Chapter 3

Eastern Arabian Sea: High Resolution Monsoon Reconstruction for the Past ~2800 years

3.1. Introduction:

Most of the earlier studies on paleomonsoon variations have concentrated on the western Arabian Sea, as it undergoes intense biogeochemical changes during the SW Monsoon (Nair et al, 1989) that are easily detectable. But most of these studies have focused on the effect of SW Monsoon winds on various processes such as wind induced upwelling, dust transport etc (e.g. Clemens et al, 1991; Anderson and Prell, 1993; Sirocko et al, 1993; Naidu et al, 1993, Reichart et al (2002 a), Gupta et al, 2003 and references therein). and not on the precipitation signal. Stronger SW Monsoon winds do not necessarily mean higher monsoon precipitation as, the latter depends on various other parameters such as the moisture content of the air-masses, which is probably influenced by the SST of southern Indian Ocean (Clemens et al, 1996), air parcel convergence and convection etc. (Gadgil, 2003). So it becomes very important to test how the wind speed correlates with the precipitation and how this relationship varied in the past. The eastern Arabian Sea receives abundant fresh water as either direct overhead precipitation or surface runoff from the adjacent hills, present along the western Indian coast (Western Ghats), which induce intense orographic precipitation during the SW monsoon (June – September). The influx of copious amounts of fresh water into the coastal eastern Arabian Sea reduces the sea surface salinity (SSS) that is reflected in the various proxies that ultimately get preserved in the sea sediments. A sediment core *viz*. SK145-9 has been strategically chosen from the eastern Arabian Sea, where sedimentation is fast enough to provide a high time resolution comparable to studies from the western Arabian Sea. This can help in the comparative study of past changes on two different aspects of the monsoon: (i) wind induced upwelling and productivity (ii) rainfall and runoff to the ocean and its effect on surface salinity. Furthermore, because of the high-resolution sampling, it can delineate centennial and sub-centennial scale variations in the monsoon rainfall during the past ~2800 years, corresponding to the studied length of the core SK145-9.

3.2. Core location:

Core SK 145-9 has been raised from the eastern continental margin of the Arabian Sea from a water depth of 400m off the Mangalore coast. It is from a depth that falls well within the oxygen minimum zone (OMZ), which is 250 – 1250 m in the present day Arabian Sea (Naqvi, 1987, Wyrtki, 1971; Deuser et al, 1978, Olson et al, 1993). For further details regarding the core location, please refer to Table 2.1. The core location is shown in Fig.3.1 with the locations of other cores from the Arabian Sea with which results are compared.

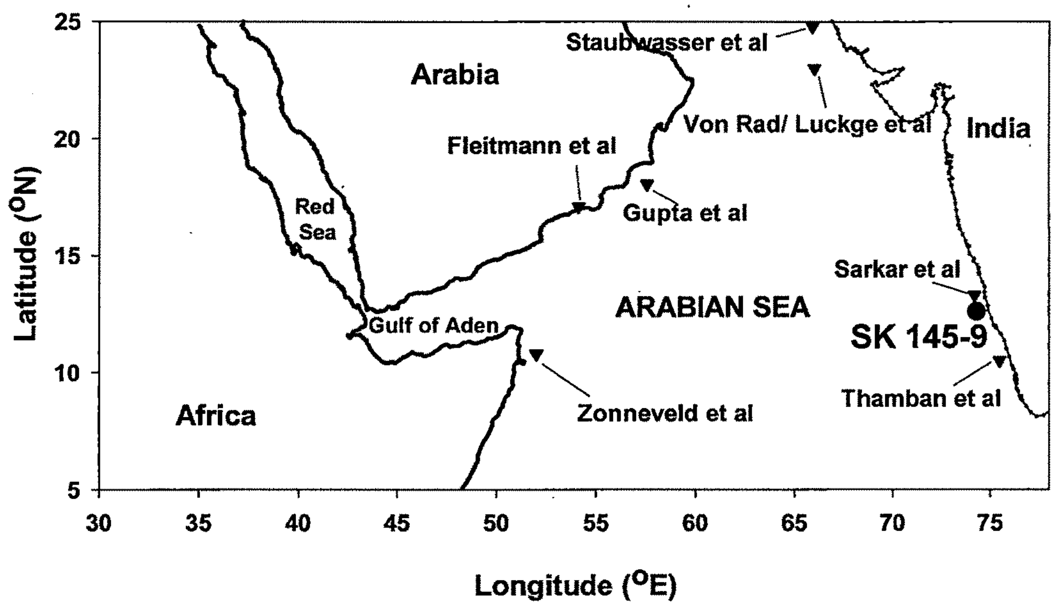


Fig.3.1. Locations of the core SK145-9 (this study, shown by circle) and other cores with which it has been compared.

3.3. Oceanographic conditions at the core site:

During the SW monsoon abundant orographic precipitation takes place over the Western Ghats (upto 4000 mm yr^{-1}, Sarkar et al, 2000) that lie parallel to western Indian coast from ~20^0N to ~10^0N latitudes. This freshwater ultimately gets into the coastal Arabian Sea as surface runoff and reduces the sea surface salinity considerably. This reduction in the surface salinity is evident in the Fig.3.2, during September. The salinity contours were taken from the website www7320.nrlssc.navy.mil/global_ncom/ara.html maintained by the Naval Research

Laboratory, United States Navy. Along the southwestern Indian coast, the salinity contours become north-south with low salinities of upto 34.5 PSU pointing towards the fresh water influx and away from the coast, salinities rapidly increase.

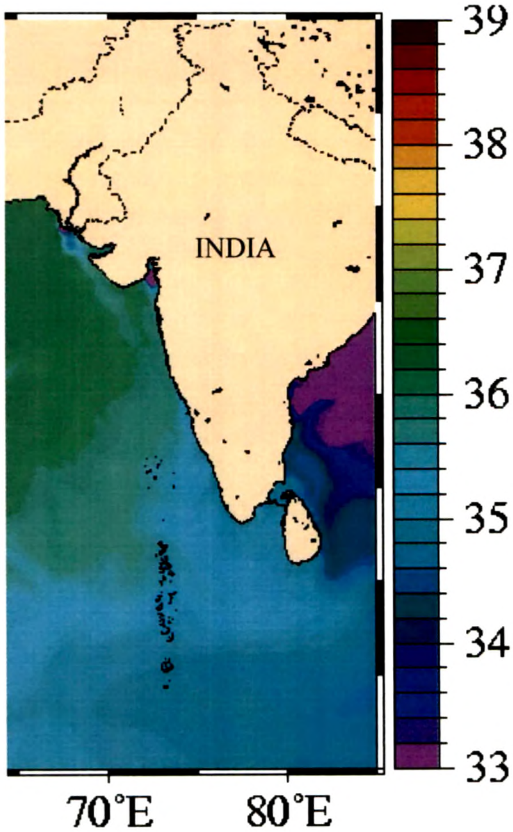


Fig.3.2. September Salinity contours in the eastern Arabian Sea. Salinity units are in PSU.

