelf off Morocco (see Fig. 1). This has recently been confirmed by studies which point to a fluvial contribution off northwest Africa (e.g. Holz et al., 2004; Kuhlmann et al., 2004). The total discharge of suspended sediment by northwest African rivers is estimated at 110 million tons per year (Hillier, 1995).

The modern climate of northwest Africa is dominated by two climate systems, the Mediterranean and the northwest African monsoonal climate systems, which are separated by the Saharan desert belt (Nicholson, 2000). South of ~20–24°N, summer monsoonal rains play a major role in subtropical African climate whereas north of this, precipitation is dominated by North Atlantic and Mediterranean winter rains (Knippertz et al., 2003). Therefore, gravity core GeoB 6007-2 (30°51.0′N, 10°16.1′W), which was retrieved during RV METEOR cruise M 45/5 (Neuer et al., 2000) at a water depth of 900 m (Fig. 1), was anticipated to have recorded variations in these winter rains and to be influenced by the North Atlantic climate (Kuhlmann et al., 2004). The sediment core was recovered from a region where hydroacoustic profiles indicate layered sediments and an undisturbed sediment cover (Neuer et al., 2000). Furthermore, the homogenous fine-grained sediment record does not show indications of gravity flow. With an average sedimentation rate of ~85 cm/kyr for the past 13.5 kyr, the marine sediment record reflects variability

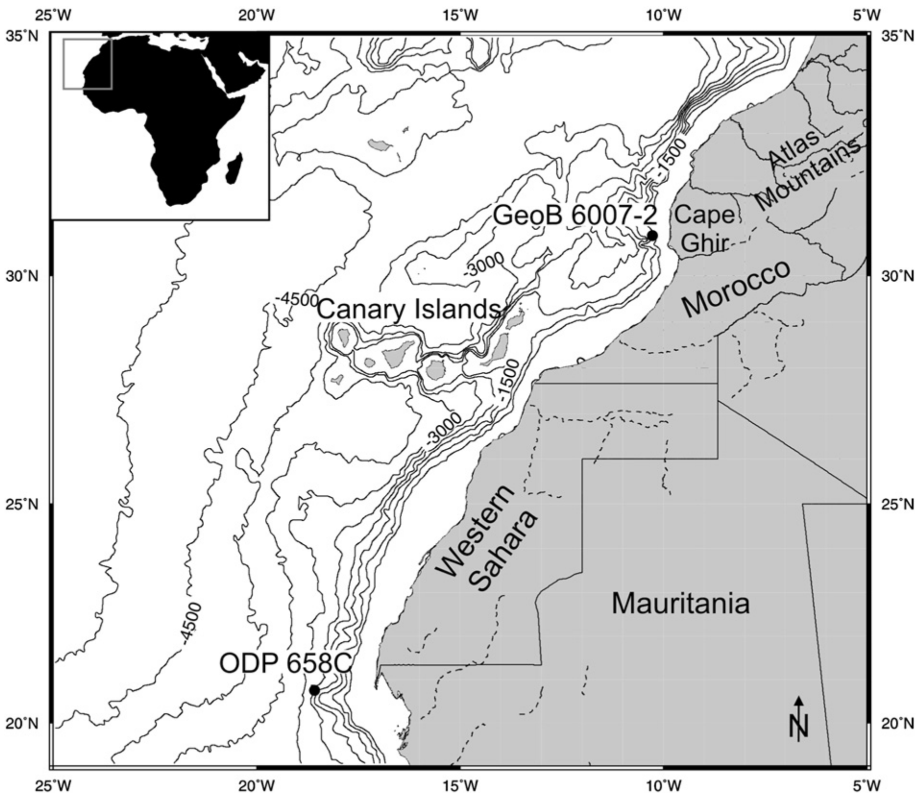

Fig. 1. Contour map (500 m) of the northwest African continental margin showing locations of site GeoB 6007-2 off Cape Ghir, Morocco, and of Ocean Drilling Program (ODP) Site 658C off Cape Blanc, Mauritania. All permanent and intermittent rivers of northwest Africa are indicated. The figure was created using Generic Mapping Tools (Wessel and Smith, 1991).

in terrigenous sedimentation off Cape Ghir and provides a continuous palaeoclimate record which reflects aridity/humidity changes in northwest Africa.

