CHAPTER 7
Summary and Conclusions

The primary goal of this study is to understand sub-orbital changes of seasonal SST and OMZ fluctuations, which have strongly coupled with intensity of the Indian Monsoon, a system that dominates climatic change over east Africa, the Arabian Peninsula, Pakistan and western India. This study focused on four sediment cores to address the objectives outlined in Chapter 1. Ocean Drilling Program (ODP) Site 723A is located in the western Arabian Sea at a water depth of 808 m. This site is located in the region of strongest upwelling causing highest seasonal SST changes in the Arabian Sea. Therefore, this site is suitable to understand seasonal SST contrasts over the last 20 kyr. Cores AAS 9/19 and 9/21 are collected from the eastern Arabian Sea. Core AAS 9/19 located in the vicinity of OMZ at 367 m water depth in the Arabian Sea and Core AAS 9/21 is from outside OMZ at a water depth of 1807 m. These two cores have selected to understand the variability OMZ fluctuation in the Holocene and in Late Quaternary. Core SK 239 is located at 3074 m water depth in the NE Arabian Sea, this region experiences maximum winter cooling and convective mixing during NE monsoon. Hence, this core used to reconstruct winter cooling through the time in the NE Arabian Sea. In addition, ODP Site 723A from the region of upwelling and Core AAS 9/19 are suitable to address the controlling factors of planktonic foraminifera shell weights from the upwelling and non-upwelling regions.

Although upwelling occurs in the Arabian Sea from June through September, the intensity of upwelling is highest during the August (Fig. 3.1). SST variation during August show greater amplitude changes than SST variations during May in the Holocene (Fig. 3.3a and b), suggesting that the timing of the intensity of upwelling, or the intensity itself has varied significantly. Though the intensity of upwelling was high from 10 to 5 ka as shown by the upwelling indices (Naidu and Malmgren, 1996; Overpeck et al., 1996), the August SST was higher than the modern-day SST at this site. This indicates two features: i) intensity of upwelling during August was not as intense as that in the modern day, and ii) upwelling must have been more intense during summer months (June, July) than in the August.

Comparison of the solar isolation changes at 20°N and the SST for the months of May and August reveals that the SST variability for the month of August overall
follows the solar insolation changes (Fig. 3.3b). On the other hand, May SST and the solar insolation patterns are not similar: for example between 19 and 12 ka the strongest incoming solar insolation at 20°N was in May, with relatively low SST (Fig. 3.3a). This suggests that the early initiation of upwelling could have suppressed May SST. Although modern May insolation is not as strong as it is from 19 to 12 ka, the modern strong SW winds in the northern Arabian Sea are active in the month of May.

Comparison of SST reconstructions for the eastern Arabian Sea (EAS) for August based on the modern analogue technique (MAT) (Cayre and Bard, 1999) and ANN methods for the WAS (this study) show a 4°C East - West gradient, with 23°C in the WAS and 27°C in the EAS. Furthermore the SST record from the core MD77194 in the EAS documents minimum SST fluctuations over the Holocene, reflecting the fact that the August SST in the non-upwelling regions of the Arabian Sea generally did not vary as much as those in the upwelling regions of the Arabian Sea. Similarly, SST reconstructions based on Mg/Ca ratios in the planktonic foraminifer species *Globigerinoides ruber* in the EAS and WAS (Dahl and Oppo, 2006; Anand et al., 2008) also confirm that the Holocene-to-glacial SST shift is greater in the EAS than in the WAS.

Trace elemental concentration of foraminifera have been used to reconstruct the SST and pH of the oceans (Elderfield and Ganssen, 2000; Yu et al., 2007). The trace elemental concentrations and isotopic ratios of planktonic foraminifera vary depending on the size of foraminifer shells (Spero and Lea., 1993). In this study an attempt has been made to address the factors which controls the planktonic foraminifera shell weights and sizes in the Arabian Sea. Spero et al., (1997) was the first to report that planktonic foraminifer species *Orbulina Universa* shell weights are controlled by concentration of carbonate ion \([\text{CO}_3^{2-}]\) in the water column. Subsequently, Barker and Elderfield (2002) studies from North Atlantic also confirmed that planktonic foraminifer shell weights are controlled by \([\text{CO}_3^{2-}]\) values in ambient waters. Later studies have shown that factors which control shell weights are more complex than previously thought (de Villiers, 2003) and Highest foraminiferal shell-weights are observed within the optimum ecological niche of each planktonic species (de Villiers, 2004).
In Western Arabian Sea it was observed that from recent to 16 kyr shell weights of *G. bulloides* and *G. ruber* were correlated to shell size which suggests that shell calcification was controlled by optimum growth conditions driven by intense upwelling. From 16 to 22 kyr, shell weights of *G. bulloides* were not correlated to shell sizes but showed a significant negative correlation with annual SSTs which suggests that surface water \([\text{CO}_3^-]\) may have controlled shell calcification of *G. bulloides*. Thus, different factors may control planktonic foraminifera shell calcification over a period of time. Hence foraminifera shell weights of *G. bulloides* and *G. ruber* cannot be utilized as a proxy of surface water \([\text{CO}_3^-]\) in the upwelling region of the Arabian Sea.

The down core study from the eastern Arabian Sea reveals that variation in shell weights of *Globigerinoides sacculifer* during the Holocene and the last glacial period are mainly related to the variation in surface water \([\text{CO}_3^-]\) through time in response to changing atmospheric CO\(_2\). Hence carbonate ion concentrations estimated using shell weights of *G. sacculifer* shows that ~8\(\mu\)mol/kg and ~36 \(\mu\)mol/kg variations during Holocene and last glacial period respectively, in the eastern Arabian Sea.

