Quaternary Geochronology and Palaeoclimatology of the Indian Ocean

Summary of the thesis

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by

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INTRODUCTION:

Monsoon is the most important climatic phenomenon occurring in the Indian subcontinent and the adjoining regions. It forms the backbone of Indian economy, which is primarily agriculture-dependent. Deficient rainfall resulting in droughts, or floods ensuing excess rainfall, cause havoc in terms of economic backlash. So it becomes very important to understand the inherent natural variability in monsoon and the factors controlling it, perhaps for predicting its future trend. It is known from previous studies that the South Asian monsoon exhibits variance at different time scales viz. decadal, centennial, and millennial. Decadal scale variations can be studied using recorded meteorological data, which is available for the last century or so, but limited to the four metros where weather stations are located. For longer time scales we must take recourse to various paleoclimatic proxies, such as sediments deposited in world oceans. Most of the previous studies on sea sediments concentrated on millennial scale climate changes using relative dating methods or radiocarbon dates on bulk sedimentary matter that might prove to be relatively inaccurate. Recently with the advent of AMS (Accelerator Mass Spectrometry) one can obtain highly accurate chronologies because, here, instead of dating bulk sediments, planktonic foraminifera are dated (no contamination from detrital carbonate material). If suitable cores from appropriate regions (such as continental margins) are available then one can explore paleomonsoon variations on centennial to decadal time scales (comparable to human lifetime).

STUDY AREA:

My study area is the Arabian Sea, which forms a major, distinctive, part of the Northern Indian Ocean. The Arabian Sea is most suited for monsoonal studies as it experiences intense biogeochemical changes associated with monsoons (Nair et al, 1989). The Arabian Sea can be divided into three distinct regimes:

*Western Arabian Sea, off the Somalian coast (near the mouth of the Gulf of Aden): it experiences intense upwelling during the Southwest Monsoon resulting in an increased organic/inorganic productivity (Nair et al, 1989) and negligible fresh water run off due to meager precipitation over the adjoining landmass.

*Eastern Arabian Sea off the Western Indian coast: it experiences moderate upwelling along the coastal regions of western India and copious fresh water runoff due to intense precipitation (1000-4000 mm/yr) on adjoining land (between Mumbai and Cochin; Sarkar et al, 2000).

*Southern/equatorial Arabian Sea (east of Maldives), which represents the open ocean regime, which experiences moderate equatorial upwelling/ wind induced mixed layer deepening. In addition, part of it receives low salinity water from the Bay of Bengal. Most importantly, the strongest winds are during the intermonsoon period (spring & fall) that are called as Indian Ocean Equatorial Westerlies (Hastenrath et al, 1993; Beaufort et al, 1997).

OBJECTIVES OF THE PRESENT STUDY:

This study is an endeavor to reconstruct the climate history of the Arabian Sea with special reference to monsoon for the Late Quaternary period (~35,000 a BP to present) with a high time resolution. Most of the earlier work was confined to the Western Arabian Sea, where the Southwest monsoon signal is the strongest. Any given study focused its attention on only one of the three regions of the Arabian Sea. I have chosen three sediment cores in such a way that they represent each of the three above-mentioned broad regimes and thus record the signatures of climate variations in different parts of the Arabian Sea. The cores were strategically chosen from the locations where sedimentation is fast enough to provide a high time resolution. Further, my thesis is a comparative study of past changes in two different aspects of the monsoon: (i) wind induced upwelling, productivity etc. (ii) rainfall and runoff to the ocean, surface salinity etc. It also looks at changes during intermonsoon periods, by the study of the equatorial core. The specific aims of this study are:

1. To obtain accurate Radiocarbon chronology on planktonic foraminiferal separates for sediment cores and to determine the past monsoon variations on millennial to centennial scales by high-resolution analysis using isotopic and chemical tracers.

2. There are significant variations in the paleoclimatic observations from place to place in a single geographical region (e.g. Arabian sea). This is because the rainfall/ wind patterns show strong spatial variability. Therefore one of the

aims of the present study is to assess that how different regions/proxies respond to the same climatic forcing on different time scales.

3. It has been proposed that during Last Glacial Maximum (LGM), SW Monsoon was weaker & NE Monsoon was stronger resulting in enhanced influx of low salinity water from the Bay of Bengal (Duplessy, 1982; Sarkar et al, 1990). We also aim to verify this and if true, study how this transport varied in the past, in relation to paleoclimate & paleomonsoon variations using the equatorial core.

