ELSEVIER

Earth and Planetary Science Letters 188 (2001) 509–519

EPSL

www.elsevier.com/locate/epsl

New insights into the glacial latitudinal temperature gradients in the North Atlantic. Results from $U^{K'}_{37}$ sea surface temperatures and terrigenous inputs

Eva Calvo [a,*], Joan Villanueva [a], Joan O. Grimalt [a], An Boelaert [b], Laurent Labeyrie [b]

[a] *Departament de Química Ambiental, Institut d'Investigacions Químiques i Ambientals de Barcelona (C.S.I.C.), c/Jordi Girona, 18, 08034 Barcelona, Spain*

[b] *Laboratoire des Sciences du Climat et de l'Environnement, Domaine du CNRS, Av. de la Terrasse, 91191 Gif-sur-Yvette Cedex, France*

Received 14 September 2000; accepted 19 March 2001

Abstract

Sea surface temperatures (SST) and input of continental materials have been reconstructed from the study of the long-chain alkenones and *n*-alkanes, respectively, in a core located in the western side of the Mid-Atlantic Ridge (MD952037, 37°05′N 32°02′W, 2630 m depth). Both the long- and short-term variability recorded by the temperatures and the planktonic $\delta^{18}O$ are basically the same over the last 280 kyr, showing a clear glacial/interglacial evolution. Comparison with core SU90/08, located only 6° north and directly influenced by the cold polar waters associated with the polar front during glacial times, revealed different climatic conditions during glacial periods at both locations. Whereas core MD952037 recorded similar SST values during the last two glacial periods (ca. 14–15°C), the northern core displayed colder conditions during isotopic stage 2 (8–10°C) than in stage 6 (13–15°C). These results indicate the existence of a well-developed steep north–south gradient between 37 and 43°N during the last glacial period but not during stage 6, which suggests a southern expansion of the polar front during the last glacial maximum.

Keywords: North Atlantic; sea-surface temperature; alkenones; terrigenous materials; alkanes; Eemian

1. Introduction

The position of the polar front in the North Atlantic Ocean during the last glacial maximum (LGM) has been constrained by studies based on foraminiferal assemblages. According to CLIMAP [1] this front was situated at 42–46°N extending in an east–west direction. The area located between 38° and 45°N was therefore characterized by a steep south–north sea surface temperature (SST) gradient (Fig. 1) that separated the water masses dominated by subtropical and polar foraminiferal assemblages. A similar SST distribution pattern was proposed for isotopic

* Corresponding author. Tel: +34-93-4006100; Fax: +34-93-2045904; E-mail: eccqam@cid.csic.es

PII: S0012-821X(01)00316-8

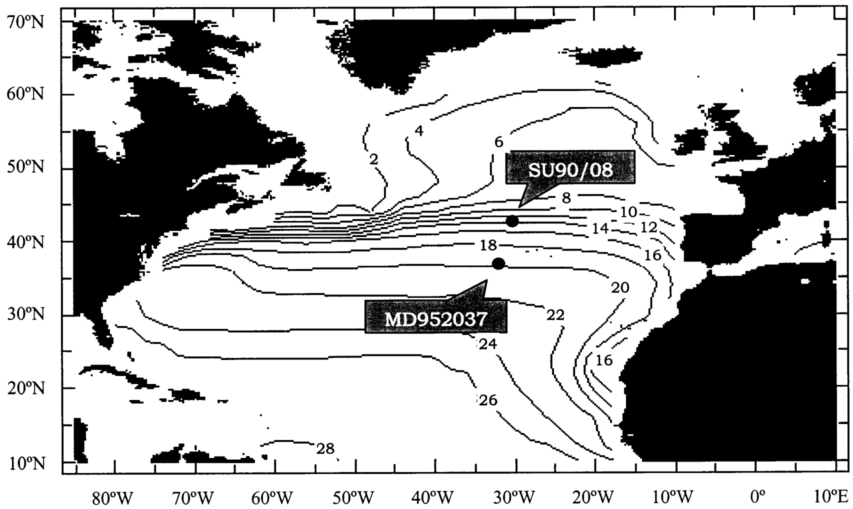

Fig. 1. Summer SSTs during the LGM [32] including the location of the cores cited in the text. Cores SU90/08 and MD952037 have been collected within and below an area of strong latitudinal SST gradient.

stage 6 (IS6) [2] although in other studies a displacement further south was hypothesized [3].

In contrast, $U^{K'}_{37}$ measurements at 43°N showed 4–5°C warmer SST during IS6 than LGM [4]. The colder SSTs during the LGM were coincident with higher accumulation rates of terrestrially derived materials, suggesting a reduction in the influence of polar waters during IS6 [4]. These warmer $U^{K'}_{37}$-SST estimates during IS6 are not restricted to the Central North Atlantic. Most $U^{K'}_{37}$-SST profiles arriving at this stage record colder values during the last glacial period, indicating a globally warmer IS6 [5]. This finding has been correlated to changes in the insolation at low latitudes, which are strongly modulated by the precession and eccentricity orbital cycles. On the other hand, changes in the intensity of the thermohaline overturn have also been related to major variations in the distribution of heat over the North Atlantic Ocean, leading to significant SST latitudinal and longitudinal contrasts [6]. These previous results outline the need for a better understanding of the SST distribution in the North Atlantic during the last glacial and interglacial periods.

