

## Radiolarian abundance - a monsoon proxy responding to the Earth's orbital forcing: Inferences on the mid-Brunhes climate shift

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**Abstract:** Radiolarian fluxes from the sediment traps moored in the southern Bay of Bengal suggested that radiolarians were invariably higher at times of higher sea surface temperature ( $SST \geq 28^{\circ}C$ ) and moderately lower salinity ( $\sim 33.5$  psu) during the summers of 1991-93. It implied that higher SSTs due to summer heat and lower salinity due to rains might have affected the radiolarian fluxes during the monsoon. Hence, the down core radiolarian-yield in the unit weight as the percentage abundance may shed light on monsoon-sensitive radiolarian production through the geological past. It is tested in a well-dated radiolarian ooze-bearing sediment core collected from the central Indian Ocean in the southwest of the trap site. Radiolarian tests/g dry bulk sediment (Rads/g) yield from the sediment samples at every 4750 years (4.75 ka) time interval ( $\delta t$ ) produced a time series for the last 485000 years (485-ka) during the late Quaternary. Rads/g was higher during the upper last 200-ka record than the lower section of the core implying higher radiolarian production in the upper part than in the lower part of the core. Blackman-Tukey and maximum entropy spectral analyses of the Rads/g time series revealed multiple cycles at  $\sim 400$ -, 126-, 95-ka due to the Earth's orbital eccentricity,  $\sim 54$ -, 41-, and 31-ka due to axial tilt, 23-, 19-, and 17-ka due to changes in the precession of equinoxes, besides the 15-, 13- and 11-ka sub Milankovitch cycles. The spectral results are further verified by multi-taper method using 90% reshaped spectrum, adaptive narrowband and high-resolution harmonic signals with robust noise and the statistical significance test (F-test), and the  $>90$ -99% significant cyclic components are reconstructed to visualize the variation in their cyclic amplitude through time. The reconstructed cyclic components revealed a conspicuous change in the trend of the amplitudes of  $\sim 95$ -, 54-, 41-, 17-, 15-, and 13-ka cycles suggesting an effect of the mid-Brunhes epoch climate shift at around  $\sim 300$ -350-ka before present. The results substantiates the existence of multiple cycles at the eccentricity ( $\sim 400$ -, 126-, and 95-ka), tilt ( $\sim 54$ -, 41-, and 31-ka) and precession (23-, 19-, and 17-ka) and sub-orbital bands ( $\sim 15$ -, and 13-ka) as proposed by Berger (1977) in the astronomical data. These results strengthens the growing belief in multiple orbital cycles reported from pollens (Mommersteeg et al, 1995) and the radiolarian assemblages (Gupta, 2003), suggesting the cyclic changes in the summer-monsoon productivity during the Late Quaternary in the Central Indian Ocean sediments.

### Introduction

The summer monsoon is the lifeline of agricultural economy of the Indian subcontinent and the southeast Asian countries. Excessive or scanty monsoon rains play havoc in the form of devastating floods and droughts affecting millions of people in this region. Considering vagaries in monsoon rains, there is a growing interest to study the past behavior of the monsoon, so that future trends of rains can be modeled. To derive such models, the information on past monsoon changes is a prerequisite, which can be generated by studying the records of monsoon in the geological past. Earlier, Prell (1984) and Clemens *et al.* (1991, 1996) have studied Indian summer monsoon using monsoonal-wind induced upwelling-indices of planktonic foraminifer *G. bulloides*, calcium carbonate, barium, and organic carbon contents in the sediments from the Arabian Sea. They established the role of the 100-ka Earth's orbital eccentricity, 41-ka axial tilt and 23-, and 19-ka precession of equinoxes in Indian summer monsoon. However, these cycles invariably exist in most of the paleo-climatic record from sub-tropics to pole (Hays *et al.*, 1976; Imbrie *et al.*, 1992, 1993), and they are generally attributed to changes in the ice-volume during the late Quaternary glacial and inter glacial cycles. Nevertheless, studies also pointed out that the signatures of the Earth's orbital eccentricity, axial tilt and precession are different (relatively more important) at different latitudes, for example - tilt signal is most dominant at the higher latitude in mean solar incoming radiation on Earth's surface (insolation), whereas precession and eccentricity relatively dominated in the low and mid-latitudes (Berger, 1993).

