PALEOPRODUCTIVITY VARIATIONS IN THE EQUATORIAL ARABIAN SEA: IMPLICATIONS FOR EAST AFRICAN AND INDIAN SUMMER RAINFALLS AND THE EL NIÑO FREQUENCY

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ABSTRACT. We analyzed a sediment core from the equatorial Arabian Sea, chronologically constrained by accurate accelerator mass spectrometry (AMS) radiocarbon dates on selected planktonic foraminiferal species, for paleoproductivity variations corresponding to the variations in the Indian Ocean Equatorial Westerlies (IEW). The IEW in turn are positively correlated to the Southern Oscillation Index (SOI), which is a measure of El Niño, Southwest monsoon (SWM), and east African rainfall (EAR). The productivity data show that Indian and east African rainfalls declined from 35,000 calendar yr BP up to the last glacial maximum (LGM), with the maximum El Niño frequency during the last glacial period. From ~14,500 to ~2000 calendar yr BP (i.e. core top), we find strengthening SWM and EAR along with declining El Niño frequency.

INTRODUCTION

The equatorial/southern Arabian Sea is the least studied region of the Indian Ocean, as most of the earlier paleomonsoon studies have focused on either the western/northern or eastern Arabian Sea (e.g. Morrill et al. 2003 and references therein). Furthermore, the South Asian monsoon (Southwest monsoon, SWM, and Northeast monsoon, NEM) periods have received much attention since they involve planetary-scale atmospheric and hydrospheric changes. In contrast, the monsoon transition periods in April–June and September–November have not been studied in detail, although they are the main rainy seasons for eastern Africa and feature a short-lived but intense upper oceanic jet in the equatorial Indian Ocean (Wrytki 1973; O'Brien and Hulburt 1974; Hastenrath et al. 1993). In the equatorial Indian Ocean, winds are strongest during April–November with maximum variability during the monsoon transition periods, namely April–June and October–November. These winds are termed the Indian Ocean Equatorial Westerlies (IEW; in contrast, in the rest of the Indian Ocean, winds reach their maximum intensity during the SWM or NEM). The IEW cause short-lived but intense eastward upper-ocean water currents termed Eastward Equatorial Jets (EEJ) (Wrytki 1973; Schott and McCreary Jr. 2001; Hastenrath et al. 1993; Beaufort et al. 1997). The strong variability during the monsoon transition period is the result of strong wind bursts capable of causing deeper mixing of the surface water. Therefore, maximum productivity in this region occurs during the inter-monsoon periods (McIntyre and Molfino 1996; Beaufort et al. 1997). The IEW are the result of the Walker circulation and exhibits a positive correlation with the Southern Oscillation Index (SOI), a measure of the intensity of the Walker circulation/El Niño events (Bjerkness 1969; Hastenrath et al. 1993). El Niño affects the Indian monsoon in the way that the rising limb of the Walker circulation and the tropical convection, which is usually located in the western Pacific, shift towards the central and eastern Pacific. This shift results in subsidence over the western Pacific and the Indian subcontinent, which suppresses convection and precipitation over the Indian landmass (Pant and Parthasarthy 1981; Rasmusson and Carpenter 1983; Ropelewski and Halpert 1987). The high Southern Oscillation (SO) phase is related to a low El Niño activity and hence a strengthened Indian SW monsoon (Hastenrath et al. 1993). Moreover, eastern Africa possesses 2 rainy seasons. The first, which is more abundant in terms of rainfall, occurs during March–June with its core around April–May (called the "long rains" in Kenya and "Gu" rains in Somalia). The second season occurs from September–November and exhibits more interannual variability in precipitation, with its core around

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October–November (called the "short rains" in Kenya and "Der" rains in Somalia). High correlation of these rainfalls with the SO phase have been reported by various authors. During the high SO phase, enhanced "long rains" have been found by several authors (e.g. Hastenrath et al. 1987; Bhatt 1989; Beltrando and Camberlin 1993; Ogallo et al. 1998) and strengthened "short rains" have been reported by Van Heerden et al. (1988), Martarira (1990), and Walker (1990). Thus, past variations in the intensity of the IEW can be related to past fluctuations in the El Niño/SOI, Indian summer monsoon, and east African rainfall. A sediment core (SS3827G) was raised from the equatorial Indian Ocean that can help in documenting past variations in the oceanic and atmospheric conditions during the intermonsoon periods.

