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High resolution U_{37}^{K} sea surface temperature reconstruction in the Norwegian Sea during the Holocene

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Abstract

A study of the C_{37} alkenone distributions in core MD952011 from the Norwegian Sea (about 65°N) has allowed the evaluation of the applicability of the U_{37}^{K} and $U_{37}^{K'}$ indexes in these cold waters. The use of the first defined U_{37}^{K} appears to be the most appropriate to estimate sea surface temperatures (SST) allowing a high resolution SST reconstruction for the Holocene section. At this site, the warmest SST values were recorded during the first-half of the Holocene, between 8.5 and 5.5 ka BP, after a gradual warming. Since then, the SST evolution of the late Holocene exhibits a cooling trend towards present values, in concordance with the decreasing summer insolation at these high latitudes. In terms of variability, higher SST changes were observed in the warmer than in the cooler periods, $\pm 2°C$ and $\pm 0.5°C$, respectively. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Holocene has been regarded as a more or less stable period when compared to the last glacial. However, over the last decade, paleoclimatic studies have documented higher instabilities than previously thought. Abrupt millennial scale anomalies in temperature, ice rafting and deep water flow strength can be recognized in marine sediments of the North Atlantic Ocean (Bond et al., 1997; Bianchi and McCave, 1999; Bond et al., 1999) ice cores from Greenland (O'Brien et al., 1995; Mayewski et al., 1997) and terrestrial evidences of the surrounding continental areas (Denton and Karlen, 1973; Campbell et al., 1998). These oscillations have become clearer as the number of high resolution climatic records available increases.

One of the areas more sensitive to climatic change is the North Atlantic, since switching between glacial and interglacial periods is mediated by changes in the flow of warm and saline water masses from the Gulf of Mexico to the high latitudes of the Norwegian Sea. In the Holocene, cooling of these saline water masses in the high latitudes results in the formation of North Atlantic Deep Water (NADW) and the release of important amounts of heat and moisture to the atmosphere (Gordon, 1986). In contrast, the cold East Greenland Current (EGC), driven by outflow of cold, fresher waters from the Arctic Ocean, flows southward (Fig. 1). These two current systems define two water masses, the Atlantic and the Polar, which are separated by the Arctic front, giving rise to strong east to west SST gradients across the Norwegian–Greenland Sea (Hurdle, 1986). This area has therefore high potential for the identification of the climatic oscillations that occurred in the Holocene. To this end, the changes in SST may provide direct evidence of the climatic changes resulting from variations in meridional heat flux at high latitudes.

Accordingly, the alkenone U_{37}^{K} index has been measured at high resolution for SST reconstruction in MD952011 core (66°58′N, 7°38′E, 1048 m water depth, 17.5 m long). This core was collected in the Vöring Plateau in the eastern Norwegian Sea, a site located under the direct influence of the present-day pathway of the Norwegian Current, the northward branch of the North Atlantic Current (6–10°C, >35‰; Swift (1986)) (Fig. 1). The Holocene section documents a high sedimentation rate and has been analyzed in order to

