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Precessional forcing of productivity in the North Atlantic Ocean

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Abstract. The sedimentary C_{37} alkenone fluxes in core SU90/08 situated in the North Atlantic (43°N) showed that export productivity related to some Haptophyta was driven by precession (1/23 kyr^{-1}) in the last 260 kyr during the glacial periods. In the interglacial stages these alkenones were strongly depleted. This different behaviour is attributed to the displacement of Ekman pumping to lower latitudes and to thermocline stability decreases in the glacial periods. The alkenones were coherent and nearly phased with boreal winter insolation, suggesting a link between productivity and the strength of the westerlies. They were also coherent with the precessionally driven nutriocline minima and winter sea surface temperature in the equatorial Atlantic Ocean. The combination of the measurements at these different latitudes point to a strong coupling in the dynamics of the Hadley and Ferrel cells and to a dominant North Atlantic modulation of marine productivity to precession during the glacial stages.

1. Introduction

Marine productivity has been proposed to be one of the funda-mental factors determining CO_2 transport from atmosphere to deep sea waters and sediments [*Broecker*, 1982; *Shackleton et al.*, 1983; *Mix*, 1989]. This process has been referred as the "biological pump" by which CO_2 is removed from surface waters by algal in-take and transported to deep levels in the form of sinking organic particles. Unfortunately, whereas the atmospheric CO_2 record during the last glacial-interglacial cycles has been well determined from the studies of the ice-trapped air [*Neftel et al.*, 1982; *Barnola et al.*, 1987], the changes in marine productivity are still far from being described with accuracy. Several studies have shown that productivity was higher during the last glacial maximum than in the Holocene [*Boyle*, 1986; *Sarnthein et al.*, 1987; *Berger et al.*, 1989], but the aspects determining its evolution, particularly those concerning the interaction with climatic forcing, are poorly under-stood. One difficulty of getting insight into this question is the scarcity of continuous marine productivity records that can be used for orbital frequency analysis.

Organic carbon models [*Müller and Suess*, 1979; *Berger and Herguera*, 1992; *Sarnthein et al.*, 1992; 1981; *Mix*, 1989] and studies on foraminiferal populations [*Mix* 1989; *Herguera and Berger*, 1991; *Thomas et al.*, 1995] have been used to estimate paleoproductivity changes in glacial and interglacial periods. These proxies have provided interesting results. However, their usefulness is constrained by problems such as interferences from terrigenous sources (organic matter [*Villanueva et al.*, 1997a]) or complex food webs (foraminifera).

In the present paper we use two direct algal biomarkers for productivity measurements, heptatriaconta-8,15,22-trien-2-one ($C_{37\,3}$) and heptatriaconta-15,22-dien-2-one ($C_{37\,2}$). These com-pounds are the major homologues of a complex distribution of C_{37}-C_{39} diunsaturated and triunsaturated methyl and ethyl ketones that are uniquely synthesized by some Haptophyta [*Volkman et al.*, 1980a; *Marlowe et al.*, 1984]. In the Holocene the predomi-nant synthesizing species is *Emiliania huxleyi* [*Conte and Eg-linton*, 1993; *Marlowe et al.*, 1990], constituting ~8% of the total organic carbon (TOC) in living cells [*Prahl et al.*, 1988]. The sedimentary fluxes of these alkenones can be used to measure the changes in organic matter remains from some species of Hapto-phyceae algae accumulated in the underlying sediments. The ex-port productivity due to this class of algae can therefore be deter-mined from these fluxes.

The high-resolution study of these compounds in a core situ-ated in the subtropical gyre of the North Atlantic (SU90/08, Figure 1) has allowed the elucidation of the influence of orbital cyclicities in the productivity changes of this area along the last two glacial-interglacial periods. The results obtained parallel other independ-ent measurements such as the ice core accumulation rate of non-sea-salt sulphate (nss-SO_4^{2-}) in the Vostok ice core (Antarctica [*Legrand et al.*, 1988]).

2. Materials and Methods

2.1. Stratigraphy

Core SU90/08 was retrieved in the central North Atlantic (43°30'N 30°24'W). Reference ages between 0 and 64 kyr were determined using 10 accelerator mass spectrometry (AMS) ^{14}C date measurements, ash layer 2 level (55 kyr [*Ruddiman and Glover*, 1972]) and the transition age between isotopic stages 4/3. The AMS ^{14}C dates were determined on monospecific samples of *Neogloboquadrina pachyderma (sp.) and Globigerina bulloides* and were corrected for the ocean reservoir effect of 400 years [*Bard*, 1988]. Chronostratigraphic control of deeper levels was