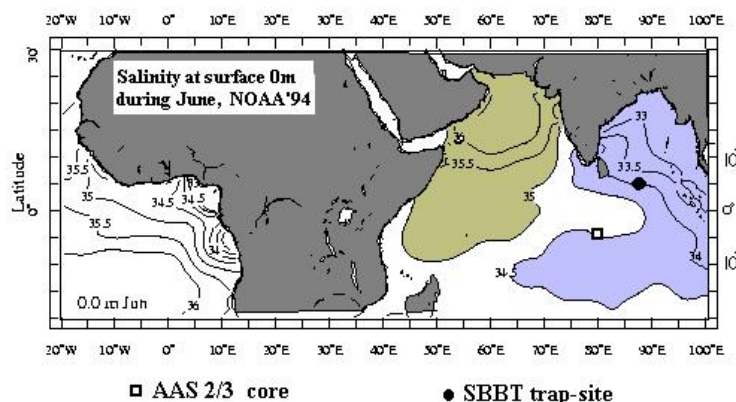
The summer monsoon rains are primarily a result of the tropical ocean heat (SST causing excessive evaporation) and the atmospheric pressure-gradient (winds) resulting into oscillation of Inter Tropical Convergence Zone (ITCZ) across the equator. The ITCZ changes its shape from a narrow rainy band parallel to equator round the year to accumulation of clouds over the Indian subcontinent during the summer monsoon (Gadgil *et al.*, 1984; Gadgil *et al.*, 2002). Although, there are other numerous factors like surface albedo, Indian Ocean dipole, and to some extent ENSO, which play their role in intensity and onset of the monsoon (Ashok *et al.*, 2001), the main limiting factors are the prolongation of critical SSTs ( $\leq 28^{\circ}C$ ) generating excessive evaporation resulting in formation of cumulonimbus clouds (Gadgil *et al.*, 2002), which are transported by southwesterly winds at equatorial region towards the Indian subcontinent. Obviously, monsoon is a unique tropical phenomenon, which would possibly display a different orbital signature from the typical glacial and interglacial climate records at the mid and higher latitudes. Moreover, the nature of the so called single peaks of the 100-ka eccentricity, and 41-ka tilt cycles (Prell, 1984; Imbrie *et al.*, 1992, 1993) has recently been found to be of multiple cycles at  $\sim 400$ -, 126-, 91-ka for eccentricity (Gupta *et al.*, 1996; Muller and McDonald, 1997, Clemens and Tiedemann, 1997), and  $\sim 54$ -, 41-, and 31-ka for the tilt (Melice *et al.*, 2001; Gupta, 2003), concurring to astronomical calculations of the Earth's orbital parameters (Berger, 1977). Therefore, one would expect different results in the monsoonal rain dominated region than from the westerly wind induced Arabian Sea upwelling records, which are often analogous to the typical glacial cycles at the 100-, 41-, and 23-ka in the higher latitudes (Imbrie *et al.*, 1992, 1993).

Radiolarians are the exclusively marine zooplanktons thriving in abundance in the normal open ocean salinity condition (34-36 psu). Radiolarian population is scanty in the low salinity regions such as the river mouths, estuaries, fjords, deltas, and in the bays receiving the large amount of fresh water which decreases the salinity, for example the Bay of Bengal. A recent study of radiolarian fluxes during 1991-1993 from the sediment traps moored in the southern Bay of Bengal suggested that radiolarians were invariably higher at times of higher sea surface temperature ( $SST > 28^{\circ}C$ ) and moderately lower salinity ( $\sim 33.5$  psu) during the summers of 1991-93 (Gupta *et al.*, 2002, cf. fig. 4). The period of 1991-1993 was, if not full El Niño years, at least characterized by

warmer than normal years. Nevertheless, radiolarian fluxes in this slightly warm period could possibly hint to somewhat similar radiolarian fluxes with varying magnitude, and provide insight on similar conditions in geological past. It implied that higher SSTs due to summer heat and lower salinity due to monsoon rains might have affected the radiolarian fluxes during the monsoon. Hence, the down core radiolarian-yield in the unit weight (g) as the percentage abundance may shed light on monsoonal radiolarian production through the geological past. It is studied in a well-dated radiolarian ooze-bearing sediment core collected in the southwest of the trap site from the central Indian Ocean, and the results are presented herein.

## Oceanographic Setting

Most (>80%) of the terrestrial monsoon rains result into fresh water run-off through the rivers into the Bay of Bengal, which is in addition to rains over the bay itself, that causes a hypo-saline condition in the Bay of Bengal. It is in contrast to hyper-saline waters in the Arabian Sea which does not receive major river input except by the Indus, Narmada and Tapti (Gupta, 2003, cf. fig.1). These two salinity extremes are separated by the 34.5 psu isohaline in the central Indian Ocean (Fig.1) from where the radiolarian ooze bearing sediment core is collected, and is used for Rads/g study to ascertain the variations in the monsoon during geological past. Radiolarian abundance is used the surface nutrient and productivity indicator generally associated with upwelling or other hydrographic conditions like sea surface temperature (SST) and salinity. It is assumed that production of radiolarians (being exclusively marine zooplankton) varied with changes in monsoonal SST (high) and salinity (low) in the region. The core is located well within the region of outgoing long wave radiation (OLR) which is a climatologically monsoon index (Gadgil *et al.*, 2002) in central Indian Ocean (Gupta and Fernandes, 1997, cf. fig. 5a).



**Fig. 1. Surface salinity of the tropical Indian and Atlantic Oceans during June (NOAA-1994 CD) with the locations of sediment trap site SBBT (circle), and location of core AAS 2/3 (rectangle). Note the salinity contrast in the Arabian sea (hyper salinity in olive) and the Bay of Bengal (hypo salinity in blue), and location of the core is on the salinity front.**

## Sediment core, radiolarian yield and the time control

The core AAS 2/3 is located at 7°48'S, 80°E (water depth 5463 m; core length 512 cm) near the 34.5 psu isohaline (Fig. 1). It exhibited color laminations of dark and light brown layers of ~1 cm thickness and was sub sampled in 1 cm thick slices at a regular interval of 5 cm. Radiolarian ooze was dried, weighed, treated with sodium hexa-meta-phosphate and hydrogen-per-oxide for dispersal into individual grains. The container with radiolarian grains was put into ultrasonic cleaner for a minute to dislodge the clay infillings from the radiolarian tests, and then sieved onto a 62 µm mesh screen. The sieved material was dispersed into a large container filled with water and stirred thoroughly to bring radiolarian test into suspension and then decanted onto sieve. It resulted into the radiolarian ooze without heavier mineral/glass shards, which got retained into the large container. The resultant radiolarian ooze was dried, weighed, and weight was converted into the percentage of radiolarian ooze yield from the dry sediment weight processed as the radiolarian tests/g of dry bulk sediment (Rads/g).

