Evidence for a warm Last Glacial Maximum in the Nordic seas or an example of shortcomings in $U^K_{37}{}'$ and U^K_{37} to estimate low sea surface temperature?

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Abstract. The occurrence of ice-free conditions in the Nordic seas during the Last Glacial Maximum has been demonstrated using microfossil and biomarker approaches. An accurate picture of the prevailing oceanographic conditions may be more difficult to ascertain. Thus, uncertainties for most proxies increase at the cold extreme of temperature calibrations and glacial sediments contain small amounts of microfossils and biomarkers. Here we discuss sea surface temperature estimates derived from alkenone indices for the Last Glacial Maximum in the Nordic seas that provide a surprising scenario, where surface temperatures were warmer than at present. We conclude that the $U^K_{37}{}'$ and U^K_{37} estimates may not be interpreted in terms of sea surface temperature as several factors may have conspired to bias the molecular signal. However, using an alternative index based on the abundance of the $C_{37:4}$ alkenone, we estimate a maximum temperature of 6°C.

1. Introduction

It has been assumed for some time that during the Last Glacial Maximum (LGM) a perennial sea ice cover existed on the whole of the northern North Atlantic. This scenario was convincingly described by Climate: Long-Range Investigation, Mapping, and Prediction (CLIMAP) [1976, 1981], and since then climate modelers have been trying to reproduce it in their simulations [e.g., Ganapolski et al., 1998]. However, increasing evidence is being collected, from the analysis of microfossil and chemical proxies in sediment cores, that during the LGM at least seasonally open sea conditions occurred in the Nordic seas (i.e., Greenland, Iceland, and Norwegian Seas) [Hebbeln et al, 1994; Sarnthein et al., 1995; Weinelt et al., 1996; Rosell-Melé and Koç, 1997, Rosell-Melé et al., 1998; de Vernal et al., 1999].

Using transfer functions of foraminifera, it has been argued that summer sea surface temperatures (SSTs) during the LGM in the Nordic seas were between 3° and 5°C, with a prevailing cyclonic surface circulation [Sarnthein et al., 1995; Weinelt et al., 1996]. However, both these results and those from CLIMAP [1976,1981] were obtained using the same basic approach (foraminiferal assemblages transfer functions), albeit with significant variations in the statistical analysis and the number of sediment cores employed, which have led to opposite conclusions. The variance and occurrence of microfossils can also be influenced by dissolution of their skeletons in the water column and within the sediment [Koç et al., 1993; Samtleben et al., 1995]. In addition, the diversity of planktonic foraminifera in subarctic glacial sediments is very low, mainly composed of one species (>97% of Neogloboquadrina pachyderma) [Sarnthein et al., 1995; Weinelt et al., 1996], which restricts the sensitivity for reconstructing different water masses and for obtaining representative SST values [e.g., Bond et al., 1997], as the errors of the reconstruction in the Nordic seas can be as large as 3°C [Weinelt et al., 1996]. Hence it is important to have alternative methods to contrast with the evidence derived from microfossil analyses. In this paper we will discuss the use of alkenone proxies (U^K_{37} and U^K_{37}') [Brassell et al., 1986; Prahl and Wakeham, 1987] to derive SST estimates in sediment cores from the Nordic seas during the LGM.

2. Methods

2.1. Alkenones

The procedures employed to determine alkenone indices have been described in detail elsewhere [Rosell-Melé, 1994; Rosell-Melé et al., 1995b]. Briefly, after retrieval, core samples were generally kept cool, in the dark, before being subsampled at 1-5 cm intervals. Subsamples were freeze dried, weighed (1-2 g), and solvent extracted (dichloromethane/methanol, 3:1 x 3) using a robotic workstation. After solid-phase extraction of the total extracts on silica and subsequent derivatization with bis-(trimethyl-silyl)-trifluoro-acetamide (BSTFA) the C_{37} alkenones (i.e., ketones with 37 carbon atoms) were quantified by gas chromatography-mass spectrometry (GC-MS) with ammonia chemical ionization (CI).

