Chapter 6

Conclusions

6.1. Major Conclusions:

This study was carried out to document the centennial to millennial scale variations in the monsoon intensity using high-resolution analysis of accurately dated sediment cores from three different locations of the Arabian Sea. Further, it compared the past variations in SW monsoon wind intensity (from the western Arabian Sea) and the SW monsoon precipitation (eastern Arabian Sea) to assess that how different locations/proxies respond to same climatic forcing. It also looked at the past variations in the relative strengths of SW and NE monsoon and compared the proxy record of SW monsoon precipitation with the high latitude climatic fluctuations. Moreover this study made an attempt to look into the intermonsoon period and the related climatic phenomena. The possibility of a solar connection with the SW monsoon has also been explored by the spectral analysis of various SW monsoon proxies. The major conclusions reached are:

6.1.1. Past variations in the SW monsoon intensity:

I. 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 interstadials. During the early deglacial period the SW monsoon was still weak with a major intensification centered around ~14.5 ka BP that matches with 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 during summer that can strengthen the SW monsoon.

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

III. 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.

IV. The SW monsoon strengthened during the Holocene as evident from the multi-proxy isotopic and chemical data from both the western as well as equatorial Arabian Sea cores. It does not appear to have decreased during the Holocene as proposed by a few earlier studies.

V. A high-resolution study has been carried out to document the SW monsoon variations on centennial to subcentennial timescales for the past three millennia in a 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 proxy records such as varved sediments and speleothems from the regions around the Arabian Sea.

VI. To quantify SW monsoon precipitation variations during 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 such as during ~ 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.

6.1.2. NE monsoon intensification:

I. 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 infer that the NE monsoon intensified during the early deglacial period (~19 to ~17 ka BP) concurrent with a weaker than present SW monsoon. The NE monsoon does not appear to have strengthened during the LGM as proposed earlier. During the LGM both the SW as well as NE monsoon appear to have declined in tandem. There is no evidence for an episode of NE monsoon strengthening subsequent to the early deglacial period.

6.1.3. Correlation between SW monsoon wind strength and SW monsoon precipitation:

I. Our measurements on the eastern Arabian Sea core, which records signal of monsoon precipitation over the Western Ghats was compared with the data of 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.

6.1.4. Correlation between SW monsoon precipitation and high latitude climate:

I. 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 planktonic 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.

II. But the correlation is not that good during the Holocene as the prominent 8200 a BP cooling event observed in the ice 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 record with no counterparts in the ice record.

III. Inspite of the above mentioned discrepancies, it appears that SW monsoon fluctuations correlate very well with the high latitude climate as even the rapid events like Dansgaard/Oeschger interstadials, T IA, T IB, Oldest, Older and Younger Dryas have counterparts in the sedimentary record. Similar variations observed in the tropical/equatorial and the North Atlantic climates indicate 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.

6.1.5. Past variations in the IEW and the relatable SO index, SW monsoon, East African rains and El Nino frequency:

I. Past productivity variations in the equatorial core, which are governed by the strength of the Indian Ocean Equatorial Westerlies (IEW) has aided in documenting the past variations in the Southwest monsoon and East African rains along with the El Nino frequency. The Southwest monsoon and East African rains have exhibited a declining trend from ~35 ka BP to LGM with the minimum values at LGM as evident from decreasing productivity. It also suggests that El Nino frequency was 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 a sharp increase at ~14.5 ka BP that coincides with the Termination IA implying strengthened Southwest monsoon and East African rains.

II. 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.

6.1.6. Regional Climatic evolution:

I. To look into the regional climatic evolution the productivity records from the equatorial (this study) and eastern Arabian Sea (Agnihotri et al, 2003 a) 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. It appears that the Indian Ocean Equatorial Westerlies 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.

6.1.7. The solar influence:

I. The $\delta^{18}O$ record (SW monsoon precipitation signal) 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 timescales. 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.

II. Spectral analysis of various SW monsoon proxies indicate that on Milankovitch timescale, 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 the fact that a common link exists 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 in both by monsoon proxies as well as solar activity proxy *viz.* TSI.

