DYNAMICS OF THE MONSOON IN THE EQUATORIAL INDIAN OCEAN OVER THE LAST 260,000 YEARS

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The coccolithophorids are excellent indicators of the variations in ocean productivity. As an example, the relative abundance of Florisphaera profunda, a species which lives exclusively in the deepest part of the photic zone, constitutes a reliable monitor of the depth of the nutricline as a function of climatic variability. Productivity in the Indian Ocean is closely linked with the monsoon. Its intensity affects the depth of the mixing zone which deepens as the wind stress increases. During the monsoon season, the nutricline is shallower resulting in a higher productivity. The variations in composition of coccolith assemblies in well-dated oceanic sediments allows to describe the dynamics of productivity and therefore the fluctuation of the monsoon intensity. Core MD900963 was retrieved in the equatorial Indian Ocean, East of the Maldives at a water depth of 2400 m. A precise chronology was established by fine-tuning the high resolution 81sO record with the SPECMAP Stack. Coccoliths were counted from samples taken at 10 cm intervals in the core, providing a resolution of 2000 years for the last 260,000 years. The productivity estimates made from coccolith counts show that productivity varied greatly in the Maldives area during this time. The variations of the coccolith productivity index match the variations of the organic carbon content in the sediment. Spectral analysis reveals strong precessional cycles, and weak obliquity and eccentricity cycles. This implies that the solar radiation has a dominant effect on the monsoon variability South of India. The productivity maxima occur during even-numbered 81sO stages. This may indicate that the productivity events are related to increase of the winter monsoon. However the analysis of the phase between the palaeoproductivity and seasonal solar radiation curves calculated for the past 260,000 years suggest an alternative hypothesis: the westerlies which blow in April in the Maldives area (there, the onset of the Monsoon is in advance on the Arabian Sea) would have a major effect on productivity, since the insolation curve of the end of March at 5°N is in perfect phase with the paleoproductivity record for the last 260,000 years.

INTRODUCTION

The Asian Monsoon climate, driven by differential land–ocean sensible heating, produces seasonal reversals in the wind direction which affect strongly the Northern Indian Ocean. Palaeoclimate studies have shown that the intensity of the monsoon has varied through time, during the Last Glacial Maximum the summer monsoon was weaker (Prell et al., 1980; Duplessy, 1982), and the winter monsoon was stronger (Duplessy, 1982; Fontugne and Duplessy, 1986; Sarkar et al. 1990). Clemens et al. (1991) suggested that the variations of the summer monsoon intensity are associated with changes in the seasonal pattern of the solar radiation, whereas variability in global ice volume is not a primary factor controlling this intensity, which is not in agreement with general circulation model. The summer monsoon variability is recorded particularly well in the Arabian Sea where the strongest winds appears during summer (e.g. Knox, 1987). The seasonal variations of the wind stress over the surface water induce dramatic changes on oceanic productivity (e.g. Ittekkot et al., 1992; Curry et al., 1992) which can be identified in the fossil records from palaeoproductivity proxies (e.g. Cullen, 1981; Prell and Curry, 1981; Clemens and Prell, 1990; Caulet et al., 1992). The effects produced by the summer monsoon are particularly well observed in the areas of the Somali and Arabian margins where seasonal upwelling are induced by the SW (summer) monsoon while it is stopped by the NE (winter) monsoon. The record of palaeoproductivity variations in these upwelling systems corresponds essentially to the dynamic of the summer monsoon. At the opposite, records of the variability of the winter monsoon were found in the Bay of Bengal and Andaman Sea (Fontugne and Duplessy, 1986) where this monsoon season is predominant. Today, very little is known about the variability of the seasonal winds over the rest of the Indian Ocean, where seasonal contrasts are less pronounced (regions where both monsoon seasons are recorded). The giant piston core MD900963 retrieved during the SEYMAMA expedition of the French R/V Marion Dufresne in 1990, at the junction between the Bay of Bengal and the Arabian Sea, provides an excellent record for investigating the dynamics of the monsoon in the equatorial Indian Ocean.