The U^K_{37} and U^K_{37}' indices have been calculated as [Brassell et al., 1986; Prahl et al., 1987]

$$U^K_{37} = \frac{37:2 - 37:4}{37:2 + 37:3 + 37:4} \qquad U^K_{37}' = \frac{37:2}{37:2 + 37:3},$$

where U^K_{37} stands for unsaturated ketones with 37 carbon atoms and 2, 3, or 4 double bonds.

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2.2. Analytical Appraisal of the Data

In view of the very low concentration of alkenones in the samples (<30 ng/g dry weight of sediment) we were concerned that some of the alkenone data might have suffered from a systematic shift toward warmer values. A lower threshold of 100 ng alkenones/g sediment (~10 ng per GC peak area) has been recommended for reliable palaeotemperaure determination (error <0.5°C) [*Villanueva and Grimalt*, 1996]. As this threshold may vary between laboratories and methods, it has not been considered here. For instance, for the chemical ionisation mass spectrometry (CIMS) system this limit could be even lower than 1 ng per peak area [*Rosell-Melé et al.*, 1995b]. Instead, mixtures of the synthetic 37:3 and 37:2 alkenones were prepared at different concentrations and analyzed at the same time as the samples to keep track of the occurrence of any preferential adsorption of the alkenones in the analytical system. In all cores analyzed a bias was observed (e.g., see Table 1), and samples likely to be affected by more than $\Delta U^K_{37}'{=}0.03$ (~ 1°C) were reanalyzed or reinjected in the GC.

For our sample set, reliable alkenone data could only be obtained with the CIMS technique, unless a larger amount of sediment (>5g) was used, which was not usually possible because of limited sample availability. The CIMS method also allowed quantification of the 37:4 alkenone with a similar precision as the other members of the U^K_{37} index because each peak was integrated from its mass chromatogram and a comparable snr was obtained [*Rosell-Melé et al.*, 1995b]. In this case the relative errors of both U^K_{37} and U^K_{37}' are comparable. It may be the case that the 37:4 alkenone may increase the relative error of U^K_{37} as compared to U^K_{37}' [*Sikes et al.*, 1997], but the difference is not likely to be climatically significant.

2.3. Age Model and Selection of Time Slices

Details on accelerator mass spectrometry (AMS) ^{14}C measurements and identification of ash layers and tie points in the $\delta^{18}O$ curve to obtain the depth/age model for each core (Table 2) have been described elsewhere [*Sarnthein et al.*, 1995; *Weinelt et al.*, 1996]. The time slices have been selected following the approach and rationale of *Sarnthein et al.* [1994, 1995], and biomarker data have been averaged within the time interval corresponding to the LGM (18.5-21.2 cal kyr).

Table 1. Results From the Analysis of Alkenone Standards Used As Controls During the Analysis of Core Samples

	Concentration, ppm	U^K_{37}'	T, °C
expected value		0.38	10
	0.32	0 41	11
	0.64	0 42	11
	1 27	0.41	11
	1 27	0 38	10

Temperatures are calculated using the equation of *Prahl et al.* [1988]. Concentration (ppm) is equivalent to ng/mL injected in the gas chromatograph of total triunsaturated and diunsaturated alkenones.

Table 2. Coordinates and Water Depth of Locations Shown in Figures 2 and 3

Core	Latitude	Longitude	Depth, m
M17725	77°28'N	4°35'E	2580
M17728	76°31N	3°57'E	2485
M17724	76°N	8°20'E	2354
HM94-34	73°46'N	2°23'W	3004
M23294	72°22'N	10°36'W	2224
M23260	72°08'N	11°27'E	2084
M23269	71°27'N	0°40'E	2872
M17732	71°37'N	4°13E	3103
M1171-1	67°59'N	18°32' W	850
M23068	67°50'N	1°30'E	2230
M23074	66°40'N	4°55'E	1157

3. Results

We have measured both U^K_{37} and U^K_{37}' in the glacial samples, although for the area considered, U^K_{37}' shows a more equivocal correlation with SST than U^K_{37} [*Rosell-Melé et al.*, 1995a; *Rosell-Melé*, 1998]. U^K_{37} in core tops from the Nordic seas show a general agreement with overlying water temperatures, but some important discrepancies exist (Figure 1). These may be partly due to the type of water masses in the area and their influence on the biosynthesis of alkenones [*Rosell-Melé et al.*, 1998], lateral advection of resuspended sediments [e.g., *Andruleit*, 1997], and the uncertainty associated with assigning temperature and salinity values from a database to a particular location. Using sediment traps in the Nordic seas, *Flügge* [1997] has shown that the temperature of the mixed layer during the maximum production season (summer) is preserved in the U^K_{37} of sinking particles and transferred to the surface sediments.

