CHAPTER 7

Summary

The Indian monsoon is an important component of global climate because monsoon transport heat and moisture from the warmest part of the tropical ocean across the equator and to higher latitudes. In India summer monsoon precipitation accounts for a large part of the annual total precipitation and significantly affects the annual gross national product, an important index to measure the economic growth of the country. Therefore, understanding the forcing mechanism of the monsoon is very important because it has wide impact on the socio-economic development in the country. The monsoon fluctuates with large amplitudes on various timescales such as inter annual, decadal and centennial, millennial time scales. Multi proxy based monsoon variability from the western Arabian Sea reveal that in general monsoons were stronger during interglacials (warm periods) and weaker during glacial period (cold periods).

Scientific consensus exist that most of the monsoon variability during glacial and interglacial were caused due to Earth’s orbital parameter changes. However, high-resolution studies on monsoon variability questions the linear linkages between monsoon and insolation changes caused due to Earth’s orbital changes and proposed that air temperature changes in the Arctic and Greenland play an important role in controlling the monsoon variability. Reconstruction of monsoon variability on glacial and interglacial time scales as well as on millennial time scale was carried out from western Arabian Sea because the strength of SW monsoon winds is linearly related with the intensity of upwelling. Thus various upwelling proxies have been used to trace the SW monsoon intensity for last two decades.

Although Bay of Bengal and Eastern Arabian Sea receives more amount of rainfall during SW monsoon as compared to western Arabian Sea, very limited studies were carried out to reconstruct the monsoon variability from these regions. Therefore, here an attempt has been made to reconstruct the sea surface temperature, sea surface salinity by using the Magnesium/Calcium and oxygen isotopic ratios in planktonic foraminifer species G. ruber in sediment cores from the Bay of Bengal and eastern Arabian Sea, in order to understand the variability of monsoon at centennial time scale.
Reconstruction of sea surface temperatures (SST) based on Magnesium/Calcium thermometry and Artificial Neural Network Technique (ANN) reveals that both western and central Bay of Bengal was 3°C colder during LGM than the modern Holocene. This provides an evidence that the tropics were much cooler than it was believed earlier and CLIMAP (1981) reconstruction of sea surface temperature by using the transfer function technique of Imbrie and Kipp (1973) underestimated the LGM temperatures of the Indian Ocean. Furthermore within glacials (MIS 2 and 4) and interglacials (MIS 1 and 3) about 1 to 2°C SST change was noticed in the Bay of Bengal.

Oxygen isotopic values of *G. ruber* ($\delta^{18}O$) from the Bay of Bengal shows striking similarities with the GISP2 ice core $\delta^{18}O$ record which essentially represents changes of air temperature in the high latitudes of the northern hemisphere from 65 to 12 kyr. Conspicuously, oxygen isotopic values of surface water ($\delta^{18}O_{sw}$) (monsoon signal) and SST changes at the SK-218/1 core site from the Bay of Bengal lead the Dansgaard-Oeschger (D-O) events. Therefore, it is suggested here that the monsoon could initiate the start of millennial scale abrupt climate changes through the shifts of the Intertropical Convergence Zone (ITCZ) and associated convection, water vapor supply to the tropical troposphere and latent heat penetration. Thus, monsoons and associated convection process in the tropics play an important role in driving the abrupt climate shifts on a global scale.

$\delta^{18}O_{sw}$ variability demonstrates that the evaporation was higher than the precipitation from 32 to 16.5 during last glacial period and in the initial phase of MIS 3 representing weak SW monsoon. A striking shift from more evaporative phase to high precipitation phase took place around 16.5 kyr as strengthening of SW monsoon initiated around this time. During the Holocene descending strength of monsoon started around 3.5 kyr. Overall, the monsoon variability reconstructed by the $\delta^{18}O_{sw}$ corroborates well with the monsoon reconstructions based on upwelling indices from the western Arabian Sea.

In the eastern Arabian Sea SST has varied from 24.5 to 25.5°C (1°C change) during MIS 2 and this region was 4°C cooler during last glacial maximum (LGM) than in the Holocene. A 4°C cooling during the LGM in the Arabian Sea as well as in the other parts tropics might have driven synchronous climate shifts between high and low latitudes. Earlier studies mostly from the upwelling influenced region of western

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Arabian Sea have underestimated the SST shift from LGM to Holocene (CLIMAP 1981; Naidu and Malmgren 2005) because these studies could not isolate the SST changes related to upwelling and cooling associated with the LGM. Present studied core AAS-9/21 is from the eastern Arabian Sea where upwelling does not occur in any season, therefore this core location is expected to provide actual SST shift between LGM and Holocene. Therefore, it is concluded that Arabian Sea was 4°C cooler during LGM than in the Holocene.

Transition of MIS 4 to MIS 3 was marked with a conspicuous shift from higher to lower δ¹⁸Osw values, which reflects that a changeover from more evaporative phase to more precipitation phase was initiated during the MIS 3 in the eastern Arabian Sea. Eastern Arabian Sea document more or less similar δ¹⁸Osw values during MIS 3 and in core top revealing that SW monsoon precipitation during MIS 3 was as strong as the modern precipitation.

In both eastern Arabian Sea and Bay of Bengal during last glacial period (MIS 2) two warm excursions were noticed at 17 and 19 kyr. These warm excursions were associated with enriched δ¹⁸Osw. Similar warm events (ASW 1 and ASW 2) were reported earlier from the western Arabian Sea (Sahe et al., 2007). This appears to suggest that these two warm events have a large spatial variability in the Northern Indian Ocean. SW monsoon strength was relatively weaker than the NE monsoon during last glacial period (Duplessy et al., 1982). Therefore, the reduction of cold NE winds from continent to ocean could result these two warm events during the last glacial period.