4. SW monsoon has been shown to exhibit correlation with the high latitude climate in the cores from the northern and western Arabian Sea (Reichart et al, 1998, 2002; Schulz et al, 1998; Altabet et al, 2002) based on the organic carbon content and denitrification intensity. We plan to verify that whether such a correlation is exhibited by the SW monsoon precipitation proxy such as the oxygen isotope ratio of the surface dwelling foraminifera.

5. In the equatorial region the winds are strongest during April to November with maximum variability during the intermonsoon periods, which are known as Indian Ocean Equatorial Westerlies (IEW; Hastenrath et al, 1993; Schott and McCreary Jr., 2001). In this region productivity is mostly due to IEW induced mixed layer deepening during the intermonsoon periods (Beaufort et al, 1997). The IEW is positively correlated to Southern Oscillation (SO) index, which in turn is positively correlated to Southwest monsoon and East African rains and negatively to the El Nino frequency (Hastenrath et al, 1993 and references therein). Thus another aim of this study is to document the past variations in SW monsoon, East African rains and El Nino frequency by studying the past productivity variations in this region.

6. Recently there has been a renewed interest in the solar forcing of the climate (Bond et al, 2001; Neff et al, 2001; Agnihotri et al, 2002; Foucal et al, 2003). This study aims to check how the SW monsoon is affected by the changes in solar activity on a centennial timescale by comparing the high-resolution

eastern Arabian Sea data with the reconstructed Total Solar Irradiance (Bard et al, 2000).

7. Lastly, spectral analysis has been carried out on various SW monsoon proxies to detect the underlying periodicities that might help in delineating the various forcing factors for the SW monsoon from centennial to Milankovitch timescales.

To achieve the above objectives, I have measured various chemical (such as $CaCO_3$, C_{org}) and isotopic proxies e.g. $\delta^{15}N$ in the sedimentary organic matter and $\delta^{18}O$, $\delta^{13}C$ of selected planktonic foraminiferal species.

OUTLINE & IMPORTANT RESULTS OF THE THESIS:

This thesis has been divided into six chapters.

CHAPTER 1 contains a brief introduction to the monsoons, also discusses the area of the present study i.e. Arabian Sea and the various hydrological and biogeochemical changes it undergoes during the monsoons. A brief review of the earlier work done on paleomonsoon variations, the significant findings and limitations are also presented. The objectives of the present study and thesis outline are stated at the end of this chapter.

CHAPTER 2 gives details of the sediments cores collected and the experimental techniques employed. Firstly it discusses the core locations, which are shown in the table on the next page:

S. No.	Core Name	Type	Lat. (^{0}N)	Long. (^{0}E)	Len--gth (cm)	Water depth (m)	Resolution	Age limit (a BP)
1.	SK 145-9	Piston core	12.6^0	74.3^0	400 (252)*	400	~50 years per cm	13,180
2.	SS 3827 G	Gravity Core	3^0 42'	75^0 54.5'	196 (100)*	3118	~350 years per cm	34,730
3.	SS 4018 G	Gravity Core	13^{0}21.8'	53^{0}15.4'	130 (130)*	2830	~150 years per cm	19,020

* values in bracket denote the dated length

Secondly, it provides a brief introduction to the foraminifera, which are microorganisms that inhabit the world oceans and secrete calcium carbonate shells on which radiocarbon dating and oxygen and carbon isotopic analysis are carried out. Thirdly, the AMS technique, used to obtain the radiocarbon dates, and its advantage over the conventional radiocarbon dating method is explained. For Radiocarbon dating we chose planktonic foraminifera namely *Globigerinoides ruber, Globigerinoides sacculifer, Orbulina universa* and *Neogloboquadrina dutertrei* (size range chosen for dating as well as isotopic analysis is 250μ-500 μ). We selected planktonic foraminifera for our study because they inhabit the surface and near surface oceans (upto ~100 m) and therefore readily incorporate changes occurring in the surface ocean into their calcitic shells. For AMS radiocarbon dating about 10mg of foraminifera is required. This means approximately 200 individuals have to be handpicked for every date. C-14 dating was carried out at 12 depths for SS3827G, at 15 depths for SS4018G & 11 depths for SK145-9. It was done using the Accelerator Mass Spectrometer at NSF Facility, University of Arizona, USA. The C-14 dates are calibrated to calendar ages after accounting for variation in the production rate of cosmogenic ^{14}C (Stuiver et al, 1998) and also for the reservoir age correction of 500±30 years for SS3827G and SK145-9 and 563±30 years for SS4018G (Dutta et al, 2001).