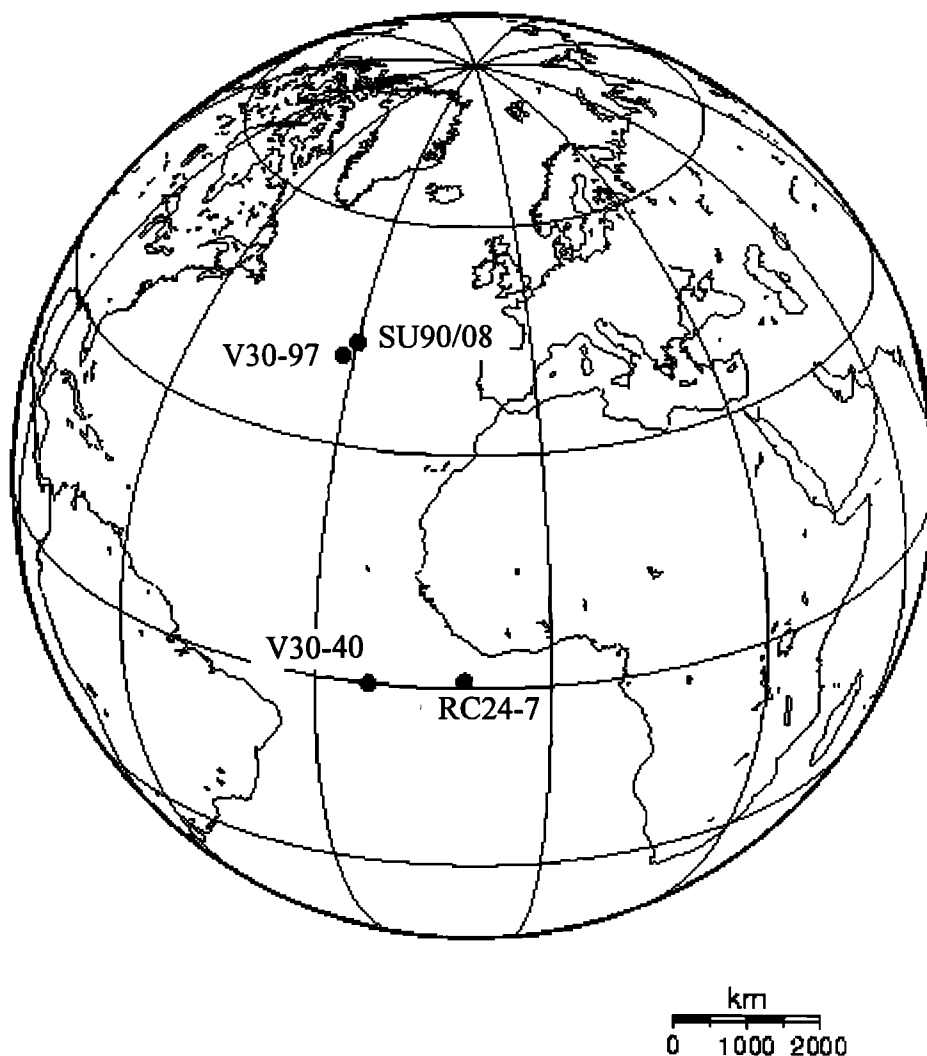[1]Also at Department of Earth Sciences, Université Paris-Sud Orsay, 91405 Orsay, France.

Figure 1. Map showing the location of the cores indicated in this study.

determined by correlation of the benthic $\delta^{18}O$ record of *Cibicides wuellestorfi* with the SPECMAP normalized isotope curve [*Martinson et* al. 1987]. The complete age-model construction is reported elsewhere [*Cortijo et al.*, 1997; *Vidal et al*, 1997]. Ages are expressed in radiocarbon dates. This core has not turbiditic episodes and exhibits regular sedimentation rates. A detailed stratigraphic description is given by *Grousset et al.* [1993].

2.2. Core Sampling and Analysis

Alkenone analysis was performed every 2 cm in the top 7 m (average resolution 440 years) increasing to 1 cm at all profile discontinuities. Between 7 and 12 m the sampling rate was 10 cm (average resolution 2000 kyr). In all cases the samples were collected in sections of 0.5 cm (~ 55 years).

A detailed description of the analytical methods is given by *Villanueva and Grimalt* [1997] and *Villanueva et al.* [1997b]. Sediment samples were freeze-dried and manually grounded for homogeneization. Then they were extracted in an ultrasonic bath with dichloromethane. The evaporated extracts were digested in 6% methanolic potassium hydroxide, and nonacidic compounds were recovered by extraction with *n*-hexane. The acidic fractions

were recovered by acidification with 6N hydrochloric acid and re-extraction with *n*-hexane. These extracts were derivatized overnight with 10% methanolic boron trifluoride and were used to calculate the concentrations of *n*-octadec-9-enoic acid ($C_{18\,1}$) and *n*-octadecanoic acid ($C_{18\,0}$) which can be used to compile a fatty acid preservation index (FAPI: $C_{18\,1}/(C_{18\,0} + C_{18\,1})$)

Prior to instrumental analysis all extracts were derivatized with bis-trimethylsilyl-trifluoroacetamide (BSTFA) at room temperature. These extracts were analyzed by gas chromatography (GC) in a Varian Model 3400 equipped with a septum programmable injector (SPI), a flame ionization detector, and a CPSIL-5 CB (Chrompack, Middleburg, Netherlands) capillary column (length 50 m, i.d. 0.32 mm) coated with 100% dimethylsyloxane (film thickness 0.25 µm). Selected samples were also analyzed by GC coupled to mass spectrometry (GC-MS) using a Fisons MD-800 instrument. Spectra were obtained in the electron impact mode (70 eV) through scanning from mass 50 to 550 every second.

2.3. Figures of Merit

The quantitative determinations of C_{37} alkenones and *n*-alkanes were performed in triplicate. All calculations were performed us-

ing the mean values. Absolute concentration errors of these lipids were below 10%. U^k_{37} and FAPI errors were below 0.015 and 0.01, respectively.

2.4. Time Series Analysis

Time series were studied with the Analyseries program [Paillard et al., 1996] using Fourier transforms and the Blackman-Tuckey method. Correlation studies with core RC2407 data were performed using the data provided by A. McIntyre. Prior to calculation minor corrections of age scale were performed by cross comparison of the $\delta^{18}O$ G. bulloides record with that of SU90/08 (Figure 2).

3. Results

The total C_{37} alkenone fluxes downcore SU90/08 range between 9.5 and 0.2 μg cm^{-2} kyr^{-1} (Figure 2), but they decrease further in the Holocene section and during the episodes of massive inputs of ice rafted detritus, the so-called Heinrich events [Heinrich, 1988]: H1, H2, H4, and H5 [Grousset et al., 1993]. These sedimentary fluxes are intermediate between other values found in oxic sedimentary environments from diverse open ocean sites. Thus C_{37} alkenone fluxes of 0.25 and 0.33 μg cm^{-2} kyr^{-1} are found in the northeast and central equatorial Pacific Ocean, respectively [Prahl et al., 1989, 1993], and high productivity zones such as the Maldives Islands area exhibit C_{37} alkenone sedimentation rates between 1 and 20 μg cm^{-2} kyr^{-1} [Rostek et al., 1994]. These values are significantly lower than those found in marine basins where anoxic or dysoxic depositional conditions predominate. In these cases the C_{37} alkenone sedimentation fluxes range between 200 and 1200 μg cm^{-2} kyr^{-1} [Sun and Wakeham, 1994; McCaffrey et al., 1990; Summerhayes et al., 1995].