MATERIALS AND METHODS

SS3827G is a gravity core with a total length of 196 cm. It was recovered during R/V *Sagar Sampada* cruise nr SS152 in 1997 from a water depth of 3118 m, and thus represents an open-ocean regime. Its location is east of the Maldives Islands at 3°42′N and 75°54.5′E (Figure 1).
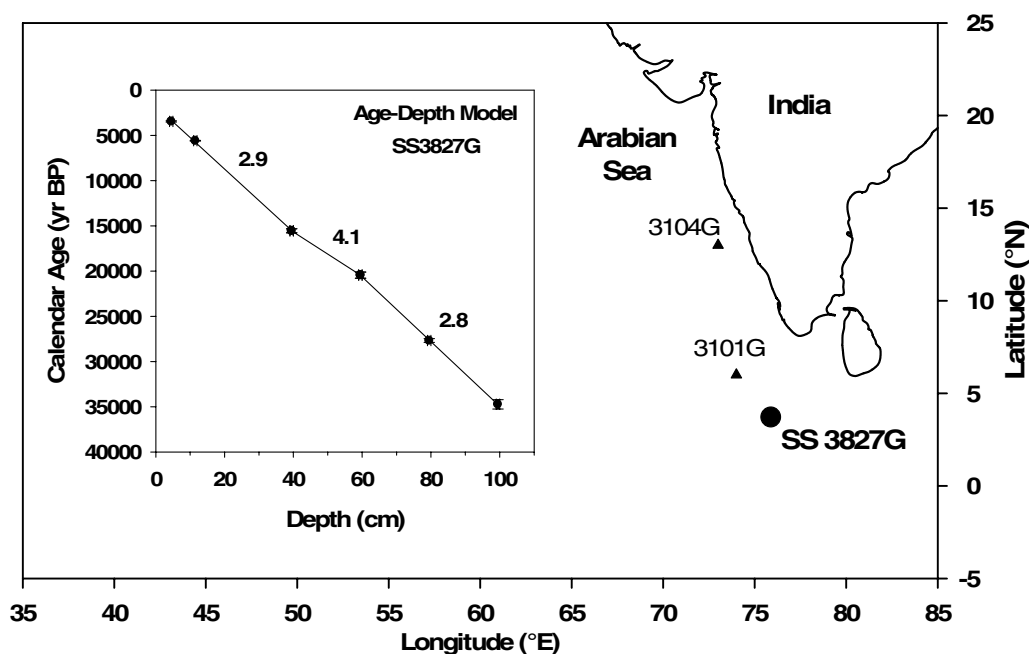

Figure 1 Locations of the core SS3827G and other cores (depicted by triangles) with which it has been compared; inset: calibrated ^{14}C ages and sedimentation rates (cm/kyr) for the core SS3827G.

In this core, 6 accelerator mass spectrometry (AMS) radiocarbon dates were obtained on planktonic foraminiferal separate, namely *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Orbulina universa*, and *Neogloboquadrina dutertrei*, spanning the past 34,700 ± 500 cal yr (inset, Figure 1). The size range 250–500 µm was chosen, but care was taken to pick shells predominantly falling in the size range 300–400 µm. CO_2 was evolved from the calcitic foraminiferal shells using phosphoric acid. The CO_2 was then reduced to CO over hot zinc and was further reduced to graphite over iron fillings maintained at about 600 °C. The graphite powder samples (~0.5 mg) were put into the target holder of the AMS and analyzed. [14]C dating was carried out using the accelerator mass spectrometer at the NSF Arizona AMS Facility, University of Arizona, USA (Linick et al. 1986; Jull et al. 1989).