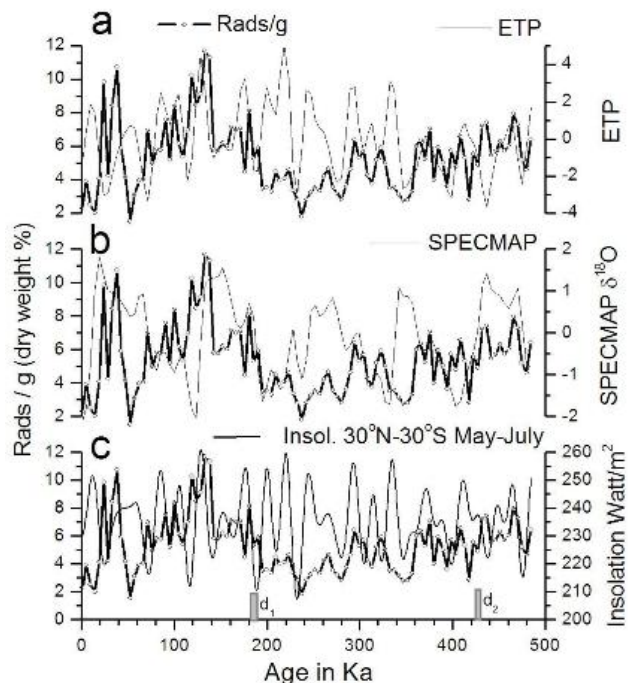
As the core is from a depth >CCD, it is devoid of calcium carbonate and hence the  $\delta^{18}\text{O}$  stratigraphy and AMS  $^{14}\text{C}$  dating was not possible. The core is dated using the first appearance datum of *Buccinosphaera invaginata* at 185 cm (~180 ka) and extinction of *S. universus* at ~435 cm (425 ka: Gupta, 1999, cf. fig. 2) radiolarian synchronous magnetobiostratigraphic datum levels (Gupta, 2003, cf. fig. 2a) of Johnson *et al.* (1989). In addition, the Pyloniid abundance stratigraphy for the tropical radiolarian ooze (Gupta, 2002), which is similar to *C. davisiana* abundance stratigraphy (Morley and Hays, 1981), is used to define the age model of the core. Radiolarian biostratigraphy (Gupta, 1999, cf. fig. 2) and Pyloniid abundance stratigraphy (Gupta, 2002) based age model yields a sedimentation rate of 1.05 cm/ka with a time spacing of  $\delta t=4.75$  ka, dating the core-base at ~485,000 years (Gupta, 2003, cf. fig. 2a). Besides, close correspondence of the Pyloniids with cumulative effective of the Earth's orbital forcing of the eccentricity, tilt and precession (ETP), insolation at 65°N during June and over the core site 8°S during May-July, and the SPECMAP-  $\delta^{18}\text{O}$  stack (Imbrie *et al.*, 1984) provided additional confidence in the time control of the core AAS 2/3 (Gupta, 2003, cf. figs. 2a-d).

## Results and Discussion

### Time-series:

Radiolarian abundance as the percentage of Rads/g dry weight of >62 µm yield varied from 2-12% of the dry sediment processed in the last 485-ka during the late Quaternary. The amplitude of Rads/g variation in the upper younger section of the core is higher than lower older part of the core, suggesting that either the radiolarian production has progressively increased during the last 250-ka or the radiolarians in the older section went under dissolution with time. Although it is difficult to ascertain, the general trend of high amplitude fluctuations in the younger part of the time series compared to the older portion could be attributed to the mid-Brunhes amplitude shift in climate at ~250-300 ka from mild to pronounced contrast in climatic changes. Such mid-Brunhes climatic changes are reported in the strength of trade winds (Björns and Rao, 1988). The Rads/g in the last 485 ka plotted against

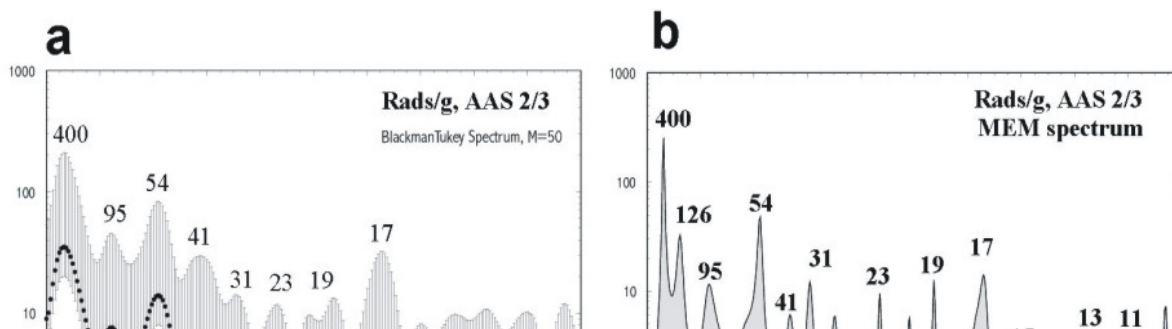
Climate changes are reported in the strength of trade-winds (Fistas and Rea, 1988). The Rads/g in the last 485-ka plotted against the Earth's orbital forcing – the ETP, global ice-volume – the SPECMAP  $\delta^{18}\text{O}$  (Imbrie et al 1984) and the differential insolation at 30°N-30°S during 21 April to 21 July, an insolation index for the summer monsoon (Leuschner and Sirocko, 2003), exhibited close similarities in these time series (Fig. 2). Differential insolation at 30°N-30°S during 21 April to 21 July is calculated in Analyseries (Paillard *et al.*, 1996) using astronomical equations of Berger (1978) for the last 485-ka. The ETP is considered as the orbital index for summer monsoon (Prell, 1984) and has been compared with *G. bulloides* and organic carbon, which are the Arabian Sea monsoonal upwelling index for winds and productivity respectively. Therefore comparison of Rads/g time series with the orbital forcing ETP, SPECMAP-  $\delta^{18}\text{O}$  and insolation index for monsoon helped in ascertaining the monsoonal history in the geological past.