This chapter also discusses the usefulness of various proxies used in this study for paleomonsoon reconstruction, which are as follows:

1. Stable isotopes of oxygen and carbon (viz. $\delta^{18}O$ & $\delta^{13}C$) in selected species of planktonic foraminifera i.e. *Globigerinoides ruber, Globigerinoides sacculifer* & *Globorotalia menardii.*

2. Stable isotopes of nitrogen (viz. $\delta^{15}N$) in sedimentary organic matter, which is an indicator of the strength of the denitrification process that can be correlated to productivity variations.

3. Downcore variation in calcium carbonate ($CaCO_3$) is an excellent indicator of the productivity changes provided there is no terrestrial source for it and the core has been raised from a depth that is above the lysocline (~3500 m).

4. C_{org} i.e. organic carbon variations can mirror the productivity shifts provided the core has not undergone diagenesis, which would result in the loss of carbon and nitrogen. Similarly, if the core is free of diagenesis then the ratio of organic carbon to nitrogen i.e. C/N (weight ratios) can act as an index of the source of the organic matter.

Furthermore, this chapter also deals with different analytical schemes followed to measure the above-mentioned proxies, their analytical precision and reproducibility. The precision on $\delta^{13}C$ measurement is ± 0.1 per mil, for $\delta^{18}O$ it is ± 0.2 per mil, while for $\delta^{15}N$ it is 0.38 ‰. The precisions in measuring $CaCO_3$, total carbon and nitrogen are 3%, 4% and 6% respectively. C_{org} was determined by deducting inorganic carbon values (obtained from $CaCO_3$ measurements) from the Total Carbon values. The precision in measuring C_{org} is 5%. Isotopic standards were also analyzed to check the accuracy of the measurements.

CHAPTER 3 deals with the results obtained for the core SK 145-9, which is from the eastern continental margin of the Arabian Sea. 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 a resolution of ~50 year per cm.

The top 50 cm have been sampled at every cm & thereafter the sampling has been done at every 2 cm. Thus it offers high-resolution and therefore will aid in understanding sub-centennial scale variability in SW monsoon precipitation. The top 50cm of this core (sampled with high resolution), covering a time span of approximately 2800 years, has been taken for further studies. To have a quantitative estimate of the precipitation, an empirical equation involving the $\delta^{18}O$ of *G.sacculifer* was used that provided the past variation in the P-E (excess of precipitation over evaporation) values (Fig1, 2nd panel). The actual SW monsoon precipitation signal obtained from this core has been compared with the SW monsoon wind strength record from the western Arabian Sea (Gupta et al, 2003) to verify that whether weak winds are accompanied by reduced precipitation or not (Fig.1). Further, the high-resolution precipitation signals are compared with the reconstructed Total Solar Irradiance (TSI) curve (Bard et al, 2000) to explore the possibility of solar influence on SW monsoon on centennial timescales.