The surface circulation in the eastern Arabian Sea is characterized by seasonally reversing West Indian Coastal Current (WICC). Please refer to the Fig.1.1 and 1.2 for schematic diagrams of the Indian Ocean circulation during the summer and winter monsoons respectively. During the summer monsoon (SW monsoon), WICC flows southward along the western Indian coast involving the Laccadive Low (LL) and meets the Southwest Monsoon Current (SMC) that flows eastward (Cutler and Swallow, 1984; Shetye and Shenoy, 1988). There is a weak northward flowing undercurrent carrying the low salinity waters at 150-200 m (Antony, 1990; Shetye et al, 1990). During the winter monsoon (NE monsoon), the westward flowing Northeast Monsoon Current (NMC) supplies water to the WICC that now flows northward. This northward flowing WICC is associated with a southward flowing undercurrent

(Shetye et al, 1991) at a depth of 150-200 m. During this season an anticyclonic gyre develops just north of the Laccadive Islands at the southern end of WICC, which is known as Laccadive High (LH) as sea surface height increases by ~12 cm during that time (Bruce et al, 1994).

3.4. Age-Depth Model:

The core SK145-9 has eleven dates covering ~13,000 calendar years (spanning 252 cm length) providing an average sedimentation rate of 19 cm/10^3 years. This core has an average resolution of ~50 year per cm. The top 50 cm have been sampled at every cm and below 50 cm the sampling was done at every 2 cm. Thus it offers a high-resolution and therefore will aid in understanding sub-centennial scale variability. The top 50cm of this core (sampled closely), covering a time span of approximately 2800 years, has been taken for further studies. The top of the core (*viz.* 0-2 cm) has a calibrated age of 410 ± 80 yr. For dates in the tabular form and other related information please refer to Table 2.2.

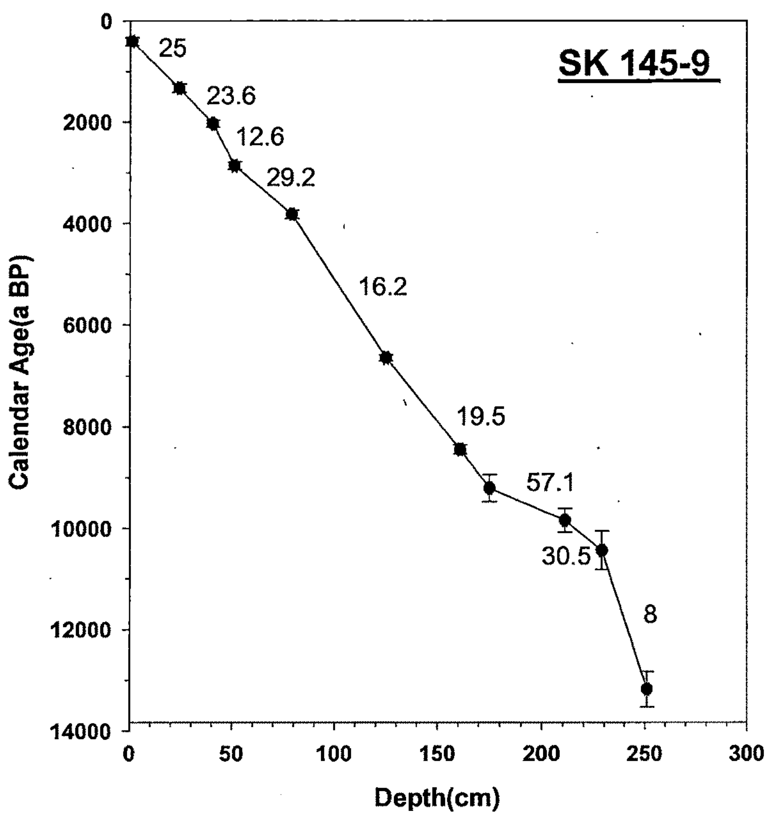


Fig. 3.3. Calibrated radiocarbon ages and sedimentation rates (cm/ka) for various intervals in the core SK145-9.

The radiocarbon dates in this core have been converted to calendar ages using the calibration program "Calib 4.1 (INTCAL 98)" (Stuiver et al, 1998) with a reservoir age correction of 500 ± 30 years (deviation from the assumed value of 400 years i.e. ΔR = 100 ± 30 yr, Dutta et al, 2001). Dutta et al (2001) measured gastropod and bivalve shells from western Indian off the Dwarka (in Saurashtra) coast and southern India off Rameshwaram. They reported a ΔR value of 163 ± 30 yrs for Saurashtra coast and 32 ± 20 yrs for southern Indian coast. So an approximate value falling midway between these two values was taken as the ΔR value for the core location. Later Southon et al (2002) have reported a ΔR value of 126 ± 64 yr for a location very close to the core site, which is similar to that of Dutta et al (2001).

3.5. Precipitation Signals as Manifested by Oxygen Isotopes:

Oxygen isotopic analyses have been carried out on three different species of foraminifera *viz. Globigerinoides ruber*, *Globigerinoides sacculifer*, *Globorotalia menardii* as shown in the Fig.3.4. *G.ruber* and *G.sacculifer* are surface dwelling species predominantly inhabiting top 25 m and 50 m respectively whereas *G.menardii* is a deeper dwelling species predominantly inhabiting 100-150 m (Be, 1977, Fairbanks et al, 1980; Fairbanks et al, 1982). Thus an oxygen isotope signal arising due to any surface processes (e.g. salinity change) will be most pronounced in the surface dwelling species *viz. G.ruber* and *G.sacculifer* and will be subdued in the deeper dwelling species i.e. *G.menardii*. As evident from Fig. 3.4, all the three species show similar signals that are somewhat restrained in the deeper dwelling one. Furthermore comparative analysis with *G.bulloides* data from the ODP Site 723A and a box core RC2730 from the adjacent Oman margin, western Arabian Sea (Gupta et al, 2003) has been carried out to check whether high/low SW monsoon wind intensity results in higher/lower precipitation. *G.bulloides* is a temperate water species and can occur in tropics where cooler water is present due to upwelling. Thus their abundance as expressed as percentage of total planktonic foraminifera is an excellent indicator of upwelling, which in turn is controlled by the wind strength (Anderson et al, 2002).