COCCOLITHS AS PALAEOPRODUCTIVITY INDICATORS

The coccolithophores (Prismesiophyceae) constitute one of the major phytoplanktonic group. As primary producers their growth depend on the amount of light and nutrients available in the photic zone. The photic zone in a stratified ocean presents strong contrasts of these two parameters on a vertical scale: the upper photic zone (0 to ~60 m) is depleted in nutrients, whereas light is strongly limited in the lower photic zone (~60 to ~180 m). The phytoplanktonic communities are adapted to these physicochemical differences and in consequence, their composition differs with depth (Venrick, 1982, 1990). At low latitude, the lower-photic-zone coccolithophore communities are dominated by Florisphaera profunda and Thalassiosira fiabellata while most of the other species live in the upper part of the photic zone (Okada and Honjo, 1973). That aspect of the coccolith vertical zonation has been used successfully for palaeoproductivity studies by Molfino and McIntyre (1990),
who use the abundance of *F. profunda* in fossil assemblages to monitor the climatic control of the depth of the nutricline. *F. profunda* increases in abundance in coccolith assemblages when the upper photic zone is impoverished in nutrients, hence, when productivity decreases. In contrast, the abundance of species such as *Emiliania huxleyi* and *Gephyrocapsa oceanica* are high when productivity increases in a given oceanic area. Productivity in the Indian ocean is closely linked with the monsoon intensity. The wind stress affects the depth of the mixing zone (deeper when wind stress is high). In other words, during the monsoon season, the nutricline is shallower, resulting in a higher productivity. The coccolith index based on the relative abundance of *F. profunda* is a good tool for reconstructing the past variations of the windstress and thus of the monsoon.

**MATERIAL AND METHOD**

Core MD900963 was retrieved on the eastern slope of the Maldives Islands at 5°03'30 N and 73°52'60 E in 2446 m of water depth (Fig. 1). More than 50 m of calcareous nannofossil ooze with foraminifera were recovered. Oxygen stable isotope measurements were performed on the planktonic foraminifer *Globigerinoides ruber* (white) (Bassinot et al., 1994) providing a detailed chronological framework when compared to the δ¹⁸O SPECMAP stack (Fig. 2). The average sedimentation rate is 5 cm/1000 year. The core was sampled at a 10 cm interval which corresponds to a chronologic resolution of about 2000 years. The upper 13 m of the core studied here provides a continuous record for the last 260,000 years. A smear slide was prepared from each sample; 300 coccoliths per slide were counted and the percentage of *F. profunda* was established from this count. The 95% confidence interval varies between ±2 and ±6% depending on the percentage (Mosimann, 1965). Settling slides were prepared from 56 levels which permit to count the absolute abundance of coccoliths (Beaufort, 1992). The number of view fields needed to obtain a total number of 300 coccoliths (*F. profunda* excluded) were counted. The number of coccoliths per gram of sediment is calculated using the equation in Beaufort (1992).

**RESULTS**

Large variations of the *F. profunda* index are observed, which range between 5 and 85% (Fig. 3), much above the confidence interval. All peaks and troughs which shape the curve are well defined, being delineated by several successive points. The sampling interval in thus sufficient enough to characterize the variations is the core. Based on our knowledge, of the ecology of *F. profunda* (Okada and Honjo, 1973), an increase of the relative abundance of this species in coccolith assemblages reflects a deepening of the nutricline equivalent to a decrease of primary productivity in the photic zone (Molfino and McIntyre, 1990). The curve is presented on a reverse scale, in order to have higher productivity in the upper part of the graph (Fig. 3).

Rostek et al. (1993) measured the C*org* content in the upper 10 m of the Core MD900963. An increase in the organic carbon content in the sediment is often interpreted as a result of an increase of productivity in the surface water (e.g. Müller and Suss, 1979). Similar variations in productivity, are inferred independently from percentage variations of *F. profunda* and C*org* (Fig. 3). The good match between the two series conforts the interpretation of *F. profunda* as a palaeoproduction indicator. Higher productivity is observed in both series around 18, 70, 90, 110, 130, and 160 kyr during even-numbered δ¹⁸O stages.

Bassinot et al. (1994) found that the planktonic foraminifera fragmentation in Core MD900963 was more important at levels of high organic content, indicating that the dissolution of the foraminifera was higher during high productivity events due to a higher oxidation of the organic matter incorporated into the sediments. The *F. profunda* index cannot reflect dissolution for at least two reasons: (1) no evidence of dissolution was seen qualitatively on the coccolith as seen in the light microscope, (2) the total abundance of the coccoliths increases at level richer in organic carbon and foraminifera fragments, levels where the dissolution should have been greater. The decrease of the relative abundance of *F. profunda* results therefore from an increase of the absolute number of coccoliths due to higher productivity and not from increased dissolution.
SPECTRAL ANALYSIS

The good chronological framework and the high resolution in the series are favourable for spectral analysis. The statistical techniques used are standard procedures based on the Fourier transform, which permits an estimation of the power density spectrum of series, of the coherency and phase between two series, and of filtering of the series at given frequencies (band pass filtering). The programmes used belong to a package written by D. Paillard (CFR, Gif-Yvette, France) in a large part inspired from routines of SPECMAP programs and Numerical Recipes (Press et al., 1986).
Spectral estimates of these records are made using both Blackman–Tukey and maximum entropy algorithms (e.g. Jenkins and Watts, 1968; Press et al., 1986). The maximum entropy method gives very high resolution spectra which help to precisely estimate frequencies peaks. With this latter method, however, there is no test of evaluating the significance of the peaks. Also, an abundance of spurious peaks may be found when too high an order of resolution is chosen (Press et al., 1986). These authors recommend the use of this algorithm in conjunction with more conservative methods. The Blackman–Tukey technique is used for this purpose with the maximum entropy because it is usually considered statistically robust, allowing an estimation of the significance of peaks; it is often used by palaeoclimatologists. The phases and coherencies between series are calculated by Cross–Blackman–Tukey.