2. Methods

The age model for sediment core GeoB 6007-2 is based on 12 accelerator mass spectrometry (AMS) radiocarbon dates for the last 9 kyr BP (Kuhlmann et al., 2004), another seven AMS radiocarbon dates for the lower part of the record (from 9 to 13.5 kyr BP, Table 1), and linear interpolation between these dates. All ages used in this study are given as calendar years before present, kyr BP.

Biogenic silica contents are generally low in the sediments off northwest Africa (Koopmann, 1981). Thus, the carbonate-free fine fraction is considered here as the terrigenous fine fraction. In addition, the previous study by Koopmann (1981) on silt-sized sediments off northwest Africa indicates that biogenic silica is relatively uniformly distributed over the grain-size spectrum. The terrigenous content of the fine fraction (<63 μm) was determined by dissolving the carbonate fraction using 1 N HCl. Following several rinses in demineralised water, the sediment samples were washed until the pH was neutral. Grain-size distributions of the terrigenous fine fraction (<63 μm) between 0.63 and 63 μm were measured at 5-cm intervals for a high-resolution record of 221 samples using a Micromeritics SediGraph 5100. Weight percentages of 48 subpopulations for the grain sizes of the terrigenous fine fraction (0.63–63 μm) were calculated, resulting in various polymodal grain-size distributions.

Siliciclastic components in deep-sea sediments can be supplied by different transport processes from various sources, which may result in polymodal distributions. If so, recognition of the various source subpopulations and their interpretation in terms of sediment transport processes is very difficult, moment statistics (e.g. Folk and Ward, 1957) being often unable to distinguish these processes. Hence, an end-member modelling algorithm based on Weltje (1997) was applied to all grain-size distributions of the terrigenous fine fraction of the marine sediment core collected off Cape Ghir. This numerical–statistical algorithm aims to explain the variance in the dataset with discrete subpopulations, so-called grain-size end members. The contradictory requirements of a minimal number of end members and the best approximation of the variance in the dataset are met by calculating the coefficient of determination (r^2). The coefficient of determination represents the proportion of the variance of each grain-size class which can be reproduced by the approximated data. This proportion is equal to the squared correlation coefficient of input variables and their approximated values (Weltje, 1997; Prins and Weltje, 1999). The algorithm has been shown to be particularly suitable for the ‘unmixing’ of grain-size distributions into end members which can be related to different transport processes (e.g. Weltje, 1997; Prins and Weltje, 1999; Moreno et al., 2002; Stuut et al., 2002; Frenz et al., 2003).

3. Results

We employed the end-member modelling algorithm to describe the dataset of grain-size distributions from the marine sediment core collected offshore northwest Africa. The goodness-of-fit statistics for the 221 terrigenous grain-size distributions of the sediment record are shown in Fig. 2. For each size class, the coefficient of determination (r^2) is shown versus grain size for different end-member models ranging from two to ten end members (Fig. 2A). Moreover, the mean coefficients of determination (r^2) are plotted for each of these end-member models (Fig. 2B). The two-end-member model reveals low coefficients of determination ($r^2 < 0.6$) for grain sizes between 5 and 13 μm, and larger than ~25 μm. The three-end-member model ($r^2_{mean} = 0.77$) represents the grain-size spectrum up to ~35 μm with a coefficient of determination of more than 0.7. Evidently,

Table 1
AMS radiocarbon dates and calibrated ages for the lower part of sediment core GeoB 6007-2 from 9 to 13.5 kyr BP. For the age model, see also Kuhlmann et al. (2004)

Core depth (cm)	Lab. ID	Species	^{14}C ages	Error ±	Calibrated age	Calibrated age range
558	KIA16975	Mixed surf. dwelling	8630	40	9028	8982–9301
608	KIA16974	Mixed surf. dwelling	8855	45	9434	9100–9744
668	KIA20508	Mixed surf. dwelling	8980	55	9606	9450–9806
733	KIA16980	Mixed surf. dwelling	9660	45	10,312	10,279–10,579
838	KIA16979	Mixed surf. dwelling	9920	60	10,682	10,371–11,118
978	KIA16986	Mixed surf. dwelling	10,635	60	11,844	11,493–12,264
1048	KIA20528	Mixed surf. dwelling	11,095	60	12,735	12,325–12,859