6.1.8. Limitations of Corg, $\delta^{15}N$ and $\delta^{13}C$ at the equatorial core site:

I. In the equatorial region C_{org} and $\delta^{15}N$ are not useful as productivity indicators due to very low amount of sedimentary organic matter present, which makes their measurement imprecise. Moreover in the equatorial region the $\delta^{13}C$ of the foraminifera can not act as a useful productivity proxy as it is distorted by two competing *viz.* upwelling and productivity.

6.2. Recommendation for future studies:

Although this thesis has documented the past variations in monsoon intensity in great detail for the past 35 ka but still additional studies can be helpful to understand various processes that control the vagaries of SW and NE monsoon.

- This study has pointed out that the period of NE monsoon intensification was not the LGM but the early deglacial period. To corroborate this more well-dated cores from the equatorial Arabian Sea should be analyzed with high-resolution.

- We have clearly shown that the SW monsoon strengthened during the Holocene as evident from the multi proxy isotopic and chemical studies in the core from the western and equatorial Arabian Sea in contrast to some of the earlier studies that proposed that SW monsoon declined during Holocene based on single proxy analysis. This indicates the need of multi proxy analyses as in nature various processes are occurring simultaneously and relying on a single proxy might mislead us. To confirm our conclusion more high-resolution cores from different regions of the Arabian Sea employing the multi proxy technique should be analyzed. Also the existence of threshold for the responses of the proxies need to be examined.

- Our study in comparison with another carried out in the western Arabian Sea has shown that the SW monsoon precipitation exhibits good correlation with the SW monsoon wind strength on centennial timescale, but this correlation appears to be non linear. It warrants the study of more well dated cores covering longer time spans from the eastern and western Arabian Sea that posses comparable resolutions so that the correlation between the wind strength and precipitation can be further elucidated.

- One of the major handicaps in quantifying the past precipitation fluctuations using the foraminiferal $\delta^{18}O$ is that it is affected by both the salinity and temperature and hence it becomes very important to decouple them. For this purpose alkenone unsaturation index in the sedimentary organic matter and elemental ratios in the foraminiferal calcitic shells should be measured in the same sample. Alkenone unsaturation index ($U^{K'}_{37}$) acts as a Sea Surface Temperature (SST) proxy as certain marine phytoplanktons (e.g. coccolithophorid *Emilyania huxleyi*) respond to water temperature changes by changing the molecular composition of there cell walls (Bradley, 1999). Moreover there are several elements (Sr, Ba, Mn, Cd, Mg) that are chemically similar to Ca, so their trace amount can be incorporated in the calcitic foraminiferal or coralline shells depending on the calcification temperature (Elderfield and Ganssen, 2000; Lea et al, 1999). Thus by measuring their relative concentration (e.g. Sr/Ca, Mg/Ca etc.) we might be able to independently quantify temperature effect.

- Spectral analysis of various SW monsoon proxies along with visual matching with the reconstructed TSI curve has shown that the solar forcing is probably the major governing factor for the SW monsoon precipitation on centennial to millennial timescales. But more studies with annual to decadal scale resolution are needed to understand the full regional variability of SW monsoon and its relation to solar forcing. Such high-resolution records can be obtained from the sedimentary cores from the continental margins that have very high sedimentation rate. Further archives like corals and tree rings can be studied that could provide annual to seasonal resolutions.

- The major debate regarding paleoproductivity proxies such as C_{org} is that whether they are manifestation of overhead productivity or are controlled by preservation characteristics. To overcome this, various major (Al, Mg, Fe, Ti) and trace (Mn, Cr, V, U) elements can be studied in marine sediments. Al, Mg, Fe, Ti are major components of alumino-silicate minerals and are not affected by redox changes (except Fe that takes part in the redox reactions in the continental margin regions but that is negligible compared to its total abundance) and hence are unaffected by changing preservation characteristics. These elements denote terrestrial inputs relatable to aeolian /alluvial discharge that in turn can be related to the intensity of monsoon precipitation. Similarly downcore variations in the concentrations of trace elements such as Sr, P, Ba, Cu, Ni, Zn that act as micronutrients for marine productivity can be studied to document changes in the paleoproductivity. Downcore variations in Mn, Cr, V, U signify ambient redox conditions as Mn is found to be concentrated in oxic conditions whereas the other three are precipitated in reducing conditions (Bonatti et al, 1971; Piper and Issacs, 1996). Thus the past fluctuations in the redox conditions can throw light on the preservation of productivity proxies such as C_{org}.