Spectral analysis of the F. profunda series shows significant power rising at 23 kyr, periods which closely correspond to precession cycle (Berger and Loutre, 1991) (Fig. 4). This indicates that it is the Earth's precession cycles which have the dominant effect on the monsoon climate. Smaller peaks correspond to other known orbital cycles: 111 kyr correspond to the eccentricity and 40 kyr cycle is the period of the obliquity. The secondary importance of the obliquity signal is not surprising, since this parameter does not affect dramatically the solar radiation at low latitude. The eccentricity has a strong effect on the monsoon strength, because the climatic conditions (e.g. sea-surface temperature, sea level, land albedo and CO2 concentration) during glacial periods were different enough from those in interglacial times to affect the timing and strength of the monsoon (Prell and Kutzbach, 1987) (the glacial cycles in the late Pleistocene are closely linked to the eccentricity periods, see Imbrie et al., 1993). A small (but significant) peak in the eccentricity band of the F. profunda series is in this aspect surprising. Clemens et al. (1991) reached to the same results in their study of the monsoon in the Western Arabian Sea. This study provides additional evidence in favour of a dominant effect of the solar radiations on the long-term variability of the monsoon. Cross-spectral analysis between the F. profunda series (the curve is inverted to give the increase of productivity in a positive way) and the δ18O SPECMAP Stack shows significant coherencies in the Milankovitch frequency bands (Fig. 5). The series are almost in phase opposition (173°). This corresponds to the fact that the productivity events were observed during even-numbered isotopic stages. Cross-spectral analysis between the F. profunda series and the solar radiation received 21 June at 65°N (which has the greatest influence on glaciations; Berger, 1978) indicates a significant coherency (0.94) at 23 kyr with a phase of 83° (not shown).

**DISCUSSION**

It is not the summer monsoon which influenced past changes in productivity in the Maldives. There, the situation is opposite to what is observed in the western Arabian Sea where the summer monsoon is well recorded. This opposition is visualized on the precession phase wheel, in which the phase of palaeoproductivity index of the western Arabian Sea from results of Clemens et al. (1991) have been also plotted (Fig. 6).

The simplest explanation which may be given for this phase opposition, is that the variations of intensity of the winter monsoon induced the fluctuations of productivity observed in Core MD900963. From studies of cores retrieved in the eastern Bay of Bengal and in the Andaman Sea, the winter monsoon appears to have been stronger during the Last Glacial Maximum (Fontugne and Duplessy, 1986; Sarkar et al., 1990). This could correspond to the present case. However, these studies are based on variations of salinity, which are related to the amount of precipitation over India and the Indian Ocean, and thus to the SW monsoon or to productivity variations in the area of winter upwelling. These studies address a seasonal problem, the effect of the summer monsoon being not recorded, whereas the present study describes an index of the annual windstress. The effect of an increase of the winter monsoon may be easily balanced by the decrease of the summer monsoon. It is therefore complex to imagine that the winter monsoon has varied, while the summer monsoon intensity remained constant. Moreover, it is difficult to predict a strong effect of
the winter monsoon on productivity east of the Maldives. If a local upwelling were to be created seasonally in this zone, it would be with a SW wind, therefore during summer. It would be logical that the summer monsoon have the dominant effect on the long-term variation of the annual and wind stress in this area.

An alternative explanation of this opposition between the western Arabian Sea and the Maldives on the phase wheel may be given. The summer monsoon has an abrupt onset at the end of May in the Arabian Sea. But further south, the onset occurs earlier, and corresponds to the position of the low-level Jets. For example, wind stress observations made at Gan in the Maldives during several years indicate that the onset occurs between the end of March and the beginning of April (Knox, 1987). The 'windy season' is usually over by the end of May. The difference of phase obtained between the F. profunda series and the insolation curve for June 21, may be due to the lag existing between the timing of the maximum production season and June 21. Looking at the phase wheel this way, the maximum of production is in phase with a maximum of insolation of March 27, which is the time of the onset of the monsoon season on this area. This is visualized by comparing the precession component of the F. profunda series (filtered series at 23 kyr) and the insolation received March 27 at 5°N (Fig. 7). The correspondence between the two curves is striking. If this explanation is correct, it would imply that the records of past activity of the monsoon should be diachronous in the Indian Ocean, occurring earlier in the south-east and progressing towards the north-west. The seasonal position of the low-Jets over the Indian Ocean would be the key for reconstructing the timing of these maximum production events.

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