The total length of the dated core was 100 cm. Thus, the average sedimentation rate was ~3 cm/10^3 yr, which is typical of open-ocean locations. The time resolution was approximately 350 yr/cm. ^{14}C dates in this core have been calibrated using the calibration program Calib 4.1 (IntCal98, Stuiver et al. 1998) with a reservoir age correction of 500 ± 30 yr ($\Delta R = 100 \pm 30$ yr, Dutta et al. 2001; Southon et al. 2002). Refer to Table 1 below for the dates.

Table 1 Calibrated and uncalibrated ^{14}C dates obtained on selected species of planktonic foraminifera in core SS3827G with a reservoir age correction of 500 ± 30 yr.

Laboratory nr	Depth in the core (cm)	Sample nr	δ^{13}C (‰)	^{14}C age (BP)	Calibrated age (BP)
T14775A	(4–5)	AA43839	1.33	3692 ± 48	3460 ± 70
T14776A	(11–12)	AA43840	1.56	5338 ± 52	5590 ± 40
T14778A	(39–40)	AA43842	1.51	13,523 ± 87	15,550 ± 220
T14779A	(59–60)	AA43843	1.54	17,780 ± 100	20,450 ± 340
T14780A	(79–80)	AA43844	1.76	24,040 ± 180	27,680 ± 210
T14781	(99–100)	AA43845	1.7	30,280 ± 440	34,730 ± 510

In this study, several productivity proxies were measured, including $CaCO_3$ (wt%), C_{org} (wt%), and C/N ratio in sedimentary organic matter, along with the δ^{13}C of 3 species of planktonic foraminifera (*G. ruber*, *G. sacculifer*, and *G. menardii*). Higher organic productivity in the photic zone will enrich ^{13}C in the dissolved HCO_3^- and hence in planktonic foraminiferal shells. Microorganisms such as foraminifera and coccolithophores produce calcitic shells as a protective covering for their soft body, and the overhead rain of calcitic shells is a major constituent of the sea sediments. Thus, the calcium carbonate percentage in sea sediments can indicate the overhead productivity, provided the core has been raised from depths above the lysocline (~3800 m in the Arabian Sea; Peterson and Prell 1985) and there is no contamination from the terrigenous inputs (Sirocko et al. 1993). Organic carbon (C_{org}) preserved in the sea sediments is derived from particulate organic carbon (POC) and is a manifestation of the overhead primary productivity if there are no alterations after the deposition (Muller and Suess 1979; Schulz et al. 1998). Organic matter in sea sediments can be from marine as well as terrestrial sources. It is therefore necessary to ascertain the source of the organic carbon before determining if its downcore variations are due to overhead surface productivity. The C/N ratio of recent sediments comprising marine organic matter has a value of 8–10, whereas the ancient sediments have a value of 12–15 (Mackenzie 1980). Terrestrial sources yield C/N values between 20 and 100 (Premuzic et al. 1982; Meyers 1994). In this study, C_{org} was calculated by subtracting inorganic carbon values (C_{inorg}, calculated from $CaCO_3$ content) from the total carbon values (C_{total}, measured using a CN analyzer), i.e. $C_{org} = C_{total} - C_{inorg}$. The precision percentages in measuring $CaCO_3$, total carbon, and nitrogen were 3%, 4%, and 6%, respectively, while the precision of C_{org} was 5%. All the uncertainties quoted are 1 σ. Analytical precision for δ^{13}C was ±0.1‰. Burial fluxes for the $CaCO_3$ and the organic carbon were calculated by multiplying the respective concentrations (g/g) with sedimentation rate (cm/kyr) and dry bulk densities (DBD, g/cc). DBD were estimated using a non-linear regression equation based on samples that were free of ice-rafted debris (Clemens et al. 1987). Further experimental details are discussed elsewhere (Bhushan et al. 2001; Ramesh and Tiwari 2005).

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Figure 2 Downcore variations in the calcareous and organic burial fluxes, wt%, and C/N ratio in SS3827G. Open squares denote burial fluxes (g m^{-2} yr^{-1}), filled circles designate concentration (wt%), and crosshairs in the first panel indicate the age at which the sedimentation rate changes.

increasing monsoon during the period. This study from the equatorial Arabian Sea reinforces the conclusion that the SWM enhanced during the Holocene.