The low concentrations of C_{37} alkenones near the Heinrich events are in agreement with other observations in the North Atlantic showing low abundances of phytodetritus foraminifera and low benthic accumulation rates [Thomas et al., 1995]. These events are therefore characterized by low productivity. Neither the alkenone nor the foraminifera results support an iceberg-related physical mechanism for productivity increase in the past oceans [Sancetta, 1992].

The most distinct feature of the C_{37} alkenone record in SU90/08 is the predominance of a cyclic pattern. Blackman-Tuckey spectral analysis with a bandwidth of 0.018 kyr^{-1} shows a large peak (35% of the total alkenone variance over the width of the peak) at the precessional component of the Milankovitch orbital forcing (0.043 = 1/23 kyr^{-1}). The mean coherency is 0.92 over this peak (for comparison, 0.52 corresponds to the 80% significance level; Figure 3). This C_{37} alkenone signal is in opposition of phase with summer insolation at 43°N (phase angle $\Phi = -149° \pm 10°$ and coherence $\kappa = 0.89$; Table 1). No response to the other orbital cycles (1/100 and 1/40 kyr^{-1}) is observed. The 280 kyr time span covered by this SU90/08 is sufficient to show prominent frequency in the case that these existed.

All the other climatic records in core SU90/08 show significant intensities at the 1/100 and 1/40 kyr^{-1} bands (Figure 3). The single 1/23 kyr^{-1} frequency signal of the C_{37} alkenones stands out among the other proxies. Even the ratio between diunsaturated and triunsaturated alkenones (U^k_{37}; Figure 2) that records sea surface temperatures (SST Brassell et al., 1986a,b; Prahl and Wakeham, 1987] exhibits a spectral pattern coincident with the $\delta^{18}O$ curves (Figure 3). The frequencies at 1/100 and 1/40 kyr^{-1} reflect the influence of the ice sheet evolution and constitute a major compo-

nent of the North Atlantic variability, including the latitudes where core SU90/08 is situated [Imbrie et al., 1992].

4. Discussion

Only a small fraction of the C_{37} alkenones produced in the euphotic zone by algal synthesis is preserved in the underlying sediment. This process is general for the organic carbon arriving to the bottom sediments after water column transport in association with settling particles [Manighetti and McCave, 1995]. However, the C_{37} alkenones range among the lipids more refractory to biodegradation [Volkman et al., 1983; Kennedy and Brassell, 1992; Sun and Wakeham, 1994]. This context prompts the evaluation of the factors determining the distinct precessional signal of the C_{37} alkenones in SU90/08, paying particular attention to the influence of preservation changes in the development of this cyclic pattern.

4.1. Preservation Effects

Comparison of the C_{37} alkenone flux and sedimentation rate provides a first evaluation of possible correspondences between depositional and diagenetic effects. As shown in Figure 4, the downcore trend of both variables is rather independent. In some episodes, higher sedimentation is reflected in higher alkenone flux. However, higher sedimentation rates are never reflected in decreases of C_{37} alkenone flux, evidencing that the C_{37} alkenone raises cannot be attributed to fictitious effects derived from depositional depletion.

The influence of oxidation and other degradation processes in the precessional record may be addressed by examination of the sedimentary composition of lipid molecules that are more labile to preservation effects than the C_{37} alkenones. Fatty acids are more sensitive to degradation [Volkman et al., 1983; Kennedy and Brassell, 1992; Sun and Wakeham, 1994], and the unsaturated fatty acids are degraded faster than the saturated homologues [Sun and Wakeham, 1994]. This is the case of n-octadec-9-enoic acid which is eliminated from the sedimentary environment faster than its saturated homologue n-octadecanoic acid [Grimalt et al., 1992]. According to these differences these acids have been used to calculate a fatty acid preservation index as defined in section 2. Higher abundances of $C_{18:1}$ (higher FAPI values) must correspond to less degradation and vice versa. This ratio essentially reflects the changes in algal organic matter since C_{18} acids are of algal origin [Parker, 1969; Boon et al., 1978; Volkman et al., 1980b].

The analysis of the fatty acid composition in selected sections of core SU90/08 having maximal and minimal C_{37} ketone content shows that the FAPI values range between 0.09 and 0.23 (Figure 2). These values are consistent with the composition of sinking particles in the northeastern Pacific Ocean [Grimalt et al., Seasonal trends in ascending and descending fluxes of particulate lipids in the abyssal water column of the northerastern Pacific Ocean, submitted to Deep-Sea Research I, 1998]. Sediment traps deployed over 1 year and seasonal collection of the sinking material showed that the average FAPI at 1235 and 3785 m depth are 0.77 and 0.43, respectively. The values recorded in SU90/08 probably reflect the combined effects of water column and post-depositional degradation. However, the most interesting aspect of the FAPI values in core SU90/08 is the lack of correlation with C_{37} alkenone fluxes (or concentrations) which is consistent with the lack of influence of depositional conditions in the precessional pattern recorded by these Haptophytae compounds.