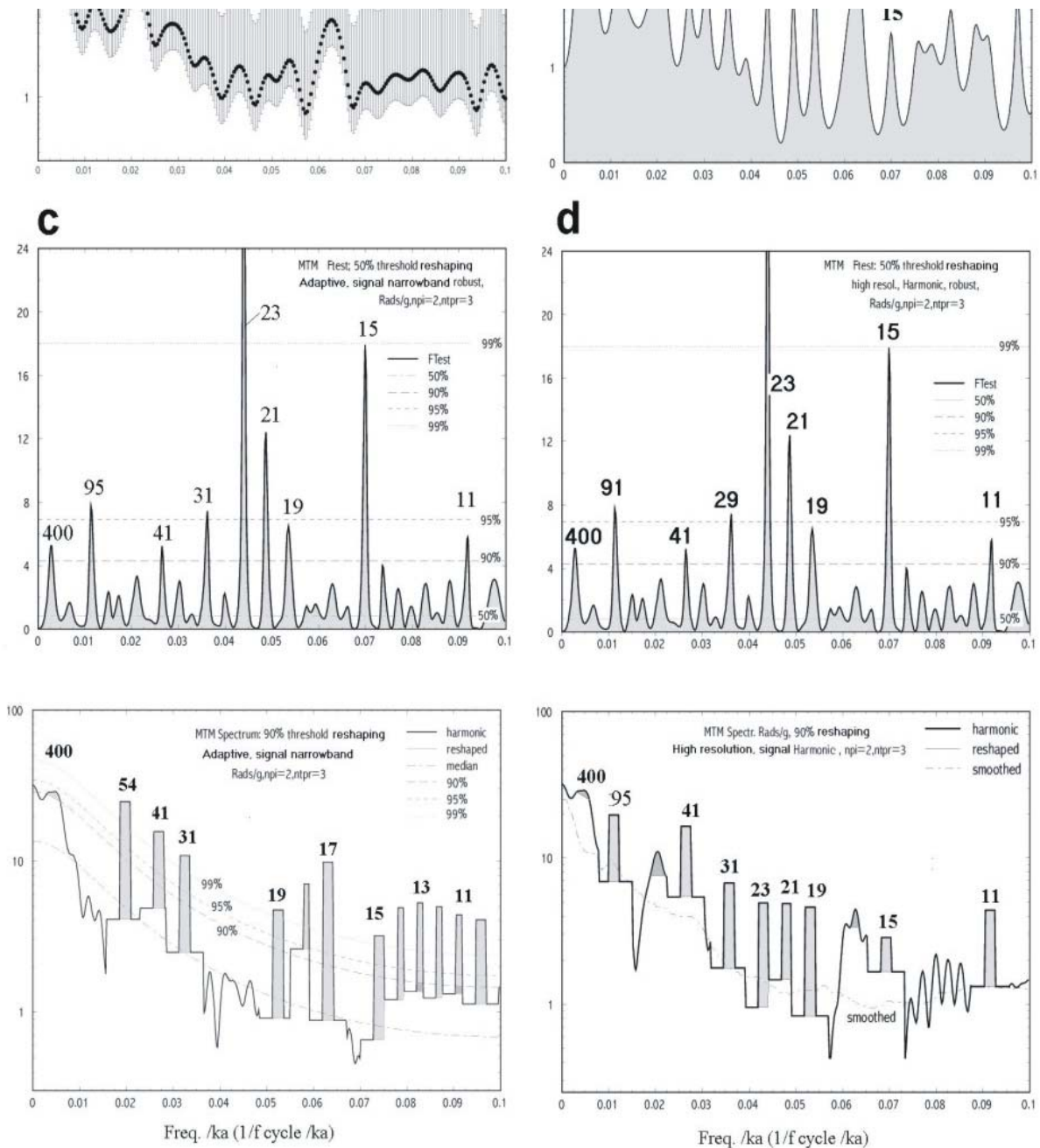


**Fig. 2. Time series of Rads/g in core AAS 2/3 compared with (a) the Earth's orbital forcing ETP, (b) SPECMAP  $\delta^{18}\text{O}$  stack (Imbrie et al. 1984), and (c) differential insolation at 30°N-30°S during 21 April to 21 July calculated by Analyseries (Paillard et al., 1996) using astronomical equations of Berger (1978) for the last 485-ka. Note striking similarities between pairs of time series. Synchronous radiolarian biostratigraphic datum d1 is the first appearance *Buccinosphaera invaginata* at ~180-ka and d2 is the last appearance of *Stylatractus universus* at ~425-ka in core (Gupta, 1999) are also shown (c).**