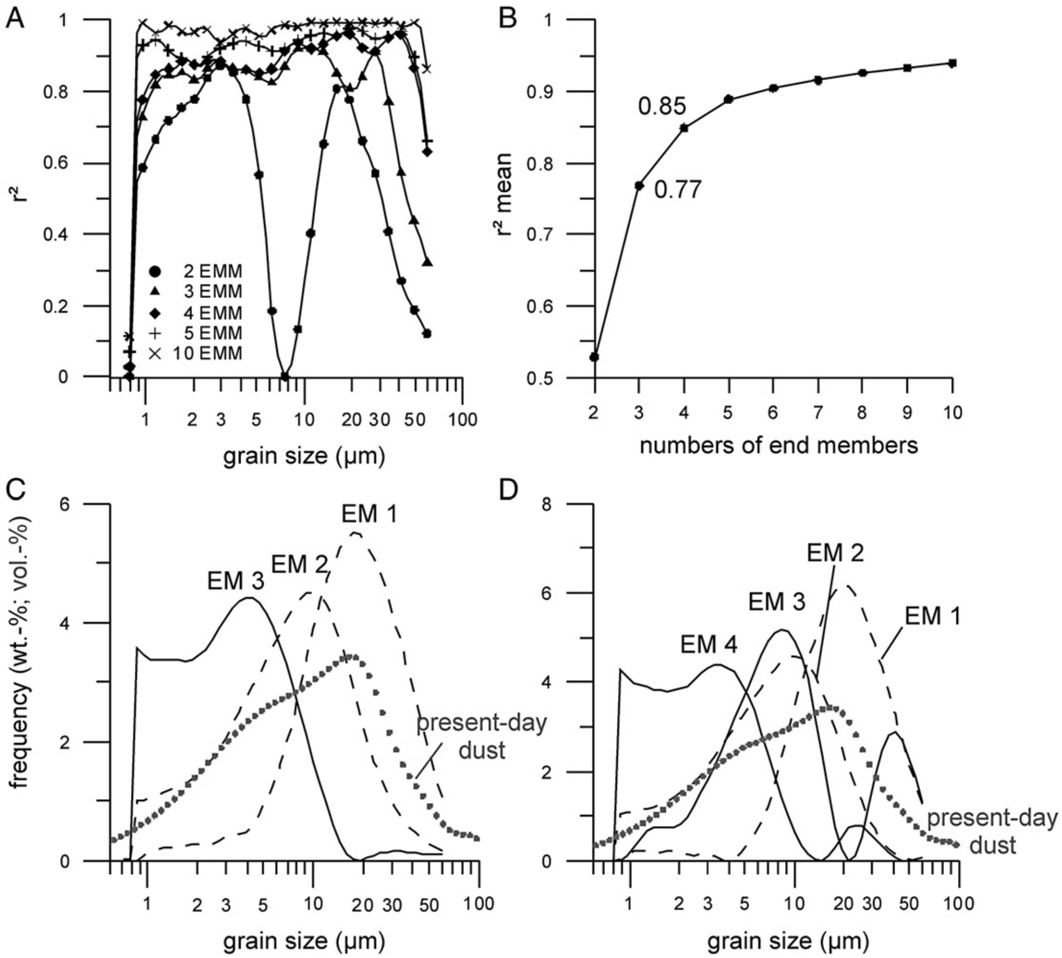

Fig. 2. End-member modelling results of 221 grain-size distributions for the high-sedimentation marine sediment core off Cape Ghir. A, Coefficients of determination (r^2) for each size class of two- to ten-end-member models. B, Mean coefficient of determination (r^2_{mean}) for the different end-member solutions. C, D, Modelled end members of the carbonate-free silt fraction of sediment core GeoB 6007-2 off Cape Ghir, compared with a grain-size distribution of aeolian dust collected off northwest Africa (Stuut et al., 2005). The sample collected offshore Morocco is plotted as dotted line. This modern dust sample was collected along a long transect between ~32°24′ and ~28°29′N, which might explain a small shoulder in the finer part of this distribution. In addition, adjacent dust samples collected south of this transect show unimodal distributions with generally finer modal grain sizes around 8 µm (cf. Stuut et al., 2005). Dashed lines represent aeolian end-member grain-size distributions; end-member grain-size spectra interpreted as fluvial mud are displayed as black lines.

the goodness of fit increases with growing number of end members. The four-end-member model reveals a better statistical fit with $r^2_{mean}=0.85$ but the shapes of the end-member grain-size distributions (EM 3 and EM 4) are bimodal (Fig. 2D), which makes them difficult to interpret in terms of sediment transport processes. Additionally, downcore relative proportions of the four end members do not reveal more details than the downcore relative proportions of the three-end-member model in terms of terrigenous variability and climate changes of the hinterland environment. Moreover, three end members are consistent with an end-member model of marine surface samples off northwest Africa (Holz et al., 2004) which includes a seabed sample recovered at the core site of this study.