Another aspect to be considered, in addition to the examination of the fatty acid composition, is the fact that postdepositional degradation usually affects all lipid compounds tending to uniformize
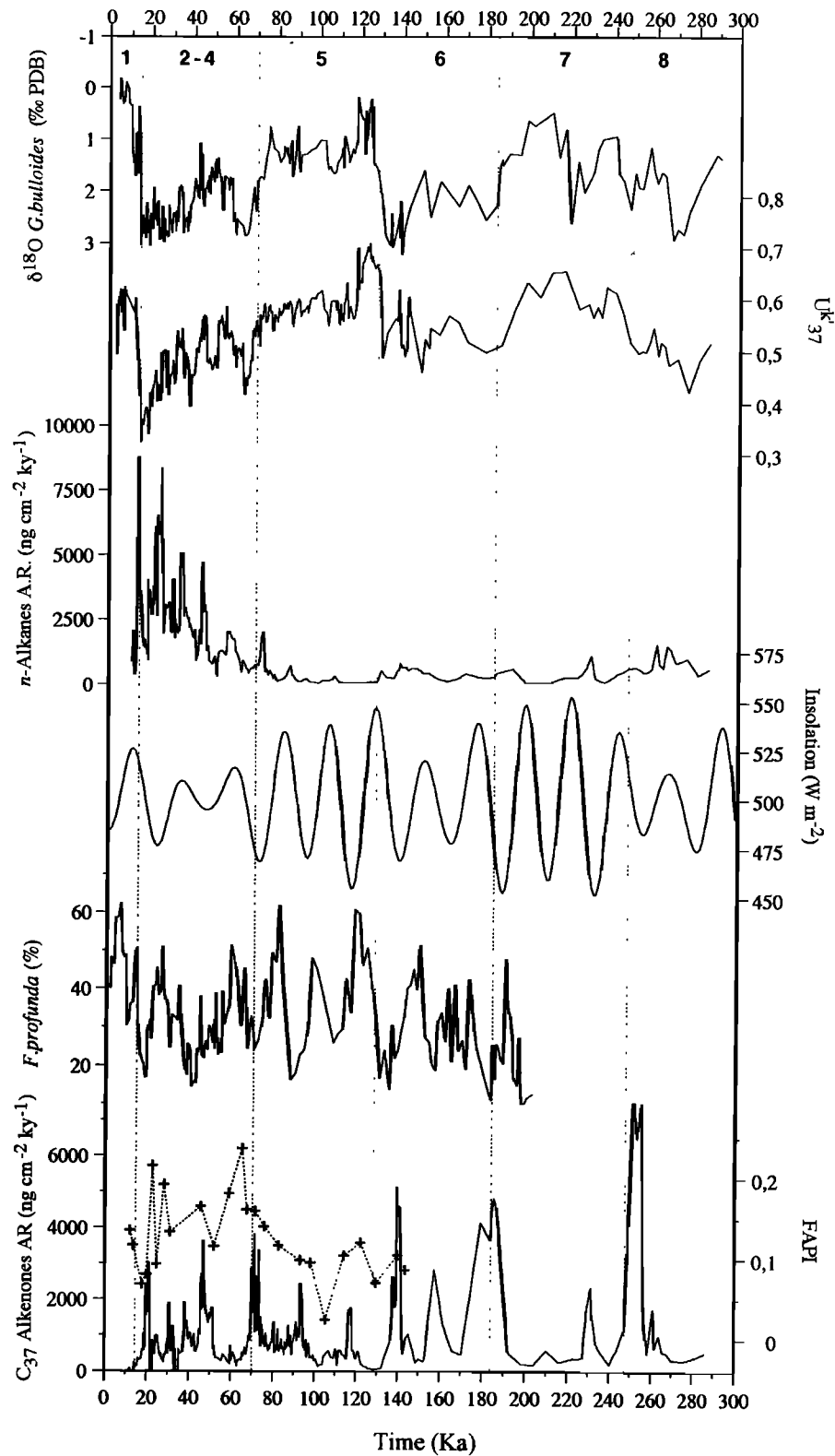
Figure 2. Downcore profiles of the $\delta^{18}O$ record of *Globigerina bulloides*, $U^k{}_{37}$ index, C_{23}-C_{33} odd carbon numbered$n$-alkane flux, June 15 insolation at 43°N [*Berger*, 1978], and C_{37} alkenone flux in SU90/08 core (43°30'N, 30°24'W). FAPI is the fatty acid preservation index (n-octadec-9-enoic acid / (n-octadec-9-enoic acid + n-octadecanoic acid)).
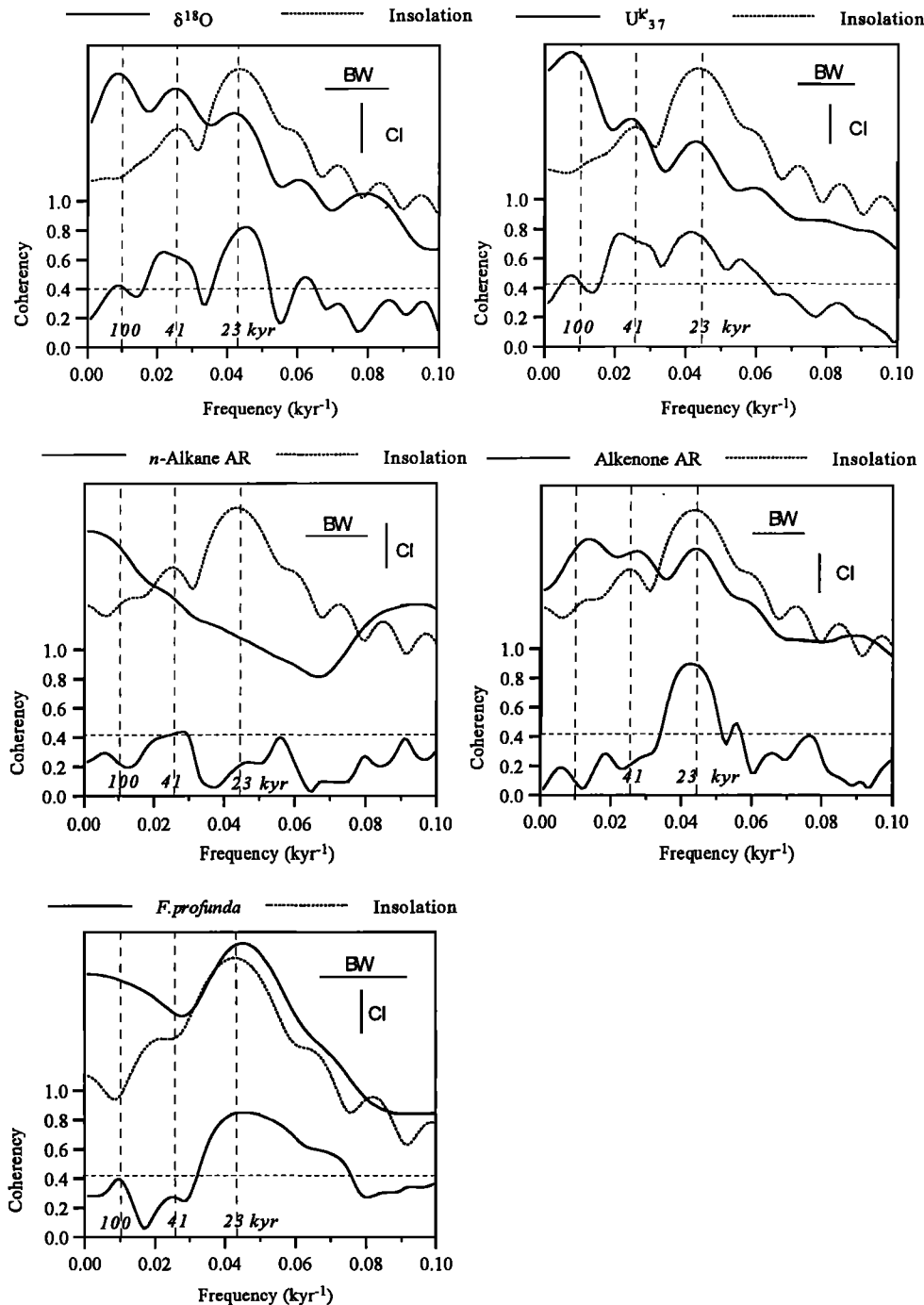
Figure 3. Variance spectra of the core profiles shown in Figure 2 (expressed as the logarithm of spectral power density versus frequency in cycles kyr⁻¹, using the Blackman-Tuckey method and where lags = 30 [*Jenkins and Watts*, 1986]) compared with the spectrum of boreal summer insolation at 43°N. Bandwith (BW) and 80% confidence interval (CI) are indicated with a line segment. The three main orbital periods of eccentricity (100 kyr), obliquity (41 kyr), and precession (23 kyr) are marked with a vertical line. The coherency spectra between core profiles and insolation are shown at the bottom of each profile. The horizontal lines indicate the level of nonzero coherence at the 80% confidence interval.