### Spectral results:

There are several methods for spectral analyses with their inherent merits and demerits. Hence, it is advised to confirm the results by multiple methods (Pestiaux and Berger, 1984). Spectral analyses of the Rads/g data were performed at 4.75-ka time interval ( $\delta t$ ) by Blackman-Tukey correlogram, maximum entropy (MEM: Burg, 1971) and multi-taper (MTM: Thompson, 1990) methods by using Sun-Solaris based spectrum program of Dmitri Kondrashov (University of California, LA). Blackman-Tukey correlogram of Rads/g revealed 400-, and 95-ka eccentricity, 54-, 41-, 31-ka tilt, 23-, 19- and 17-ka precession related cycles, while MEM spectrum exhibited the similar cycles, in addition to 126-ka eccentricity cycle, and suborbital 15-, 13-, and 11-ka cycles (Fig. 3a-b). MTM analysis (setting: 90% reshaping threshold, adaptive-spectrum, narrowband/high-resolution harmonic signal, robust noise estimation, and f-test for levels of significance) resulted in significant (>90-99%) cycles, which were reconstructed and compared with Rads/g time series to visualize the changes in the amplitudes with time. MTM spectral analyses by harmonic signal and narrowband high resolution criterion revealed ~400-, ~91-ka eccentricity, ~54-, 41- and 31-ka tilt, 23-21-, 19- and 17-ka precession, and 15-, 13-, and 11-ka sub orbital cycles (Fig. 3c-d) conforming to MEM results (Fig.3b). As the time series length is ~485-ka, the ~400-ka cycle present in these spectral results should be taken with caution for the limitation of multiple folding frequency (2 cycles of the 400-ka, i.e. 800-ka) record. Similarly, the 11-ka cycle should also be taken with caution as it is just above the critical criterion of nyquist frequency ( $nf=2*\delta t$ : ~9.5-ka).



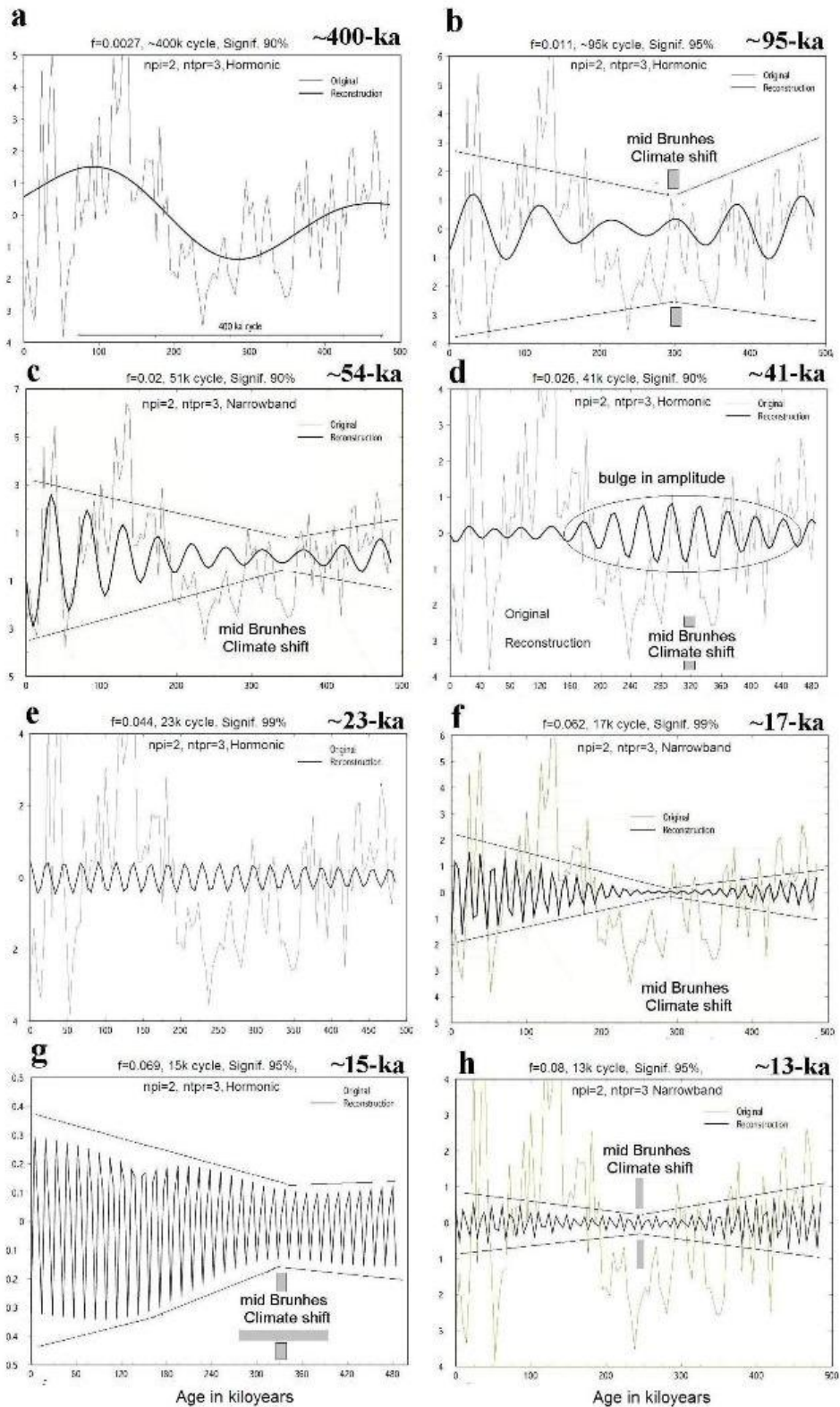


**Fig. 3. Time series analyses by Sun\_Solaris Spectrum program of Kondrashov showing (a) Blackman-Tukey correlogram with Bartlett window and error bars as confidence level, (b) maximum entropy spectrum, (c) multi-taper analyses with 90% reshaping threshold for adaptive and narrowband signal and (d) high resolution harmonic signal showing horizontal lines with the degree of freedom at 90%, 95% and 99% statistical significance for F-test (upper panel) and the respective amplitudes of reshaped and tapered spectrum (lower panel). Significant cycles (>90%) are identified with periodicities in kiloyears (ka).**