The presence of alkenones in the Nordic seas during the LGM has been previously demonstrated and could be taken as an indication of ice-free marine conditions [*Rosell-Melé and Koç*, 1997]. In Figure 2 both U^K_{37} and U^K_{37}' SST estimates in the LGM time slice are mapped. U^K_{37} temperatures are always colder than U^K_{37}' estimates because the abundance of 37:4 is between 4 and 10% of the total abundance of C_{37} alkenones (Figure 3). Thus 37:4 abundance is large enough to increase significantly the difference between estimates of both indices by ~2 °C, even for U^K_{37}' estimates above 10°C. This relationship between U^K_{37} and U^K_{37}' is unlike the one found in modern surface sediments, and the abundance of the 37:4 alkenone appears to be higher in the LGM samples compared to modern surface sediments in the Nordic seas for a given value of U^K_{37}' [*Rosell-Melé et al.*, 1994; *Rosell-Melé*, 1998]. The large difference in the estimates from U^K_{37} and U^K_{37}' is also related to some extent to the calibration equations employed, which are different for each proxy. U^K_{37} values have been converted to SST using the equation derived from North Atlantic sediment core tops [*Rosell-Melé et al.*, 1995a] corresponding to annual values at 0 m depth, whereas for U^K_{37}' we have used the *Prahl et al.* [1988] equation based on algal cultures of *Emiliania huxleyi*. *Müller et al.* [1998] have shown that this equation, however, can also be obtained using core tops of the global ocean. For the range of values in the samples the equation of *Rosell-Melé et al.* [1995a] provides colder estimates, by ~2°C, than if the *Prahl et al.* [1988]
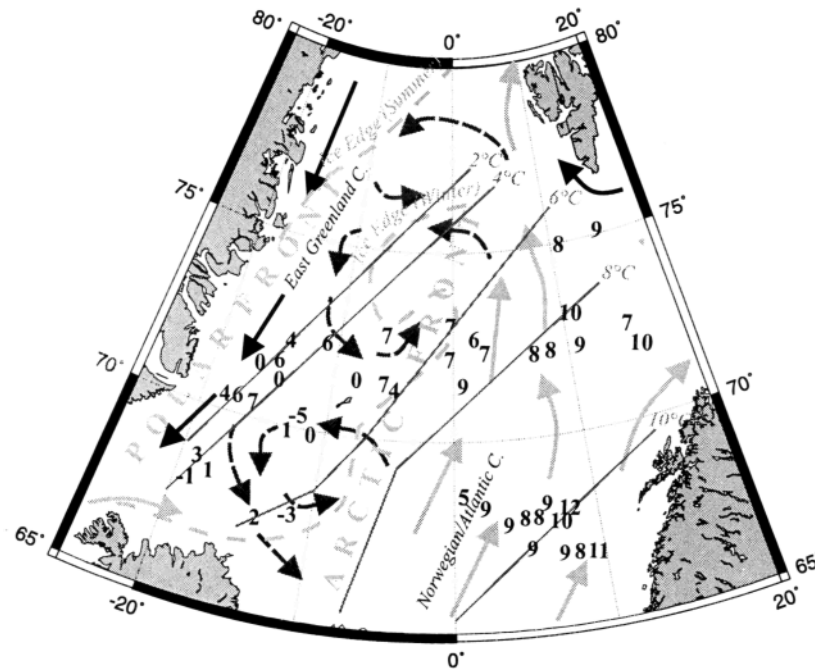
Figure 1. Map of the Nordic seas with modern surface current patterns, with black arrows corresponding to polar waters, shaded arrows corresponding to Atlantic waters, and dashed arrows corresponding to Arctic waters. Black numerals are data on U^K_{37} from core tops transformed into temperature values using the calibration equation of *Rosell-Melé et al.* [1995a] corresponding to annual values at 0 m depth. The sketchy isolines of temperature are drawn as an approximation of the August monthly data from the *Reynolds and Smith* [1995] climatology.
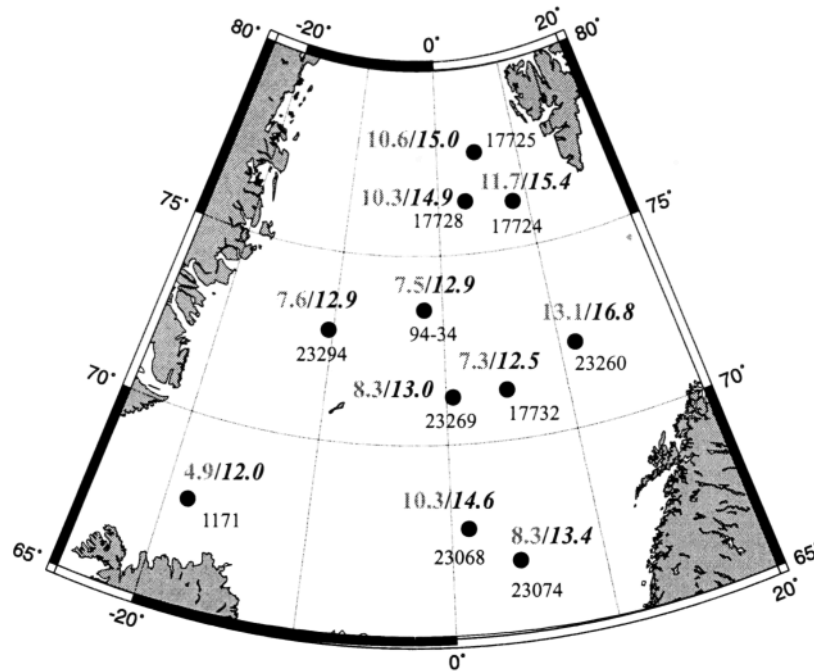