the differences in source input variability [*Grimalt et al.*, 1992; *Haddad et al.*, 1992; *Sun and Wakeham*, 1994]. Information on specific inputs is contained in the deviations of individual molecules from the general trend [*Grimalt et al.*, 1992; *Haddad et al.*,

1992; *Brassell*, 1993]. In core SU90/08 the dominant 1/23 kyr⁻¹ cyclicity of the C₃₇ alkenones is specifically different from the downcore concentration trend of many other lipids, i.e., the C₂₅-C₃₃ odd carbon numbered *n*-alkanes (Figures 2 and 3). This spe-

Table 1. Correlation and Phase Angle of Summer Insolation (June 21) at 43°N With the Variables Studied in SU90/08, Sea Surface Temperature (SST) in Core V30-97, and *Florisphaera profunda* Abundance in Core RC2407

Period, kyr	Sedimentation Rate	$\delta^{18}O$ *Globigerina bulloides*	U^k_{37}	C_{23}-C_{33} n-Alkanes	C_{37} Alkenones	SST V3040	*Florisphaera profunda* Abundance
23	0.66	0.82	0.78	0.18	0.89	0.87	0.85
		-71±11°	86±15°		-149±10°	20±11°	77±13°
41	0.48	0.65	0.76	0.43	0.43	0.37	0.27
		-111±24°	58±18°				
100	0.39	0.41	0.48	0.30	0.10	0.33	0.39

cific signal is different from the concentration record of the other lipid molecules which makes unlikely that it responds to preservation effects.