#### Mid Brunhes amplitude shift in cycles:

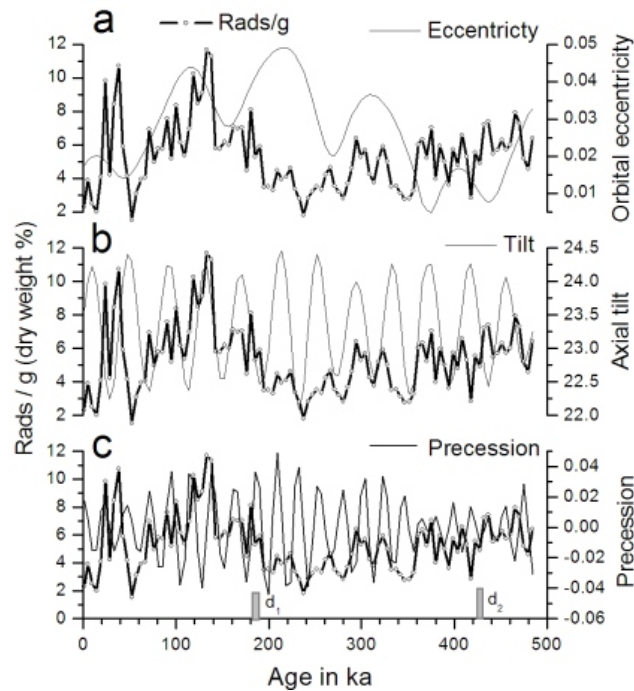
Significant (>90-99%) cyclic components of recognized orbital and suborbital cycles are reconstructed and plotted along with the Rads/g time series to visualize the variation in their amplitudes with time (Fig.4). The ~400-ka eccentricity cycle (90% significant) is represented by peaks at ~75ka and at ~475-ka (Fig. 4a). It should not be mistaken with a long term trend in time series, as similar 400 ka eccentricity cycles are the real one and well documented in recent climatic records (Gupta *et al.*, 1996; Clemens and Tiedemann, 1997; Muller and MacDonald, 1997). The ~95-ka eccentricity cycle (95% significant) exhibited a pinch with minimum amplitude at ~300 ka time, while the ~54-ka tilt cycle (90% significant) had minimum amplitude at 350-ka (Fig. 4b-c). The 41-ka tilt (90% significant) cycles show a progressively bulging amplitude between ~180 to ~480-ka with a maximum bulge at ~300-ka (Fig. 4d). The 23 ka precession cycle is 99% significant with uniform amplitude throughout the core (Fig. 4e). The ~17-ka precession cycle (99% significant), 15- and 13-ka sub orbital cycles (95% significant) exhibited a pinching amplitude with minima located between 250-300ka (Fig. 4f-h). The 17-ka precession and 15- and 13-ka suborbital cycles are most interesting as they depicted a conspicuous decreasing trend till ~350-400-ka, and thereafter again have increasing amplitude the down core. The amplitudes of all the significant cyclic components (except the 400-ka eccentricity and 23-ka precession cycles) in the Rads/g data invariably suggested a change between 200-250 ka ( $\pm 20$ ) which may be attributed to the mid Brunhes climatic shift (Dise-

data invariably suggested a change between 300-350-ka ( $\pm 20$ ) which may be attributed to the mid-Brunhes climatic shift (Pisias and Rea, 1988). Finally, as the results suggested that the Rads/g data responding to the orbital forcing - the ETP, the Rads/g time series is plotted (Fig. 5) against the Earth's orbital eccentricity, axial tilt and precession of equinoxes calculated using Analyseries (Paillard *et al.* 1996) by astronomical formulae of Berger (1978), which further substantiates the results.



**Fig. 4. MTM reconstructions of the significant (>90-99%) harmonic/narrowband cyclic components at ~400-, ~95-, ~54-, ~41-, ~31-, ~23-, ~17-, ~15-, and ~13-ka are compared with Rads/g time series (a-h). Note pinching in the**

amplitudes of the 95-ka eccentricity, 51-ka tilt, and 17-ka precession, and 13-ka sub orbital cycles, and bulging in 41-ka tilt cycle between ~300-350 ka time slice. Most of the cyclic components (except 400-ka eccentricity and 23-ka precession) exhibited remarkable change in their amplitudes at ~300-350-ka, which may be attributed to the climate shift during the mid Brunhes epoch (Pisias and Rea, 1988).



**Fig. 5. Rads/g time series compared with the Earth's orbital eccentricity, axial tilt and precession of equinoxes for the last 485-ka suggesting that most of the peaks / troughs of Rads/g data correspond (with lag/lead) to the peaks / troughs present either in eccentricity, tilt or the precession. Cross spectral analyses suggested coherency with tilt and precession cycles (not shown).**