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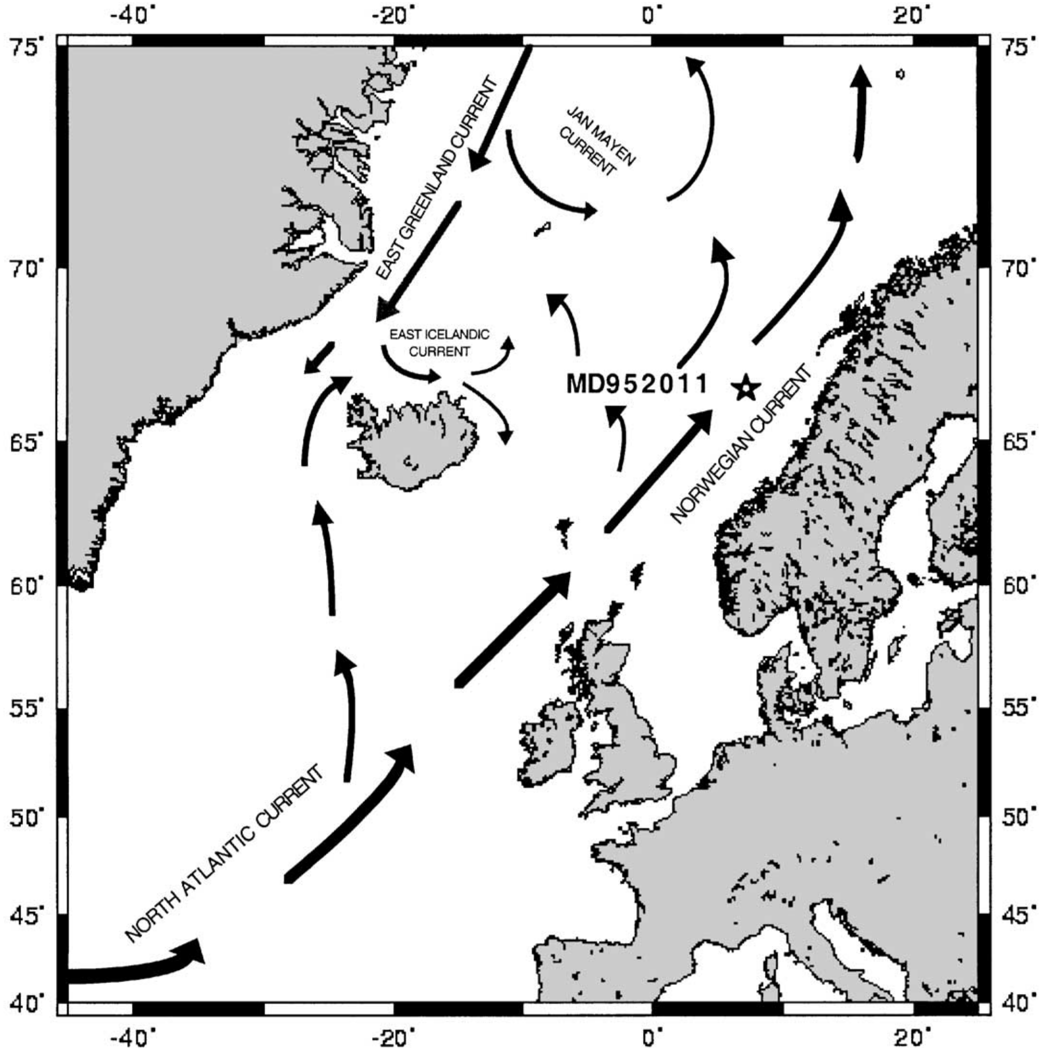

Fig. 1. Location of core MD952011 and main currents of the modern surface circulation of the studied area.

evaluate the short- and long-term evolution of the poleward current of warm waters from the last deglaciation till the present (the last 15 ka).

The U^K_{37} index is based on the relative abundance of the diunsaturated ($C_{37:2}$), triunsaturated ($C_{37:3}$) and tetraunsaturated ($C_{37:4}$) methyl ketones of 37 carbon atoms (Brassell et al., 1986):

$$U^K_{37} = (C_{37:2} - C_{37:4})/(C_{37:2} + C_{37:3} + C_{37:4}).$$

In the open oceans, these compounds are biosynthesized by some Haptophyceae algae, the coccolithophorid *Emiliania huxleyi* being the main producer (Volkman et al., 1980). This alga is widespread in all present oceans, from tropical to polar waters (Okada and Honjo, 1973; Okada and McIntyre, 1979). However, the $C_{37:4}$ alkenone is rarely detected in open sea sediments from low- and mid-latitudes and only becomes important with decreasing temperature ($<10°C$). This observation allows the simplification of the U^K_{37} index in the following expression:

$$U^{K'}_{37} = C_{37:2}/(C_{37:2} + C_{37:3}).$$

This index has been successfully used in a wide variety of locations (e.g. Schneider et al., 1995; Villanueva et al., 1998; Cacho et al., 1999a; Pelejero et al., 1999). However, when $C_{37:4}$ is present the use of U^K_{37} should be considered. This is the case of high latitude areas, such as the northern North Atlantic and the Southern Oceans (Rosell-Melé et al., 1995; Sikes et al., 1997).

The SST–U^K_{37} estimations reconstructed in core MD952011 allow the study of the temporal evolution and millennial scale variability of this sensitive area since the last deglaciation till the present time. It also allows the evaluation of the relevance and sensitivity of northern high latitude areas to the summer insolation changes induced by the Earth's orbital variations (Imbrie et al., 1992).

2. Materials and methods

2.1. Stratigraphy

The IMAGES piston core MD952011 was recovered by the RV Marion Dufresne in 1995. Core chronology was performed at the University of Kiel and in the Centre des Faibles Radioctivités from Gif-sur-Yvette and is based on 11 AMS-^{14}C dates of monospecific samples of *Neogloboquadrina pachyderma (s)* with precisions ranging from ±25 to ±90 yr (Table 1). The age model was constructed by linear interpolation between the different ^{14}C-AMS dates. The uncorrected ^{14}C ages have been converted to calendar ages using the Calib 4.2 program according to Stuiver et al. (1998). The position of the Vedde Ash layer has also been used as an age control point (Grönvold et al., 1995). The time period covered in this study, which comprises the upper 8 m, spans over the last 16 ka. Sedimentation rates encompass extremely high values from 25 to 270 cm/ka, and according to our sampling intervals (2–5 cm depending on the section), correspond to a temporal resolution within a range of 7 to 200 years for the last 16 ka.