In order to contribute to this goal, new $U^{K'}_{37}$ SST estimations along a core obtained at intermediate latitudes (37°N) are reported in the present study. This IMAGES core, MD952037, is situated south of the maximum extent of the polar front as recorded by CLIMAP [1]. Comparison of the SST evolution in areas under and outside the periodic influence of polar waters will provide a better understanding of the climatic implications of the paleotemperature records. The two SST profiles at 37° and 43°N considered here (Fig. 1) show parallel features, with the notable exception of IS2 and IS3, when there is evidence for the development of a steep north–south SST gradient. This structure was not observed during IS6, indicating different climatic conditions in these glacial periods.

2. Materials and methods

2.1. Core location and stratigraphy

Gravity core SU90/08 (43°30′N 30°24′W, 3100 m depth, 12 m long) and piston core MD952037 (37°05′N 32°02′W, 2630 m depth, 36 m long) were retrieved in the North Atlantic during PALEOCINAT I (1990; *Le Suroît* vessel) and IMAGES 101 (1995; *Marion Dufresne II* vessel) campaigns, respectively. Both cores are located in the western side of the Mid-Atlantic Ridge. The modern oceanographic setting at this location is

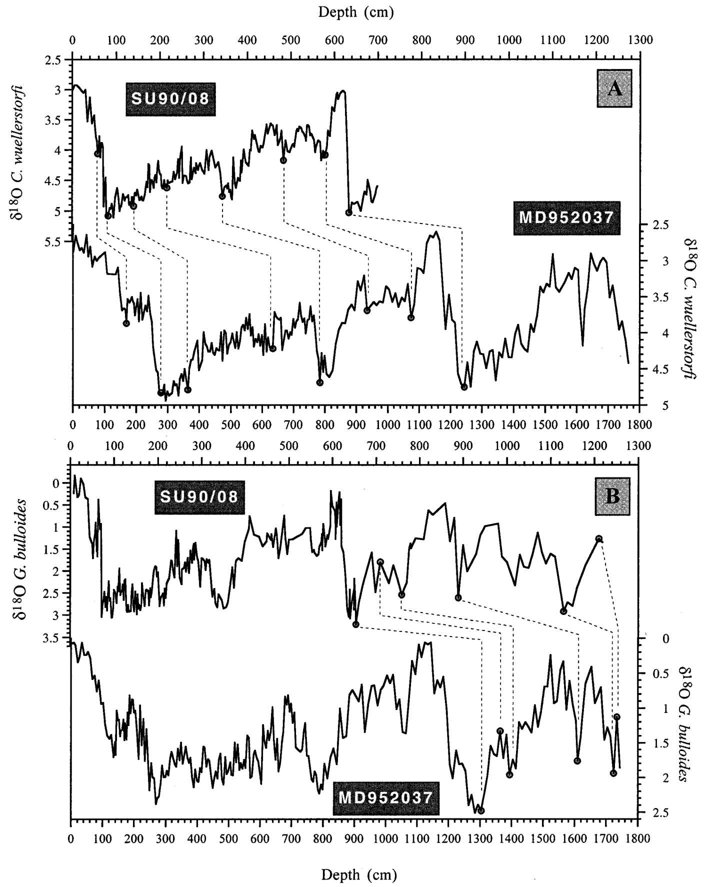

Fig. 2. Detailed chronostratigraphy of core MD952037 performed by comparison with the well-studied age model of core SU90/08. (A) The ages of the upper 13 m are based on comparison of the *C. wuellerstorfi* $\delta^{18}O$ curves in both cores. (B) In deeper sections the comparison is based on the *G. bulloides* $\delta^{18}O$ record, since there were no *C. wuellerstorfi* $\delta^{18}O$ data available for core SU90/08. The dashed lines connecting open circles mark all control points used.

dominated by relatively warm conditions associated with the subtropical North Atlantic Gyre. During the LGM, site SU90/08 was affected by polar waters and core MD952037 was located south of the maximum expansion of these polar water masses (Fig. 1).

The age scale of core SU90/08 is based on 10 AMS ^{14}C measurements, ash layer 2 level (55 kyr [7]) and on the correlation of the $\delta^{18}O$ records of *Cibicides wuellerstorfi* and *Globigerina bulloides* with the SPECMAP normalized isotope curve [8,9]. The AMS ^{14}C dates were determined on monospecific samples of *Neogloboquadrina pachyderma* (sp.) and *G. bulloides* and were corrected for an ocean reservoir effect of 400 years [10]. The temporal scale of this core is fully described elsewhere [11–15]. The age model of core MD952037 has been constructed by correlation to SU90/08. From 150 kyr BP until present the model is based on the parallel features observed on *C. wuellerstorfi* $\delta^{18}O$ curves (Fig. 2A). In the rest of the record (270–150 kyr BP) it was determined by comparison of the $\delta^{18}O$ records of the planktonic species *G. bulloides* (Fig. 2B).