The grain-size distributions of the three end members, illustrated in Fig. 2C, are all unimodal, well sorted, and have relatively fine modal grain sizes. Given the high sedimentation rates at the core site, each sample analysed represents at least several decades of accumulation, and probably thousands of dust transport events which have thoroughly been mixed together. Therefore, they can only be considered as a mixture. This mixture can be described by two end members, which represent the beginning and end process of a set of wind-depositional events, with its accompanying downwind decrease in the size of wind-blown material reflecting the downwind decrease in the transporting capacity of the wind. The coarsest end member (EM 1) has a clearly defined modal grain size of ~18 μm whereas EM 2 has a mode of ~10 μm. This is consistent with mean modal and median grain sizes of transported Saharan dust generally ranging between 5 and 30 μm in diameter (Goudie and Middleton, 2001). In addition, present-day aeolian dust, collected along a transect of the northwestern African coast between ~33°N and ~12°S, was shown to vary between 8 and 48 μm (Stuut et al., 2005). Although coarser wind-blown dust particles were identified offshore equatorial Africa, aeolian dust fallout off northwest Africa was shown to consist of rather fine-grained particles between 8 and 18 μm (Stuut et al., 2005). This observation fits nicely with the two coarser modelled end-member grain-size distributions (EM 1 and EM 2) of this study, although initial grain-size distributions of soils in the source regions might be different (Alfaro and Gomes, 2001). Results obtained from a dust production model illustrate that aerosols smaller than 20 μm are releases from coarser soil aggregates and that, in addition to the effects of the dry size distribution of the aggregates and the roughness length, the release of these particles depends also on the wind velocity (Alfaro and Gomes, 2001). Smaller grain sizes are generally produced at increasing wind friction velocities (Alfaro and Gomes, 2001). Consequently, and in accordance with our studies of seabed samples along the northwest African continental margin (Holz et al., 2004), we interpret the coarsest two end members as the beginning and end process of aeolian deposition and label them 'coarse' and 'fine' aeolian dust. Obviously, the size of wind-blown sediments depends predominantly on the source-to-sink distance. Distal dust is very fine grained and, especially when the result of wet deposition, it usually is finer-grained than hemipelagic mud (e.g. Rea, 1994; Rea and Hovan, 1995). However, in our case of a relatively short source-to-sink distance, the wind-blown sediment fraction is much coarser than the sediment fraction supplied by rivers. As a result, we interpret the coarsest two end members as aeolian dust, and the finest end member (EM 3), which has a modal grain size of about 4 μm, to result predominantly from fluvial input (Koopmann, 1979, 1981; Holz et al., 2004).

Keeping the high sedimentation rates at the core site in mind, one might expect a much more prominent fluvial discharge. An alternative interpretation could therefore potentially come from the four-end-member model, where the fluvial component would be split up into a 'fine' and a 'coarse' fluvial end member. Indeed, in the four-end-member model, the finest end member (the fluvial end member, EM 3 of the three-end-member model) is split up into two end members (Fig. 2D, EM 3 and EM 4). However, the extra end member (EM 3 in the four-end-member model) is bimodal (Fig. 2D) and therefore difficult to explain in terms of transport processes. It is predominantly used in the model to describe the variance in the coarser part of the grain-size spectrum (Fig. 3A). Moreover, the finest end member in the four-end-member model has a stronger bimodality than the finest end member in the three-end-member model, which shows that the model attempts to describe 'noise' in the dataset. Besides, the positions of the modes of the end members in the three- and four-end-member models hardly change. We therefore argue that the three-end-member model satisfactorily describes the variance in the dataset while meeting the contradictory requirements of parsimony (Weltje, 1997; Prins and Weltje, 1999). The downcore proportion of the fluvial end member (EM 3) varies from 0 to 61% (Fig. 3A), which explains the high sedimentation rates in this core.