The factors controlling the oxygen isotopes in foraminiferal shells are the sea surface salinity (SSS) and sea surface temperature (Shackleton, 1967, Niitsuma et al, 1991). For the past ~3 ka there has been no salinity fluctuations due to the global ice-volume effect as there were no significant global ice-melting episodes affecting sea level (Fairbanks, 1989). Moreover the SST variations in the tropics for the past 10 ka are very small (~0.5^0C, Rostek et al, 1993). The studied species are known to grow predominantly during the SW monsoon months and hence are likely to record the signals arising mainly due to SW monsoon fluctuation (Guptha et al, 1997). In the eastern Arabian Sea, SSS variation is mainly controlled by the variation in the supply of fresh water as surface runoff from the adjacent Western Ghats during the southwest monsoon. Furthermore, a weak upwelling system occurs in the eastern Arabian Sea along the western Indian coast prior to the SW summer monsoon that gets established from February onwards (Shetye, 1984). This upwelling is controlled by factors other than the SW monsoon winds. Studies by Shankar and Shetye (1997) and McCreary et al (1993) have shown that the early upwelling is a result of the remote forcing by winds in the Bay of Bengal and southwest coast of India that generate the northward propagating Kelvin and westward propagating Rossby waves. It is further confirmed by the study carried out by Thamban et al (2001) on a sediment core near the Cochin coast (southwest continental margin of India). They suggest that the remote forcing on upwelling could have been more active during the past. With the onset of SW monsoon winds, the upwelling intensifies and the SST drops by upto 3°C (Levitus and Boyer, 1994). But as the upwelling is affected by basin-wide remote processes in Arabian Sea and Bay of Bengal (McCreary et al, 1993), the variation in the local upwelling intensity will only affect the interannual SST changes in a small way (Thamban et al, 2001). We therefore assume that the dominant factor controlling the $\delta^{18}O$ signals in the eastern Arabian Sea is the SSS changes induced by the variation in the SW monsoon precipitation. A reduction in SSS occurs due to the influx of large amount of fresh water, depleted in ^{18}O, as surface runoff into the coastal eastern Arabian Sea during intense SW monsoon precipitation events. In the eastern Arabian Sea, for every per mil decline in salinity, the $\delta^{18}O$ value decreases by 0.33 ‰ (Duplessy et al, 1981; Sarkar et al, 2000). Thus a depleted $\delta^{18}O$ signal indicates enhanced southwest monsoon precipitation whereas an enriched $\delta^{18}O$ signal points towards reduced precipitation due to weaker southwest monsoon (indicated by arrows in the Fig. 3.4).

In order to have a quantitative estimate of the rainfall variation over the southeastern coastal Arabian Sea, a parameter P-E i.e. excess of precipitation over evaporation has been approximately estimated. Ramesh Kumar and Prasad (1995) calculated P-E values for this region during the monsoon season (the primary data being temperature, salinity and wind stress). The core top $\delta^{18}O$ values of *G.sacculifer* (predominantly inhabits top ~50 m and major growing season is during SW monsoon) have been calibrated with the P-E data and an approximate transfer function has been obtained (Ramesh, 2001) for the eastern Arabian Sea, which is as follows:

$$(P\text{-}E)\ mm \sim -800\ \delta^{18}O - 1400$$

The P-E values are depicted at the top of the second panel of the Fig.3.4, as shown below:

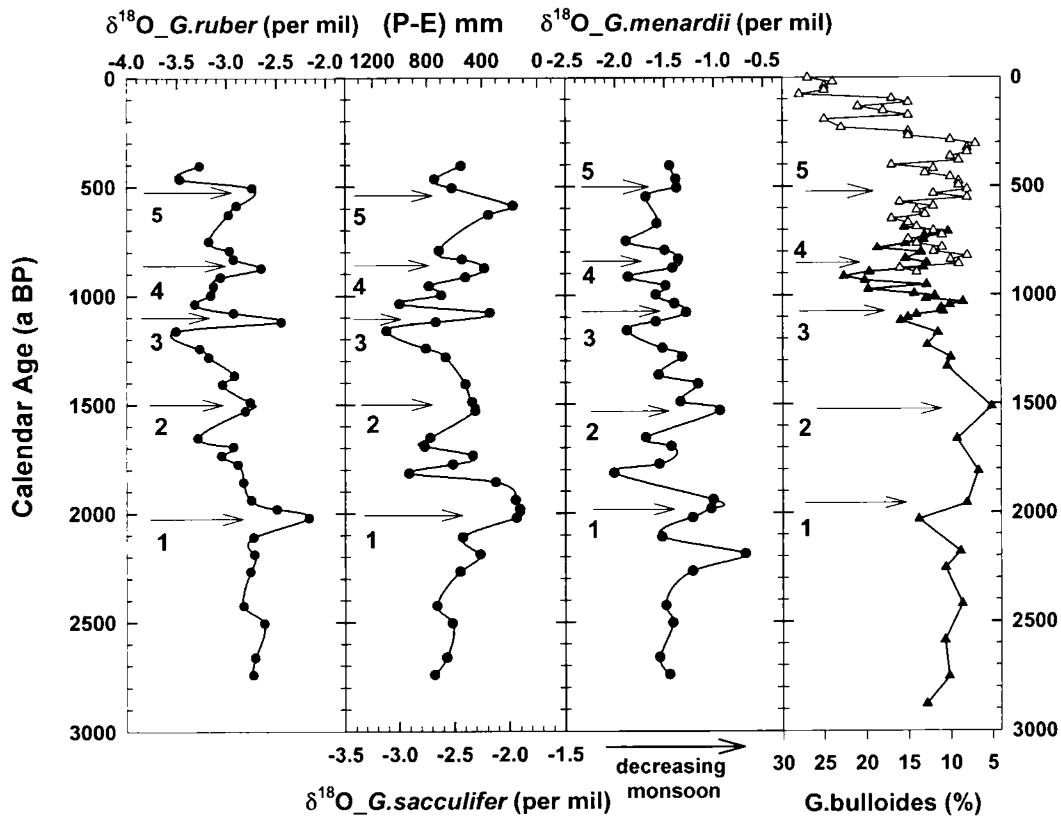


Fig.3.4. Downcore variations of $\delta^{18}O$ of three species of foraminifera in the core SK 145-9 (shown by closed circles, this study), % *G.bulloides* data from the ODP Site 723A (closed triangles) and the Oman margin box core RC2730 indicated by open triangles (Gupta et al, 2003), P-E values shown at the top of the 2nd panel.

The first enriched $\delta^{18}O$ signal observed at 2000 a BP (indicated by arrow-1 in Fig.3.4) points towards an increase in SSS and hence a reduction in the monsoon intensity at that time. This arid event is reflected not only in both the surface dwelling species i.e. *G.ruber* and *G.sacculifer* (which will be more affected by the increase in SSS) but also in the deeper dwelling species *G.menardii* in which it is quite pronounced. This points towards the severity of the 2000 a BP arid event. This arid event centered at 2000 a BP has been widely seen in many terrestrial and marine records. Yadava and Ramesh (2005) noted a prominent arid event (enriched ^{18}O) in the speleothem deposits in a cave from Orissa, eastern India. Similarly Von Rad et al (1999) and Luckge et al (2001) analyzed a core from the northern Arabian Sea off the Karachi coast covering the past 5000 years, which is influenced by the river runoff from Pakistan. They have reported low precipitation at 2000 a BP based on the Ti/Al and varve thickness data. Our observation above, the low SW monsoon precipitation at 2000 a BP, is based on an entirely different proxy from a different location in the Arabian Sea. The 2000 a BP arid event is also observed in the % *G.bulloides* (Gupta et al, 2003) record that shows a decrease at that time indicated by the arrow-1 pointing towards reducing wind intensity. A reduction in monsoon is also indicated by a hiatus in the growth of speleothem in Oman from 2500 a BP to 1500 a BP (Fleitmann et al, 2003). Staubwasser et al (2003) found reduced precipitation on the basis of increasing $\delta^{18}O$ in *G.ruber* from a core off the Pakistan coast. Zonneveld et al (1997) obtained a core from the Somalian coast, western Arabian Sea and found a decline in the upwelling intensity ~2000 a BP on the basis of dinoflagellates cysts and inferred that SW monsoon strength declined during that time. Similarly, Sarkar et al (2000) and Thamban et al (2001) have taken sediment cores from the eastern Arabian Sea near to the Manglore coast and Cochin coast respectively and measured $\delta^{18}O$ values in planktonic foraminifera. Although their cores have coarser resolution, still they exhibit reduction in SW monsoon precipitation during ~2 ka BP. Thus it is clear that this 2000 a BP arid event was recorded in diverse proxies not only in the Arabian Sea but also on the Indian Subcontinent. Thereafter the monsoon tends to strengthen upto 1600 a BP as exhibited by the decreasing $\delta^{18}O$ signal and P-E values that increased from 100 mm to 1000 mm (Fig. 3.4).