Finally, sedimentary bulk organic matter studies in the equatorial Atlantic upwelling zone, where the productivity signal and other climatic proxies are modulated to precession have shown that postdepositional preservation is not related to precession but to the 1/100 and 1/41 kyr^{-1} cycles [*Verardo and McIntyre*, 1994]. This reflects that organic matter oxidation rates are influenced by the dynamics of the bottom waters, namely, the rates of production
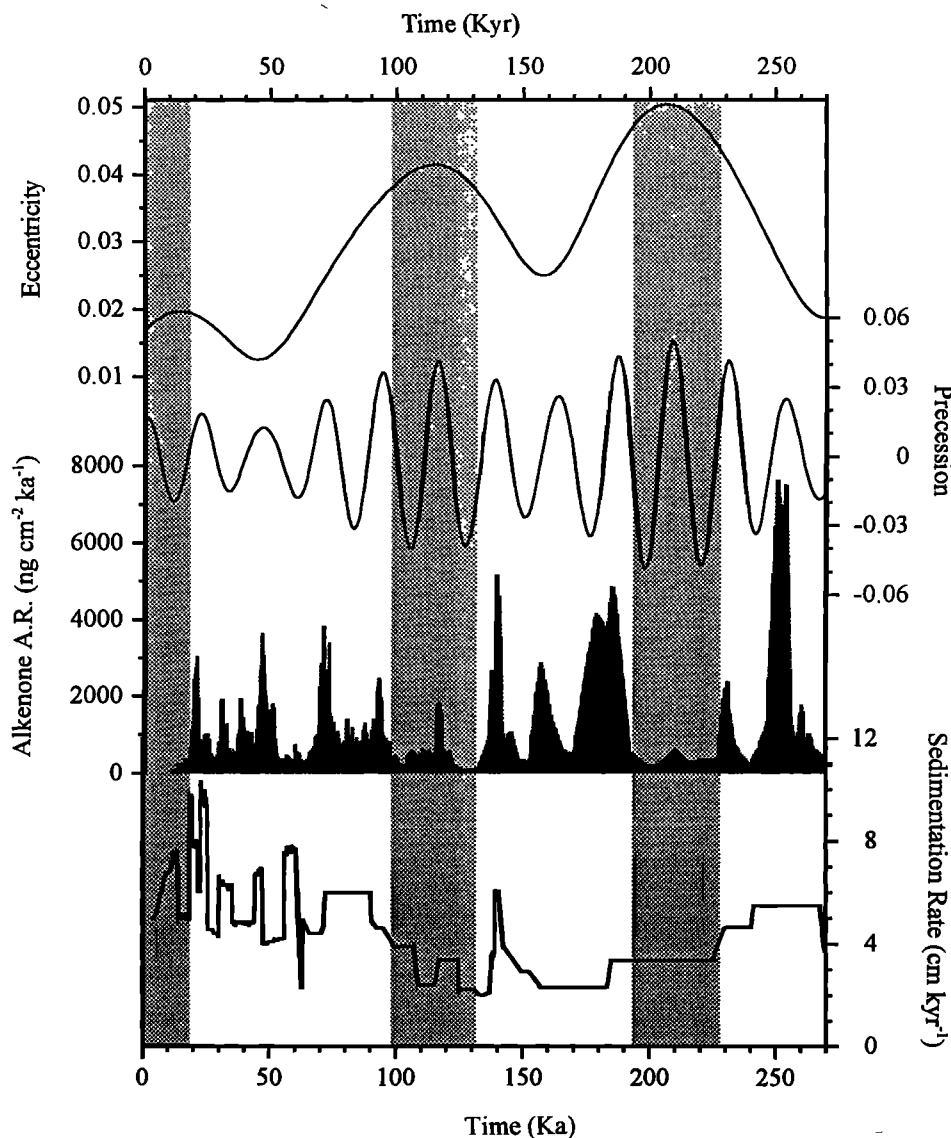
Figure 4. Comparison of the C_{37} alkenone record in SU90/08 with the precession and the eccentricity cycles. The shaded bands outline the low productivity (low C_{37} alkenone flux) of the interglacial stages (maximum eccentricity) irrespectively of precession. The SU90/08 sedimentation rate is also included for comparison.

of North Atlantic Deep Water (NADW), which is modulated to the ice sheet response to insolation [*Imbrie et al.*, 1992, 1993]. Conversely, water productivity is determined by surface water phenomena, such as nutriocline changes. These changes respond to direct insolation effects driven by precession in the equatorial zone.

All these aspects indicate that the dominant precessional alkenone signal in SU90/08 does not reflect changes in preservation. This alkenone record points to a direct link between Haptophyte productivity in the central North Atlantic gyre and the precessional pattern.

4.2. Precessionally Driven Proxies at High Latitudes

The U^k_{37} index in SU90/08 (Figures 2-3) shows that SST at 43°N essentially follows the $\delta^{18}O$ curve, exhibiting significant intensities at the 1/41 and 1/100 kyr^{-1} bands. Examination of modern analogue foraminiferal SST transfer functions reveals the same trend [*Vautravers*, 1996]. These variables also have a significant maximum at the 1/23 kyr^{-1} band, although at a lower intensity than the other Milankovitch periods. As shown in Table 1, correlation with summer insolation at 43°N reveals significant coherences of U^k_{37} and $\delta^{18}O$ at 1/23 ($\kappa = 0.78$ and 0.82, respectively) and 1/41 kyr^{-1} ($\kappa = 0.76$ and 0.65, respectively). These two variables also exhibit significant cross correlation and counterphasing at 1/23, 1/41, and 1/100 kyr^{-1} ($\kappa = 0.9$, 0.9, and 0.92, respectively; Table 2). The overall spectral pattern is consistent with the latitudinal position of core SU90/08 since oceanic processes in high and intermediate latitudes are preferentially driven by the 1/41 and 1/100 kyr^{-1} bands following the ice sheet response to insolation forcing [*Imbrie et al.*, 1989, 1992, 1993].

The C_{37} alkenones are only correlated with U^k_{37} and $\delta^{18}O$ at 1/23 kyr^{-1} ($\kappa = 0.78$ and 0.94, respectively; Table 2). Likewise, these alkenones are only correlated with summer insolation at 1/23 kyr^{-1}, exhibiting high coherence ($\kappa = 0.89$) and counterphasing ($\phi = -149° \pm 10°$; Table 1). Oceanic processes dominated by 1/23 kyr^{-1} are scarce and mostly located at low latitudes, such as the equa-

Table 2. Cross Correlation of the Variables Determined in Core SU90/08 and Correlation of C_{37} Alkenones With *F. profunda* Abundance in Core RC2407

Sedimentation Rate		$\delta^{18}O$ *G. bulloides*	U^k_{37}	C_{23}-C_{33} *n*-Alkanes	*F. profunda* Abundance
		23 kyr Period			
$\delta^{18}O$ *G. bulloides*	0.3				
U^k_{37}	0.38	0.9			
		-163±13°			
C_{23}-C_{33} *n*-alkanes	0.46	0.5	0.6		
C_{37} alkenones	0.5	0.94	0.78	0.37	0.82
		77±13°	-123±20°		-133±16°
		41 kyr Period			
$\delta^{18}O$ *G. bulloides*	0.45				
U^k_{37}	0.51	0.9			
		-167±12°			
C_{23}-C_{33} *n*-alkanes	0.85	0.68	0.79		
	17±14°		176±16°		
C_{37} alkenones	0.27	0.33	0.3	0.23	0.38
		100 kyr Period			
$\delta^{18}O$ *G. bulloides*	0.28				
U^k_{37}	0.43	0.92			
		-162±11°			
C_{23}-C_{33} *n*-alkanes	0.39	0.62	0.6		
C_{37} alkenones	0.47	0 62	0.63	0.2	0.72
					165±17°

torial Atlantic Ocean where the activity of the Hadley cells controls the divergence intensity [*Imbrie et al.*, 1989].