Figure 2. Estimates of sea surface temperature for the Last Glacial Maximum derived from U^K_{37} (shaded) using the calibration equation of *Rosell-Melé et al.* [1995a] corresponding to annual values at 0 m depth, and derived from U^K_{37}' (black) using the calibration equation of *Prahl et al.* [1988] from algal cultures. The corresponding core number is indicated next to each location (coordinates and water depth in Table 2).
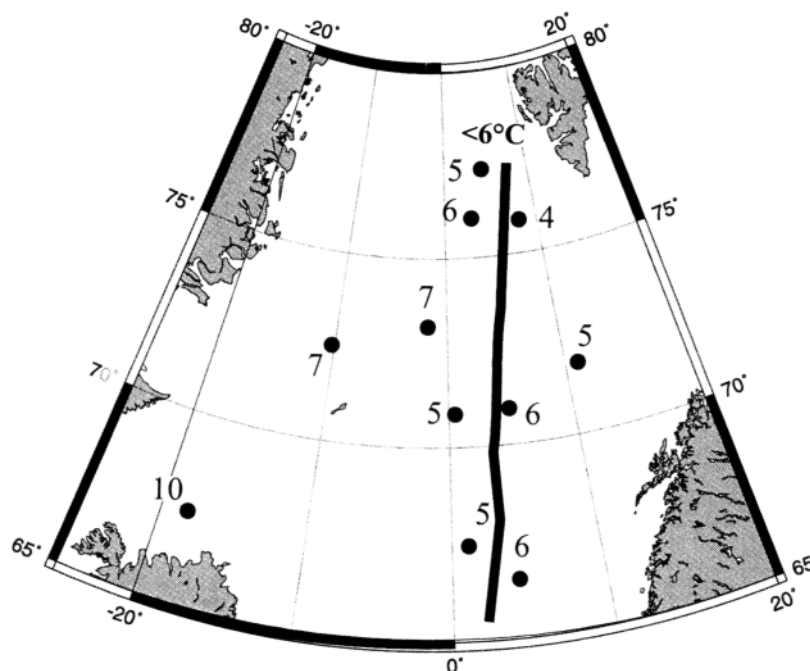
Figure 3. Data for each sediment core location (Table 2) corresponding to values of the relative abundance of the tetraunsaturated C_{37} alkenone (37:4) to the total of C_{37} alkenones (37:4%) for the Last Glacial Maximum time slice. The back line depicts an approximate isotherm of maximum sea surface temperature.

equation had been used for U^{K}_{37}. In contrast, the equation corresponding to summer temperatures at 0 m depth from the North Atlantic core-top compilation yields estimates (not shown) that are very close to those from the *Prahl et al.* [1988] equation. In any case the estimates from U^{K}_{37}, obtained using any of the above equations, are still several degrees lower than the estimates from U^{K}_{37}' (Figure 2).