Both benthic foraminifer $\delta^{18}O$ profiles evidence a clear concordance (Fig. 3), inferring the same response to the major ice volume changes in these two close locations. Both cores span over the last 280 kyr BP with sedimentation rates in the range of 2–10 cm/kyr and 2–50 cm/kyr for cores SU90/

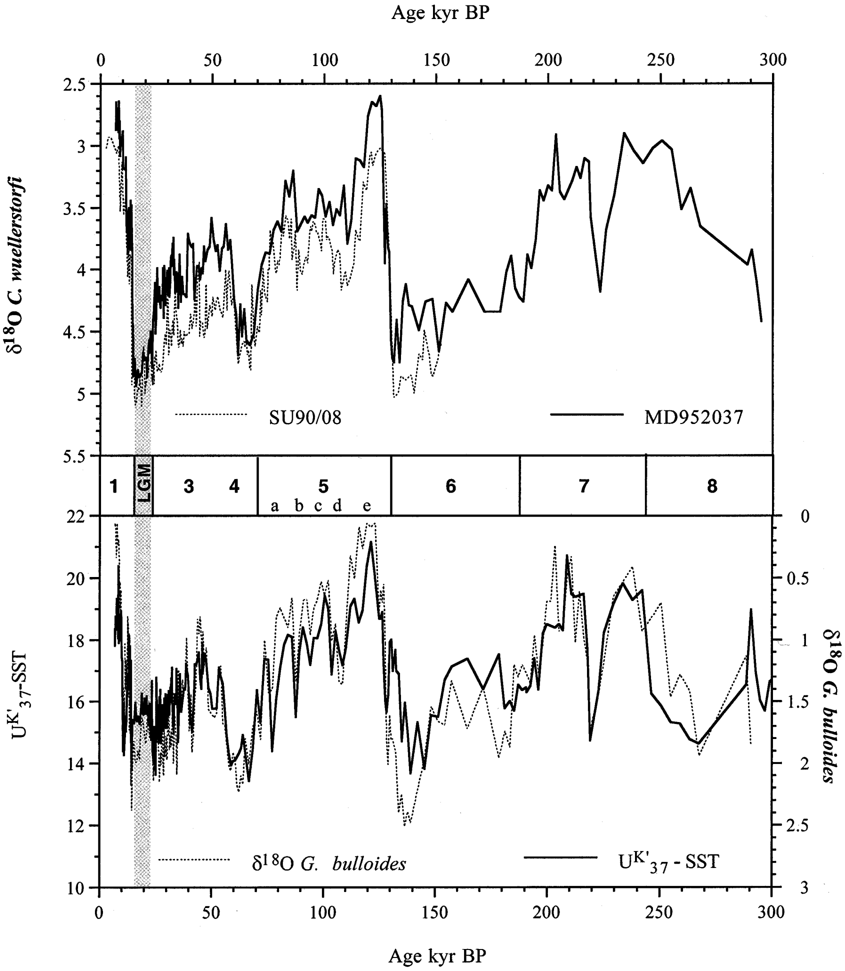

Fig. 3. Upper panel: comparison of $\delta^{18}O$ in the benthic foraminifer *C. wuellerstorfi* from cores MD952037 (solid line) and SU90/08 (dotted line). Lower panel: comparison of the $U^{K'}_{37}$ SST record (solid line) with the profile of $\delta^{18}O$ of the planktonic foraminifer *G. bulloides* (dotted line) in core MD952037.

08 and MD952037, respectively. According to our sampling intervals, the temporal resolution ranges between 400 yr and 2 kyr in the northernmost core and between 50 yr and 4 kyr in the southern one, the period from 150 kyr until present being the most detailed in both cases.

2.2. Analysis

The procedures and equipment used for C_{37} alkenones in deep sea sediments are described elsewhere [16]. Briefly, sediment samples were freeze-dried and manually ground for homogeneity. After addition of an internal standard containing *n*-nonadecan-1-ol, *n*-hexatriacontane and *n*-tetracontane, dry subsamples (ca. 3 g) were extracted with dichloromethane in an ultrasonic bath. The extracts were hydrolyzed with 6% potassium hydroxide in methanol for the elimination of wax ester interferences. The *n*-hexane extracts were then evaporated under a N_2 stream, derivatized with bis (trimethylsilyl) trifluoroacetamide and analyzed by gas chromatography with flame ionization detection. The concentration of *n*-alkanes was determined using hexatriacontane as an internal standard, and is expressed as ng/g of dry