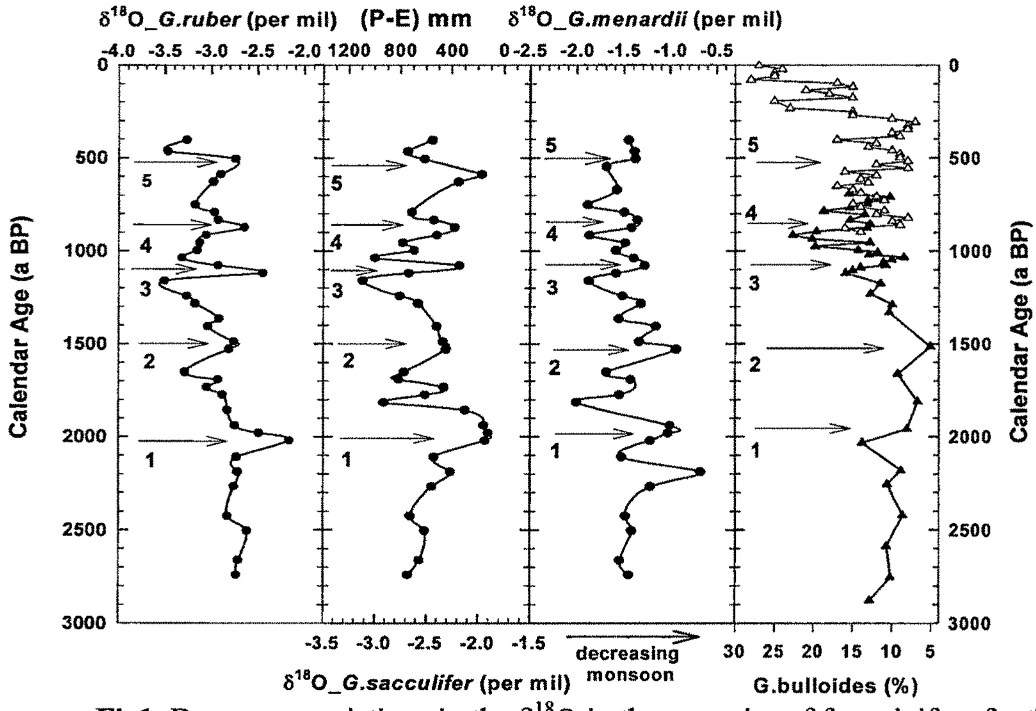

Fig1. Downcore variations in the $\delta^{18}O$ in three species of foraminifera for the core SK 145-9 (shown by closed circles, this study), % *G.bulloides* data from the ODP Site 723A (closed triangles) and the Oman margin box core RC2730 indicated by open triangles (Gupta et al, 2003), P-E values shown at the top of the 2nd panel.

The main results obtained from this core are:

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 have also been seen in other records such as varved sediments and speleothems in this region.

ii. The precipitation – evaporation (P-E) values ranged from ~100 mm for arid episodes like ~ 2000 a BP and ~500 a BP to ~1000 mm for high monsoon events like 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 an excellent correlation with the SW monsoon precipitation over southwestern coastal India on a centennial timescale. But the relationship appears to be non-linear as the 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 scale.

The **FOURTH CHAPTER** discusses the results obtained for the core SS3827G. In this core seven dates going up to 34,730 calendar years covering the LGM (Last Glacial Maximum; ~21,000 calendar years BP) have been obtained (depth~100cm). The average sedimentation rate is ~3 cm/10^3 years, which is typical of open ocean locations. After 100cm, reversal of the dates was found which is possible if there was a double bounce during coring. The time resolution is approximately 350 years per cm. This core is located at a strategic location that it can document the past variations in NE Monsoon Current, which is an indicator of NE monsoon strength. The precipitation signal obtained from this core has been compared with the polar ice record that can elucidate possible correlation between the high latitude and low latitude climates (shown below in the Fig.2). Further the winds are strongest in this region during the intermonsoon period (Hastenrath et al, 1993; Schott and McCreary

Jr., 2001) known as Indian Ocean Equatorial Westerlies (IEW) that cause mixed layer deepening and hence enhance productivity (Beaufort et al, 1997). IEW is positively correlated to Southern Oscillation (SO) index, which in turn is positively correlated to Southwest monsoon and East African rains and negatively to the El Nino frequency (Hastenrath et al, 1993 and references therein). The past variation in SW monsoon, East African rains and El-Nino frequency were studied by analyzing the past productivity variations in this region.

