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Climatic changes along the northwestern African continental margin over the last 30 kyrs

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Abstract. Two sediment cores were investigated to study the regional climatic variability of the NW African upwelling over the late Quaternary. Biomarker data and Sea Surface Temperatures (SSTs) predicted from alkenones at 25°N and 21°N exhibited distinct features. The amplitude of the last deglaciation was estimated to 4.5°C at 25°N and 2-2.5°C at 21°N. At 25°N, terrestrial and marine glacial inputs were higher than Holocene ones as a result of a strengthening of the trade winds and intensification of oceanic production. In contrast, at 21°N, warmer SSTs and lower organic carbon and alkenone productions during the last glacial suggest a regression of the upwelling and therefore a change of wind regime. Low glacial *n*-alkanols are consistent with the migration of the vegetation belt during the maximum of African aridity, while their decrease towards the core-top may be indicative of anthropogenic disturbances.

Introduction

The Mauritanian continental margin is one of the five major and persistent coastal upwelling regions of the world's ocean, today. This coastal upwelling is driven by northeast trade winds blowing longshore (Figure 1a). The most intense upwelling cells today occur off Cape Blanc giving rise to high productivity and high sedimentation rates of up to 20 cm kyrs⁻¹ and organic carbon (OC) content up to 2% [Ruddiman *et al.*, 1988]. The wind-driven Canary Current, which carries cold waters to the South, is another hydrological component of the oceanic circulation pattern along NW Africa. More intense upwelling and a stronger Canary Current occur when trade winds are at their maximum intensity. Mid-tropospheric easterlies also contribute to dust outbreaks at the continental margin. Therefore, the sedimentary history of the NW African margin is thought to be mainly linked to past changes of the wind regime. Earlier studies in this region have shown enhanced intensity of the trades winds during the last glacial period [Sarnthein *et al.*, 1981; Hooghiemstra, 1988] promoting higher coastal upwelling and productivity as compared to the Holocene [Müller and Suess, 1979; Müller *et al.*, 1983; Bertrand *et al.*, 1996]. However, because of the lack of detailed sedimentary records, it is still not known how the intensity and spatial pattern of the upwelling circulation have been affected by the atmospheric circulation along this

margin, over the Late Quaternary. In this respect, the two sites studied here, which are separated by about 5° of latitude, provide an opportunity to study regional variations of OC accumulation off NW Africa. One core (SU94-20bK) was taken at 25°01'N, 16°39'W, at a water depth of 1445 m off Cape Bojador. A second one (SU94-11K) was recovered from a water depth of 1200 m at 21°29'N, 17°57'W, offshore Cape Blanc (Figure 1a). Both cores were collected, during the Sedorqua cruise, in March 1994, aboard the R/V *Le Suroit*. For this study, sea surface temperatures (SSTs) were derived from the alkenone U_{37}^K index to characterize cold upwelled waters while abundances of target biomarkers were used to assess ocean production and terrigenous supply. Previous papers have shown that sedimentary records of biomarkers other than alkenones provide valuable information to the understanding of climatic changes [Prah *et al.*, 1989; Madureira *et al.*, 1997; Villanueva *et al.*, 1998a]. Therefore, high molecular weight *n*-alkanols, in the C₂₀ - C₃₂ range, produced by higher plants were considered here for the description of long-term variations of the trade wind system. These compounds have shown longevity during aeolian transport and durability in soils and have been used successfully as terrigenous indicators [Gagosian, 1986; Gagosian and Peltzer, 1986; Gagosian *et al.*, 1987]. Alkenones, which are biosynthesized mainly by the marine coccolithophorids *Emiliania huxleyi*, have been used to assess past changes of the planktonic production [Rostek *et al.*, 1997; Villanueva *et al.*, 1998b].

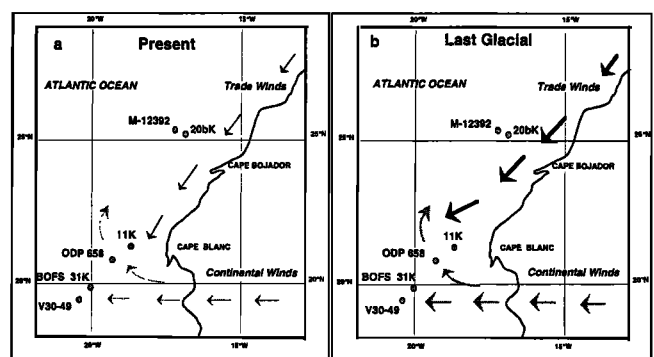


Figure 1. Maps showing the locations of cores SU94-20bK, SU94-11K (this study) and cores from previous studies: M-12392, ODP 658, BOFS 31K and V30-49 off NW Africa. (a) Present day wind circulation. (b) Schematic view of the wind circulation proposed for the last glacial period. Thick arrows indicate stronger winds.