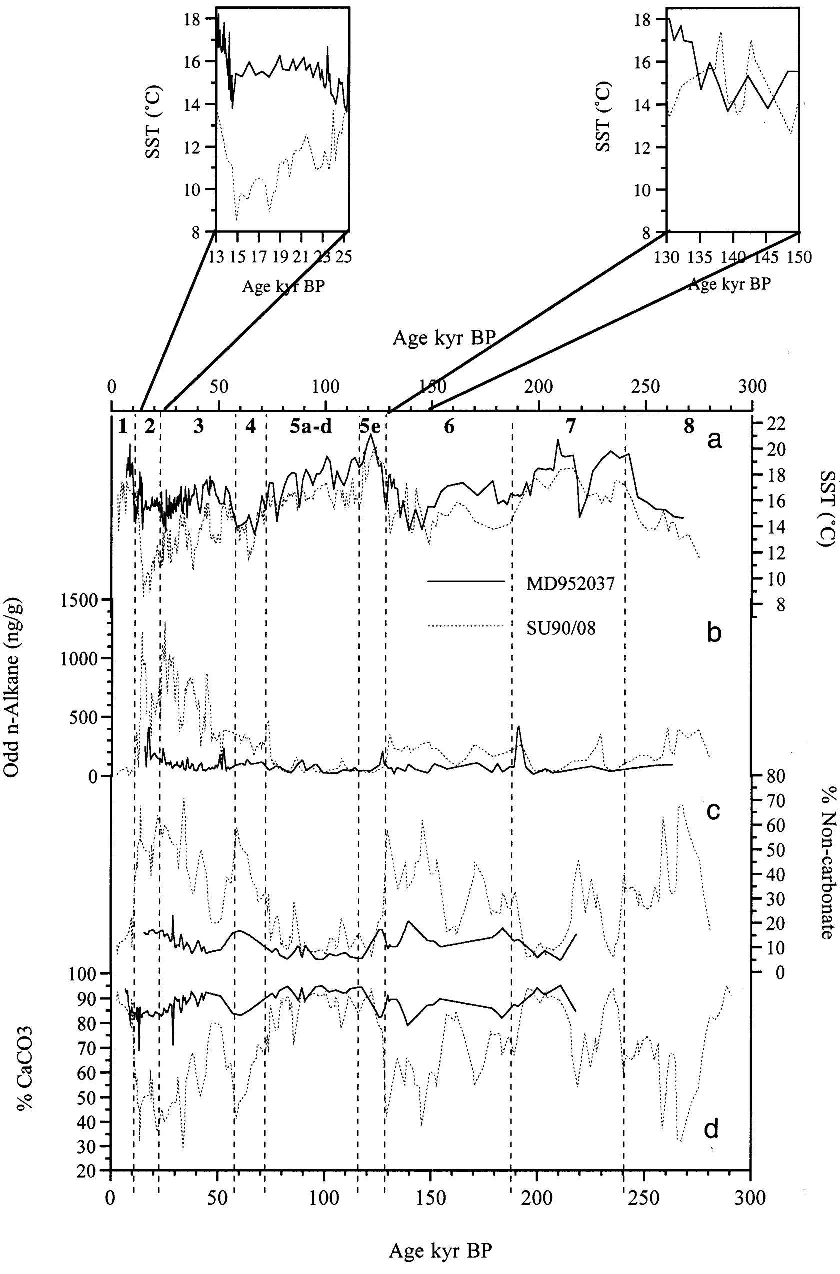

Fig. 4. Selected data from cores MD952037 (37°N, solid line) and SU90/08 (43°N, dotted line). (a) $U_{37}^{K'}$-SST. On top, zoom boxes of the last two glacial periods. (b) Odd-numbered *n*-alkane concentrations. (c) Percentage of the non-carbonate fraction. (d) Percentages of carbonate. Both SST records show parallel profiles reflecting similar climatic and oceanographic conditions. This correspondence is interrupted between IS2 and 3, where the SST difference at both locations increased until a maximum value of 8°C. During this period the concentration of terrigenous materials at the northern location increased substantially.

weight sediment. Absolute concentration errors of *n*-alkanes were below 10%.

3. Results

3.1. Alkenone-derived SST records

The $U^{K'}_{37}$-derived SST record of core MD952037 ranges between 21 and 13.5°C, with the warmest estimates occurring during IS5e and the coldest during IS4. The temporal variability of this record shows a remarkable parallelism with the planktonic $\delta^{18}O$ profile (Fig. 3). Both records reflect the same glacial–interglacial pattern for the last 280 kyr. Also, the short-term variability is basically the same. For example, both records show a relatively warm LGM, delimited by two cold events, one at the transition IS3–2 and the second one just before the deglaciation. This feature is not well defined for stage 6, and the lowest SST estimates of this glacial period correspond to the maximum extent of global ice volume, at the end of stage 6, resulting in a colder glacial period than the LGM (Fig. 3). Note that most comparisons made in the text refer to IS2 and the latest part of IS6 but sometimes we refer only to IS6 for simplification, whole IS6 would be equivalent to the last glacial period which includes IS2, 3 and 4.

The SST estimates corresponding to the interglacial stages 7, 5 and 1 are 19.5, 21 and 18.5°C, respectively. Warmer SST estimates during IS5e compared to the Holocene have been described for most of the $U^{K'}_{37}$-SST records published to date throughout the world oceans [4,17–20].

The $U^{K'}_{37}$ records between present and IS6 have been classified into three groups based on the comparison of the $U^{K'}_{37}$ and $\delta^{18}O$ profiles [5]. Core MD952037 belongs to group 3, defined as those exhibiting a close resemblance between both records. This coincidence has rarely been found in the Atlantic Ocean since most long alkenone records belong to group 2 [21]. In this sense, core SU90/08 (43°N) displays a large SST difference between the last two glacial maxima which is not observed in the isotope data [4].

A detailed comparison of the $U^{K'}_{37}$ SST estimates between cores MD952037 and SU90/08 highlights a striking parallelism on the short-term variability (Fig. 4a). SST changes during stages 5–8 are almost the same in both records, keeping a SST difference of 1.4°C between the northern and the southern locations. The main exception to this trend is late IS6 and IS5e, when SST values are roughly coincident (Fig. 4, inset boxes). In contrast, the temporal variability recorded in both sites between IS3 and IS2 presents marked discrepancies. SSTs diverge gradually until a maximum difference of ca. 8°C occurring at the LGM.