Regional Climatic Evolution: Comparison with the Eastern Arabian Sea

The calcareous productivity record of SS3827G was compared with other such records to further explore the regional climatic conditions in the eastern and southern Arabian Sea. Agnihotri et al. (2003b) analyzed 2 cores from the eastern Arabian Sea, SS3104G and SS3101G (Figure 1), from water depths of 1680 m and 2680 m, respectively. The chronologies of the cores were obtained by AMS ^{14}C dating on selected planktonic foraminifera species. They attributed the productivity variations to variations in the SWM strength. Figure 3 depicts the comparison of productivity variations in these 3 cores for the past 35,000 calendar yr BP.

All 3 cores exhibit more or less similar downcore variations in calcareous productivity, showing a decreasing trend up to the LGM (shaded area in Figure 3) from 35,000 calendar yr BP. It appears that both the SW monsoon winds and the IEW declined in tandem up to the LGM, suggesting that the
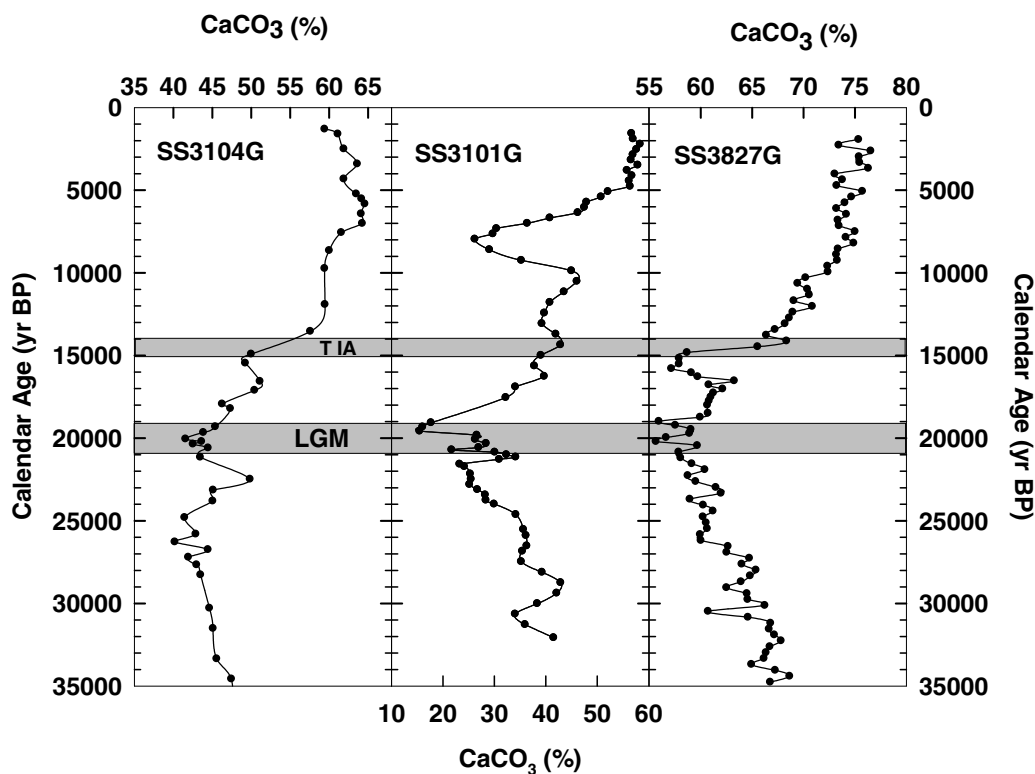
Figure 3 Comparative study of the core SS3827G (last panel; this study) with other cores from eastern Arabian Sea, SS3104G and SS3101G (Agnihotri et al. 2003); LGM and T IA denote last glacial maximum and Termination IA, respectively.

same forcing factor (most probably insolation; Beaufort et al. 1997) governs both. Around 14,500 calendar yr BP, another episode of SWM winds and IEW strengthening are observed as indicated by a sharp increase in the calcareous productivity. During the Holocene, all the cores show a general increase in the calcareous productivity, except for the core SS3101G, which suffers an abrupt decline during 7000–9000 calendar yr BP. This decline is quite intriguing as it is not observed in the cores from the north and south of it due to some local effect that dominates the productivity signal. Agnihotri et al. (2003a) point out that the timing of this decline coincides with the Holocene humid interval, a period of intensified SW monsoon in the Arabian Sea (Sirocko et al. 2000). They speculate that this sharp decline could be due to the build-up of low salinity cover due to an influx of fresh water from the coastal regions that would inhibit upwelling and hence reduce the productivity (Thamban et al. 2001).