The temperature range of the U^{K}_{37}' estimates in Figure 2 is 12.0°-16.8°C, which is much higher than the estimates of ~3°-5°C for glacial summers derived from foraminiferal transfer functions [*Sarnthein et al.*, 1995; *Weinelt et al.*, 1996], and in fact they are even higher than modern SST values (see Figure 1) [*Reynolds and Smith*, 1995]. SSTs derived from U^{K}_{37} are in the range of 4.9°-13.1°C, lower than those from U^{K}_{37}', although still generally warmer than modern SSTs, especially for the northernmost samples (Figure 1), and much warmer than those indicated by the data from *Sarnthein et al.* [1995] and *Weinelt et al.* [1996]. The alkenone data seem to be anomalously high, providing warmer glacial than interglacial SSTs. The SST gradient is also difficult to understand (Figure 2), with increasing temperatures toward the northeast, i.e., the Barents Shelf/Spitsbergen, rather than toward the southeast. The distribution of U^{K}_{37}/U^{K}_{37}' SST estimates (Figure 2), if considered representative of the circulation during the LGM in the Nordic seas, would thus reflect a situation very different from that in the modern oceanographic regime (see Figure 1) and certainly difficult to comprehend. In view of these results it is easy to conclude that certainly U^{K}_{37}' and probably U^{K}_{37} are not suitable to estimate SST in the LGM in the area studied. However, SST estimates from dinoflagellate transfer functions are similar in magnitude to those of U^{K}_{37}/U^{K}_{37}' [*de Vernal et al*, 1999]. The similarity between the absolute values of SST (~15°C for the

eastern Nordic seas) from these two independent proxies is remarkable, but it could be a coincidence. Conversely, it does not seem justified to give more credibility to the estimates from foraminifera transfer function approaches [*Sarnthein et al.*, 1995; *Weinelt et al.*, 1996] solely on the basis that as they are colder, the SSTs make more sense.

4. Discussion

Reasons for possible anomalous "warm" U^{K}_{37} and U^{K}_{37}' data can be diverse.

4.1. Analytical Bias

Alkenone data may be biased toward high values because components are in too low abundance (less than 30 ng/g dry sediment) to be measured accurately. Hence coelution of the alkenones with minor components during GC analysis and/or preferential adsorption of the more unsaturated components in the analytical system may have occurred [*Rosell-Melé et al.*, 1995b; *Villanueva and Grimalt*, 1996]. However, as described in section 2, sample data have been contrasted with standards used for reference, and analytical errors are not larger than 1°C. Moreover, the mass spectrometric method employed to quantify the alkenones precluded coelution problems [*Rosell-Melé et al.*, 1995b]. Hence the large magnitude of U^{K}_{37} and U^{K}_{37}' in Figure 1 is dependent on environmental rather than analytical factors.

4.2. Failure of the Modern Analog

In cold and relatively low salinity environments, when the relative abundance of the tetraunsaturated component is enhanced, the temperature dependences of U^{K}_{37} and U^{K}_{37}' is equivocal [*Conte et al.*, 1994; *Ficken and Farrimond*, 1995;

Rosell-Melé, 1998]. In fact, the Nordic seas already appear as an area where the temperature dependence of the alkenones is not as evident as in other oceanic locations, for instance, in comparison to the global compilation of *Müller et al.* [1998]. This situation may have been aggravated during the LGM because the type of surface water mass throughout the Nordic seas was equivalent to that of the present Arctic domain rather than the Atlantic domain in the east [*Weinelt et al.*, 1996]. In this situation the relative abundance of 37:4 to the abundance of C_{37} alkenones (37:4%) is larger than 5% [*Rosell-Melé*, 1998], and $U^K_{37}{}'$ does not correlate with SST. In the Nordic seas data set for the LGM the percentages of 37:4 are larger than or equal to 5% for all locations except one, which is 4% (Figure 3). Hence the relatively high abundance of 37:4 in the samples could indicate that $U^K_{37}{}'$ and U^K_{37} are not reliable as SST proxies. Nevertheless, the SST estimates derived from $U^K_{37}{}'$ are much higher than those found currently in the Nordic seas for similar values of 37:4%, which suggests that perhaps additional factors might also be responsible for the high $U^K_{37}{}'$ values in Figure 2.