On the other hand, while the SST estimates for the last two glacial periods are roughly coincident in MD952037 (ca. 14–15°C), in the northern site they were ca. 4–5°C colder during IS2 (8–10°C) than during IS6 (13–15°C). Comparison of the $U^{K'}_{37}$ values and coccolith composition in core SU90/08 shows the absence of $U^{K'}_{37}$ shifts as a consequence of changes in the alkenone-producing species [22]. Thus, the 4–5°C SST difference between the last two glacial periods in core SU90/08 cannot be attributed to this origin. In addition, the evolution of coccolithophorid species has been shown to be uniform in the whole area [23] and therefore the $U^{K'}_{37}$ SST differences between the two sites cannot be attributed to differences in coccolith species.

3.2. Tracers of continental input

The input of continental materials to the central North Atlantic Ocean can be studied from the concentration and accumulation rates of long-chain odd *n*-alkanes, as markers of terrestrial higher plant input [24,25] and the non-carbonate fraction, mostly related to ice-transported detrital matter [26] (Figs. 4 and 5). In core SU90/08 the *n*-alkanes display a concordant temporal variability with magnetic susceptibility and sand particle counting during IS2–3, being associated with ice-transported debris [27].

The *n*-alkane concentration values in core MD952037 range between 50 and 300 ng/g. They do not follow a glacial–interglacial pattern (Fig. 4). In contrast, the non-carbonate fraction displays a weak but consistent parallelism with

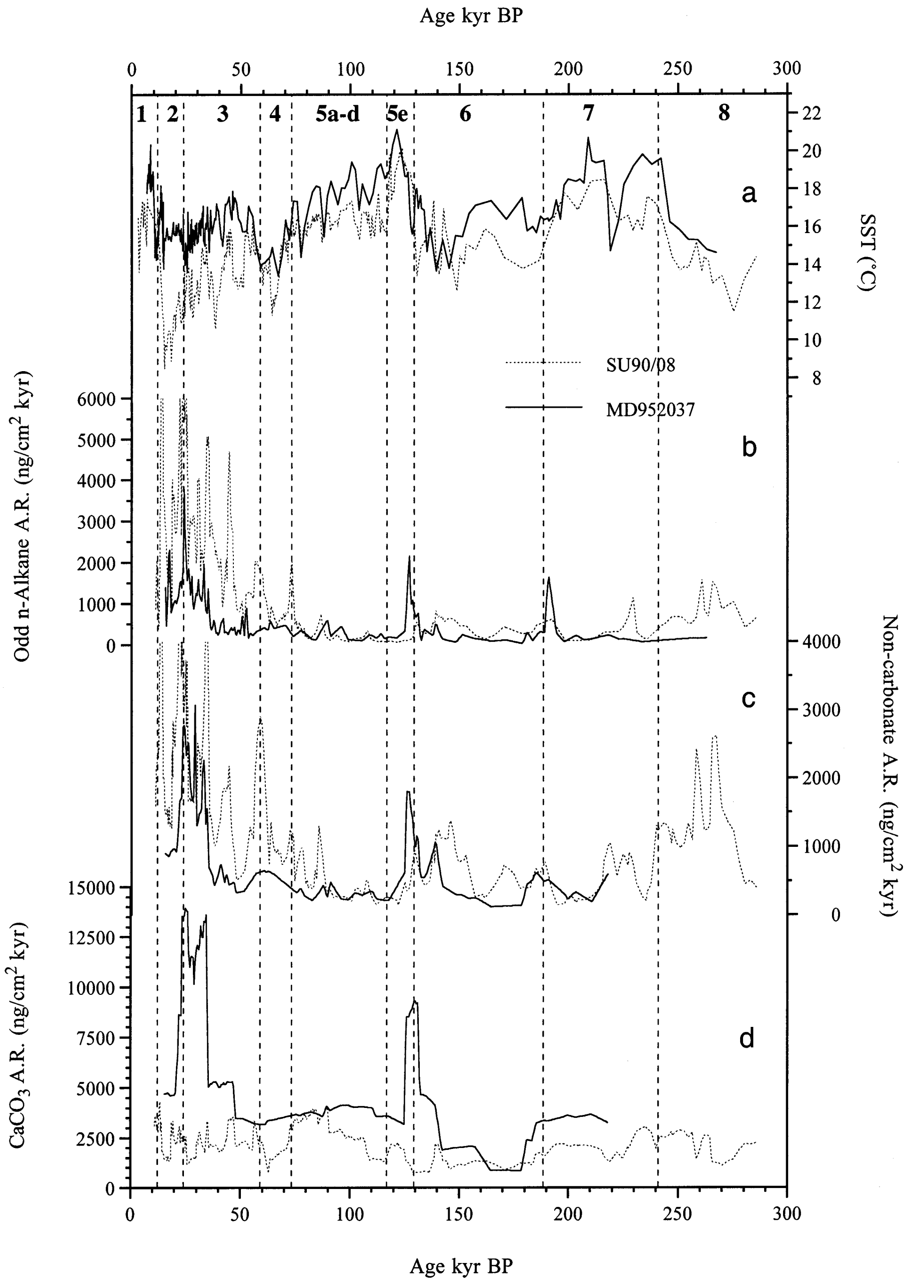

Fig. 5. Comparison of the SST records in cores MD952037 (37°N, solid line) and SU90/08 (43°N, dotted line) (a); with the estimated accumulation rates of odd-numbered *n*-alkanes (b); non-carbonate fraction (c); and carbonate fraction (d). Higher accumulation rates of detrital material are generally observed during IS2 and 3. This increase is not observed in the previous glacial period. In contrast, the accumulation of carbonate shows an independent pattern.