The relative contributions of the end-member grain-size distributions, their ratios and the proportion of the aeolian end members can be used as proxies for wind intensity and continental aridity (cf. Stuut et al., 2002), although one has to be aware that seasonal changes in wind intensities and, therefore, dust transport at different altitude levels exist (cf. Ratmeyer et al., 1999), an aspect not a focus of this study. As mentioned above, each sediment sample analysed represents at least several decades of accumulation, and thus various dust transport events and seasonal cycles. The temporal variation of these proxies is shown in Fig. 3.

Generally, these records vary on sub-millennial timescales (Fig. 3). If the interpretation of the three-end-member model is correct, there is an abrupt change within the two aeolian records and therefore a probable change within the wind intensity around 12.7–12.4 kyr BP. The contribution of coarse aeolian particles is strongly reduced around this time whereas the supply of fine aeolian particles is intensified (Fig. 3A). This rapid change in the aeolian fraction is not reflected in the finest end-member record (EM 3), i.e. in the fluvial supply. The latter shows a relatively continuous decrease from the end of the record until ca. 11.5 kyr BP, followed by a slow but steady increase in continental runoff until the mid-Holocene (Fig. 3A). Moreover, Fig. 3A displays a generally reduced fluvial supply during the mid-Holocene, with one minimum of EM 3 at about 6.6–6.1 and another at ca. 5.5–5.2 kyr BP, followed by increasing fluvial input until ca. 3.5 kyr BP. Prior to very high proportions of fluvially discharged mud during the last 1.3 kyr BP, fluvial supply is slightly