Stretching of parts of cores obtained by the CALIPSO-coring system has been documented (Y. Balut pers. comm., 1999; C. Kissel, pers. comm., 1999). Yet, the stretching is not uniform, and varies substantially from core to core. In the case of core MD952011, this effect cannot be ruled out, but we do not think that this affects the fidelity of the record, although it may affect the apparent sedimentation rates, in particular near the top. The sediments are texturally very uniform, and consist of >80% silt and clay in the late glacial and Holocene. The ^{14}C ages indicate quite homogeneous age/depth relations, allowing for the effect of compaction, and no obvious error appears in relation to possible stretching.

Table 1
Overview of tie points used to establish the age model for core MD95-2011. The AMS-^{14}C dates have been corrected for a reservoir age of 400 yr. Calibrated 4.2 was used to translate to calendar years

Identifier	Depth (cm)	AMS ^{14}C-age (years)	Error± (years)	Cal. age BP (years)
GifA96471	10.5	980	60	551
KIA 3925	30.5	1040	40	625
KIA 5601	47.5	1160	30	689
KIA 3926	70.5	1460	50	987
KIA 6286	89.5	1590	30	1159
KIA6287	154	2335	25	1942
GifA96472	170.5	2620	60	2309
KIA 10011	269.5	3820	35	3763
KIA 463	320.5	4330	50	4434
KIA 464	520.5	7260	60	7697
	709.5			11 980[a]
KIA 465	750.5	12 220	90	13 806

[a] Denotes the age of the Vedde Ash layer, which was taken from the GRIP age from Grönvold et al. (1995).

2.2. Alkenone analysis

The procedures and equipment used for the analysis of C_{37} alkenones in deep sea sediments are described elsewhere (Villanueva et al., 1997). 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 an N_2 stream, derivatized with bis(trimethylsilyl)-trifluoroacetamide and analyzed by gas chromatography with flame ionization detection (GC-FID). Samples with low concentration of alkenones were reinjected by gas chromatography–mass spectrometry with ammonia chemical ionization (GC–MS-CI) for better identification and quantification of these compounds. Six times replication of sediment samples with similar lipid content and U^{K}_{37} index showed standard deviations of ±0.15°C in temperature estimation.

3. Results and discussion

3.1. U^{K}_{37} *and* $U^{K'}_{37}$ *indexes*

The sedimentary C_{37} alkenones of core MD952011 have been analyzed along the top 8 m. In addition to the most common $C_{37:2}$ and $C_{37:3}$, $C_{37:4}$ is also found in some of the studied sections. This compound has been found in the last 2.7 ka and before 8.5 ka. Data from both U^{K}_{37} and $U^{K'}_{37}$ are plotted versus age, together with the percentage of the tetraunsaturated alkenone (% $C_{37:4}$, Fig. 2). Between 2.7 and 8.5 ka there is no trace of $C_{37:4}$ and, therefore, the values obtained for both temperature indices are the same (mean value 0.37 units). Between 2.7 ka–present and 8.5–11.8 ka, where the percentage of $C_{37:4}$ is below 5%, U^{K}_{37} shows colder values than $U^{K'}_{37}$ but the difference is only of about 0.04 units (≈1.2°C). However, prior to 11.8 ka, $C_{37:4}$ is about 15% of the total C_{37} alkenones and there is a strong disagreement between U^{K}_{37} and $U^{K'}_{37}$. In this period, $U^{K'}_{37}$–SST does not give a signal that is consistent with other paleoclimatic records such as δ^{18}O and $U^{K'}_{37}$–SST is therefore difficult to interpret.

High amounts of $C_{37:4}$ (up to 15–20%) have also been reported in core-top samples from western Nordic Seas areas where no correlation between $C_{37:4}$ content and SST was found (Rosell-Melé et al., 1994). In these cold waters (below 5°C), there is no correlation of U^{K}_{37}