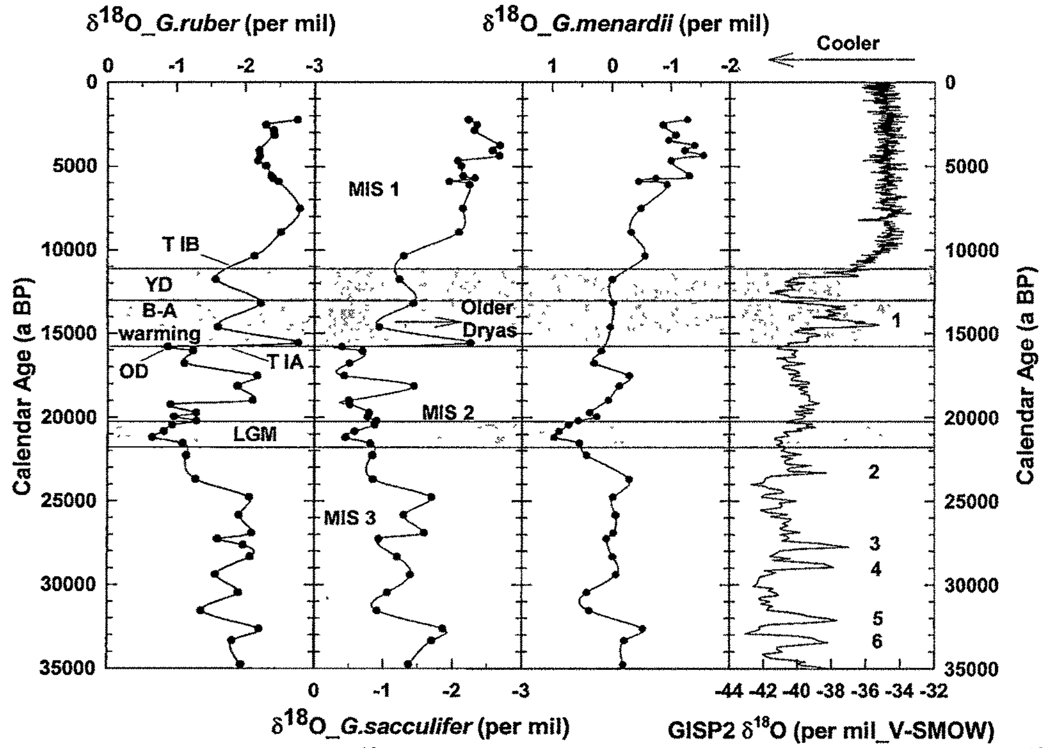

Fig.2. Comparison of the $\delta^{18}O$ record of the core SS3827 G with the GISP2 $\delta^{18}O$ record; OD, T IA, B-A warming, YD and T IB shown in the first panel refers to Oldest Dryas, Termination IA, Bolling-Allerod warming, Younger Dryas and Termination I B respectively (Stuiver et al, 1995); MIS 1, MIS 2, MIS 3 in the second panel refer to standard SPECMAP (Martinson et al, 1987) Marine Isotope Stages 1, 2 and 3; Arabic numerals in the last panel (1 to 6) indicate Dansgaard/Oeschger Interstadials.

The main inferences drawn from this core are:

i. The NE monsoon did not strengthen during the LGM as proposed earlier based on the bulk dating methods. In fact it intensified during the early deglacial period from ~19 ka BP to ~17 ka BP as shown by this study on three different species of planktonic foraminifera with better age control.

ii. Oxygen isotope values of all the three species of foraminifera exhibit a good correlation with the GISP2 $\delta^{18}O$ record on centennial to millennial timescales. The warm interstadial periods are accompanied by stronger SW monsoon and cooler stadials correspond to reduced SW monsoon. Although during the Holocene, the correlation was not as high.

iii. The similar variations observed in the tropical/equatorial climate and the North Atlantic climate indicates that tropics could have been instrumental in bringing high latitude climatic changes, most probably via atmospheric forcing through greenhouse gases or *vice versa* by albedo feedback.

iv. The minimum SW monsoon precipitation at LGM is indicated by the oxygen isotope analysis as well as calcareous productivity.

v. At T IA, an increase in SW monsoon precipitation is evident from the negative $\delta^{18}O$ values due to influx of Bay of Bengal water, which is of lower salinity due to glacier melting and higher river runoff.

vi. During the Holocene, SW monsoon intensified uniformly upto the core top as exhibited by the oxygen isotopes as well as the calcareous productivity.

vii. The calcareous productivity indicates a decreasing IEW and hence decreasing Indian and east African rainfalls upto LGM with minima at LGM with the maximum El Nino frequency during the last glacial period. Thereafter the IEW strengthened upto 16.5 ka BP after which it fell back sharply to LGM values in a millennium (~15.5 ka BP). Thereafter IEW exhibits a sharp increase at ~14.5 ka BP that coincides with the Termination IA implying strengthened Southwest monsoon and East African rains.

viii. Since ~14.5 ka BP to the core top (~2.2 ka BP) including the Holocene, calcareous productivity exhibits a uniformly increasing trend implying a uniformly strengthening IEW and Southern oscillation index and hence strengthening SW monsoon and east African rains along with a declining El Nino frequency.