Thus, based on the comparative analysis of these 3 cores, we infer that the productivity trends in the eastern and equatorial Arabian Sea were similar (barring some local effects). The IEW and SWM winds strengthened and weakened synchronously due to a common forcing factor.

Sedimentary Organic Matter Not Related to Productivity

Schulte et al. (1999) have shown that the equatorial Indian Ocean near the core site of SS3827G has remained under oxic conditions for the past 330,000 yr. C_{org} (%) is a traditional proxy for organic productivity (Muller and Suess 1979; Ganeshram et al. 1999; Rixen et al. 2000). On the basis of

studies carried out on a single giant piston core, MD900963, raised from the equatorial Arabian Sea just east of the Maldives, many colleagues (Bassinot et al. 1994; Beaufort et al. 1997; Rostek et al. 1997; Schulte et al. 1999; Pailler et al. 2002; Schulte and Bard 2003) have proposed that the true representative of overhead surface productivity is C_{org} and not the $CaCO_3$ content, which has suffered supralysoclinal dissolution. Apart from C_{org}, they have measured various other markers, such as microfossil assemblages and molecular species (e.g. C_{37} alkenone, cholesterol, brassicasterol, C_{30} keto-ol), based on which they argued that higher productivity was observed during glacial periods, whereas low productivity characterized interglacials. Yet, because of the prevailing oxic conditions, the preservation of organic carbon seems to be very poor, as seen by very low values of C_{org} in the present core, with most of the values being less than 0.5% and in many cases even less than 0.1%. The C_{org} preservation is reasonable (~1%) only during the LGM. Sarkar et al. (1993) also observed a similar phenomenon, which they ascribed to bottom water anoxia in the eastern/equatorial Arabian Sea based on uranium enrichment, coinciding with an increase in C_{org} concentration. Later, Agnihotri et al. (2003b) also recorded a positive excursion in C_{org} during the LGM in cores SS3104G and SS3101G (see Figure 1 for location). They also measured redox-sensitive elements, such as Mn, Cr, V (normalized to Al), to detect past changes in redox conditions but found none, i.e. the water has remained oxic (Schulte et al. 1999). Agnihotri et al. (2003b) proposed that during glacial periods, large areas of continental shelves were exposed due to the fall in sea level. Continental shelves are known to be a major sink of organic carbon and uranium (Borole et al. 1982; Somayajulu et al. 1994). These exposed shelves provided regions of vigorous erosion, and finer particles were advected and redeposited, leading to the observed increase in C_{org} and U during the LGM, as well as enhanced sedimentation. Agnihotri et al. (2003b) found an increased sedimentation rate along with higher concentration and accumulation rate of Al in the LGM, indicating a supply of clayey material from land. They argue that the enhanced supply of clay and detrital material along with reduced $CaCO_3$ concentration has led to better preservation of C_{org}, which is also observed by Bhushan et al. (2001 and references therein). Sarkar et al. (1993), though, did not report on this aspect (increased sedimentation rate during the LGM hence more of U and C_{org}) probably because of poorer chronological control (^{14}C dating on bulk sediments).

We also observe a similar pattern in the equatorial Arabian Sea. The sedimentation rate increases at the LGM (inset, Figure 1), which is concurrent with the increase in organic carbon concentration and burial flux. This increase in sedimentation rate is the only factor that led to enhanced C_{org} and a sudden jump in $CaCO_3$ burial flux during the LGM (between the 2 crosshairs in Figure 2). Furthermore, $CaCO_3$ (%) variation has been used by others as an indicator of overhead surface productivity (Sirocko et al. 1993; Naidu and Malmgren 1999; Agnihotri et al. 2003b). Tribovillard et al. (1996) have observed that C_{org} enrichment does not correspond to enhanced primary productivity during glacial-interglacial transitions. Others who report enhanced C_{org} (and other organic productivity markers) during glacial stages might also be experiencing redeposition of organic material from shelf regions, as their core is also very near to the Maldives coast. Thus, we believe that the C_{org} variation at our core site represents preservation rather than overhead surface productivity. The burial flux of organic carbon (Figure 2) closely follows the C_{org} concentration, indicating that the factor governing the burial flux is concentration.