the evolution of the northern hemisphere ice sheets. The non-carbonate fraction constitute the 5–10% and 20–30% of the sediments during interglacial and glacial times, respectively. No significant differences in *n*-alkanes or non-carbonate fraction are observed between IS2 and IS6. The absence of coarse materials of continental origin in this core indicates the lack of ice-transported matter pointing to eolian sources for the non-carbonate fraction. Significant amounts of wind-blown terrigenous materials have been reported in glacial and modern sediments of the North Atlantic Ocean south of 40°N [28]. Wind-transported materials increased during glacial periods probably as a consequence of increased erosion over drier land masses and/or enhanced intensification of the wind system.

4. Discussion

4.1. Evolution of the polar front

The strong parallelism in the $U^{K'}_{37}$ records of both locations indicate a similar SST glacial–interglacial evolution, including IS6. The main exception is observed during IS2–3, involving a maximum difference of 6–7°C in less than 6° of latitude. This difference between such close sites in LGM has not been reported anywhere else in the world's oceans [5] and is due to the strong cooling in core SU90/08 during IS2. In contrast, in site MD952037 $U^{K'}_{37}$-SST was ca. 1°C warmer than at the end of the previous glacial stage.

In periods of negligible input of ice-rafted materials, such as interglacial periods 5e, 5c, 5a and 1, the concentrations of *n*-alkanes and non-carbonate sediment are basically the same in both cores, probably reflecting uniform wind-blown inputs (Figs. 4 and 5). In contrast, during IS2–3 the *n*-alkane concentrations at 43°N are one or two orders of magnitude higher than at 37°N. This huge difference cannot be attributed to eolian inputs since the two locations are only latitudinally separated by 6° and must be accounted for by ice-transported material.

These data clearly indicate the development of a very steep SST south–north gradient between 37 and 43°N during the last glacial period in coincidence with the accumulation of large quantities of ice-rafted detrital matter in the northern location. The intensity of this strong latitudinal SST gradient is compatible with the one already described by CLIMAP [1] based on foraminifera and sand material, pointing to a SST difference between both locations of ca. 8°C.

In contrast, the lack of this steep SST gradient during IS6, average differences of 1.4°C, similar to the value observed in the interglacial periods, and the lack of significantly higher accumulation of continental matter than during the interglacials evidence that the polar front did not extend so far south during the previous glacial period.

Previous $U^{K'}_{37}$-derived studies have also described warmer SST in IS6 than in IS2–3 at intermediate latitudes of the North Atlantic (core T88-9P, 48°N 25°W [29]). This difference has not been observed further north (core SU90/39, 52°N 21°W), nor south of 40°N (core ODP-977, 36°N 5′W in the Alboran Sea; Cacho, unpublished results). The global picture arising from these $U^{K'}_{37}$ records points to a longitudinal area of marked IS2–IS6 SST difference. North and south of this band SSTs in the last two glacials were similar, suggesting that the polar front was located in a northward location during stage 6, somewhere north of 48°N.

4.2. Paleoceanographic implications

Using the $U^{K'}_{37}$ record of core SU90/08 alone, [5] proposed that the finding of warmer IS6 was related to the input of warmer tropical water masses associated with generally warmer tropical Atlantic waters. This hypothesis is not supported by the data of core MD952037 that show colder SST at the end of IS6. The SST records now available show that core SU90/08 reflects the presence/absence of polar waters at 43°N, while core MD952037 traces the SST evolution of water masses from the subtropical gyre.

In addition to the SST differences observed between both core locations during IS2 (6°C), but not during IS6 (average span of 1.4°C), the temporal evolution of $U^{K'}_{37}$ within the two glacial periods is also different. In this sense, whereas core SU90/08 shows a clear cooling trend towards the coldest SST values registered during the LGM, core MD952037 shows a relatively stable warm SST period at ca. 15–25 kyr, delimited by two events of lower SST (Fig. 4, top). This pattern is confirmed by the $\delta^{18}O$ data of the planktonic foraminifer *G. bulloides* of core MD952037 showing lighter (warmer) values during the period of maximum global ice volume (Fig. 3). The same temporal evolution can be observed during IS6, but now even in the northern location, when the polar front retreated to a northern position. During the end of IS6, SST estimates in core SU90/08 were unusually warm and the latitudinal SST gradient between 37 and 43°N dropped to nearly 0°C (Fig. 4).

Overall, these results indicate that relatively warm water masses accumulated just south of the position of the polar front (at 37°N during IS2 and at 43°N during IS6). The development of an east–west front associated with the polar front resulted in a barrier to the transport of heat towards high latitudes. Recently, an independent SST reconstruction based on foraminiferal assemblages (core SU90/03, 40°N 32°W) also suggested the accumulation of heat within the subtropical ocean during the LGM, indicating the existence of a strong meridional gradient between 40 and 50°N associated with the LGM position of the polar front [30]. A more active and cold polar–subpolar gyre during glacial times prevented the northward heat transport from low to high latitudes, causing the warming of the tropical and subtropical Atlantic [31]. This accumulation of warm waters is more evident in the western tropical North Atlantic where periods of intense cooling at high latitudes (e.g. the Younger Dryas and Heinrich event H1) were registered as warmings in this area [6].