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Sampling and Methods

Freeze-dried sediments were extracted for lipids by solvent extraction in an ultrasonic bath. The two first extractions were performed with $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{OH}$ (2:1, v/v) and the third one with pure CH_3OH . Lipids were fractionated into compound classes by silica gel chromatography [Ternois *et al.*, 1997]. Alkenones were analyzed on a Delsi DI 200 gas chromatograph equipped with a fused CP-Sil-5 silica capillary column (50 m x 0.32 mm i.d.) (J&W Scientific) and a flame ionization detector. Helium was used as carrier gas. The oven temperature was programmed from 100°C to 300°C at 10°C min⁻¹. Injections were repeated three times. Analytical precision obtained for U_{37}^K ratios after triplicate injections was calculated to be 0.01 unit ratio. *n*-Alkanols were treated with bis(trimethylsilyl)-trifluoroacetamide (BSTFA) in 1% trimethylchlorosilane (TMCS). TMS derivatives were analyzed on a fused silica capillary column (30 m x 0.32 mm i.d., DB5, J&W Scientific) with a temperature program from 60°C to 300°C at heating rate of 7°C.min⁻¹. Quantitation of individual *n*-alkanol and alkenones was achieved by comparison of chromatographic peak areas with α -cholestane added prior injection. Oxygen isotope analyses were performed on planktonic foraminifera *Globigerina bulloides* (>250 μm) on a Finnigan 251 mass spectrometer calibrated in PDB via NBS19. External precision was $\pm 0.07\text{‰}$ $\delta^{18}\text{O}$ (1 sigma value). The $\delta^{18}\text{O}$ chronology was obtained by correlation with the SPECMAP stacked $\delta^{18}\text{O}$ record of Martinson *et al.* [1987]. Mass Accumulation Rates (MAR) were calculated as previously described by Van Andel *et al.* [1975], based on measurements of physical properties, such as wet bulk density, porosity, linear sedimentation rates and biomarker concentrations.

Results and Discussion

Stage boundaries were obtained from the $\delta^{18}\text{O}$ curves shown in Figures 2a (SU94-20bK) and 3a (SU94-11K). SSTs were predicted from U_{37}^K index of alkenones and the calibration published by Prahl *et al.* [1988]. Figures 2b and 3b show the fluctuations of SSTs over the last 30 kyrs for the two cores.

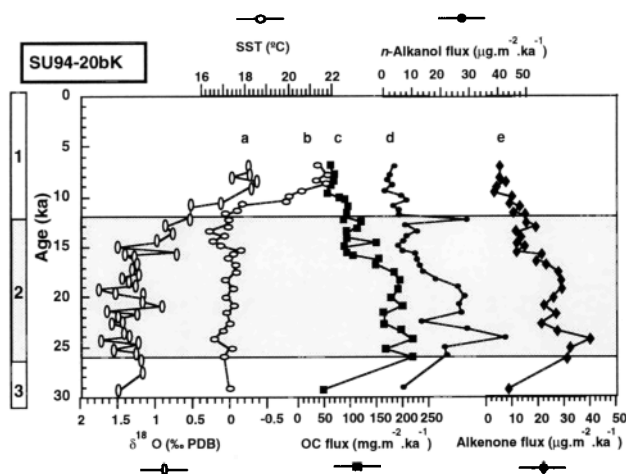


Figure 2. $\delta^{18}\text{O}$, SSTs, Mass Accumulation Rates (MAR) of OC and biomarker alkenones and *n*-alkanol along core SU94-20bK as a function of ^{14}C age, in kyrs. $\delta^{18}\text{O}$ curves were obtained from the planktonic foraminifera *Globigerina bulloides* (>250 μm). SSTs were derived from the U_{37}^K index and the calibration established by Prahl *et al.* [1988].