An earlier, short aridity signal in the form of enhanced $\delta^{18}O$ value at 2200 a BP is seen only in the deeper dwelling species i.e. *G.menardii* (~150-200 m water depth). One possible explanation could be the following. During SW monsoon, southward flowing West Indian Coastal Current (WICC) is accompanied by a northward flowing undercurrent carrying low salinity waters at a depth of 150-200 m (Antony, 1990; Shetye et al, 1990). If SW monsoon strength reduced, then it would weaken the WICC as well as the undercurrent and the $\delta^{18}O$ values of only the deeper dwelling species would increase as the inflow of low salinity water reduced.

Another arid event of a smaller magnitude is observed at 1500 a BP (shown by arrow-2), shown by all the three species of foraminifera. At that time % *G.bulloides* exhibits minimum abundance (~5 %) in the western Arabian Sea (Gupta et al, 2003) pointing towards an extreme reduction in upwelling and hence the wind strength. But this minimum wind strength does not correspond to minimum precipitation, which happens at ~2000 a BP as evident by the maximum $\delta^{18}O$ values during that time. This indicates that variation in the monsoon wind strength is not linearly related to the variation in monsoon precipitation.

Thereafter, precipitation intensity strengthens upto ~1200 a BP after which it shows a sudden decline centered at ~1100 a BP (shown by arrow-3) and then monsoon intensified as rapidly. This sudden reduction and subsequent enhancement in monsoon intensity is also observed in the wind intensity record of the western Arabian Sea as shown by sharp decline in % *G.bulloides* during the above period. It is also observed in the speleothem records (Yadava and Ramesh, 2005), varve record (Von Rad et al, 1999; Luckge et al, 2001), sediment record (Staubwasser et al, 2003) and the Oman stalagmites (Fleitmann et al, 2003).

Another episode of precipitation reduction is observed at the ~800 a BP to ~900 a BP that is reflected all the three species of the foraminifera (arrow-4). This reduction is accompanied by a corresponding reduction in the SW monsoon wind intensity (Gupta et al, 2003). This event is seen by Von Rad et al (1999) in varve thickness records and by Staubwasser et al (2003), who find a prominent $\delta^{18}O$ enhancement at that time. Fleitmann et al (2004) also observed this event in the stalagmites from the southern Oman.

The next arid event as evident by the $\delta^{18}O$ record of the core SK145-9 occurs at ~500 a BP (indicated by arrow-5) that is shown by all the three species. The % *G.bulloides* also exhibits a decrease at that time implying reduced wind strength. This event is also observed in the varve thickness record (Von Rad et al, 1999) and sediment record (Staubwasser et al, 2003). Luckge et al (2001) measured Ti/Al ratio in the varve sediments (Von Rad et al, 1999) indicating fluvial input. They found reduced fluvial input during that time indicating reduced monsoon precipitation. Furthermore, Fleitmann et al (2004) observed a reduction in precipitation at ~500 a BP in stalagmite deposits from southern Oman.

Thus the above discussion proves that the periods of aridity observed in the eastern Arabian Sea were widespread and were reflected in diverse proxies from different regions around it. Also, wind speed indicators from the western Arabian Sea exhibit a good correlation with the precipitation signals from the eastern Arabian Sea at least during the last 2800 years. Reduced precipitation was accompanied with weakened winds and vice-versa. But the relationship appears to be non-linear as precipitation minimum occurred at ~2000 a BP while the wind minimum occurred at ~1500 a BP.

3.6. Temporal variation in productivity:

Various productivity indicators such as $CaCO_3$ %, organic carbon content and $\delta^{13}C$ of the three different species of foraminifera along with $\delta^{15}N$ in the sedimentary organic matter were also measured in the same core.

3.6.1.Productivity as manifested by $CaCO_3$ and C_{org} content:

During the SW monsoon months, strong winds might cause mixed layer deepening, which injects nutrient rich waters into the surface layer enhancing surface productivity. Another possibility is increased productivity due to nutrients derived from land in the form of surface runoff. Thus, higher productivity may result either from increased runoff or increased winds. Data from the JGOFS-India program during the 1994-1995 shows that the primary productivity reaches ~0.6 $gC/m^2/d$ during the SW monsoon whereas it is only ~0.3 $gC/m^2/d$ and ~0.2 $gC/m^2/d$ during the NE monsoon and intermonsoon respectively (Bhattathiri et al, 1996). The present core has been raised from a water depth of 400 m that lies well within the OMZ (150 m – 1250

m) in the Arabian Sea. In the oxygen depleted waters of OMZ, organic carbon is better preserved for which various reasons have been given, which include (1) the need to establish complex microbial communities for the stepwise degradation of organic substrates, (2) the buildup of toxic waste products such as H_2S, (3) due to unavailability of oxygen, benthic organisms do not inhabit the sediments overlain by OMZ waters hence lack of bioturbation, (4) the presence of compounds that resist anoxic degradation but are easily degraded aerobically via O_2-requiring oxidative enzymes (Hedges and Kiel, 1995; Emerson and Hedges, 1988; Lee, 1992, Aller, 1994). It also escapes the diagenetically active layer rapidly due to the high sedimentation rate (average ~19 cm/ka) and thus gets shielded from other oxidizing agents such as nitrate, sulphate etc. (Heinrichs, 1992).

The following figure shows the downcore variations in the calcareous and organic productivity, along with the C/N ratio.