On the basis of this hypothesis, the new data presented here indicate the existence of a warm SST anomaly just south of the polar front. This anomaly is recorded at different latitudes during the different glacial periods: at 37°N during IS2 and at 43°N during IS6.

5. Conclusions

$U^{K'}_{37}$-SST in core MD952037 (37°N), located outside the influence of the cold waters associated with the polar front, range between 21°C (IS5e) and 13.5°C (IS4) showing a very good agreement with the planktonic $\delta^{18}O$ record. Similar SSTs, 14–15°C, are recorded for the last two glacial periods suggesting similar climatic conditions during IS6 and IS2 at this site.

Comparison with core SU90/08 located further north, under the periodic influence of the polar front, shows a strong parallelism over the last 280 kyr except for IS2 and IS3. The northern location exhibits colder conditions during the LGM (8–10°C) compared to IS6 (13–15°C). This difference and the fairly coincident SST values during IS6 indicate the presence of a steep north–south gradient during IS2 but not during IS6, suggesting a further southerly position of the polar front during the LGM.

These results are consistent with the measured concentrations of long-chain odd *n*-alkanes and the non-carbonate fraction at both sites. Higher abundances of these terrestrial materials were recorded in core SU90/08 during the last glacial period in concordance with the lowest SSTs observed, whereas core MD952037 only presented slightly higher abundances during glacial periods compared to interglacial, most likely related to an eolian source.

The lack of warmer waters at 37°N during IS6 compared to IS2 (in fact SST was about 1°C lower in the previous glacial stage) militates against the previously hypothesized northward displacements of warm water masses during IS6 as justification of higher SST in IS6 than LGM [5]. Conversely, the present results show that the difference between these two last glacial periods is due to a displacement of the polar front further south in the LGM.

Acknowledgements

Thanks are due to the French MENRT,

TAAF, CNRS/INSU and IFRTP for support to the *Marion Dufresne* and the IMAGES program. J.V. is grateful for a postdoctoral contract from C.I.R.I.T (Generalitat de Catalunya). The authors are also grateful to Mark Chapman and an anonymous reviewer for constructive review of the manuscript. Financial support from the HOLOCENE EU project (ENV4-CT97-0162) is acknowledged.*[AC]*

References

[1] CLIMAP, The surface of the ice-age Earth, Science 191 (1976) 1131–1137.

[2] W.F. Ruddiman, A. McIntyre, Northeast Atlantic paleoclimatic changes over the past 600,000 years, Geol. Soc. Am. Mem. 145 (1976) 111–146.

[3] T.J. Crowley, Temperature and circulation changes in the eastern North Atlantic during the last 150 000 years: evidence from the planktonic foraminiferal record, Mar. Micropaleontol. 6 (1981) 97–129.

[4] J. Villanueva, J.O. Grimalt, E. Cortijo, L. Vidal, L. Labeyrie, Assessment of sea surface temperature variations in the Central North Atlantic using the alkenone unsaturation index ($U_{37}^{K'}$), Geochim. Cosmochim. Acta 62 (1998) 2421–2427.

[5] R. Schneider, P.J. Müller, R. Acheson, Atlantic alkenone sea-surface temperature records, in: F. Abrantes, A.C. Mix (Eds.), Reconstructing Ocean History: A Window into the Future, Plenum, New York, 1999, pp. 33–55.

[6] C. Rühlemann, S. Mulitza, P.J. Müller, G. Wefer, R. Zahn, Warming off the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation, Nature 402 (1999) 511–514.

[7] W.F. Ruddiman, G. Glover, Vertical mixing of ice-rafted volcanic ash in North Atlantic sediments, Geol. Soc. Am. Bull. 83 (1972) 2817–2836.

[8] J. Imbrie, J.D. Hays, D.G. Martinson, A. McIntyre, A.C. Mix, J.J. Morley, N.G. Pisias, W.L. Prell, N.J. Shackleton, The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record, in: A.L. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman (Eds.), Milankovitch and Climate, Part 1, D. Reidel, Norwell, Hingham, MA, 1984, pp. 269–305,

[9] D.G. Martinson, N.G. Pisias, J. Hays, J. Imbrie, T.C. Moore, N.J. Shackleton, Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000 year chronostratigraphy, Quat. Res. 27 (1987) 1–29.

[10] E. Bard, Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: Paleoceanographic implications, Paleoceanography 3 (1988) 635–645.

[11] F. Grousset, L. Labeyrie, J. Sinko, G. Bond, J. Duprat, M. Cremer, S. Huon, Patterns of ice rafted detritus in the Glacial North Atlantic (40–55°N), Paleoceanography 8 (1993) 175–192.

[12] E. Cortijo, L. Labeyrie, L. Vidal, M. Vautravers, M. Chapman, J.C. Duplessy, M. Elliot, M. Arnold, J.L. Turon, G. Auffret, Changes in sea surface hydrology associated with Heinrich event 4 in the North Atlantic Ocean between 40° and 60°N, Earth Planet. Sci. Lett. 146 (1977) 29–45.