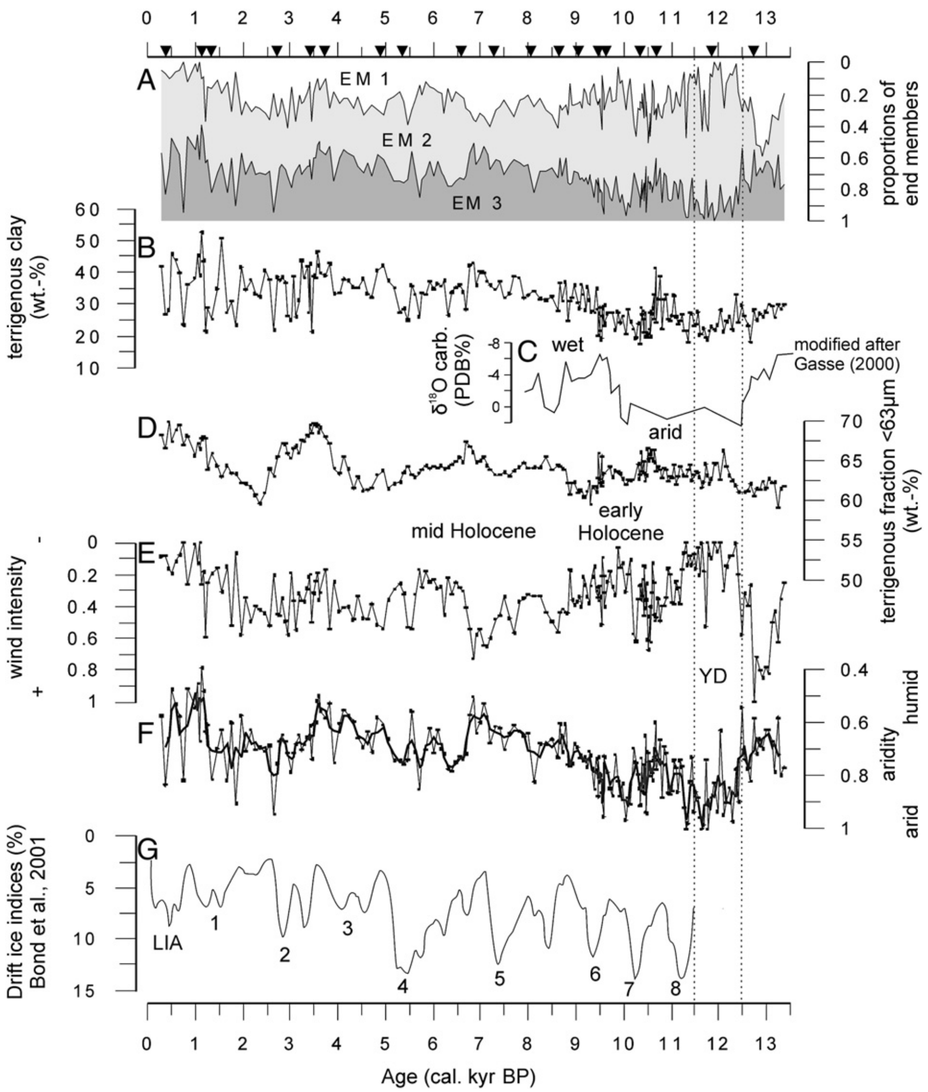

Fig. 3. Terrigenous fine sediments and their end-member grain-size distributions offshore Cape Ghir during the past 13.5 kyr BP (radiocarbon ages are indicated by filled arrows). A: Downcore proportions of end members. EM 1 and EM 2 represent coarse-grained and fine-grained aeolian dust respectively; EM 3 represents fluvially discharged mud in sediment core GeoB 6007-2 off Cape Ghir. B: Variability in the supply of terrigenous clays (wt.%) in core GeoB 6007-2. C: Changes in ^{18}O content of authigenic carbonates of lake sediments from the northern margins of the Sahara (modified after Gasse, 2000). High values reflect arid, and low values reflect wet intervals. D: Variability in the supply of terrigenous fine sediments (wt.%) in core GeoB 6007-2. Ratios of the end-member contributions and the proportion of the aeolian end members are used as proxies for wind intensity (E), and continental aridity (F) of Holocene northern Africa. A three-point running average in aridity is also shown. G: Periods of enhanced ice drift reconstructed from ice-rafted debris of a stacked record of Holocene marine sediment cores of the subpolar North Atlantic Ocean (Bond et al., 2001).

reduced. A similar variability is shown in the terrigenous clay record (Fig. 3B), which also indicates fluvial supply of finest sediments to the ocean. However, the record of the bulk terrigenous fine fraction (Fig. 3D) does not reflect this millennial-scale variability during the Holocene, which emphasises the importance of distinguishing between the different transport processes of the terrigenous sediments. The proportion of the aeolian end members, an indicator for continental aridity/humidity, documents rapid and large-amplitude shifts during the Holocene. These abrupt dry episodes in the northwest African climate, recorded at about 11.3, 10.2, 9.6, 8.1, 5.7, 3.9, 2.7, 1.8, 0.8 and 0.4 kyr BP (Fig. 3F), are superimposed upon a generally humid early to mid-Holocene interval.

4. Discussion

Climate in northwest Africa during the early to mid-Holocene was characterized by generally humid conditions, and the presently arid Saharan desert was largely vegetated (e.g. Jolly et al., 1998). Relatively humid conditions are in general reconstituted for the period ca. 9 to 6 kyr BP (Ritchie et al., 1985; Roberts, 1998), although they were shown to have initially started around 14.5 kyr BP (Gasse, 2000; deMenocal et al., 2000a) and to have been punctuated by a brief return to much more arid conditions during the Younger Dryas event (Gasse and Van Campo, 1994).

The high-resolution marine sediment record of the past 13.5 kyr BP is one of the few undisturbed continuous Holocene records retrieved from the subtropical oceans off northwest Africa. The record documents variations in terrigenous sediment deposition off the Moroccan continental margin and is very sensitive to climate changes on the African continent. At present, the core site is located under the prevailing Saharan dust path but it also records seasonally discharged fluvial mud, often supplied in the form of melt water flows from the Atlas Mountains. Hence, this core is particularly well suited for a reconstruction of continental aridity/humidity in northwest Africa during the Holocene.

Besides abrupt changes in the grain-size end-member records, clear millennial-scale variability can also be observed in the terrigenous sediment supply to the North Atlantic Ocean off Morocco (Fig. 3). The conspicuous, abrupt shift within the end-member records around 12.5 kyr BP coincides with the onset of the Younger Dryas (Broecker et al., 1988; Litt et al., 2003). General transport of aeolian dust particles (EM 1 and EM 2) is strongly increased, although the high proportions of EM 1 are restricted to events of increased wind strength. Moreover, during the Younger Dryas with its prevalent drier and cooler conditions, continental runoff (EM 3) is reduced and therefore continental aridity in the hinterland is increased.