4.3. Diagenesis

It is sometimes argued that the alkenone ratio may be biased toward warmer values during deposition because of preferential degradation or incorporation into macromolecular organic matter of the components with more double bonds (37:4>37:3>37:2) [*Freeman and Wakeham*, 1992; *Flügge*, 1997; *Hoefs et al.*, 1998]. Such diagenetic bias could thus be more important when estimating cold SST. However, the importance of the diagenetic bias may have sometimes been overemphasized and mistaken for analytical biases [*Grimalt, J., C. Pelejero, E. Calvo, E. Bard, A. Rosell-Melé, P. Müller, and R. Schneider*, Changes in $U^K_{37}{}'$ sea surface paleotemperature due to measurements close to C_{37} alkenone limit of detection, submitted to *Paleoceanography*, 1999], and in fact, some authors have not found much cause for concern regarding diagenesis [*Prahl et al.*, 1989; *Teece et al.*, 1998]. *Flügge* [1997] has estimated from two incubation experiments of *E. huxleyi* and sediments that 37:3 degrades 2-3% faster than 37:2 and 37:4 degrades 5-20% faster than 37:2, which may explain an observed increase of U^K_{37} with depth within the first 3-5 cm below the sediment surface in the Norwegian Sea [*Flugge*, 1997]. During these experiments, however, $U^K_{37}{}'$ varied by $\Delta U^K_{37}{}' = 0.04$ and 0.07 from the start of the experiment until the point when no more alkenones were being degraded. These variations would represent a potentially significant bias in the sedimentary alkenone data of $\sim 1°-2°C$ due to a relative preferential removal of $\sim 25\%$ more 37:3 than what it is left of 37:2. $U^K_{37}{}'$ values in the glacial sediments appear more than just 2°C too warm, and in comparison to foraminiferal-based estimates or modern SST values the difference is of several degrees Celsius. To account for a diagenetic bias of 6°C or more, for instance, at least $\sim 56\%$ more 37:3 than what it is left of 37:2 should be preferentially removed from the sediment, and so far, this has not been observed in any experiment or study on sediments from depositional conditions analogous to those occurring in the Nordic seas. Hence this suggests that by itself, diagenesis is not enough to explain the warm $U^K_{37}{}'$ and U^K_{37} signal.

4.4. Advected Signal

During the LGM the Nordic seas probably experienced an extreme seasonality, with winter sea ice giving way to a brief

summer melting, as southern warm waters penetrated the area [*Hebbeln et al.*, 1994; *Sarnthein et al.*, 1995; *Weinelt et al.*, 1996; *Rosell-Melé and Koç*, 1997, *Rosell-Melé et al.*, 1998]. Thus the possibility exists that alkenones in the Nordic seas were deposited after being advected by oceanic currents similar to the present North Atlantic drift/Norwegian Current, having been biosynthesized in warmer southern waters. However, warmer SST-$U^K_{37}{}'$ values occur in the northeastern rather than the southeastern area of the basin, which would imply that if there was an advected input, this came principally from the Arctic, not the Atlantic, region. Furthermore, the major type of planktonic foraminifera co-occurring in sediments with the alkenones (>97% of *N. pachyderma*) predominantly live in waters colder than 8°C [*Wu and Hillaire-Marcel*, 1994]. $U^K_{37}{}'$-SST are much warmer than this (Figure 2), so the advection mechanism discussed here cannot account by itself for the anomalously warm signal. Moreover, the uniform values of SST estimated from foraminiferal transfer functions, the abundance values of foraminifera [*Sarnthein et al.*, 1995; *Weinelt et al.*, 1996], and the 37:4% over the northeast Atlantic and the Nordic seas [*Rosell-Melé et al.*, 1998] during the LGM indicate that there was a weak latitudinal heat advection, and thus weak surface currents may be inferred.