ix. Based on the comparative study from the other two cores from the eastern Arabian Sea, it could be inferred the IEW and SW monsoon winds strengthened and weakened in unison pointing towards a common forcing factor, most probably insolation, at least during the last 35 ka.

x. Spectral analyses of various proxies indicate that SW monsoon appears to be dominated by quasi periods of the precessional cycle, which indicates that it is governed by the solar forcing on Milankovitch timescale. Common periodicities among the equatorial and north Atlantic records points towards a possible common mechanism linking them.

xi. C_{org} and $\delta^{15}N$ are not useful as productivity indicators in this region because of the very little amount of sedimentary organic matter. $\delta^{13}C$ of the foraminifera also is not useful as a productivity indicator in this region as its signal is mixed by two competing processes *viz.* upwelling and productivity.

CHAPTER 5 deals with the results obtained for the core SS4018G. This core has 15 dates covering up to ~19,000 calendar years (depth~130cm) and has an average sedimentation rate of ~7cm/10^3 years. Although this core is from an open ocean location (water depth: 2830m), yet it has a high sedimentation rate owing to the high productivity occurring over there (Nair et al, 1989). The resolution in this case is 150 years per cm but since the sampling is done at every two cm, the effective resolution becomes ~300 years. The productivity in this region is governed by the SW monsoon wind induced upwelling. Hence the past variation in productivity will document the past changes in SW monsoon intensity (Fig.3).

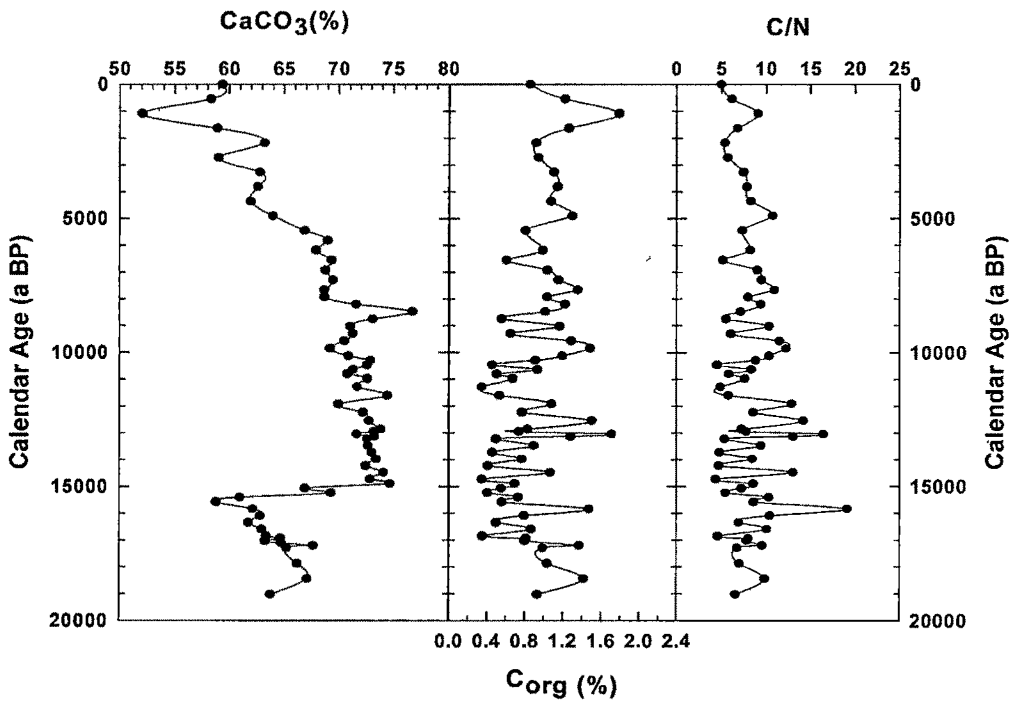

Fig.3. Downcore variations in of the productivity proxies in the core SS 4018 G

The studies carried out on this core revealed the following paleomonsoon variations:

i. Southwest monsoon was weaker during the early deglacial period as evident from the calcareous productivity and supported by organic productivity (C_{org} and $\delta^{13}C$) and $\delta^{18}O$ analysis carried out on three different species of planktonic foraminifera.