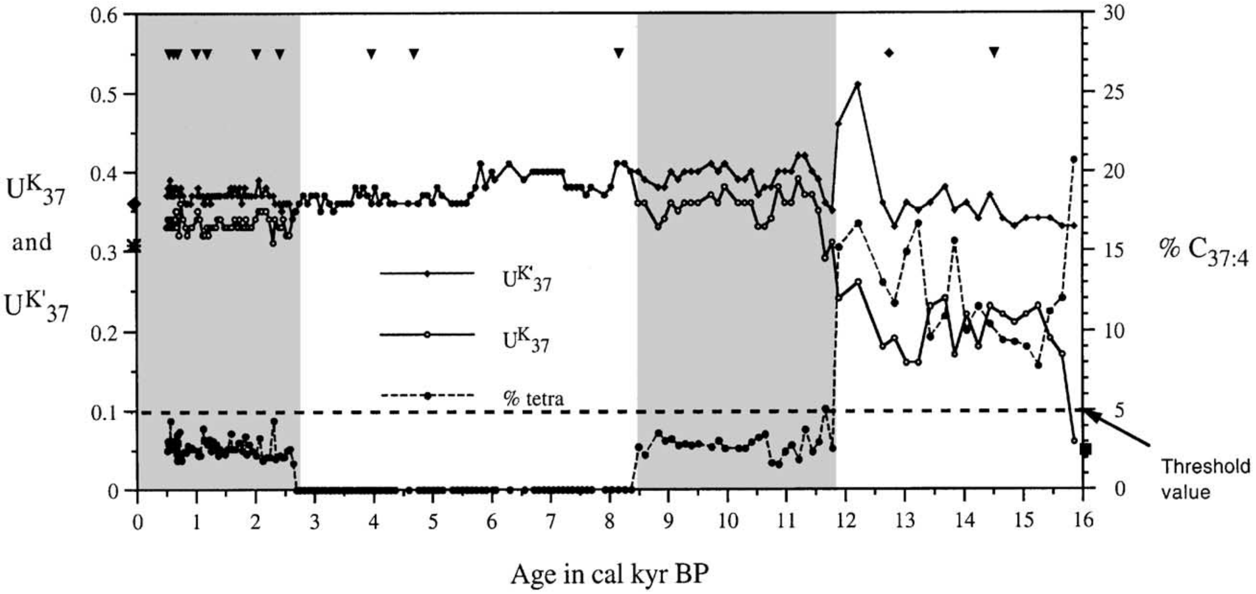

Fig. 2. U$^{K}_{37}$ and U$^{K}_{37}$ indexes and %C$_{37:4}$ plotted versus calendar age. On the left, * and ◆ indicates the core-top values of U$^{K}_{37}$ and U$^{K}_{37}$, respectively, and ● on the right indicates the core-top value for %C$_{37:4}$. At the top, ▼ indicate the AMS-^{14}C dates and ◆ shows the age of the Vedde Ash layer.

and U$^{K'}_{37}$ with temperature due to the increasing scatter of the data set. Similarly, no correlation of C$_{37:4}$ concentration and SST has been found in the Southern Ocean (Sikes et al., 1997) and the Black Sea (Freeman and Wakeham, 1992). In this respect, in the Black Sea the δ^{13}C composition of C$_{37:4}$ differs significantly from the isotopic composition of the co-occurring C$_{37:2}$ and C$_{37:3}$ alkenones (Freeman and Wakeham, 1992).

A dependence from freshwater inputs has been proposed for the alkenone distributions with high C$_{37:4}$ content (Rosell-Melé, 1998; Rosell-Melé et al., 1998). An early work of Cranwell (1985), for example, showed that some freshwater lakes contained unusual alkenone distributions characterized by high proportions of the C$_{37:4}$ component. These distributions could not be related to water temperature and suggested that the observed C$_{37}$ alkenones originated from precursor species other than *E. huxleyi*. The difficulties for the correlation of C$_{37}$ alkenones and SST have also been observed in the Baltic Sea where the mixtures in the inner basins (with less saline waters) exhibited a higher proportion of C$_{37:4}$ (Schulz et al., 2000). This enrichment may be due to a stronger influence of freshwater tributaries in these semi-enclosed areas. On the other hand, Bard et al. (2000) have recently found high abundances of C$_{37:4}$ during Heinrich events in a core located in the Iberian margin and, in agreement with the freshwater input hypothesis, the data have been interpreted to reflect the presence of both cold and low saline arctic water inputs linked to iceberg melting. In contrast, good correlations between U$^{K}_{37}$ and SST have been found in the eastern North Atlantic when the relative abundance of the C$_{37:4}$ alkenone is lower than 5% (Rosell-Melé, 1998).

Overall, the high values of C$_{37:4}$ ($>5\%$) observed in the sections of core MD952011 corresponding to ages prior to 11.8 ka may prevent reliable SST estimation, but can be taken as a good indication of the presence of colder and less saline water masses in this area. This older section involves the Younger Dryas (YD) period and the deglaciation. During the YD, for instance, the colder and less saline polar waters from the west side of the Nordic Seas extended to the east (Sarnthein et al., 1995) and the influence of the warm and more saline Atlantic waters was restricted (Koç-Karpuz and Jansen, 1992). In the rest of the core (0–11.8 ka), C$_{37:4}$ abundances are always below 5%, thus within the range of linearity between U$^{K}_{37}$ and U$^{K'}_{37}$ with SST.