The C/N ratio is obtained by dividing the C_{org} by the nitrogen content of the sedimentary organic matter, which is again very low (~0.04%) and has stayed more or less the same throughout the core. Therefore, the C/N ratio also exhibits a fluctuation similar to the C_{org} variations.

Carbon Isotopes of Planktonic Foraminifera Unrelated to Productivity

The carbon isotopic values (δ^{13}C) of planktonic foraminifera are known to be controlled by the δ^{13}C of bicarbonate ions present in the seawater (Hoefs 1997). The δ^{13}C of the bicarbonate ions, in turn, is controlled by the photic zone organic productivity and the δ^{13}C of the water coming from below due to wind-induced mixed-layer deepening or upwelling. δ^{13}C was measured in 3 different species of foraminifera (*G. ruber*, *G. sacculifer*, *G. menardii*) and the results are illustrated in Figure 4. The δ^{13}C values of the species do not exhibit the same trends shown by calcareous productivity (such as a minimum at the LGM with a sharp increase at ~15,000 cal yr BP). One possible reason for such behavior by δ^{13}C is that 2 competing processes (productivity and upwelling) govern it. During enhanced winds, productivity increases due to the influx of nutrients from below, resulting in the consumption of more of ^{12}C by the phytoplanktons, thus increasing the δ^{13}C of HCO_3^- dissolved in the seawater. However, the increased winds also enhance upwelling and bring the water from a deeper level where HCO_3^- is depleted in δ^{13}C. (Typically, water from a depth of 100 m is depleted in δ^{13}C by 0.5‰ relative to surface and increases to 1‰ by ~600 m [Kroopnick 1985].) This upwelled, δ^{13}C-depleted water essentially nullifies the enrichment due to productivity and thus reduces the signal. The core site lies in the equatorial upwelling zone and is also influenced by the wind-induced mixed-layer deepening. When productivity is higher due to stronger winds, surface mixing and upwelling are also higher, resulting in a mixed signal as discussed above. δ^{13}C can be used as a productivity signal in those regions only where the productivity signal is so strong that it masks the upwelling effect, such as in the western Arabian Sea.

SPECTRAL ANALYSIS

Spectral analysis was carried out on the time-series data of various proxies to detect the underlying inherent periodicities that might point towards the various forcing factors governing the climatic conditions at the core site. The proxies that were analyzed included δ^{18}O in all 3 species of foraminifera, along with the $CaCO_3$ % using the REDFIT 3.6 program (Schulz and Mudelsee 2002). In this region, oxygen isotopes of planktonic foraminifera depict E-P (evaporation-precipitation) balance after accounting for ice-volume effect and sea surface temperature changes (Rostek et al. 1993), which have been discussed elsewhere (Tiwari et al. 2005a,b). Proxies such as C_{org} content and δ^{13}C were excluded from this exercise, as their variations do not truly represent the changes in overhead productivity as discussed above. The various spectra that were obtained are shown in Figure 5. The δ^{18}O spectrum of the foraminiferal species *G. sacculifer* and *G. ruber* are dominated by a 17,000-yr periodicity, which is very close to the 19,000-yr cycle observed for Earth's precessional cycle. Various other authors (e.g. Clemens et al. 1991; Reichert et al. 1997; Leuschner and Sirocko 2003) have proposed that in the tropics the precessional phase (~23 kyr) dominates the SW monsoon and associated phenomenon. For example, Reichert et al. (1997) have shown that the C_{org} spectrum is dominated by the 23-kyr periodicity, while Ti/Al shows both 100- and 23-kyr periodicities. Beaufort et al. (1997) have noticed that the primary productivity record from the equatorial Arabian Sea in core MD 900963 is strongly dominated by the precession cycles of the 23- to 19-kyr periods. This led them to propose that the productivity variation at the core site is mainly governed by insolation. The δ^{18}O spectrum of the *G. ruber* also exhibits a periodicity of ~9700 yr, which seems to be a subcycle of the 19-kyr precession cycle. This result reinforces the idea that the SW monsoon (since δ^{18}O variations are mainly influenced by the evaporation-precipitation budget) is mainly governed by the insolation variations induced by the precessional cycle of Earth's orbit.