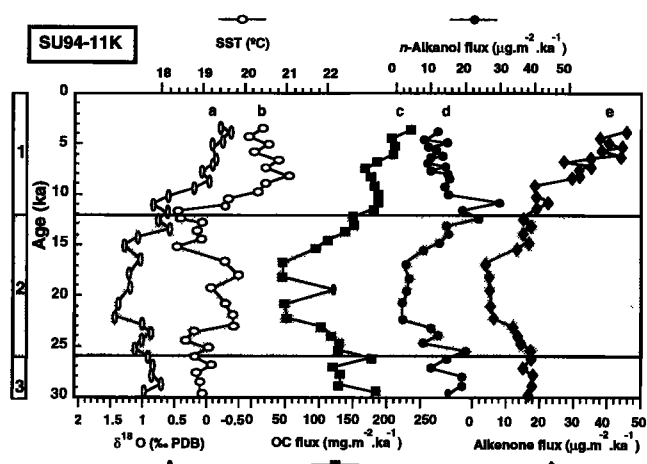


Figure 3. $\delta^{18}\text{O}$, SSTs, Mass Accumulation Rates (MAR) of OC and biomarker alkenones and *n*-alkanol along core SU94-11K as a function of ^{14}C age, in kyrs. $\delta^{18}\text{O}$ curves were obtained from the planktonic foraminifera *Globigerina bulloides* (>250 μm). SSTs were derived from the U_{37}^K index and the calibration established by Prahl *et al.* [1988].

The amplitude of the last deglaciation is about 4.5°C at 25°N (SU94-20bK) and 2-2.5°C at 21°N (SU94-11K). At 25°N, SSTs values vary from 21.8°C during the Holocene to average glacial values of 17.4°C with two minima of ~16.5°C. Along core SU94-11K (21°N), Holocene SSTs fluctuate from 21°C to mean glacial values of about 19°C with two minima of ~18.5°C. In the lower latitude core, SSTs were generally warmer except over the last 10 kyrs where they become cooler than at 25°N. U_{37}^K values measured at the sediment interface at both sites also show that, at present time, SST at 21°N (20.3°C) is slightly lower than that recorded at 25°N (20.9°C). This result may be ascribed to active upwelling cells off Cape Blanc. This interpretation is further supported by the OC content of these sediments which indicates values of 0.74% at 25°N and 2.92% at 21°N. Detailed examination of SSTs records identifies a warming of the surface waters between 24 to 15 kyrs of more than 1°C. Zhao *et al.* [1995] also reported an overall warming over the same time interval in two nearby cores 658C (20°45'N, 18°35'W) and BOFS 31K (19°00'N, 20°10'W). These authors found SSTs values similar to ours, ranging from 18°C during the last glacial to 21.5°C during early Holocene.

We then examined the variability of the OC content of the sediments to see the effect of climatic and oceanic circulation changes over OC production. The organic matter off NW Africa today is mostly marine [Summerhayes, 1983]. Maximum values of annual primary productivity at present time are higher off Cape Blanc (325 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$) than off Cape Bojador (200 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$) [Fütterer, 1983]. At 25°N, OC MAR vary from low values 30 kyrs ago to higher ones during the last glacial period followed by a decline towards the Holocene (Figure 2c). Stable carbon isotope data in the nearby site M-12392 (25°10'N, 16°51'W) indicate that enhanced glacial OC is primarily the result of higher productivity and not a larger supply of terrestrial carbon [Müller *et al.*, 1983]. Higher oceanic productivity of the glacial ocean is generally attributed to increased coastal upwelling as well as stronger mixing in response to stronger winds and currents. In contrast, OC MAR at 21°N reveal higher OC accumulation in Holocene than in

glacial sediments (Figure 3c). Lower glacial production and warmer SSTs between 24 and 15 kyrs suggest a decline of the upwelling intensity at this site.

Biomarkers were investigated to study the organic fraction by distinguishing between marine and terrestrial components in more detail. Alkenone MAR profiles in both cores show fluctuations similar to OC. While they are higher in the glacial than in the Holocene sediments at SU94-20bK (Figure 2e), they show the opposite trends in core SU94-11K (Figure 3e). During the Holocene, alkenone MAR are low ($< 10 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) at 25°N compared to a range of $10\text{--}45 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ at 21°N . Glacial MAR are on average $30 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ at 25°N and $< 5 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ at 21°N . Zhao *et al.* [1995] also observed a lowering of glacial alkenone abundances in the 658C core that they attributed to a reduction in the upwelling intensity, or its migration. In the neighbouring but deeper BOFS 31K core, late Holocene alkenone levels are only slightly higher than glacial ones [Chapman *et al.*, 1996]. However, alkenone fluxes to 658C are generally 30–50 times greater than those to BOFS 31K and sedimentation rates 3 to 4 times higher. These differences between the two cores suggest that planktonic production at BOFS 31K was probably not primarily driven by upwelling circulation and that this site remained outside its influence during glacial times [Chapman *et al.*, 1996].

