Chapter I

INTRODUCTION

The northern Indian Ocean comprises two major regions, the Arabian Sea and the Bay of Bengal. These two areas which adjoin the two sides of the Indian subcontinent play a dominant role in the climatic pattern of the region. The Southwest Summer Monsoon (SWSM) is one of the most intense systems that influence world climate. In the Indian subcontinent, SWSM is followed by a relatively weak, but nevertheless significant, North East Winter Monsoon (NEWM). These monsoon systems, so unique to this region, occur due to the combined air–sea interaction resulting in not only precipitation over the Indian subcontinent but also lead to significant changes in the sea surface temperature, salinity and biogeochemical cycles of the northern Indian Ocean.

The present investigation addresses two important issues of the northern Indian Ocean: (i) Upwelling rate in the Arabian Sea and (ii) Sediment provenance and climatic history of the Bay of Bengal since the last 50 kyr. The rationale for these objectives is based on the premise that the physical, biological and chemical environment of the Bay of Bengal is closely linked to the variation in the summer and winter monsoon. In the Arabian Sea, the summer monsoon winds induce strong upwelling resulting in enhanced productivity – a surrogate that can be used for reconstructing monsoon induced wind strength.

The Arabian Sea and the Bay of Bengal both experience seasonally reversing monsoon that induce a reversal of wind driven circulation of the surface waters. This results in upwelling along the western margin of both the regions viz. the Arabian Sea and the Bay of Bengal (Currie et al., 1973).

Although these basins experience similar circulation patterns, the upwelling in the Arabian Sea is more intense making it the most productive region of the world (Prasanna Kumar et al., 2002). As compared to this, the Bay of Bengal region experiences enhanced fresh water flux during the monsoon periods from the rivers draining into it leading to a stratification, with a lens of fresh water at the surface, that reduces the vertical mixing in the water column (Wyrtki, 1971).

The studies of ocean water circulation has been investigated with the help of radiocarbon (^{14}C) as a tracer to follow pathways of carbon across various exchangeable carbon reservoirs (Broecker et al., 1985, 1995). During the late 1950s and early 1960s, considerable amount of ^{14}C was injected into the atmosphere by nuclear weapon tests thereby leading to increase in the atmospheric ^{14}C levels (Nydal and Lövseth, 1983; Broecker and Peng, 1994). This transient of bomb ^{14}C in the environment during early 1960s has been used as a tracer and provides an opportunity for studying ocean circulation in the upper part of the water column and exchange of CO_2 at the air–sea interface processes that normally take place on decadal time scales.

The Arabian Sea and the equatorial Indian Ocean regions are typically associated with high wind speeds due to the seasonally reversing monsoon and the associated wind induced upwelling. The upwelling areas associated with high productivity are expected to experience a higher than average exchange rate. To ascertain the temporal variation in the bomb ^{14}C distribution in the upper layers of the Arabian Sea and the equatorial Indian Ocean, a number of oceanographic expeditions onboard *FORV Sagar Sampada* were made between 1994 and 1999 for the collection of samples from the water column (Somayajulu et al., 1999; Bhushan et al., 2000, 2003; Dutta, 2001). It is also expected that an understanding of upwelling rates could provide better insight into the wind driven circulation in the ocean's upper layers. In view of this, the present study aimed at determining the upwelling rates at various locations in the Arabian Sea and the equatorial Indian Ocean, based on temporal variation in the bomb ^{14}C distribution over the past two decades (Broecker et al., 1985, 1995; Bhushan et al., 2000). Towards this, vertical profiles of seawater samples from the various locations in the Arabian Sea were collected for analyses of radiocarbon, total dissolved CO_2 (ΣCO_2), nutrients and dissolved oxygen, along with other hydrographic parameters.

In the Arabian Sea and the Bay of Bengal, the denitrification layer in the subsurface waters varies between water depths of 200–1000 m. The sediment traps deployed in western, central and eastern parts of the deep northern Arabian Sea recorded strong seasonality in particle fluxes during the southwest and northeast monsoons (Ramaswamy et al., 1991; Ramaswamy and Nair, 1994). High primary productivity during the monsoons resulting from wind-induced mixed-layer deepening and the associated nutrient injection to the euphotic zone appeared to be the main factor controlling the observed particle flux pattern (Nair et al, 1989). This process had implications on the CO_2 uptake during glaciation when the wind speeds were higher. Further, the areas of high surface productivity and low bottom-water oxygen concentrations are caused by contribution of nutrients from the continental runoff. $\delta^{15}N$ analyses of sediment cores from areas with high accumulation rates off the Oman continental margin have shown millennial-scale variability in the Arabian Sea denitrification and productivity during the last glacial period. This would imply that $\delta^{15}N$ can be used as a proxy for reconstructing the monsoon driven wind strength in the past. Further, studies have shown that global marine productivity has been influenced by changes in denitrification and this could be related to climatic and atmospheric CO_2 oscillations as has been observed in the Antarctica ice cores during the past 20–60 kyr (Altabet et al., 2002).