[13] L. Vidal, L. Labeyrie, E. Cortijo, M. Arnold, J.C. Duplessy, E. Michel, S. Becqué, T.C.E. van Weering, Evidence for changes in the North Atlantic Deep Water linked to meltwater surges during the Heinrich events, Earth Planet. Sci. Lett. 146 (1997) 13–27.

[14] M. Elliot, L. Labeyrie, G. Bond, E. Cortijo, J.L. Turon, N. Tisnerat, J.C. Duplessy, Millenial-scale iceberg discharges in the Irminger Basin during the last glacial period: Relationship with the Heinrich events and environmental settings, Paleoceanography 13 (1998) 433–446.

[15] J. Villanueva, J.O. Grimalt, L.D. Labeyrie, E. Cortijo, L. Vidal, J.L. Turon, Precessional forcing of productivity in the North Atlantic Ocean, Paleoceanography 13 (1998) 561–571.

[16] J. Villanueva, C. Pelejero, J.O. Grimalt, Clean-up procedures for the unbiassed estimation of C_{37}–C_{39} alkenones sea surface temperatures and terrigenous *n*-alkane inputs in paleoceanography, J. Chromatogr. 757 (1997) 145–151.

[17] R.R. Schneider, P.J. Müller, G. Ruhland, Late Quaternary surface circulation in the east equatorial South Atlantic: Evidence from alkenone sea surface temperatures, Paleoceanography 10 (1995) 197–219.

[18] F. Rostek, E. Bard, L. Beaufort, C. Sonzogni, G. Ganssen, Sea surface temperature and productivity records for the past 240 kyr in the Arabian Sea, Deep-Sea Res. II 44 (1997) 1461–1480.

[19] C. Pelejero, J.O. Grimalt, S. Heilig, M. Kienast, L. Wang, High resolution U_{37}^{K}-temperature reconstructions in the South China Sea over the last 220 kyrs, Paleoceanography 14 (1999) 224–231.

[20] E. Calvo, C. Pelejero, J.C. Herguera, A. Palanques, J.O. Grimalt, Insolation dependence of the southeastern Subtropical Pacific sea surface temperature over the last 400 kyrs, Geophys. Res. Lett. (submitted).

[21] R. Schneider, P.J. Müller, G. Ruhland, G. Meinecke, H. Schmidt, G. Wefer, Late Quaternary surface temperatures and productivity in the East-Equatorial South Atlantic: response to changes in trade/monsoon wind forcing surface water advection, in: G. Wefer, W.H. Berger, G. Siedler and D.J. Webb (Eds.), The South Atlantic: Present and Past Circulation, Springer-Verlag, Berlin, 1996, pp. 527–551.

[22] J. Villanueva, J.A. Flores, J.O. Grimalt, A detailed comparison of the $U_{37}^{K'}$ and coccolithophorid records over the past 290 kyr: Implications to the alkenone paleotemperature method. Geophys. Res. Lett. (submitted).

[23] P.P.E. Weaver, An integrated stratigraphy of the Upper Quaternary of the King's Trough flank area NE Atlantic, Oceanol. Acta 6 (1983) 451–456.

[24] J.G. Poynter, P. Farrimond, N. Robinson, G. Eglinton, Aeolian-derived higher plant lipids in the marine sedimentary record: links with palaeoclimate, in: M. Leinen, M. Sarnthein (Eds.), Paleoclimatology and Paleometerology: Modern and Past Patterns of Global Atmospheric Transport, Kluwer Academic, Dordrecht, 1989, pp. 435–462.

[25] N. Ohkouchi, K. Kawamura, H. Kawahata, A. Taira, Latitudinal distributions of terrestrial biomarkers in the sediments from the Central Pacific, Geochim. Cosmochim. Acta 61 (1997) 1911–1918.

[26] W.F. Ruddiman, Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat 40° to 65°N), Geol. Soc. Am. Bull. 88 (1977) 1813–1827.

[27] J. Villanueva, J.O. Grimalt, E. Cortijo, L. Vidal, L. Labeyrie, A biomarker approach to the organic matter deposited in the North Atlantic during the Last Climatic Cycle, Geochim. Cosmochim. Acta 61 (1997) 4633–4646.

[28] W.L. Balsam, B.L. Otto-Bliesner, B.C. Deaton, Modern and last glacial maximum eolian sedimentation patterns in the Atlantic Ocean interpreted from sediment iron oxide content, Paleoceanography 10 (1995) 493–507.

[29] L.A.S. Madureira, S.A. van Kreveld, G. Eglinton, M.H. Conte, G. Ganssen, J.E. van Hinte, J.J. Ottens, Late Quaternary high-resolution biomarker and other sedimentary climate proxies in a northeast Atlantic core, Paleoceanography 12 (1997) 255–269.

[30] M.R. Chapman, M. Maslin, Low-latitude forcing of meridional temperature and salinity gradients in the subpolar North Atlantic and the growth of glacial sheets, Geology 27 (1999) 875–878.

[31] S. Manabe, R.J. Stouffer, Coupled ocean-atmosphere model response to freshwater input: Comparison to Younger Dryas event, Paleoceanography 12 (1997) 321–336.

[32] CLIMAP, Seasonal Reconstructions of the Earth's Surface at the Last Glacial Maximum, Geological Society America, Boulder, CO, 1981.