4.5. Input of Reworked Alkenones

In the NE Atlantic, higher $U^K_{37}{}'$-SST estimates than those from foraminiferal transfer functions, between 25 and 13 ka, co-occur with enhanced inputs of reworked Cretaceous and Paleogene nannofossils and peak delivery of ice-rafted debris [*Weaver et al.*, 1999]. This observation led Weaver et al. to hypothesize that ice-rafted allochthonous alkenones overprinted the local surface water alkenone signal, biasing $U^K_{37}{}'$. The LGM is a period characterized by the deposition of high amounts of ice-rafted debris in the sediments of the North Atlantic [*Ruddiman*, 1977]. The debris can also contain a significant amount of "terrigenous" (i.e., allochthonous) organic material, especially in the Nordic seas, where allochthonous glaciomarine sediment (coal and black shale) is related to high total organic contents in the sediments coming from the eastern Norwegian Sea. In there Jurassic-Cretaceous organic-rich sedimentary rocks crop out along the continental shelves of the Barents Sea, the Arctic borderlands, and the Norwegian Shelf [*Wagner*, 1993; *Wagner and Henrich*, 1994], which can leave a distinct mature biomarker signal in the sediments [*Rosell-Melé and Maxwell*, 1996; *Rosell-Melé and Koç*, 1997]. The possibility exists therefore that pre-Quaternary C_{37} alkenones present in organic-rich shales underlying ice caps were transported by icebergs and added to the pool of organic components present in LGM sediments, as also argued by *Weaver et al.* [1999]. Alkenones (as free, solvent soluble lipids) have been reported even in Eocene and Cretaceous sediments [see *Brassell*, 1993] and occur continuously in marine sediments throughout the Quaternary and at least since the early Miocene [*Boon et al.*, 1978; *Haug*, 1996]. The presence of Tertiary and Cretaceous coccoliths in glacial sediments from the North Atlantic seems to endorse this hypothesis [*Rahman*, 1995; *Weaver et al.*, 1999]. Allochthonous, ice-rafted alkenones would most probably contain a warm signal associated with pre-Quaternary climates and, as found in the few organic-rich shales reported to contain alkenones [e.g., *Farrimond et al.*, 1986], be dominated by diunsaturated

components. This could explain the warm U^K_{37}' distribution in Figure 2, the product of the combination of autochthonous (with probably a cold signal, SST <10°C) and allochthonous alkenones (warm signal, SST~30°C?). The sedimentary concentration of the alkenones is low, <30 ng/g. An input of an equivalent amount of ice-rafted alkenones with U^K_{37}'=1 would increase a presumed U^K_{37}' autochthonous signal of U^K_{37}'=0.2 (~5°C) to 0.6 (~16°C) and decrease the percentage of 37:4 from an expected 10 to 5%, as found in the samples (Figures 2 and 3). Furthermore, the north-south gradient of SST (Figure 2) may indicate the source of allochthonous alkenones as principally coming from the Barents Sea continental shelf. However, neither we nor *Weaver et al.* [1999] have direct proof of the hypothetical presence of "ancient" allochthonous alkenones. Conversely, the presence of 37:4 alkenone in the sediments (Figure 3) shows that autochthonous C_{37} alkenones are present in the sediment, that is, assuming that an input of allochthonous alkenones will not contain 37:4 because the occurrence of this component in marine samples relates to a cold rather than a warm signal. There is no evidence either to date that alkenones are present in any of the organic-rich shales that may be the source of the ice-rafted debris, or that they are associated to allochthonous coccoliths, so further work needs to be done to discard or prove the presence of ancient allochthonous alkenones in LGM sediments. The origin of the LGM alkenones could be found out by looking at the ^{14}C composition of the components and determining if they are substantially older than the LGM time interval. However, the sedimentary abundance of alkenones is very low, and it may be difficult to isolate enough pure material to carry out the isotopic analysis. A simpler, less costly alternative would be to look at the range of alkenone chain lengths, as ancient alkenones appear to have a larger abundance of C_{39} and C_{40} components [*Farrimond et al.*, 1986] than their contemporary counterparts. If, indeed, it is shown that reworked allochthonous alkenones are mixed with the local signal, then large parts of the glacial ocean with substantial ice-rafted debris (IRD) inputs will be affected, and the reconstruction of SST estimates from U^K_{37}' may be challenging. It will all depend, however, on the amounts of IRD in the sediments (as small contributions may not bias the signal significantly) and the sources and their relative mixing (as some IRD may be alkenone-rich and some may not contain any alkenones at all).