ii. A sudden intensification of SW monsoon is observed, which is centered at ~14.5 ka BP. It coincides with the first step of deglaciation (T IA) and such a rapid response by the monsoon system can be attributed to albedo changes over central Asia and Tibetan plateau that would enhance the land – sea air pressure difference.

iii. Monsoon intensity seems to decline during the younger Dryas as evident by excess of evaporation over precipitation. The monsoon again regained its strength during the T IB (centered at 11 ka BP).

iv. At ~9 ka BP, another episode of monsoon intensification took place just after the maximum tropical summer insolation at 10 ka BP between 20^0N and 35^0N.

v. Thereafter SW monsoon strengthened during the Holocene as observed in the multi-proxy isotopic and chemical data. Monsoon did not decrease during the Holocene as proposed by a few earlier studies in this region.

vi. Spectral analysis shows that on Milankovitch timescales, monsoon is mainly influenced by the precessional cycle of the earth. On shorter timescales the dominant periodicities exhibited by monsoon are ~1400 yrs and 700 yrs indicating correlation with high latitude climatic changes. Lastly, monsoon seems to be influenced also by the thermohaline circulation changes.

CHAPTER 6 summarizes the results obtained from this study and discusses some of the future work that can be undertaken to better understand monsoon variability in this region.

The major conclusions drawn from this study are as follows:

1. Starting from ~35 ka BP, the SW monsoon has shown a decreasing trend with minimum precipitation at LGM along with several millennial scale fluctuations to relatively higher values that correspond to the high latitude interstadials. During the early deglacial period the SW monsoon was still weak and a major intensification centered around ~14.5 ka BP that matches with the Termination Ia. This sudden enhancement can be attributed to albedo changes over the central Asia/Tibetan plateau, which can enhance the sea-land

temperature and hence air pressure contrast that leads to a stronger SW monsoon.

2. The glacial to Holocene transition period is marked with several millennial to centennial scale fluctuations in SW monsoon precipitation with higher precipitation during the periods of global warmth (*viz.* Bolling-Allerod, Termination IA, Termination IB) and reduced precipitation during cooler times (*viz.* Oldest, Older and Younger Dryas).

3. A sudden increase in SW monsoon intensity took place at ~9 ka BP, following the maximum summer insolation at 10 ka BP between 20^0N and 35^0N.

4. The SW monsoon strengthened during the Holocene as evident by the multi-proxy isotopic and chemical data from both the western as well as equatorial Arabian Sea cores. It did not decrease during the Holocene as proposed by a few earlier studies.

5. A high-resolution study has been carried out to study the SW monsoon variations on centennial to subcentennial timescale for the past three millennium in the core from the eastern Arabian Sea. A prominent arid event is observed at 2000 a BP followed by other centennial scale dry events centered at ~1500 a BP, ~1100 a BP, ~850 a BP and ~500 a BP. These arid episodes are also seen in other records such as varved sediments and speleothems from the regions around the Arabian Sea.

6. In order to quantify SW monsoon precipitation variations for the past 3000 years, a parameter *viz.* precipitation – evaporation (P-E) was calculated using an empirical equation. The P-E values ranged from ~100 mm for arid episodes like ~ 2000 a BP and ~500 a BP to ~1000 mm for high monsoon events like the ones observed at ~1800 a BP and ~1150 a BP.

7. Based on our high resolution data with better age control and which is from a site nearer to the source of North East Monsoon Current, we propose that the NE monsoon intensified during the early deglacial period (~19 to ~17 ka BP)

accompanied with a weaker than present SW monsoon. The NE monsoon did not strengthen during the LGM as proposed earlier. During the LGM both the SW as well as NE monsoon declined in tandem. Thereafter there is no episode of NE monsoon strengthening comparable to the early deglacial period.

8. Our study on the eastern Arabian Sea core, which records a signal of monsoon precipitation over Western Ghats can be compared with the study carried out by Gupta et al (2003) from the western continental margin off the Oman coast. They based their study on the *G.bulloides* abundance variation, which indicates upwelling strength controlled by the SW monsoon winds. Both the wind intensity record (west) and the precipitation signatures (east) match very well on centennial scale, weak winds were accompanied by reduced precipitation. 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.