n-Alkanols were then considered for assessing land-derived inputs. These compounds can be carried to our sites of deposition by winds or river supply. However, grain size distribution of sediments in this region indicate that terrestrial organic matter is mainly brought *via* eolian fallout and that river influence can be excluded [Sarnthein *et al.*, 1981]. The importance of aeolian transport of *n*-alkanol is strongly dependent on climatic factors, specifically wind strength and direction, which determine the effectiveness of winds carrying eolian particles. Their distribution along core SU94-20bK (25°N) indicate enhanced inputs from the continent during glacial time (Figure 2d). This result agrees with previous analyses of aeolo-marine dust deposits [Sarnthein *et al.*, 1981] and palaeoisopollen maps [Hooghiemstra, 1988] which indicate intensified glacial atmospheric circulation over the Eurafrikan margin. In contrast, the *n*-alkanol MAR record at 21°N (SU94-11K) outlines a pronounced depletion of terrestrial material deposited during the last glacial ($< 5 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) (Figure 3d), when concomitantly OC and alkenone MAR drop and SSTs rise. Beyond atmospheric circulation changes, the absence of a vegetation belt, at the time of maximum African aridity, may account for the regression of the *n*-alkanol supply. In the nearby core V30-49 ($18^{\circ}26\text{N}$, $21^{\circ}05\text{W}$), Pokras and Mix [1985] reported low glacial opal phytoliths from the leaves of vascular plants, which are abundant in grasses, and interpreted this result by the southward movement of the northern edge of the grass belt. High influxes of the freshwater diatom *Melosira* in cores 658A and V30-49 between 24 and 13 kyrs corroborate the phytolith data. Their occurrence in pelagic sediments would result from wind blown particles originating from the deflation of diatomaceous deposits of dry lake beds. They would thus be indicative of glacial aridity and dessication of African lakes bordering the western Sahara [Pokras and Mix, 1985]. While records of terrigenous indicators converge towards a major modification of the vegetation belt, the interpretation of OC, alkenones and SSTs data requires a major change in the trade wind regime to account for the regression of the upwelling. Coastal upwelling develops when the wind blows parallel to the coast inducing a

net transport of surface waters to the right of the winds. This offshore Ekman transport is compensated by upwelled subsurface waters. Moreover, upwelling circulation leads to changes in the distribution of mass which creates a geostrophic current parallel to the coast in the direction of the wind, in addition to the pure wind current also running in the direction of the wind [Smith, 1983]. The regression of the upwelling during glacial time indicates a change of the trade wind direction. This would have happened if, instead of blowing alongshore, winds were more zonal or their meridional component weaker (Figure 1b). This scenario would account for the observed warmer SSTs as well as reduced marine production. Alternatively the lowering of the sea level may have resulted in the displacement of the upwelling circulation towards the shelf edge, but data at site 658C argue against this hypothesis. The concomitant low *n*-alkanol levels suggest that easterlies may have played a dominant role in the dust transport during glacial time when the vegetation at this latitude was scarce.

During the Holocene, OC and alkenone flux values at SU94-11K are indicative of upwelling conditions from which we can conclude that trades winds were active. Therefore we would expect *n*-alkanol to parallel alkenone and OC records. Instead *n*-alkanol MAR maximize in the late Holocene and decline towards the top of the core (Figure 3d). The abundance profile of phytoliths over this time period in core V30-49, show a similar decrease as the *n*-alkanol [Pokras and Mix, 1985]. According to these authors this finding may be attributable to anthropogenic disturbance of climate during the last few thousand years caused by deforestation and soil degradation by nomadic herdsman. African monsoon circulation and precipitation resulting from increase low latitude summer insolation may have contributed to enhance continental matter inputs around 9–11 kyrs. Every 23 kyrs during the late Quaternary, when the perihelion was aligned with the boreal summer, the African monsoon intensified. The most recent alignment occurred 10.4 kyrs ago. Since African monsoon intensity is modulated by low latitude precessional forcing, enhanced alkanols should be recorded earlier in the core. However, because our record covers only the last 30 kyrs, this hypothesis cannot be discussed further.

Conclusions

Examination of biomarkers and SSTs derived from the U_{77}^K index in two cores located at 25° and 21°N off the NW African margin reveal significant differences in climatic and oceanographic features of the surface ocean, over the last 30 kyrs. At 25°N , we found that oceanic production was primarily controlled by trade wind intensity. High glacial MAR are coherent with the general idea of enhanced primary production rates as a result of wind intensification. In contrast, our results indicate that off Cape Blanc (21°N) the upwelling was active from present day throughout the Holocene but less intense during the last glacial period. A deflection of the glacial trade winds towards the West was proposed as a possible explanation for the reduction of the upwelling circulation. Easterlies may have prevailed over this time interval of arid climate and account for depleted terrigenous constituents. The unexpectedly low *n*-alkanol MAR during the late Holocene were interpreted as the result of anthropogenic disturbances due to agricultural practices.

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