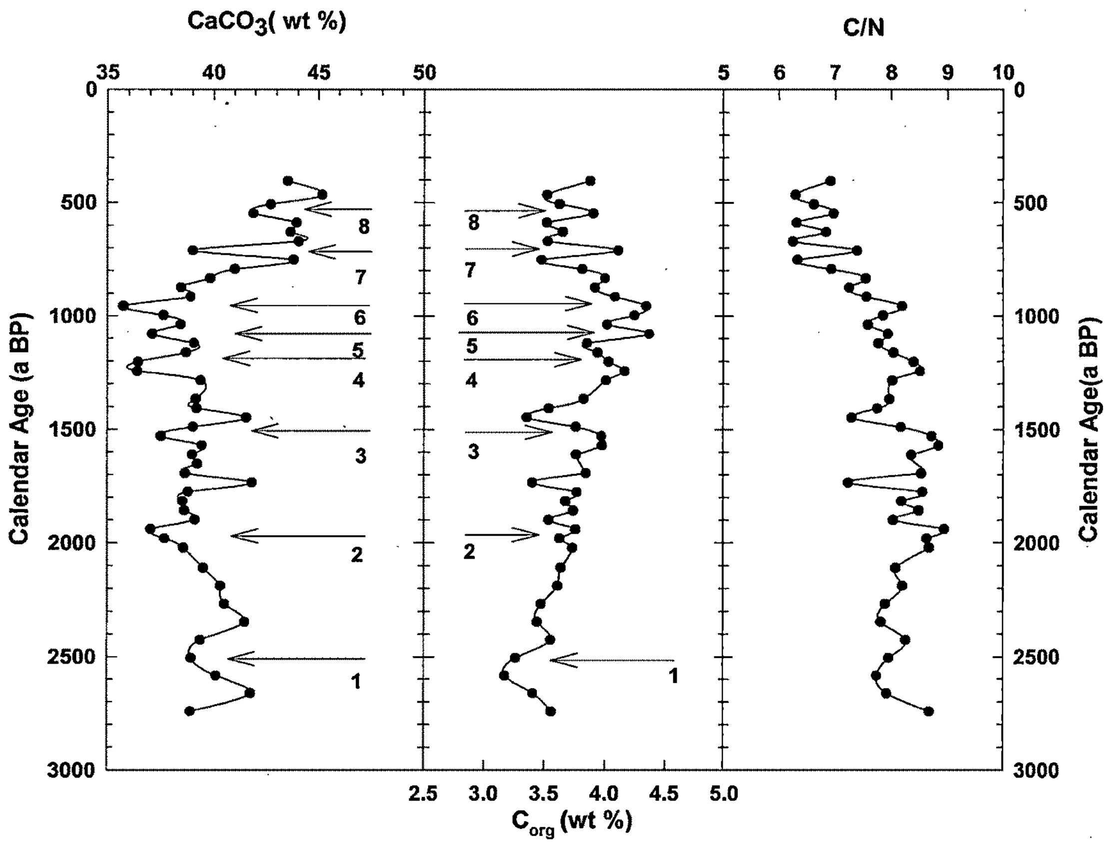


Fig 3.5. Downcore variation of $CaCO_3$, C_{org} and C/N ratio in the core SK145-9 covering the last ~2800 years.

C/N ratio has been a traditional proxy to determine the origin of organic matter. Recent marine organic matter has a typical C/N ratio of ~8 ±2 (Mackenzie, 1980) whereas the terrestrial organic matter has a C/N ratio of ~20 to ~100 (Premuzic et al, 1982; Meyers, 1994). As evident from the last panel in the Fig3.5, it is clear that the organic matter is mainly of the marine origin as all the values fall well within the marine C/N range. It indicates that although the core is from coastal region and probably influenced by terrestrial inflow, mostly the marine surface productivity governs the downcore variation of the various productivity indices.

Centered at ~2500 a BP there is a decline exhibited by the calcareous productivity, which is also reflected in the organic productivity (arrow-1, Fig.3.5). A slight decrease in monsoon intensity is observed at that time as evident from the increasing $\delta^{18}O$ values in all the three species of foraminifera (Fig.3.4). Subsequently calcareous and organic productivity show a very interesting trend. During the periods of reduced monsoon, calcareous productivity decreases whereas organic productivity increases. At 2000 a BP, which is the time of widespread aridity (seen in $\delta^{18}O$), we observe a decline in $CaCO_3$ (%) while C_{org} (%) follows an increasing trend (arrow-2, Fig.3.5). During the next major arid episode, centered at ~1500 a BP, we again find a decrease in calcareous productivity whereas organic productivity shows enhancement (arrow-3). Similarly during the next arid event as deciphered from the oxygen isotopes at 1100 a BP, the calcareous and organic productivity exhibit reduction and enhancement respectively (arrow-5). Thereafter calcareous productivity exhibits an increasing trend with decline observed at the major arid events such as at ~900 a BP (arrow-6) and ~500 a BP (arrow-8). In contrast the organic productivity stays more or less uniform or displays a slightly decreasing trend.

A possible reason for the opposite behaviour of organic and inorganic (calcareous) productivity could be: while winds mix up the ocean, providing nutrients from below and enhancing productivity, fresh water runoff from the land forms a lid and suppresses mixing; however runoff might carry nutrients from lands such as silicate and phosphate to enhance diatom and organic productivity. During the periods of reduced SW monsoon, upwelling intensity decreases considerably resulting in reduced supply of nutrients from below but surface runoff (although relatively lower) will bring a little amount of nutrients that will result in organic productivity. Calcareous organisms are not the primary producers in the oceans; instead they are the secondary consumers i.e. consume the primary producers (main contributor to organic productivity). The relatively lower organic productivity will affect calcareous organisms more as they are higher on the food web and are more sensitive to the changes in food supply. Hence a reduction in nutrient supply could result in reduced calcareous productivity but could support the organic productivity. Such a contrasting behaviour with calcareous productivity is also exhibited by $\delta^{13}C$ in the planktonic foraminifera that is further discussed in the next section (section 3.5.2) along with another probable reason *viz.* onset of *Trichodesmium* (a blue-green algae) blooms.

There are several signals of reduced calcareous productivity such as at 1200 a BP and 700 a BP (shown by arrows- 4 & 7), which are the periods of enhanced precipitation, as inferred from oxygen isotopes. A possible cause can be that productivity in the eastern Arabian Sea is an interplay of at least two factors i.e. wind induced surface layer mixing (or upwelling) and fresh water runoff from the land as discussed earlier. Thus productivity is not controlled solely by SW monsoon wind strength but depends on which factor dominates during that particular period. During reduced SW monsoon, wind intensity weakens that in turn reduces the upwelling because of which calcareous productivity reduces as is the case for 2500 a BP, 2000 a BP, 1500 a BP signals. But, during enhanced monsoonal precipitation large amount of fresh water get into the coastal Arabian Sea, which forms a low salinity lid over the seawater that inhibits upwelling (Thamban et al, 2001) and reduces calcareous productivity. But this terrestrial inflow also brings nutrients that enhance the organic productivity. When the primary productivity is relatively lower due to the reduced upwelling and is sustained by terrestrial nutrient supply only, it will affect secondary consumers more as they are more sensitive to the changes in food supply. Thus even relatively higher monsoon intensity e.g. at 1200 a BP and 700 a BP could result in reduced calcareous productivity.

3.6.2.Productivity as manifested by $\delta^{13}C$:

The $\delta^{13}C$ in foraminifera are controlled by the carbon isotopic composition of seawater, which in turn is governed by the organic productivity as discussed in the section 2.4.2. The following figure shows the temporal variations in $\delta^{13}C$ in three species of foraminifera *viz. G.ruber*, *G.sacculifer* and *G.menardii.*