Whereas the variability in the terrigenous fine fraction is relatively low during the early to mid-Holocene, the continental runoff (EM 3 and terrigenous clay fraction) increases contemporaneously (Fig. 3). This implies a general decrease in dust formation, possibly due to a consolidated vegetation cover and a successive increase in continental runoff, which supports the hypothesis of humid conditions in northwest Africa during early to mid-Holocene times. This pattern of prevalent humid climate conditions correlates with episodes of higher water levels in African lakes and palaeohydrological data from the African winter-rain domain (e.g. Gasse, 2000). Sediment core GeoB 6007-2 recovered off Morocco documents an abrupt increase in humidity from around 11.5–11 kyr BP. This period is also known as the second dramatic arid-humid transition after the last deglacial period in equatorial Africa, which is influenced by the monsoonal climate system, as well as northern Africa (Gasse, 2000), which is dominated by North Atlantic climate (Knippertz et al., 2003). Moreover, the generally humid climate conditions in northern Africa from 11–10 to ~3.5 kyr BP, with its slowly increasing continental runoff interrupted by short dry episodes, are clearly reflected by the fluctuations in terrigenous supply off Morocco (Fig. 3). These results are consistent with palaeohydrological inland records; Gasse (2000) describes the mid-Holocene of monsoonal West Africa as a phase of maximum wetness around 8–7.5 to 4 kyr BP, whereas Ritchie et al. (1985) and Roberts (1998) define the African Humid Period as occurring between ca. 9 and 6 kyr BP. In western Fezzan (Libyan Sahara), a relatively wet savannah landscape interspersed between the mountains, and the development of shallow lakes in the ergs have been described from ca. 10 to 6 kyr, while a dry period interrupted this wet interval at 8.5–8.0 kyr (Cremaschi and Di Lernia, 1998). Moreover, during the early to mid-Holocene, permanent lakes emerged along the northern margin of the Sahara. Changes in the ^{18}O content of authigenic carbonates in lake sediments from the northern margins of the Sahara (Sebkha Mellala, Algeria) indicate two freshwater lacustrine episodes between 10.3 and 5.7 kyr, separated by a dry phase at ca. 8.5–8.0 kyr (Gasse et al., 1990). However, the onshore records have to be viewed with some caution because not all Holocene climate proxy records are in agreement with each other. Cheddadi et al. (1998), for example, show a high-resolution climate reconstruction from a pollen record retrieved from a small lake from the Middle Atlas Mountains, with a high-frequency variability throughout the Holocene but with a timing of wet and dry periods which matches neither that from other onshore studies nor our results from the marine sediment archive. This discrepancy could be explained by, for instance, local vegetation effects in the mountainous landscape. Since our record is from the ocean, and sediments are derived from both the Atlas Mountains and the Saharan desert, we argue that the variability observed in our records is more representative of regional climate variations. In addition, based on grain-size spectra of marine sediments from the northern Red Sea, the termination of the humid phase, at least for the eastern Sahara, is established around 6.25 kyr BP (Arz et al., 2003).

Superimposed upon the generally humid early to mid-Holocene interval, our aridity/humidity record clearly documents a millennial-scale variability of recurring, abrupt dry episodes in the northwest African climate (Fig. 3F). Besides, the 8.2-kyr cold event, which is widely documented around the North Atlantic region, and the most recent dry phase representing the Little Ice Age (LIA) are recorded off Morocco as well (Fig. 3). In general, these short-term periods of rapidly reduced continental runoff match with Holocene climate changes described for high as well as low latitudes (e.g. Bond et al., 1997; deMenocal et al., 2000b; Zöller et al., 2003).

Based on foraminiferal faunal sea surface temperature (SST) reconstructions, deMenocal et al. (2000b) showed evidence for cold events and high trade wind activity off West Africa during early to mid-Holocene times. Still, this record off West Africa is strongly influenced by the African monsoon whereas our record from offshore Cape Ghir is dominated rather by the North Atlantic climate system (Knippertz et al., 2003).