Thus minimal SST in the equatorial Atlantic Ocean is essentially dominated by precession. This is illustrated by compilation of the SST record in core V3040 (0°12'S 23°9.0'W [*McIntyre et al.*, 1989]) that exhibits high coherence ($\kappa = 0.87$) and phasing ($\phi = 20° \pm 11°$) with summer insolation at 1/23 kyr^{-1} (Table 1). No coherence between this SST profile and insolation is observed at the other Milankovitch frequencies.

Since the C_{37} alkenone flux is related to productivity, further insight into the climatic information of this variable may be obtained by comparison with other productivity proxies. Minimal nutriocline stability in the equatorial Atlantic Ocean, estimated from the relative abundances of *Florisphaera profunda*, provides a good sedimentary record of past productivity at low latitudes [*Molfino and McIntyre*, 1990; *McIntyre and Molfino*, 1996]. The percent of *F. profunda* relative to the other coccolith species is modulated to precession being lowest (highest productivity) at boreal summer aphelion [*Molfino and McIntyre*, 1990]. Accordingly, spectral analysis of the percent of *F. profunda* in core RC2407 (1°20.5'S 11°53.3'W [*Molfino and McIntyre*, 1990]) shows that this percentage is only correlated with insolation at 1/23 kyr^{-1} (coherence $\kappa = 0.84$; Table 1).

F. profunda abundance in the equatorial Atlantic is also correlated with the C_{37} alkenones at 43°N. As shown in Table 2, these two variables exhibit a coherence coefficient of $\kappa = 0.82$ at 1/23 kyr^{-1} and are nearly counterphased ($\phi = -133° \pm 16°$) which is consistent with the fact that they measure opposite effects (*F. profunda* maxima correspond to productivity minima). No correlation between the two signals is observed at 1/41 kyr^{-1}.

Changes in *F. profunda* abundance are related with trade wind intensities. Maximal trade winds involve minimal nutriocline depth and maximal productivity (minimal *F. profunda* abundance).Trade winds are higher when perihelion is aligned with boreal winter [*Sarnthein et al.*, 1981]. These winds are counterphased with the north equatorial monsoons which are also precessionally driven [*Pokras and Mix*, 1987; *Short and Mengel*, 1986].

The activity of both trade winds and African monsoons is controlled by the activity of the Hadley cells which account for the wind circulation patterns at low latitudes. Core SU90/08 is too far north to be directly linked to equatorial divergence. Thus the C_{37} alkenone pattern in this core requires a specific mechanism determining the observed productivity changes.

4.3. Ekman Effects and Precession

Productivity in open oceanic waters is related to the vertical transport of nutrients to the photic zone which depends on the wind regime and nutriocline depth. In the Holocene the nutriocline is shallow in the upwelling equatorial zone, where the Ekman effect of the northern and southern hemisphere trade winds results in divergence and pumping of deep waters to the surface. In contrast, the nutriocline is deepened in the North Atlantic subtropical gyre (10°-55°N), where the combined Ekman components of the trade winds and the westerlies give rise to water convergence. In these downwelling conditions, productivity is low irrespective of wind capacity or water column mixing.

This situation of low productivity is reflected in the alkenone record of core SU90/08. In the Holocene the concentrations of these compounds are very low (Figure 2). In fact, the SU90/08 results indicate that this situation of nutriocline downwelling also occurred in the previous two interglacials (stages 5e and 7; Figures 2 and 5).

In contrast, the precessional alkenone pattern of core SU90/08 points to different nutrioeline conditions in the glacial times. In this period the subpolar-subtropical front was displaced southward [*Climate: Long-Range Investigation, Mapping, and Prediction*, 1984; *Keffer et al.*, 1988; *Manabe and Broccoli*, 1985] which involved considerable nutrioeline shallowing at latitudes such as 40° [*Gordon*, 1986], affording nutrient transport to the photic zone by wind mixing. Thus the westerlies could determine water productivity, similarly to the trade wind forcing of nutrioeline depth in the equatorial Atlantic [*Molina-Cruz*, 1977; *Sarnthein et al.*, 1981; *Pedersen*, 1983]. In this respect a precessional forcing of the percent of *F. profunda* has been observed in the equatorial Indian Ocean where productivity is driven by the wind intensity of westerlies, which is related to the Soutern Oscillation [*Beaufort et al.*, 1997].

In the North Atlantic (45°-60°N), recent studies on clay minerals have shown a dominant $1/23$ kyr^{-1} variance peak in the areas situated south of 52°N [*Bout-Roumazeilles et al.*, 1997]. This precessional pattern can also reflect the dominance of the westerlies in the atmospheric transport of terrigenous material to these latitudes. A predominant precessional modulation of the westerlies in the North Atlantic is also consistent with the observed precessional dominance of the insolation spectra at 40°30'N (Figure 2).

Further evidence of the precessional forcing of the westerlies is provided by studies of continental records. Thus the ammonium concentrations from Greenland Ice Sheet Project 2 (GISP2) ice cores exhibit a strong precessional cycle, indicating the influence of wind-transported terrigenous emissions to Greenland [*Meeker et al.*, 1997]. Furthermore, the magnetic susceptibility records of the loess plateau in central China show that East Asian monsoons were also precessionally driven [*An et al.*, 1991]. A teleconnexion between the North Atlantic westerlies and the East Asian winter monsoon has been observed [*Porter and Zhisheng*, 1995]. This teleconnexion effect and the precessional forcing of the East Asian monsoon are also consistent with a precessional dominance of the westerlies and Ferrel cell dynamics.

Evidence of the coupling of the changes in the dynamics of the Hadley and Ferrel cells can be obtained by examination of the results in Tables 1 and 2. The $1/23$ kyr^{-1} cross-spectral analysis of summer insolation and the productivity proxies driven by westerlies and trade winds (C_{37} alkenones and % *F. profunda* respectively) reveal high coherency ($\kappa = 0.89$ and 0.85, respectively) and phase angles of $\phi = -149° \pm 10°$ and $77° \pm 13°$, respectively. These two productivity proxies also exhibit high coherency at $1/23$ kyr^{-1} ($\kappa = 0.82$) and a phase angle of $\phi = -133° \pm 16°$. When the three angles are combined, a sum of 359° is observed, in almost full coincidence with the expected 360° value.