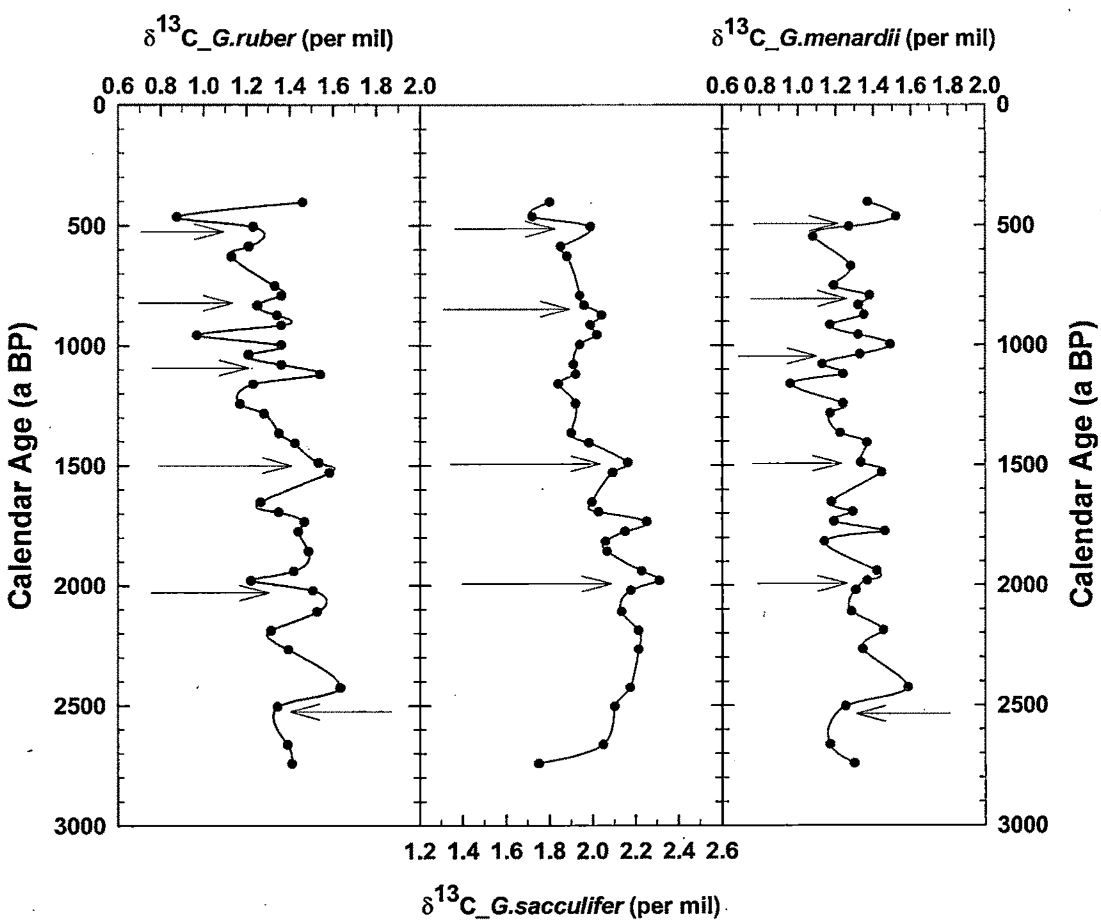


Fig 3.6. Downcore variation of $\delta^{13}C$ of three species of foraminifera in the core SK 145-9.

At 2500 a BP, we find a decrease in $\delta^{13}C$ that is conspicuously seen in the two species viz. *G.sacculifer* and *G.menardii.* Such a decrease is observed in both calcareous and organic productivity indicators along with a precipitation decline as inferred from slightly increasing $\delta^{18}O$ at that time. It implies that SW monsoon precipitation reduced at that time, which is reflected in various productivity indicators.

At 2000 a BP we find an increase in $\delta^{13}C$ values, which is the time of widespread aridity. This observation is in contrast to calcareous productivity that shows a decrease; but $\delta^{13}C$ is akin to C_{org}, which increases during that time. Thus $\delta^{13}C$ variations in foraminifera indeed reflect organic rather than inorganic productivity. A similar contrast between the calcareous productivity and the $\delta^{13}C$ in all the three species is also observed during other periods of reduced SW monsoon viz. at ~1500 a BP, ~1100 a BP, ~850 a BP and ~500 a BP. During these periods C_{org} (%), which is an indicator for organic productivity exhibits an enhancement. These observations points towards a very interesting fact that the organic productivity increases during the periods of reduced calcareous productivity, possibly due to runoff supplying nutrients as explained in the previous section.

Another explanation is possible if we take the growth of *Trichodesmium* into account in the surface waters of the eastern Arabian Sea. Genus *Trichodesmium* (Greek; *tricho* = hair, *desmos* = chain) comprises marine, planktonic, blue-green algae that form filamentous colonies. They occur dominantly in the oligotrophic (nutrient poor) tropical and subtropical waters (Carpenter, 1983). They can survive in the nutrient poor water, as they are diazotrophic i.e. directly fix dissolved N_2 rather than NH_3 or NH_4^+, which is the more preferred pathway. *Trichodesmium* possess gas vesicles that help them float on the sea surface. When the wind stress is low for an extended period of time then extensive blooms could develop, which are called as "Red Tides". In fact Red Sea derived its name from the coloration imparted by *T.erythraeum* blooms. Some species of *Trichodesmium* are toxic and prevent consumption by organisms higher in the food chain (Hawser et al, 1992; Capone et al, 1997). During reduced monsoon conditions when oligotrophic conditions develop due to reduction in vertical mixing and runoff, extensive *Trichodesmium* blooms can occur in the eastern Arabian Sea. *Trichodesmium* blooms have been reported from the eastern Arabian Sea, along the western Indian coast (Devassy et al, 1978; Sarangi et al, 2004). If toxic species of *Trichodesmium* prevails then it could reduce the production of other carbonate and siliceous shell secreting organisms but

Trichodesmium biomass will contribute to organic productivity. This could explain the contrasting behavior exhibited by the organic and calcareous productivity.

This is further supported by the depleted $\delta^{15}N$ observed in the sedimentary organic matter as discussed below.

3.7.Temporal variation in the stable isotopes of nitrogen:

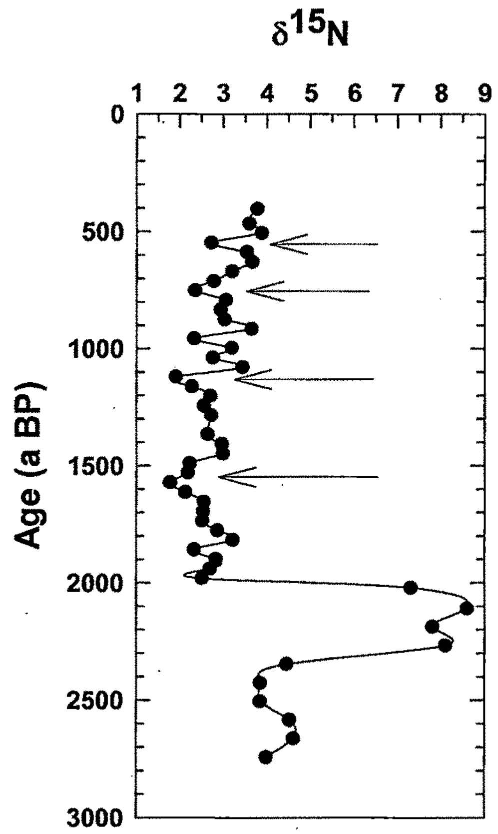


Fig.3.7. Downcore variation of $\delta^{15}N$ of the sedimentary organic matter in the core SK145-9.