In the Bay of Bengal, the boundary current shows a strong seasonal variability leading to a reversal of the local monsoon wind field by several months. This is attributed to the topography of the northern Bay and the

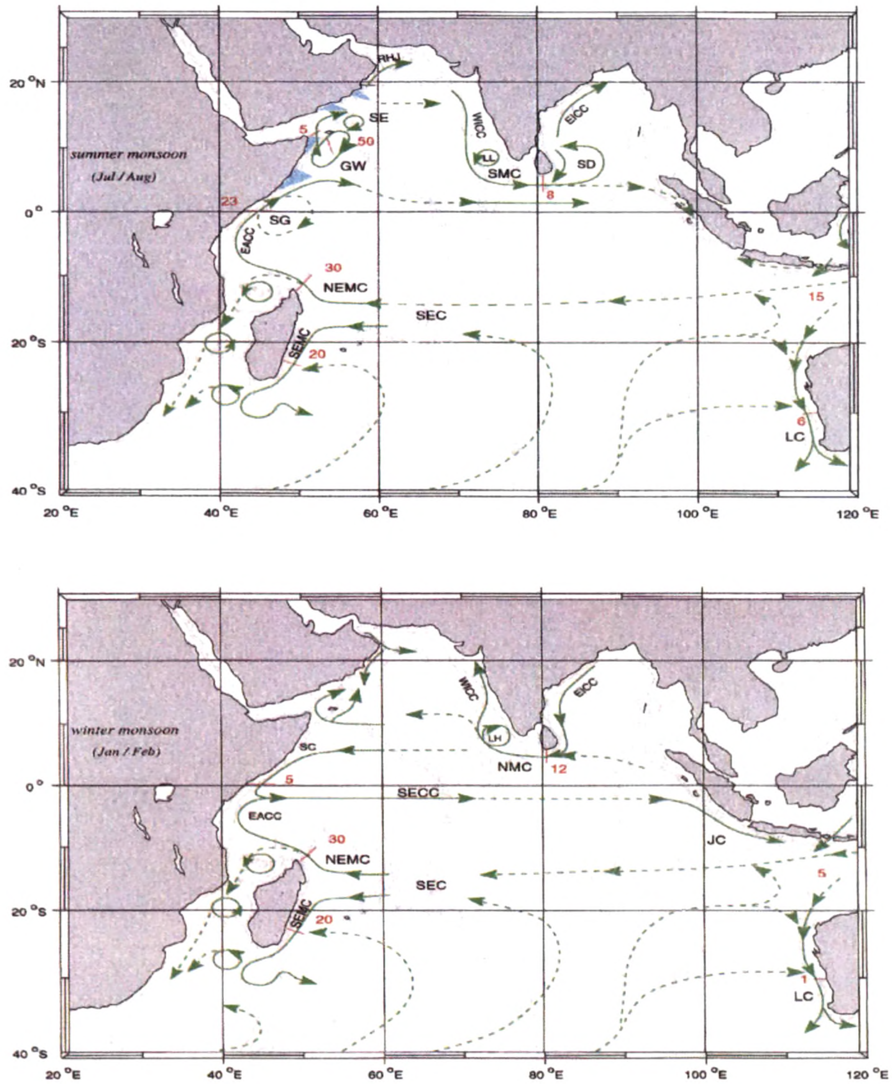

Fig. 1.1: Surface circulation pattern in the Bay of Bengal during summer and winter monsoon. Note, the reversal of East India Coastal Current (EICC) during the two seasons (after Schott and McCreary, 2001).

proximity of the Himalaya and the Tibetan Plateau (Kennett and Toumi, 2005). The total vorticity generation over the Himalayan region as a whole is at least half as that over the Bay of Bengal thus implying that the Himalayan rainfall plays a central role in amplifying the circulation of the monsoon (Kennett and Toumi, 2005).

The Bay of Bengal is characterized by the East India Coastal Current (EICC) that reverses direction twice a year, flowing northeastward from February to September, with a strong peak in March–April, and southeastward from October to January with the peak flow in November (Shetye et al., 1996). During the Southwest monsoon, currents in the entire bay are weak. The EICC is a major system in the Bay of Bengal that not only influences the coastal productivity but also seems to have a strong bearing on the sediment dispersion pattern as is evident from the present study (Fig. 1.1, Schott and McCreary, 2001).