On the other hand the phase angle between C_{37} alkenones and summer insolation at $1/23$ kyr^{-1}, $\phi = -149$, corresponds to a phase of $-31°$ when the winter insolation signal is considered. This angle involves a lag of ~ 2 kyr between insolation and the westerly driven C_{37} alkenones or about 1 month in the annual cycle. This lag is similar to that reported by *Short and Mengel* [1986] for the monsoon dynamics and can be explained by the delays in thermal response to astronomical forcing by the low heat capacity of the large land masses in the northern hemisphere.

In short the combined effect of the southward displacement of the subpolar-subtropical front and precessional forcing of the westerlies is consistent with the observed precessional change of C_{37} alkenones in SU90/08. During the glacials, when water convergence by Ekman pumping is displaced south of the 40°N band, the stability of the nutrioeline depth and therefore productivity may depend on the intensities of the westerlies. A precessional

forcing of these winds should be reflected in a precessionally driven signal of productivity markers such as the C_{37} alkenones. The phasing of the alkenone record with maximum boreal winter insolation is consistent with more active wind mixing by the westerlies and higher input of nutrients to the surface. In this respect this period is also characterized by lowest thermocline stability due to minimal boreal summer insolation. In contrast, in the interglacials the northward displacement of the subpolar-subtropical front involves strong water convergence and nutrioeline deepening that interrupts the wind-driven productivity mechanism.

4.4. Other Precessionally Driven Algal Productivity Markers

One important aspect of these observed cyclicities is their significance in terms of global marine productivity. In principle the above described C_{37} alkenones are specific markers of a rather limited group of Haptophyte encompassing the coccolithophorid producers *E. huxleyi* and *Gephyrocapsa* spp. Other haptophytes such as *Crysotila* sp. and *Isochrysis* sp. also produce C_{37} alkenones, but they occur in coastal waters and are unlikely sources of these compounds in the open ocean. Coccolithophorid species only constitute a portion of the total haptophytes [*Thomsen et al.*, 1994]. Irrespective of Haptophyte significance [*Chavez et al.*, 1990], other algal species such as diatoms also account for a substantial fraction of primary production [*Goldman*, 1993; *Claustre*, 1994]. Contributions to global productivity derived from the growth of different algal groups could reflect different limitation effects by different macronutrients or micronutrients [*Sunda and Huntsman*, 1992; 1995; *Brand* et al., 1983].

However, the wind-driven mixing mechanism outlined in the present study is unspecific. Higher water column mixing by increased westerlies strength will probably incorporate a wide range of micronutrients and macronutrients to the photic zone. Furthermore, nutrient increase currently gives rise to successive blooming of different algal groups, for example, diatoms followed by *E. huxleyi* [*Green and Leadbeater*, 1994]. Thus, despite the specific character of the C_{37} alkenones, the observed precessional cyclicity probably reflects general marine productivity in the open ocean area represented by core SU90/08.

As described above, this precessional pattern observed at intermediate latitudes is coherent with the precessional productivity regime in the equatorial Atlantic and Indian Oceans [*McIntyre and Molfino*, 1996; *Molfino and McIntyre*, 1990; *Beaufort et al.*, 1997]. Likewise, the Dole effect, which depends on the activity of marine and terrestrial biosphere [*Bender et al.*, 1994] also shows a strong precessional forcing.

On the other hand the precessional driving of marine productivity is also recorded by other global parameters such as nss SO_4^{2-} accumulation rate in the Vostok (Antarctica) ice core. This compound also exhibits a spectrum containing an almost single precessional band [*Legrand et al.*, 1988] and, like the C_{37} alkenones, very low nss SO_4^{2-} in the interglacial stages. Marine nss-SO_4^{2-} essentially originates from dimethylsulphide, a compound that is emitted as a consequence of the decomposition of oceanic phytoplankton [*Savoie and Prospero*, 1989], particularly, haptophyte algae (both C_{37} alkenone synthesizers and nonsynthesizers) and dinoflagellates [*Liss et al.*, 1993, 1994]. The interdependence between dimethylsulphide emission and the availability of iron in surface waters has been observed [*Turner et al.*, 1996]. Thus the Antarctica nss SO_4^{2-} profile is indirectly linked to marine biota paleoproductivity [*Prospero et al.*, 1991].

The close similarity of these two records obtained from such different locations and geologic materials is remarkable. In any case the elucidation of the biological, geochemical, or paleocli-

matic links between them is beyond the scope of the present study. Thus *Phaeocystis*, a non-C_{37} alkenone synthesizer Haptophyceae, is abundantly found in marine waters and produces large amounts of dimethylsulphide [*Liss et al., 1994*]. In any case their common age-dependent trend is consistent with a generalized precessional forcing of productivity in the ocean

5. Conclusions

Ice sheet responses to insolation forcing cannot account for the precessional productivity changes observed in this study since they are preferentially driven by the 1/41 and 1/100 kyr⁻¹ bands [*McIntyre et al., 1989*]. The C_{37} alkenone fluxes observed in core SU90/08 suggest that export production associated to some Haptophyta algae, and by extension, marine productivity, were modulated to precession in the glacial stages of at least the last two glacial cycles. This modulation was probably mediated by the influence of insolation in the dynamics of the Hadley and Ferrel cells. In the interglacial stages, productivity decreased because of the formation of a thick thermocline that limited the transport of nutri-

ents to euphotic zones irrespective of wind-driven water column mixing.

In short the results presented in this study are in agreement with previous reports indicating that marine productivity was higher in the glacial periods. However, they show that at least in the area represented by core SU90/08 of the North Atlantic, productivity during these periods was not constant but modulated to precession.

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