3.2. Calibration equations

Different equations have been proposed to convert U$^{K}_{37}$ and U$^{K'}_{37}$ values into SST, (e.g. Müller et al., 1998; Pelejero and Grimalt, 1997; Prahl and Wakeham, 1987; Rosell-Melé et al., 1995). In order to evaluate which calibration is the most suitable for paleotemperature reconstruction in our area of study, SST estimates resulting from different equations have been compared to modern mean ocean temperatures at core MD952011 site (Levitus, 1994). For this purpose, the U$^{K}_{37}$ and U$^{K'}_{37}$ values corresponding to the surface sediment of a box core retrieved in the same location than core MD952011 (box core JM97-948/2A) have been calculated. Since C$_{37:4}$ is present in the surface sample (3.4%), the

Tale 2
Comparison of the SST estimations obtained from different $U^{K'}_{37}$ and U^{K}_{37} calibrations with modern temperatures at 0 m water depth (Levitus, 1994)[a]

Calibration	$U^{K'}_{37} = 0.361$	$U^{K}_{37} = 0.314$
$U^{K'}_{37} = 0.044 + 0.033{*}SST$ (Müller et al., 1998), annual, 0–29°C Global core tops	 9.6°C (1.1°C)	
$U^{K'}_{37} = 0.186 + 0.026{*}SST$ (Weaver et al., 1999), summer, 0–28°C Atlantic core tops	 6.7°C (4.3°C)	
$U^{K'}_{37} = -0.082 + 0.038{*}SST$ (Sikes et al., 1997), summer, 4–17°C Southern Ocean core tops	 11.7°C (0.7°C)	
$\mathbf{U^{K}_{37} = -0.110 + 0.040{*}SST}$ (Prahl and Wakeham, 1987), 8–25°C algae culture		**10.6°C** **(0.4°C)**
$U^{K}_{37} = 0.162 + 0.029{*}SST$ (Rosell-Melé et al., 1995), annual, 0–28°C Atlantic core tops		 5.2°C (3.3°C)
$U^{K}_{37} = 0.093 + 0.030{*}SST$ (Rosell et al., 1995), summer, 0–28°C Atlantic core tops		 7.4°C (3.6°C)
Levitus, 94 Annual SST at 0 m		 8.5°C
Levitus, 94 Summer SST at 0 m		 **11°C**

[a] The $U^{K'}_{37}$ and U^{K}_{37} values correspond to the surface sediment of the box core JM97/948 retrieved at the same site as MD952011. The difference between $U^{K'}_{37}$ and U^{K}_{37} estimations and modern temperatures is shown in brackets. The calibration regression of Prahl and Wakeham (1987) is the equation that better fits with the present SST values.

corresponding U^{K}_{37} and $U^{K'}_{37}$ values are different, 0.361 and 0.314, respectively. Summer SST should be preferred for comparison of these data since at these high latitudes maximum coccolithophorid production is observed during this season (Okada and McIntyre, 1979; Baumann et al., 1997). However, annual average SST has also been considered for a more comprehensive evaluation.

In Table 2, there is a selection of the calibration equations that could reconstruct better the paleo-SST of our location and summer and annual SST obtained from (Levitus, 1994). These equations have been selected taking into consideration the oceanographic area and temperature range covered by the calibration data set. Equations including $C_{37:4}$ have been preferred. When comparing the resulting SST, large differences (up to 4.3°C) can be observed between the different calibrations (Table 2). Most of them yield too cold temperatures with respect to the modern temperatures for this location (Levitus, 1994), e.g. 5.2°C versus the actual annual mean (8.5°C), or 7.4°C versus the summer value (11°C). This is also the case for the core-tops calibration, which covers the whole North Atlantic (75°N–2°S) (Rosell-Melé et al., 1995), which always yields about 3.5°C colder SST estimates (Table 2). This equation seems to fail in the cold end due to the large scatter in the U^{K}_{37}–SST data from the western Nordic Seas ($SST < 5°C$, $C_{37:4} = 20\%$).