Overall, reconstruction of monsoon variability based on the δ¹⁸Osw values from the present study is in agreement with the monsoon reconstructions based on the upwelling indices from the western Arabian Sea. This reconfirms that the SW monsoon wind driven upwelling along the western Arabian Sea and precipitation in the Indian subcontinent and river discharge to the Arabian Sea were related at centennial time scale.

Marine Isotope Stage 4 had documented higher SST (28.1°C), more depleted δ¹⁸Oc values, enriched δ¹⁸Osw values and higher salinity as compared to MIS 2. This suggests that eastern Arabian Sea was more evaporative during MIS 4 than in MIS 2. Prevalence of higher SST during MIS 4 than in the MIS 2 would result in more evaporation during MIS 4 along the eastern Arabian Sea.
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The last deglaciation was not a smooth transition from one climate state to another, but occurred in a series of steps. It is well documented that δ¹⁸O record of the world oceans exhibit a two step deglaciation model that included two phases of rapid ice melting separated by a brief period of climate stability. Two step deglaciation i.e. termination 1A and termination 1B has occurred around 12.5 kyr and 9.5 kyr respectively (Duplessy et al., 1981) and sea level also rose during this time due to huge amount of melt water flux caused due to warming (Fairbanks 1989). It is generally believed that the timing of the transition from the Oldest Dryas to Bolling/Allerod at 14.7 kyr BP in Greenland snow accumulation record (Alley et al., 1993). SST records from eastern Arabian Sea (Core AAS-9/21) and Bay of Bengal (Core SK-218/1) show early deglaciation at 18 kyr BP. Similarly δ¹⁸Oc values of these two cores also show depleting trend from 18 kyr BP. This provides strong evidence that in the northern Indian Ocean (Arabian Sea and Bay of Bengal) deglaciation was initiated around 18 kyr B.P.

Earlier SST estimates based on alkenone unsaturation ratios document no significant change in SST with in the Holocene in the Arabian Sea. By contrast, the present study based on Mg/Ca thermometry provide an evidence that ~2°C SST change during the Holocene.

The strength of monsoon, biological productivity and lithogenic particulate supply to the sediment in the northern Indian Ocean are strongly coupled in the modern day (Nair et al., 1989). It has been debated about the linkages between productivity and monsoon strength (Gupta et al., 2005). However, it is not clear yet whether productivity changes in the northern Indian Ocean are linearly related to the strength of monsoon in the geological past or not. Enriched δ¹³C values during MIS 1 and 3 and depleted values in MIS 2 and 4 in the eastern Arabian Sea and Bay of Bengal were noticed. This suggests that higher productivity during interglacials (MIS 1 and 3) and lower productivity during glacials (MIS 2 and 4) in both Arabian Sea and Bay of Bengal. Earlier findings from the eastern Arabian Sea (Ganeshram et al., Pattan et al., 2003) and from the western Arabian Sea (Murray and Prell 1993; Naidu and Malmgren 1996) also revealed high productivity during interglacials as a result of strong SW monsoon and low productivity during glacials due to weak SW monsoon. Therefore, it is suggested here that the productivity changes of eastern Arabian Sea and Bay of Bengal are controlled by the SW monsoon strength.

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Indus Fan is one of the largest deep-sea fans in the world, totaling $5 \times 10^6$ km$^2$. Terrigenous input from the Indus River dominates sediments in the northern Arabian Sea. The primary source of sediments to the Indus Fan is derived from the Indus River, which drains the arid to semi-arid western Himalaya Mountains. Peak discharge occurs during the summer months as a result of seasonal glacier melting and the increased runoff generated by the summer monsoon. Thus, the sediment discharge from the Indus River also depends on the rainfall during SW monsoon. Detailed studies on ODP Site 720A from Indus Fan revealed two distinct sediment sequences in the Indus Fan during late Quaternary: i) Turbidite sequence from 525 to 375 ka and ii) Pelagic sequence from 375 to the present day. It is suggested here that most of the channels were buried by 375 ka BP, which caused the distributary channel to switch away from the site. This in turn result in a general decrease in turbidite deposition at the study site rather than indicating a decrease in terrigenous supply to the Indus Fan. The calcium carbonate content at the study site was controlled by terrigenous material dilution. In the pelagic sequence, the calcium carbonate was diluted by clays, whereas in the turbidite sequence it was diluted by sand and silt. Al, Ti and terrigenous material not show any consistent responses to glacial and interglacial climatic conditions. The terrigenous material supply to the site is therefore not linearly related to the sea-level changes.

The high abundance of Indus-derived clay minerals originating from the Himalayas (illite and chlorite) in both the turbidite sequence as well as the pelagic sequence suggests that the source and supply of clay minerals to the Indus Fan remained constant over last 525 ka.

Recommendations for future work:

During past 1500 years centennial-scale natural climate oscillations such as Little Ice Age and Medieval Warm Period affected broad areas of Earth. It appears that these century-scale climate oscillations were not only restricted to the high latitudes but also have involved a significant perturbations in tropical ocean temperatures and monsoon rainfall. To argue the role of tropical oceans on the global climate we need to generate centennial time scale resolution marine and terrestrial paleoclimate records with more spatial coverage from tropics. Such kind of records will enable us to answer whether tropics or high latitudes kick the start of abrupt climate changes on global scale.