These results concur to the first reported triplet eccentricity cycles at 400-, 126-, 95-ka in the tropical paleo sea surface temperatures (Gupta *et al.*, 1996), which were later found in foraminiferal sand (Muller and MacDonald, 1997) from the Sunda Sea, a site within the Asian monsoon regime, and the  $\delta^{18}\text{O}$  record (Clemens and Tiedemann, 1997). Muller and MacDonald (1997) discussed the 100-ka cycles, which are believed to be due to the eccentricity ( $e$ ), and argued to assign them to inclination ( $i$ ) of the Earth's orbital plane, as the eccentricity should have triplet cycles at ~400-, 126- and 95-ka according to Berger (1977). An excellent review on the enigma on problem of eccentricity versus inclination driving the 100-ka cycles may be found in Kerr (1997). Therefore, Rads/g cycles at ~400- (with caution), and ~95-ka are due to Earth's eccentricity (Berger, 1977, Gupta *et al.*, 1996, 1999; Clemens and Tiedemann, 1977; Muller and McDonalds, 1977), while ~54-, 41-, and 31-ka cycles of Rads/g are due to axial-tilt as discussed by Gupta (1999; 2003) and established by analysis of axial tilt data by Melice *et al.* (2001). Similarly, the suborbital cycles in Rads/g at 15-, 13, and 11-ka (Figs. 3-4) conform to the 15-ka sub-orbital cycles of Berger (1977), whereas 13- and 11-ka cycles concur to ice-core record of Treut *et al.* (1988) and Willes *et al.* (1999). Although, the radiolarian yield in a unit quantity of sediment is the most primitive data analogous to foraminiferal coarse fraction component from the ODP site in the Indonesian region analyzed by Muller and McDonald (1997), it contained almost complete spectral frequencies of the Earth's orbital forcing at the Milankovitch (<400-ka to >17-ka) and sub-Milankovitch (<15-11-ka) cycles.

## Conclusions

Radiolarian test abundance in dry weight of the sediment, although is a basic data without any sophistication as in other proxies like faunal counts and oxygen isotope analysis, it does respond to the Earth's orbital forcing, and can be served as a quick proxy to determine the climate history of a sediment core. The Rads/g revealed multiple cycles of the eccentricity at ~400-, and 95- ka; tilt at 54-, and 41-ka, precession at 23-, and 17-ka, sub-orbital 15-ka cycle as proposed by Berger (1977), and the 13-ka sub orbital cycles conforming to recent report in a radiolarian assemblage based monsoon record (Gupta, 2003). The ~400-ka eccentricity cycle is short of length of folding frequency (800-ka) and 11-ka suborbital cycle is closer to nyquist frequency ( $2 \cdot \delta t = 9.5\text{k}$ ), respectively, and so they should be taken with caution. The change in the amplitudes of ~95-, 54-, 41-, 17-ka orbital and 15-, 13-ka sub-orbital cycles at around 300 to 350-ka could be assigned to mid-Brunhes climate shift during this time. In brief, it may be surmised that salinity-sensitive radiolarian test abundance responded well to the orbital forcing, and exhibited multiple cycles due to variations in the eccentricity, tilt, precession, along with sub-orbital cycles at 15-, 13- and 11-ka during the late Quaternary in the central Indian Ocean.

**Acknowledgements:** Author thanks to the Director Dr. S.R. Shetye for the facilities and encouragement. He thanks to Prof. C.N.R. Rao (JNC, Bangalore) for the Rajiv Gandhi Foundation grant. Thanks are also expressed to Dr. Dmitri Kondrashov (University of California, LA) and Dr. D. Paillard (France) for the software used in spectral analyze and calculating differential insolation at mid latitudes during summer. respectively. Thank is extended to Drs. B.N. Nath for helps during the studv. This

paper is dedicated as the author's gratitude to his teachers. It is National Institute of Oceanography, Goa contribution No. 4486.