The lowest discrepancy between summer SST from Levitus (1994) and sediment surface data, 0.4°C, is obtained with the equation of Prahl and Wakeham (1987) for U^{K}_{37}. This calibration gives a value of 10.6°C, which is only slightly colder than the modern summer SST value of 11°C at our core location. The better performance of the Prahl and Wakeham (1987) equation is, in fact, consistent with the previous consensus on equations for the transformation of C_{37} alkenone distributions into SST. This agreement can be summarized by the equivalence between the global $U^{K'}_{37}$–SST calibration of Müller et al. (1998) based on the sedimentary data from 60°N to 60°S and the one initially proposed by Prahl and Wakeham (1987) for the $U^{K'}_{37}$ based on algal cultures. These two equations agree with many others based on regional calibration experiments, e.g. Pelejero and Grimalt (1997) and Cacho et al. (1999b). Accordingly, the equation exhibiting the best fit to the surface sediments considered in Table 2 is equivalent to this common equation but now based on the U^{K}_{37} instead of the $U^{K'}_{37}$ index. Thus, it is based on the same data set as the well-known $U^{K'}_{37}$–SST equation reported by Prahl and Wakeham (1987). Moreover, the core-top U^{K}_{37}–SST value with this equation matches almost exactly the summer temperature estimate of 10.3°C obtained from diatom transfer functions in this same core, MD952011 (Jansen and Koç, 2000). Nevertheless, the U^{K}_{37} would benefit from a revision of its initial definition, since the contribution of the $C_{37:4}$ in the numerator is probably overemphasizing the degree of cooling of waters where this compound is biosynthesized.

Accordingly, in the present study, the equation of Prahl and Wakeham (1987) is used to reconstruct the paleo-SSTs of core MD952011. It has to be stressed, however, that adequate choice of the calibration equations is essentially relevant for absolute SST estimates. In the case of estimation of time-dependent SST trends, the specific equation selected is less important since all of them are linearly dependent on SST.

3.3. SST variability during the Holocene

In Fig. 3, the reconstructed SST estimations are plotted versus age over the last 16 ka. The record covers