$\delta^{15}N$ of the organic matter is controlled by the isotopic composition of the source nitrogen species and the fractionation occurring during the uptake of the nitrogen by the organisms. The organisms such as *Trichodesmium* that directly utilize N_2 dissolved in the seawater ($\delta^{15}N$ near to 0 ‰) will have very depleted $\delta^{15}N$ signature compared to organisms utilizing NO_3^-or NH_4^+ ($\delta^{15}N$ is 5 to 6 ‰, Liu, 1989; Kumar et al, 2004). The sedimentary organic matter, which has contributions from organisms directly fixing the atmospheric nitrogen, posses a typical $\delta^{15}N$ value of 0-2 ‰

(Capone et al, 1997). Thus sediments constituting *Trichodesmium* will have lower $\delta^{15}N$ values.

The onset of *Trichodesmium* bloom took place near ~2000 a BP in the eastern Arabian Sea as evident from the sudden decrease observed in $\delta^{15}N$ values at that time. This period is the major arid event (as seen in $\delta^{18}O$), which would have led to the development of oligotrophic conditions with very low wind stress that would have facilitated the growth of *Trichodesmium*. Thereafter these blooms seem to persist for the remaining time period covered by the core.

Furthermore, several millennial scale variations are observed during ~1500 a BP, ~1100 a BP, ~800 a BP and ~500 a BP (shown by arrows) that are periods of reduced monsoon. During such periods $\delta^{15}N$ of the sedimentary organic matter exhibits depleted values that indicates that contribution of the isotopically lighter *Trichodesmium* increases.

Nitrogen percentage is sufficient in this core (typically a value of 0.7 % whereas in the other two cores that are from the open ocean location, it varies from 0.1 % to 0.05 %) and isotope measurements have been rechecked, and confirmed.

However the unusual nature of variation (a sudden jump) needs to be verified by analyzing more cores from the same location. Therefore the above interpretation is only tentative.

3.8. The Solar connection:

It has been proposed that earth's climate is sensitive to very mild changes in solar output, not only at decadal time scales but also at centennial to millennial scales (Bond et al, 2001). Currently there has been a renewed interest in climate forcing by Total Solar Irradiance (TSI), observed to show a remarkable agreement with the smoothened global temperature in the 20th century (Foucal, 2003). Precise measurement of TSI has been made using space borne radiometers, which show that it varies with an rms amplitude of about 0.1% in response to the changing area covered by sunspots. But this variation seems to be too low to cause widespread climatic changes. It is suggested that there is a large amplitude, slowly varying component of TSI that has been overlooked by the radiometric measurements. It is believed that TSI might have been lower by as much as 0.25% during the Maunder Minimum than at present (Lean et al, 1995) and even a minor variation in TSI (0.1 -

0.3%) can bring about major changes in monsoonal precipitation via various positive feedback processes such as moisture availability and changes in atmospheric circulations (Neff et al, 2001; Mehta and Lau, 1997; Bond et al, 2001). Neff et al (2001) studied speleothem samples from Oman for the period 9 ka to 6 ka and compared them with $\Delta^{14}C$ record from tree rings, which is dependent on cosmic ray fluxes modulated by solar activity. They found an excellent correlation between the monsoon and solar proxies and concluded that variation in solar radiation exhibits a prominent control over the monsoon system on centennial to decadal timescales. Similarly, Fleitmann et al (2003) analyzed Holocene speleothems from Oman and compared the $\delta^{18}O$ data with GRIP $\delta^{18}O$ and $\Delta^{14}C$ record from tree rings. They proposed that early Holocene monsoon circulation was controlled by glacial boundary conditions such as North Atlantic northward heat transport and the thermohaline circulation. After 8 ka BP, as the thermohaline circulation stabilized, the monsoon circulation responded more directly to solar forcing. Agnihotri et al (2002) obtained a core from the eastern Arabian Sea off the Gujarat coast and analyzed it for various paleoclimatic proxies for the past 1200 years and compared with TSI data. They found nearly similar trends for all these proxies and TSI variation within the radiocarbon dating errors; lower TSI is accompanied by lower productivity and reduced runoff denoting weakened monsoon precipitation. Spectral analyses of the TSI, paleoclimatic proxies and the Indian summer monsoon rainfall yielded similar periodicities, which led them to propose that solar forcing controls the monsoonal precipitation.

Bard et al (2000) reconstructed TSI data for the past 1200 years, which has been taken for the present study. They based the TSI estimation on the common fluctuations of the ^{14}C and ^{10}Be production rates obtained from tree rings and polar ice. The TSI curve used in this study assumes a 0.25% reduction in TSI during Maunder Minimum as proposed by Lean et al (1995). The TSI data is unequally spaced at 8 to 10 years interval, which is first splined for every 10-year and then a 10 point running average is taken so that resolution of the TSI data becomes comparable to the resolution for the core SK 145-9. The TSI data are compared with the $\delta^{18}O$ in all the three foraminiferal species, which is a more robust proxy for the SW monsoon intensity as discussed in the section 3.4. The productivity proxies can't be used as they are affected not only by SW monsoon wind induced surface mixing but also by surface runoff that complicate their relationship with monsoon. The figure 3.8 compares the temporal variation in TSI and paleoclimatic proxies.