9. The oxygen isotopic data from the equatorial Arabian Sea core was compared with the $\delta^{18}O$ record of the GISP2 ice core to verify the correlation between the SW monsoon precipitation changes and the high latitude climate. Oxygen isotope values of all the three species of foraminifera exhibit a good correlation with the GISP2 record on centennial to millennial timescales. The warm interstadial periods are accompanied by stronger SW monsoon and cooler stadials correspond to reduced SW monsoon.

10. But the correlation is not high during the Holocene as the prominent 8200 a BP cooling event observed in the polar record is not observed in the sedimentary record, which might be due to the much poorer resolution of the sedimentary record. Further during the Late Holocene (~5 ka BP to the core top, ~2.2 ka BP) several fluctuations, possibly due to the centennial scale variations in the precipitation were observed in the sedimentary records with no counterpart in the polar ice record.

11. Inspite of the above mentioned discrepancies, it appears that SW monsoon fluctuations correlate very well with the polar climate as even the rapid events like Dansgaard/Oeschger interstadials, T IA, T IB, Oldest, Older and Younger Dryas have counterpart in the sedimentary record. The similar variations observed in the tropical/equatorial climate and the North Atlantic climate indicates that tropics were probably instrumental in bringing about high latitude climatic changes, most probably via atmospheric forcing through greenhouse gases or *vice versa* by albedo feedback.

12. The past productivity variations in the equatorial core, which is governed by the strength of the Indian Ocean Equatorial Westerlies (IEW) was used to document the past variations in the Southwest monsoon and East African rains along with the El Nino frequency. The Southwest monsoon along with the East African rains have exhibited a declining trend from ~35 ka BP to LGM with the minimum values at LGM as evident by the decreasing productivity. It also suggests that El Nino frequency was the highest during the last glacial period. Thereafter the IEW strengthened upto 16.5 ka BP after which it fell back sharply to LGM values for a millennium (upto ~15.5 ka BP) indicating reduction in rainfall. Thereafter IEW exhibits increased sharply at ~14.5 ka BP coinciding with the Termination IA, implying strengthened Southwest monsoon and East African rains.

13. Since ~14.5 ka BP to the core top (~2.2 ka BP) including the Holocene, calcareous productivity exhibits a uniformly increasing trend implying a uniformly strengthening IEW and Southern oscillation index and hence strengthening SW monsoon and east African rains along with a declining El Nino frequency.

14. To look into the regional climatic evolution, the productivity records from the equatorial (this study) and eastern Arabian Sea (Agnihotri et al, 2003) were compared. Furthermore the core from the western Arabian Sea (this study) also exhibits similar variations such as sharp increase in SW monsoon wind intensity at ~15 to ~14.5 ka BP and an increasing SW monsoon wind intensity during the Holocene. So, it could be concluded that the Indian Ocean

Equatorial Westerlies and SW monsoon winds strengthened and weakened in unison pointing towards a common forcing factor, most probably changing insolation, at least during the last 35 ka.

15. The $\delta^{18}O$ record (SW monsoon precipitation proxy) from the high-resolution (~50 years) eastern Arabian Sea core was compared with the reconstructed Total Solar Irradiance (TSI) for the past ~1000 years to explore the possibility of a solar influence on SW monsoon on centennial timescale. Broadly, during the periods of lower TSI, the SW monsoon precipitation also reduces whereas during the periods of higher TSI, the precipitation increases. This indicates a possible solar forcing on the SW monsoon on centennial timescale.

16. Spectral analysis of various SW monsoon proxies indicate that on Milankovitch timescales, it is mainly governed by the insolation variations induced by the precessional cycle of the earth's orbit. On millennial timescales, the dominant periodicity exhibited by the monsoon lies near 1400 ± 500 years that points towards a common forcing factor for the SW monsoon as well as high latitude climatic changes, further corroborating that a common link exist between them. Moreover monsoon seems to be influenced by the thermohaline circulation changes as well on millennial timescales. On centennial timescale the solar forcing seems to control the SW monsoon variations as exhibited by the common quasi-periodicity of ~200 yrs exhibited both by the monsoon proxies as well as solar activity proxy *viz.* TSI.

17. In the equatorial region C_{org} and $\delta^{15}N$ are not useful as productivity indicators due to the very low amounts of sedimentary organic matter present, which make their accurate measurement difficult. Moreover in the equatorial region the $\delta^{13}C$ of the foraminifera can't act as a useful productivity proxy as its signal is confused by two competing processes *viz.* upwelling and productivity.

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