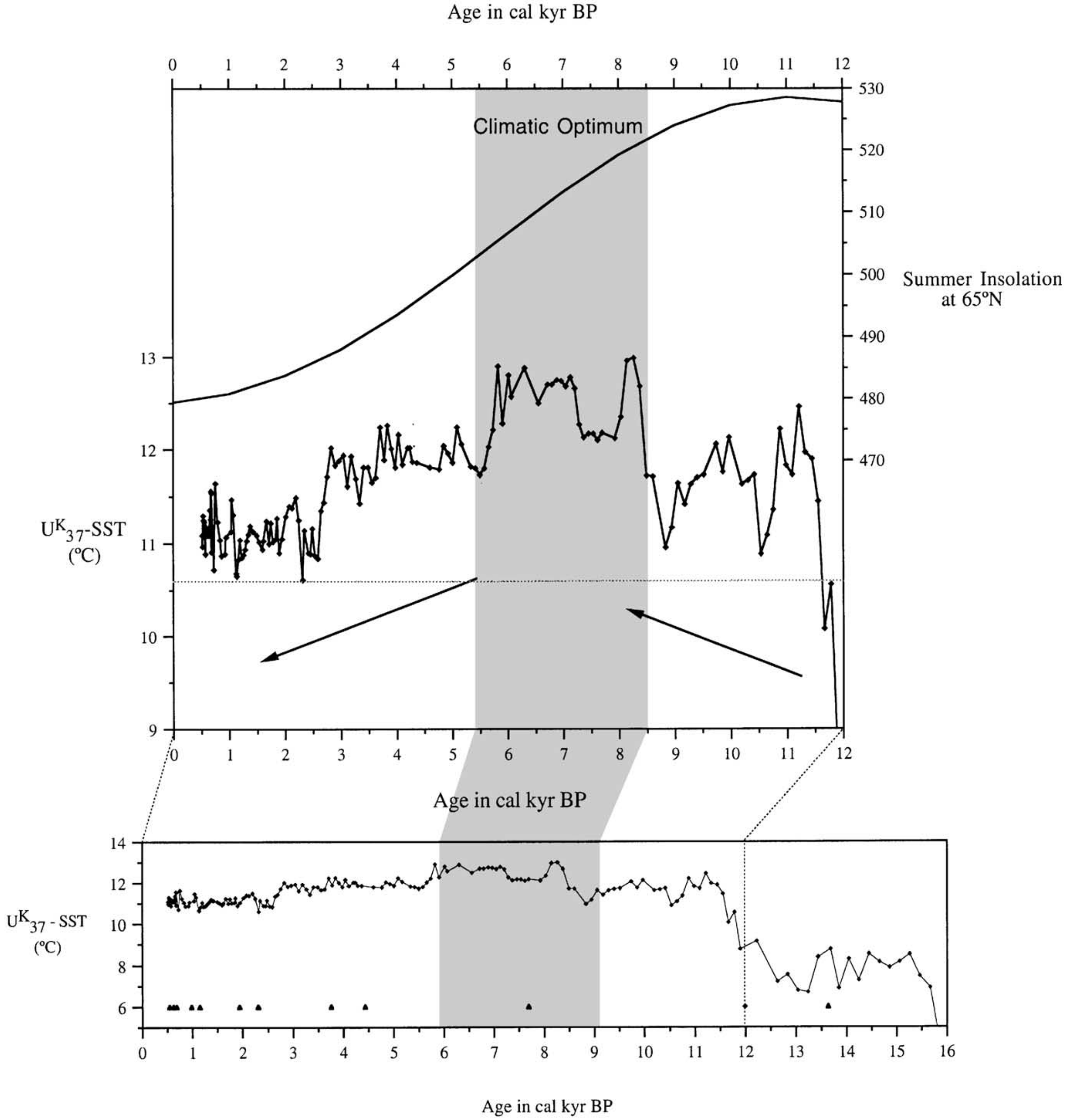

Fig. 3. SST record of core MD952011 together with the summer insolation at 65°N for the last 12 kyr. The warm temperatures of the climatic optimum were registered between 8.5 and 5.5 kyr BP. Horizontal dashed lines represent the modern mean temperatures at core location (Levitus, 1994). ▼ indicates the AMS-^{14}C dates and ◆ shows the age of the Vedde Ash layer.

the whole Holocene and part of the last deglaciation. However, as discussed above, the oldest part of the record (before 11.8 ka) cannot be used for a straightforward measurement of SST due to the high levels of $C_{37:4}$ and the low concentrations of total C_{37} alkenones. In this sense, during this period coccolith abundances in the Vöring plateau and the Norwegian basin have been found to be very sparse, mostly related to ice-rafted Cretaceous coccoliths (Baumann and Matthiessen, 1992; Andruleit and Baumann, 1998). Severe climatic conditions probably occurred in the Norwegian Sea before the Holocene, which, in fact, are in consonance with long periods of sea ice cover as reported by Koç et al. (1993). Coccoliths occurred in high abundance once the inflow of relatively warm Atlantic waters into the Norwegian Sea was fully established, about 11.5 ka ago (Baumann and Matthiessen, 1992; Andruleit and Baumann, 1998). The influence of these warm water masses is also observed in a core from the northeastern Norwegian Sea (Hald and Hagen, 1998). At this site, the planktic foraminifera fauna show warm SST similar to those of the present by about 11 ka, due to a strengthening of the North Atlantic heat conveyor by the end of the last deglaciation. At that time, the SST values recorded in core MD952011 also reached the warm Holocene values characteristic of an interglacial period (11.4°C; Fig. 3).

The SST variability during the Holocene never exceeded 2.6°C, with values ranging from 10.6°C to 13.2°C. The period with the highest temperatures was recorded in the first half, between 8.5 and 5.5 ka BP. The lowest temperatures were recorded during the last 2.6 ka BP. A prominent warming of 2°C occurred 9 ka ago, leading to an SST maximum centered around 8.3 ka BP. The subsequent cooling of 1.5°C starts at 8.1 ka BP and is almost coincident with the pronounced cooling event registered in Greenland (Alley et al., 1997) which, in turn, is also coincident with one of the ca 1500 yr periodic coolings reported by Bond et al. (1997, 1999) in Holocene sediments of the North Atlantic (11.1, 9.5, 8.2, 5.9, 4.3, 2.8 and 1.4 ka BP). In fact, the SST profile in MD952011 is punctuated by coolings that start at 10.8, 9, 8.1, 5.8 and 2.8 ka BP in coincidence, within the dating uncertainty, with the above indicated 1500 yr periodic temperature minima which were assumed to be related to changes in the thermohaline circulation of the North Atlantic (Bond et al., 1997, 1999).

These rather abrupt cooling events may reflect two mechanisms, a general cooling of the Nordic Seas high latitude areas by retreat of the northward extension of the oceanic heat flux or E–W movements of the main heat flow axis. This latter type of changes is observed at present as a consequence of shifts in the NAO index, involving the displacement of the Arctic waters towards the eastern Nordic Seas during strong westerlies (NAO+; Blindheim et al., 2000). This millenial variability has also been reported south of Iceland based on measurements of deep water flow strength (Bianchi and McCave, 1999) and on SST variations detected off West Africa, in the subtropical Atlantic (deMenocal et al., 2000) evidencing the coupling between high- and low-latitude climates of the North Atlantic. Moreover, as deMenocal et al. (2000) and Steig (1999) previously suggested, the core MD952011 SST record also detects the increase of Holocene climate variability of recent millennia compared to the early Holocene, although the amplitude of the SST changes is higher for the first half of the Holocene (Fig. 3).