## References

- Ashok, K., Guan, Z. and Yamagata, T. (2001) Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett.*, v. 28(23), pp. 4499-4502.
- Berger, A. L. (1977) Support for the astronomical theory of climatic change. *Nature*, v. 269, pp. 44-45.
- Berger, A.L. (1978) Long term variations of daily insulations and Quaternary climatic changes. *Jour. Atmospheric Sci.*, v. 35, pp. 2362-2367.
- Berger, A.L. (1993) Insolation and Earth's orbital periods. *Jour. Geophys. Res.*, v. 98, D6, pp. 10341-10362.
- Burg, J.P. (1972) The relationship between maximum entropy spectra and maximum likelihood spectra. *Geophysics*, v. 37, pp. 375-376.
- Clemens, S.C. and Tiedemann, R. (1997) Eccentricity forcing of Pliocene-Pleistocene climate revealed in a marine oxygen-isotope record. *Nature*, v. 385, pp. 301-304.
- Clemens, S.C., Prell, W.L., Murray, D., Shimmield, G. and Weedon, G. (1991) Forcing mechanisms of the Indian Ocean monsoon. *Nature*, v. 353, pp.720-725.
- Clemens, S.C., Murray, D.W. and Prell, W.L. (1996). Non-stationary phase of the Plio-Pleistocene Asian monsoon. *Science*, v. 274, pp. 943-948.
- Gadgil, S., Joseph, P.V. and Joshi, P.V. (1984) Ocean-atmosphere coupling over monsoon regions, *Nature*, v. 312, pp. 141-143.
- Gadgil, S. Srinivasan, J., Nanjundiah, R.S., Kumar, K.K., Munot, A.A. and Kumar, K.R. (2002) On forecasting the Indian summer monsoon: the intriguing season of 2002. *Current Science*, v. 43(4), pp.394-403.
- Gupta, S.M. (1999) Radiolarian monsoonal index Pyloniids respond to astronomical forcing in the last 5,00,000 years in the central Indian Ocean Basin. *Man & Environment*, v. XXIV, pp. 99-105.
- Gupta, S.M. (2002) Pyloniid stratigraphy – a new tool to date tropical radiolarian ooze from the central tropical Indian Ocean. *Marine Geology*, v. 184, pp. 85-93.
- Gupta, S. M. (2003) Orbital frequencies in radiolarian assemblages of the central Indian Ocean: implications on the Indian summer monsoon. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* v. 197, pp. 97-112.
- Gupta, S.M. and Fernandes, A.A. (1997) Quaternary radiolarian faunal changes in the central Indian Basin: Inferences to paleomonsoonal oscillation of the 10<sup>0</sup>S hydrographic front. *Current Science*, v. 72, pp. 965-972.
- Gupta, S.M., Fernandes, A.A. and Mohan, R. (1996) Tropical sea surface temperatures and the Earth's eccentricity cycles. *Geophys. Res. Lett.*, v. 23, pp. 3159-3162.
- Gupta, S.M., Mohan R. and Guptha, M.V.S. (2002) Radiolarian fluxes in the southern Bay of Bengal: A sediment trap study. *Deep Sea Research, I*, v. 49, pp. 1669-1688.
- Hays, J.D., Imbrie, J. and Shackleton, N. (1976) Variations in the Earth's orbit: pacemaker of the Ice-Ages. *Science*, v. 194, pp. 1121-1132.
- Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C, Morley, J., Pisias, N.G., Prell, W.L. and Shackleton, N.J. (1984) Orbital theory of climate: support from a revised chronology of the record. In: *Berger, A.L. et al., (Eds.) Milankovitch and Climate Part I*, D. Riedel, Dordrecht, Netherlands, pp. 269-305.
- Imbrie, J., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J, Martinson, D.G., McIntyre, A., Mix, A.C., Molfimo, B., Morley, J.J., Peterson, L.C., Pisias, N.G., Prell, W.L., Raymo, M.E., Shackleton, N.J. and Toggweiler, J.R., (1992) On the structure and origin of major glaciation cycles 1. Linear response to Milankovitch forcing. *Paleoceanography*, v. 7(6), pp. 701-738.
- Imbrie, J., Berger, A., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J, Martinson, D.G., McIntyre, A., Mix, A.C., Molfimo, B., Morley, J.J., Peterson, L.C., Pisias, N.G., Prell, W.L., Raymo, M.E., Shackleton, N.J. and Toggweiler, J.R. (1993) On the structure and origin of the major glaciation cycles 2. The 100,000 year cycle. *Paleoceanography*, v. 8(6), pp. 699-735.
- Johnson, D.A., Schneider, D.A. Nigrini, C., Caulet, J.P. and Kent, D.V. (1989) Pliocene-Pleistocene radiolarian events and magneto-stratigraphic calibrations for the tropical Indian Ocean. *Marine Micropaleontology*, v. 14, pp. 23-66.

micropaleontology, v. 14, pp. 55-66.

- Kerr, R.A. (1997) Upstart Ice age theory gets attentive but chilly hearing. *Science*, v. 227, pp. 183-184.
- Leuschner, D.C. and Sirocko, F. (2003) Orbital insolation forcing of the Indian Monsoon – a motor for global climate changes? *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, v. 197, pp 83-95.
- Melice, J.L., Coran, A. and Berger, A.L. (2001) Amplitude and frequency modulations of the Earth's Obliquity for the last million years. *Jour. Climate*, v. 14, pp. 1043-1054.
- Mommersteeg, H.J.P.M., Loutre, M.F., Young, R., Wijmstra, T.A. and Hooghiemstra, H. (1995) Orbital forced frequencies in the 975000 year pollen record from Tenagi Philippon (Greece). *Climate Dynamics*, v. 11, pp. 4-24.
- Morley, J.J. and Hays, J.D. (1981) Towards a high resolution, global deep sea chronology for the last 750,000 years. *Earth & Planetary Science Letters*, v. 53, pp. 279-295.
- Muller, R.A. and MacDonald, G.J. (1997) Simultaneous presence of orbital inclination and eccentricity in the proxy climate records from Ocean Drilling Program site 806. *Geology*, v. 25, pp. 3-6.
- Paillard, D., Labeyrie, L. and Yiou. P. (1996) Macintosh program performs time series analysis. *EOS Trans AGU*. V. 77, p. 379.
- Pestiaux, P. and Berger, A.L. (1984) An optimal approach to the spectral characteristics of deep sea climate record. *In: Berger, A.L. et al., (Eds.) Milankovitch and Climate part I*, D. Riedel, Dordrecht, Netherlands, pp. 417-445.
- Pisias, N.G. and Rea, D.K (1988) Late Pleistocene paleoclimatology of the Central Equatorial Pacific: Sea surface response to the southeast trade winds, *Paleoceanography*, v. 3, pp. 21-37.
- Prell, W.L. (1984) Monsoonal climate of the Arabian Sea during the late Quaternary: A response to changing solar radiation. *In: Berger, A.L. et al. (Eds.) Milankovitch and Climate, Part I*, D. Riedel, Dordrecht, Netherlands, pp. 349-366.
- Thomson, D.J. (1990) Quadratic-inverse Spectrum estimates: application to paleoclimatology, *Philos. Trans. R. Soc. London*, v. A-332, pp. 539-597.
- Treut, H.L, Portes, J., Jouzel, J. and Gill M. (1988) Isotopic modeling of climatic oscillations: Implications for a comparative study of marine and Ice core records. *J. Geophys. Res.*, v. 93, D8, pp. 9365-9383.
- Willes, K.J., Kleczkowski, A., Briggs, K.M. and Gilligen, C.A. (1999) Role of sub-Milankovitch climate forcing in initiation of northern hemisphere glaciation. *Science*, v. 285, pp. 568-571.



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