A time-series analysis of the $CaCO_3$ data exhibits a significant periodicity of ~1140 yr, which is similar to the 1470 ± 500-yr periodicity observed in records from different locations around the globe
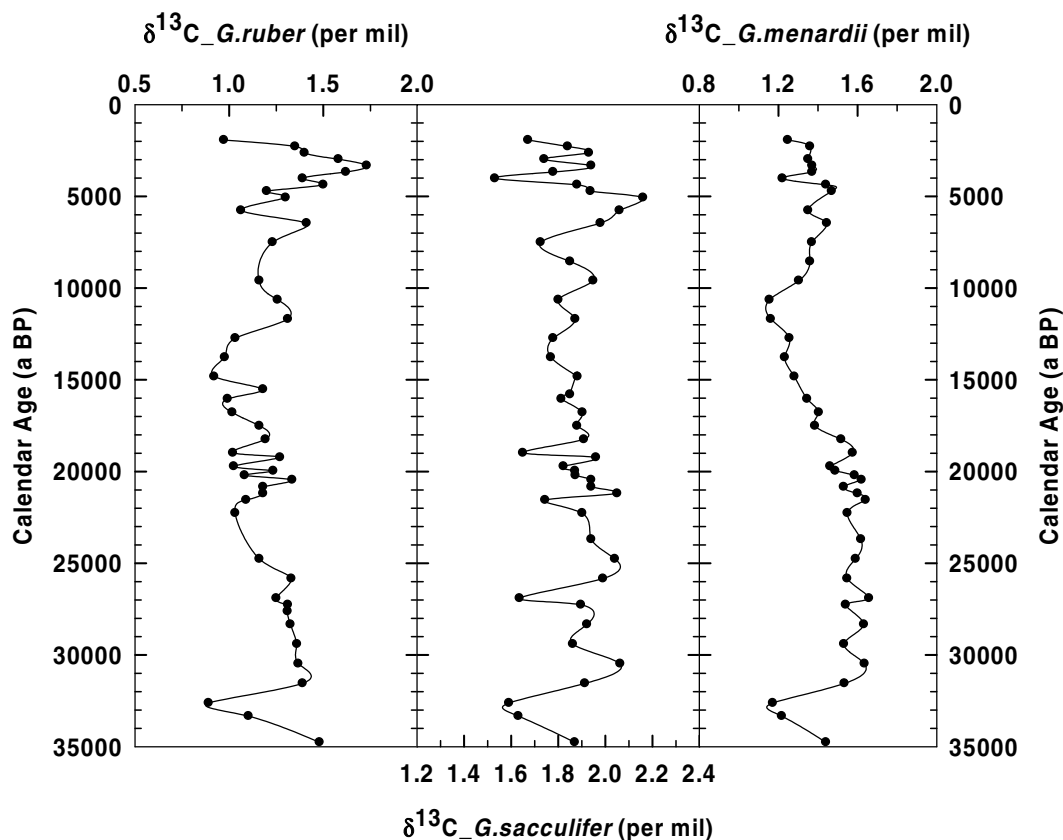
Figure 4 Downcore variation of $\delta^{13}C$ (relative to VPDB) values of 3 species of planktonic foraminifera in core SS3827G

(Sirocko et al. 1996; Bond et al. 1997; Schulz et al. 1998; Mayewski et al. 1998; Campbell et al. 1998; Agnihotri et al. 2003a). Grootes and Stuiver (1997) have shown that this 1470-yr cycle is exhibited by Dansgaard-Oeschger (D-O) events in the Greenland ice-core $\delta^{18}O$ record, which occur every ~1400 yr. The similar periodicity seen in our equatorial record points towards a common forcing factor that appears to corroborate a common link between the tropical and north Atlantic climate. A time-series analysis of $\delta^{18}O$ in *G. menardii* does not yield any periodicity; this might be due to the fact that this species dwells in deeper water and hence is mildly affected by the E-P budget that mainly controls the $\delta^{18}O$ variations at the core site.