In addition to the short-term SST variability, two distinct trends can be well differentiated between the early and the late Holocene (Fig. 3). Whereas the first half presents a slight warming towards the highest SST values of the record, with two cold phases at 10.5 and 8.8 ka, the late Holocene shows a clear cooling tendency from the warm temperatures of the mid-Holocene towards the present cooler values. The warmest SST were registered during a period, which is often referred to as the Holocene Thermal Optimum, between 5.5 and 8.5 ka BP (Fig. 3). Other marine and continental paleoclimatic studies agree with this observation. Diatom and foraminifera reconstructions in the Nordic Seas (Koç et al., 1993; Sarnthein et al., 1995; Fronval and Jansen, 1996) model simulations of North Atlantic and Arctic paleoclimatic data (Kerwin et al., 1999), together with pollen data (Huntley and Prentice, 1988), and studies on mountain glaciers displacements (Nesje and Kvamme, 1991) have shown warmer climatic conditions during the early mid-Holocene than the present. More evidences of this climatic optimum are also observed in Greenland ice core reconstructions based on borehole thermometry (2.5° warmer than today at 5–8 ka BP) (Dahl-Jensen et al., 1998) and melt layers (Alley and Anandakrishman, 1995).

Despite the warmest SST displayed between 5.5 and 8.5 ka, typical Holocene SST values have already been recorded well before this period, during the end of deglaciation and the very early Holocene (Fig. 3). Between 11.5 and 9 ka, Andruleit and Baumann (1998) reported an early maximum in coccolithophore numbers in cores of the eastern Norwegian Sea, which would support the warm values obtained for this period in our core. In addition, diatom data from a core located very close to ours (HM79-6/4, 63°N, 2°E) showed typical Holocene SST values around 11.5 ka after a rapid and drastic temperature increase (Koç et al., 1996; Koç-Karpuz and Jansen, 1992). At that time, a drastic change in climatic conditions was inferred by an important inflow of warm Atlantic waters along the eastern margin and the retreat of the polar front towards the Greenland coast (Koç et al., 1993). On the other hand, around 11 ka, summer insolation at high latitudes of the Northern Hemisphere was at its maximum (Berger, 1978; Fig. 3) pointing to a nearly simultaneous response of the high latitudes areas to orbitally induced changes in solar radiance (Imbrie et al., 1992). Despite this early response of site MD952011 to changes in summer insolation, the highest SST estimations are recorded right after the insolation maximum. This delay of the surface water response to changes in summer insolation is probably linked to the evolution of the thermohaline circulation.

Likewise, the progressive SST cooling during the late Holocene in core MD952011 responds to the decreasing summer insolation due to orbital changes. These colder climatic conditions are in agreement with the paleoceanographic reconstructions of Koç et al. (1993) showing an important drop in SSTs around 5.5 ka BP. However, besides Milankovitch forcing, changes in oceanic heat transport, strongly linked to changes in the production of NADW, are also important for the understanding of this cooling (Alley et al., 1999). Ice core data and model simulations point to a decrease in the North Atlantic oceanic heat transport to the Nordic Seas during present times compared to the mid-Holocene (Alley et al., 1999). In agreement with these calculations, reduced inflow of warm Atlantic waters, particularly during the last 3 ka, was concluded in the Greenland, Iceland and Norwegian Seas paleoceanographic reconstructions based on diatoms (Koç et al., 1993), in good harmony with the abrupt 1.2°C cooling at 2.7 ka BP in core MD952011 (Fig. 3).

4. Conclusions

Holocene SST changes in the Norwegian Sea exhibit two distinct trends. The first half (between 5.8 and 12 ka) shows a warming towards the highest values, from 11°C to about 13°C, and the second (between present and 5.8 ka BP) displays a cooling to present-day temperatures, ca. 11°C. This first half has higher SST amplitude changes, about 2°C, and the second, namely the more recent period (from 2.6 ka to present), exhibits more uniform values (variations of ±0.5°C). The warmest SST were registered during the climatic optimum, between 5.5 and 8.6 ka, which is in agreement with other marine and continental paleoclimatic studies in the Nordic Seas and Greenland.

SST evolution follows, on average, the summer insolation curve at these latitudes. In this respect, the sharp increase corresponds to the summer insolation maximum at about 11.5 ka, pointing to the rapid response of high latitudes to orbitally induced changes in solar radiance. Besides Milankovitch forcing, changes in oceanic heat transport strongly linked to changes in NADW formation may also explain the cooling of the recent period.

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