Thus the causes for such warm SST values in Figure 1 remain unclear. From the second and fourth points above, however, there are enough reasons to suspect that the U^K_{37}' and U^K_{37} data cannot not be relied upon. If we assume that allochthonous alkenones (mainly the diunsaturated component) have biased the alkenone indices, the autochthonous signal will be better represented by the 37:4 component, in this case the distribution of 37:4%, which does not show the same patterns as U^K_{37}' (Figures 2 and 3). Could 37:4% be used to obtain an estimate of SST? Not directly, as 37:4% might have been originally higher, as shown in Figure 2, if allochthonous alkenones diluted the marine autochthonous signal, and when 37:4% > 5%, 37:4% is not temperature-dependent [*Rosell-Melé*, 1998]. In fact, the distribution of 37:4% in the LGM samples (Figure 3) is not too dissimilar to that found in the modern surface sediments [*Rosell-Melé*, 1998] except (1) the values are higher in the east; that is, there is more 37:4 relative to the total of C_{37} ketones in the LGM than at present; (2) 37:4% is lower in the west than in present

surface sediments, i.e., less 37:4; and (3) the longitudinal and latitudinal gradients of 37:4% are not so pronounced as at present. From these 37:4% data it can be inferred that Arctic domain-type waters prevailed throughout the Nordic seas during the LGM as the 37:4% values are in the range of those found at present under Arctic domain waters. Thus it does not seem likely, from the alkenone data, that warmer and more saline southern Atlantic waters (with low 37:4%) [*Rosell-Melé*, 1998; *Rosell-Melé et al.*, 1998] reached the area, in agreement with the conclusions of *Sarnthein et al.* [1995] and *Weinelt et al.* [1996]. However, interpretation of palaeocirculation is limited as the geographical distribution of 37:4% can be due to both oceanographic conditions and hypothetical dilution of the alkenone signal by ice-rafted alkenones from a predominantly eastern source. Nevertheless, in the Arctic domain region of the Nordic seas, in modern sediments, when 37:4% ≥ 5%, then SST is approximately ~≤6°C [*Rosell-Melé*, 1998]. Thus a maximum SST of 6°C for the Nordic Seas can be inferred from 37:4%, which corresponds to the highest temperature of an Arctic water mass and a value not too dissimilar from the estimates of *Sarnthein et al.* [1995] and *Weinelt et al.* [1996] obtained using foraminifera transfer functions.

5. Conclusions

Sea surface temperature estimates derived from alkenone indices (U^K_{37}' and U^K_{37}) provide a surprising picture of the Last Glacial Maximum in the Nordic seas, with surface temperatures warmer than at present. We conclude that the alkenone estimates cannot be taken at face value and that one or more factors may have conspired to bias or modify significantly the molecular signal. One factor is that the oceanographic conditions in the Nordic seas during the Last Glacial Maximum were equivalent to those found in modern waters belonging to the Arctic domain and hence seasonally ice free. In this case, U^K_{37}' and U^K_{37} do not relate to water temperature. An additional factor may be the hypothetical presence of allochthonous, ice-rafted, ancient alkenones incorporated in the glacial sediments masking the autochthonous molecular signal [*Weaver et al.*, 1999]. The allochthonous alkenones might contain a warm signal that might have forced U^K_{37}'/U^K_{37} to much higher values. Although confirmation is required, we would urge caution on the interpretation of alkenone-derived palaeotemperatures in sediments with high concentrations of ice-rafted debris. However, the presence of an autochthonous signal can be inferred from the widespread occurrence of the tetraunsaturated alkenone. The relative abundance of 37:4 allows us to estimate a maximum temperature for the Nordic seas during the Last Glacial Maximum of, at most, 6°C, which is similar to, or within the error range of previous estimates derived from foraminiferal transfer functions [*Sarnthein et al.*, 1995; *Weinelt et al.*, 1996].

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