Kuhlmann et al. (2004) argue that, during the Holocene, the northern part of northwest Africa (north of 27°N) was possibly dominated by the North Atlantic climate whereas the region south of 27°N was dominated by the monsoonal climate system throughout the Holocene. Their reconstruction was based on the assumption that the chemical element potassium (K) found in two sediment cores, one off Morocco and the other off Mauritania, can be taken as a proxy for bulk terrigenous sediments. In an area where the terrigenous sediment fraction so clearly contains a dominant wind-blown portion, however, one evidently needs to distinguish between fluvial and aeolian sediments. On the basis of the grain-size distributions of the terrigenous fine fraction which originates ultimately from both the Atlas Mountains and the Saharan desert, we are able to 'zoom in' on the terrigenous sediment fraction, quantitatively distinguish between wind-blown dust and fluvial sediments, and express these in terms of humidity in the source regions of the sediments. As the precipitation in north-western Morocco shows a clear link to the baroclinic activity over the North Atlantic during the boreal winter (Knippertz et al., 2003), we hypothesize that our record can be compared to proxy records from the high latitudes in the Northern Hemisphere. Therefore, we compare the continental aridity of northwest Africa (Fig. 3F) with a drift-ice record of marine sediment cores from the subpolar North Atlantic (Bond et al., 2001; Fig. 3G) representing Holocene climate variability on centennial to millennial timescales. Bond et al. (2001) suggest variations in solar irradiance to be the primary forcing mechanism of these centennial to millennial timescale changes in Holocene climate, and do not preclude that solar forcing may excite atmospheric variability. The comparison of enhanced ice drift in the North Atlantic (Fig. 3G) with dry episodes in northwest African climate (Fig. 3F) reveals a possible correlation between subpolar North Atlantic climate and continental aridity in northwest Africa, especially for the early and late Holocene. A possible correlation between the drift-ice cycles (Bond et al., 2001) and Holocene dry events in northwest Africa is also indicated for the mid-Holocene, although a clear recognition of drift-ice cycle 4 and 5 is difficult in the aridity record.

Risebrobakken et al. (2003) suggest more pervasive strong westerlies during early and mid-Holocene as result of a stronger influence of Arctic water, which was observed from a combined isotope and foraminiferal record of the Nordic Seas. Furthermore, during this time interval a reconstruction of mean winter precipitation in western Norway indicates increased winter precipitation (Nesje et al., 2000), which can also be attributed to a stronger westerly circulation. Based on an atmospheric general circulation model, Harrison et al. (1992) have shown that, during the early and mid-Holocene, the Icelandic Low and the westerly jet stream were displaced further north, producing mild and wet winters in northern Europe. All these signals of high and low latitudes are similar to a positive North Atlantic Oscillation (NAO) situation, which is characterized by stormy conditions over the North Atlantic Ocean, wet but warm conditions in northern Europe and cold, dry conditions in the Mediterranean region (Hurrell et al., 2003). In the present study, the millennial-scale variability in terrigenous sediment supply (aeolian versus fluvial sediments) off Morocco indicates recurring dry conditions also for northwest Africa during the Holocene. Therefore, we suggest an influence of intensified westerlies on northwest African climate throughout the Holocene. A possible link between northwest African climate variability and decadal NAO-like situations can only be suggested, since our sediment core is restricted in its temporal resolution.

5. Conclusions

This study provides a comparison of a marine sediment record close to an ephemeral river system draining the Atlas Mountains with several inland records as well as high- and low-latitude marine records to understand ocean–continent–atmosphere interactions in African palaeoclimates and the hydrological cycle of northern Africa during the last deglaciation. As it was shown in onshore records of northwest African Holocene climate change, we demonstrate from the marine sediment archive that the northern African continent has experienced rapid hydrological changes throughout the

Holocene. Because the precipitation in the source region of the sediments is dominated by winter rains, ultimately constrained by North Atlantic climate variability, we hypothesize that the northwest African climate can be related to high-latitude Northern Hemisphere climate changes. From observed variability in terrigenous supply, we infer an alternation of dry and wet episodes in the African hinterland during the last 13.5 kyr. We demonstrate that the phases of maximum wet or dry events recognized in the continuous high-resolution offshore record coincide with established onshore datasets of northern Africa. Furthermore, we speculate that millennial-scale recurring NAO-like situations influenced the northwest African hydrological cycle during the Holocene.

Acknowledgements

We thank the crew onboard the RV METEOR during cruise M 45/5 in 1999. Gert Jan Weltje is thanked for providing the end-member algorithm. Data are available at http://www.pangaea.de. The manuscript benefited from the reviews of three anonymous referees. This is publication RCOM0391. The work was funded by the Deutsche Forschungsgemeinschaft as part of the DFG-Research Center 'Ocean Margins' of the University of Bremen.

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