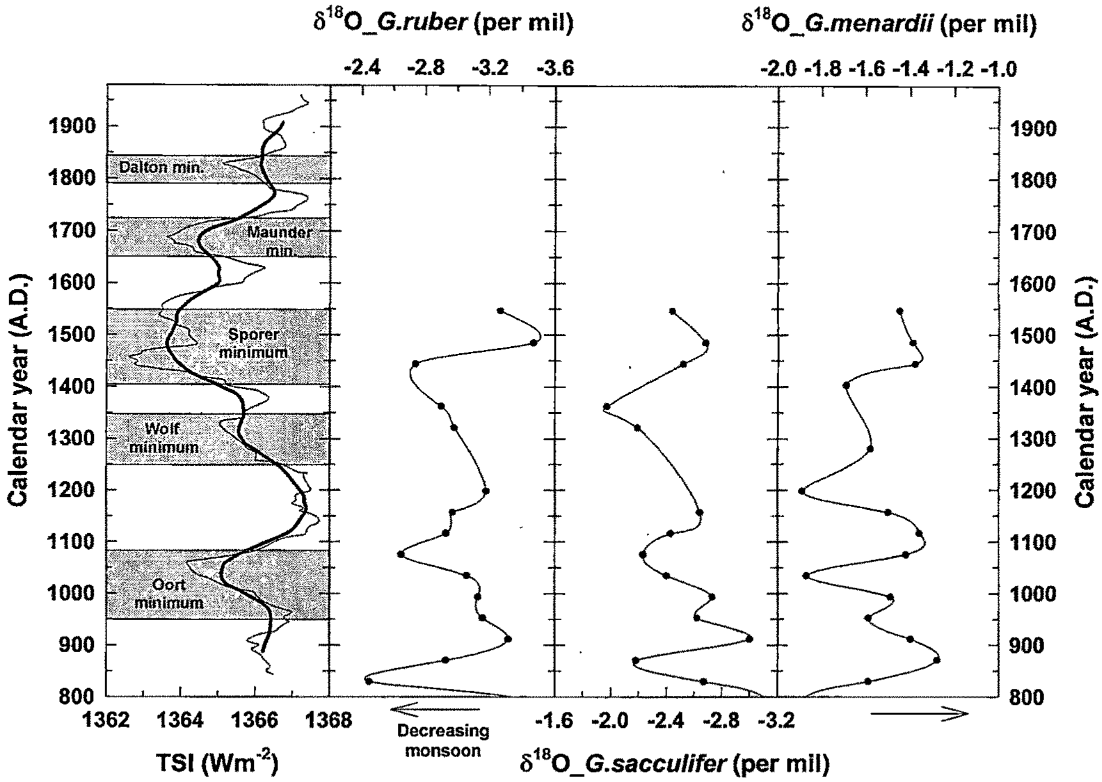


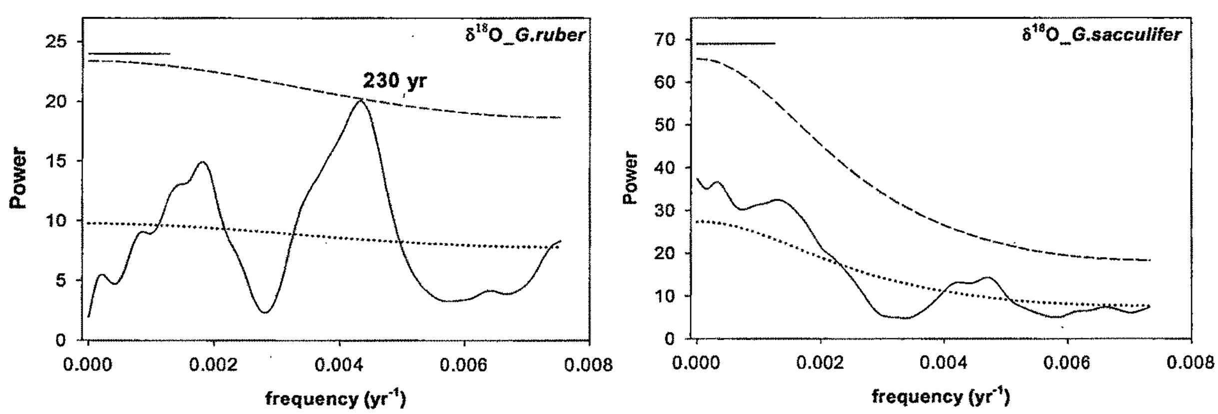
Fig. 3.8. Comparison of the TSI data and precipitation proxies ($\delta^{18}O$ in the three species of the foraminifera *viz. G.ruber*, *G.sacculifer* and *G.menardii*) for the past 1200 years. The thick line in the first panel depicts the 10-year running average of the splined data showing centennial scale variations.

The core SK 145-9 does not extend above 1550 A.D., hence comparison for the last four centuries can't be made. As evident from the above figure, the precipitation signal from all the three species matches reasonably well with the TSI fluctuations within the radiocarbon age uncertainties (~80 years). In general, during periods of lower TSI values, we get lower precipitation implying a solar forcing on the SW monsoon precipitation on a centennial timescale. Thus our study appears to confirm earlier findings of Agnihotri et al (2002) from this region.

3.9. Spectral analysis:

Spectral analysis can possibly help in delineating the factors forcing the monsoon. Spectral analysis has been carried out in the oxygen isotope timeseries of all the three species of foraminifera using the REDFIT 3.6 program (Schulz and Mudelsee, 2002). The spectral analysis is performed only on oxygen isotope data because they are directly governed by the SW monsoon strength whereas other productivity proxies are manifestation of at least two competing processes (wind strength and surface runoff) that tend to confuse their correlation with monsoon intensity.

The $\delta^{18}O$ in *G.menardii* exhibits a significant periodicity of ~215 yr and in *G.ruber* it shows a periodicity of ~230 yr that is just below the 95% significance level. This points towards the fact that SW monsoon follows a dominant quasi periodicity of ~200 yr as evident from the oxygen isotope time series. In the case of *G.sacculifer*, all the frequencies are suppressed and well below the 95% significance level.



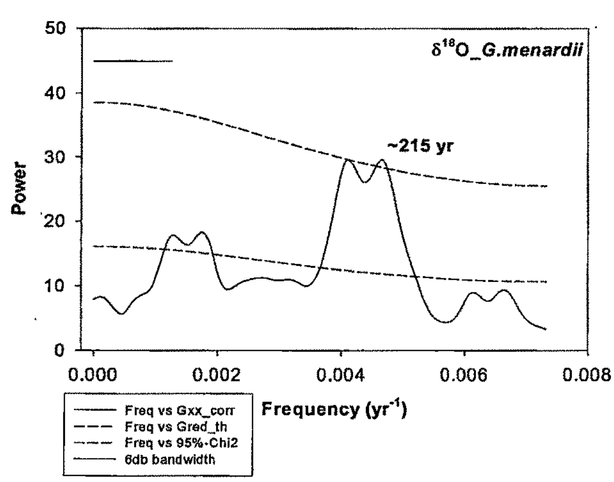


Fig.3.9. Power spectra of oxygen isotope timeseries in 3 species of foraminifera. Horizontal line at the upper left-hand corner represents 6db bandwidth of the spectral resolution. Gxx_corr denotes amplitude or power of various frequencies; Gred_th shown by dotted line is the background signal; dashed line denotes the 95% significance level calculated using the chi^2 test.

Earlier, ~200 yr, 113 yr, ~77 and ~53 yr periodicities have been observed by Agnihotri et al (2002) in the TSI (Total Solar Irradiance) data obtained from sunspot numbers (Lean et al, 1995) and ^{10}Be (Bard et al, 2000). Furthermore, power spectra of various proxies controlled by monsoon strength in a core raised from the northeastern Arabian Sea by Agnihotri et al (2002) show significant periodicities of ~200, ~110 and 56 years. Lower frequencies are not observed in this core due to the average sample resolution, which is ~65 years. This along with the periodicities observed in this study probably indicates that SW monsoon intensity on a centennial scale is governed by the variation in TSI. The exact linking mechanism is not yet clear. It is also unclear why *G.sacculifer* responds differently.

3.10. Inferences:

Based on a high-resolution geochemical data from the eastern Arabian Sea, the following inferences have been drawn:

i. A widespread arid period is observed at ~2000 a BP. Thereafter several arid periods are observed at ~1500 a BP, ~1100 a BP, ~850 a BP and ~500 a BP. These arid events are also seen in other proxy records such as varved sediments and speleothems.

ii. The precipitation – evaporation (P-E) values ranged from ~100 mm for arid episodes e.g. ~ 2000 a BP and ~500 a BP to ~1000 mm for high monsoon events such as at ~1800 a BP and ~1150 a BP.

iii. Comparison with a study from the western Arabian Sea indicates that SW monsoon wind intensity exhibits excellent correlation with the SW monsoon precipitation over southwestern coastal India on centennial timescales. But the relationship appears to be non-linear as precipitation minimum occurred at ~2000 a BP while the wind minimum occurred at ~1500 a BP.

iv. Productivity in the eastern Arabian Sea is not only a manifestation of SW monsoon wind intensity but also governed by various other processes such as fresh water inflow, and probably *Trichodesmium* blooms etc.

v. Spectral analysis and visual matching with TSI reconstruction point towards a possible solar control over the SW monsoon on centennial timescales.