CONCLUSION

Calcareous productivity indicates a decreasing IEW and hence decreasing Indian and east African rainfalls from 35,000 calendar yr BP up to the LGM, with a minimum value at the LGM, indicating a maximum El Niño frequency during the last glacial period. Thereafter, the IEW strengthened until 16,500 calendar yr BP, after which it fell back sharply to LGM values for a millennium (~15,500 calendar yr BP), thus signalling a reduction in Indian and African rainfalls. Subsequently, the IEW sharply increased at ~14,500 calendar yr BP (coinciding with the Termination IA), implying a strengthened SWM and EAR. Since ~14,500 to ~2200 calendar yr BP, including the Holocene, calcareous productivity uniformly increased, signifying a uniform strengthening of the IEW and SOI and hence stronger SWM and EAR along with declining El Niño frequency. Based on the compar-
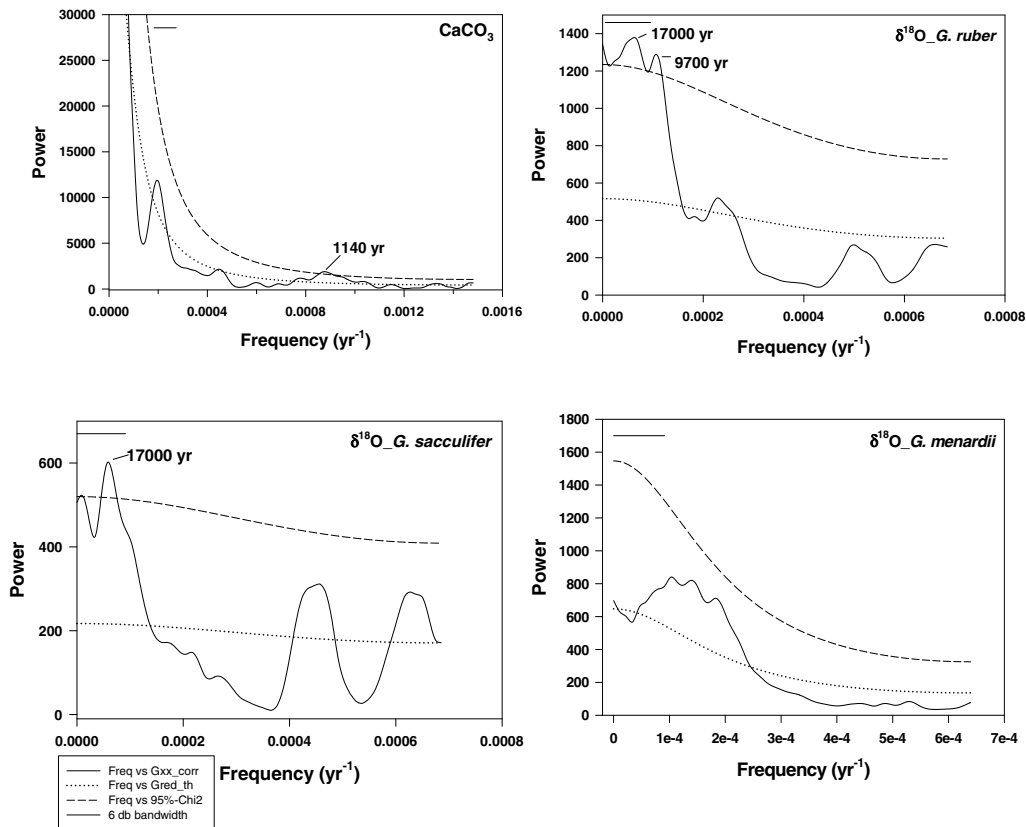
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