During the Holocene the atmospheric pCO\(_2\) was typically close to 280 ppmv, whereas during the last glacial period, atmospheric pCO\(_2\) was around 180 to 200 ppmv (Petit et al., 1999). Glacial to Holocene surface water carbonate ion concentration calculated from AAS9/21 was compared with the CO\(_2\) record from Taylor Dome Ice from Antarctica (Smith et al., 1999) and the results show a good match between the two (Fig. 4.3).

Planktonic foraminifera *G. ruber* flux and shell weights measured from sediment traps exhibit significant positive correlation during southwest and northeast monsoon in the western and eastern Arabian Sea suggesting that optimum growth conditions for *G. ruber* prevailed during monsoons which influences the shell calcification. Strikingly, there was no distinct difference in shell weights of *G. ruber* between the western and eastern Arabian Sea. The lack of influence of elevated CO\(_2\) and lowered SST as a result of intense upwelling in the western Arabian Sea, on *G. ruber* shell weights suggests that temperature or carbonate ion may not be the
primarily control on *G. ruber* shell calcification in these regions on a seasonal timescale.

In the Arabian Sea, the combination of high surface water productivity, intense carbon respiration in the water column and restricted intermediate water circulation produces a severe and extensive OMZ between 150 and 1250 m water depths (Wyrtki, 1973). Paleoceanographic studies have reported rapid variations in productivity, OMZ intensity and thermocline ventilation over last 100 ka in the Arabian Sea. (Altabet et al., 1995; Reichart et al., 1998; Ivanochko et al., 2005). Productivity proxies such as OC, $\delta^{13}$C$_{org}$, and $\delta^{13}$C$_{G.ruber}$ in the eastern Arabian Sea Core AAS 9/19 reveal that productivity was higher during the Late Holocene (~7 to 0 kyr) as compared to early Holocene. Down core variations in $\delta^{15}$N of sedimentary organic matter appear to be controlled by the surface productivity. Temporal variation in $\delta^{15}$N demonstrates that the intensity of subsurface denitrification has increased from ~7 kyr BP, in response to increasing surface productivity during this period. Redox sensitive elements such as Molybdenum and Chromium indicate that the OMZ intensity also increased simultaneously suggesting a strong coupling between productivity and OMZ intensity in the eastern Arabian Sea. The increase in OMZ intensity further lead to an increase in calcite dissolution as seen in the low CaCO$_3$ content, lower shell weights of planktonic foraminiferal species *G. ruber* and visible dissolution features on *G. ruber* shells, during the Late Holocene. This calcite dissolution is probably a result of an increase in DIC in waters of the OMZ releasing CO$_2$ to the atmosphere most likely contributing to the Holocene CO$_2$ rise. On a longer timescale of 70 kyr, denitrification intensity was seen to be higher during MIS 1 and 3 and lower during MIS 3 and 4. Molybdenum variations lend further support to the concept that as denitrification intensity increased, so did the bottom water sub-oxic conditions. Increase in sub-oxic conditions also leads to calcite dissolution which was most intense during the Early-Holocene and MIS 3.

A combination of multi proxies (Seasonal SST, winter SST anomalies, $\delta^{13}$C, fertile planktonic foraminifer species abundance) were used to reconstruct the winter cooling and NE monsoon variability from a sediment a core collected in the NE Arabian Sea. Winter SST and winter SST anomaly both show minimum values during MIS 2 than in MIS 3 and 1 representing that winter cooling was stronger during MIS 2 than in MIS 3 and 1. The productivity proxies $\delta^{13}$C and fertile planktonic
foraminifera species abundance also display higher values during MIS 2 than in MIS 1 and 3, which supports that productivity trends and winter cooling are strongly coupled at this site. Planktonic foraminifera species *Globorotalia truncatulinoides* is more abundant during the winter cooling in the Arabian Sea (Reichart et al., 1998). High abundance of *G. truncatulinoides* during MIS 2 (Fig. 6.8) further supports that the intensified NE monsoon winds enhances the winter cooling at the core location during MIS 2.

Comparison of the SW and NE monsoon intensity variations over last 40 kyr reveals that an inverse relationship between these two monsoon systems. For the first time it is reported here that when cold temperature prevails in the Greenland the strength of NE monsoon and associated winter cooling intensifies in the NE Arabian Sea. Thus, the cold temperatures in the Greenland would provide a positive feedback to the NE monsoon and negative feedback to the SW monsoon.

Winter SST and NE Monsoon wind strength are tightly coupled in the NE Arabian Sea. In addition to general variability of NE monsoon, here an attempt has been made to explore if any periodicity exist in the variability of NE Monsoon. Analyses of winter SST through Multi Taper Method (MTM) spectral program (Ghill et al., 1995) revealed that an existence of a significant 500 years periodicity (Fig. 6.10), which is indicative of 500 years cyclicity in NE monsoon. Next question is what forces the 500 years cyclicity? A pollen lake record from the East Asia (region highly influenced by East Asian Monsoon) also shows 500 years periodicity (Xu et al., 2014). For the first time it is reported here a winter monsoon periodicity of ~500 years which was driven by the combination of two processes; 1. Total Solar Irradiance and 2. Boundary conditions in the Siberia.

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