The Bay of Bengal is a natural repository of sediments brought in by the various river systems draining the Indian subcontinent. During the last few decades as a part of the ocean circulation studies, large number of sediment cores were collected form a wide geographical area in the Bay of Bengal. The sediment distribution in the Bay of Bengal is dominated by three sediment sources viz. the Ganga–Brahmaputra River system (henceforth G–B River system) in the north, the peninsular river system in the west and the Irrawaddy–Salween River system in the Andaman Sea to the east. About 30% of the sediment load of the G–B River system gets deposited in the shelf region, another 40% in the sub–aqueous delta, while the remainder 30% reaches the *"Swatch of No Ground"* (Goodbred and Kuel, 1999). In the case of the Irrawaddy, nearly 15% of the sediment load is deposited beyond the delta shelf (Rodolfo, 1969). The sedimentation rates in the central and southern Bay of Bengal ranges from 2–4 cm/kyr (Prell et al., 1980). The average accumulation rate in the Andaman Basin (15 cm/kyr) is higher than that in the Bay of Bengal (10 cm/kyr) (Frerichs, 1968; Sarin et al., 1979; Venkatchala et al., 1992).

The enormous fluvial input to the Bay during the South West Summer Monsoon (SWSM) is reflected in the high average content of lithogenic matter with a relative increase in the flux of biogenic opal. In addition, the high carbonate–dominated flux observed during SWSM and Northeast Winter Monsoon (NEWM) is mainly due to wind–induced nutrient supply, while the high opal–rich fluxes during SW–NE inter–monsoon is due to both upwelling as well as supply of riverine and shelf derived matter (Unger et al., 2003). In the northeastern part, the sediment flux is dominated by inputs from the G–B River system, while in the western part it is the peninsular rivers that drain regions of India that contribute largely to the sediment budget. The narrow margins along the coastal regions in the Bay of Bengal are dominated by sand, silt and clay with a large area covered only by clay (Rao, 1991; Rao and Kessarkar, 2001). In the G–B delta region, silt deposits occupy a wide area while west of the Andaman coast, silty–clay is the dominant material that occupies a very large area extending westwards almost to the central region of the Bay of Bengal (Kolla and Coumes, 1984). The transport of clastic material from the land to the deep sea results in turbidite sedimentation. Sediments brought by the G-B River system are deposited partly near the shelf and in the *"Swatch of No Ground"*, a submarine canyon deeply incised into the shelf off Bangladesh. The *"Swatch of No Ground"* connects the present shelf depocenter to a channel–levee system. There is a general increase in foraminifera as well as unidentifiable calcareous fragments towards the central and southeastern parts of the Bay with a decrease in terrigenous material and insoluble matter (Siddiquie, 1967). The Bengal Fan, one of the world's largest submarine fan systems is formed by long–term input of riverine sediments moderated by glacio–eustatic sea–level fluctuations, climate change and tectonic activity (Flood et al., 1995).

The average annual particle flux to the Bay of Bengal is highest in the central Bay area (~50 $g.m^{-2}.yr^{-1}$) and lowest in the southern part of the Bay (~37 $g.m^{-2}.yr^{-1}$) and this coincides with the freshwater discharge pattern of the G–B River system (Ramaswamy and Nair, 1994). Based on the sediment trap studies, it has been noticed that the southern Bay of Bengal (~1500 km away from major rivers) has the highest lithogenic flux as compared to western or eastern Arabian Sea areas located ~400 km away from landmasses and in areas known for high aeolian and fluvial input (Kolla et al., 1981; Nair et al., 1989; Ittekot et al., 1991; Sirocko et al., 1991). Sarin et al. (1979) reported sedimentation rates of 2 to 40 mm/kyr during the Holocene in the Bay of Bengal which is comparable to the trap fluxes in the northern Bay of Bengal.

In terms of biogenic contribution to the surface sediments of the Bay of Bengal, carbonate constitutes a major component which acts as a dilutant for the terrigenous fluxes (Kolla et al., 1976). The sediment brought into the Bay of Bengal comprising varied mineralogical assemblages, due to complex provenances sources (lithology) and is dispersed as per the changing circulation patterns. For example, high quartz and low calcium carbonate percentages in the surface sediments of the Bay of Bengal adjacent to the Indian subcontinent result from the massive influx of terrigenous clastics. Mineralogy and heavy minerals assemblages in the surface sediments of the western margins of the Bengal Fan suggest that they have been derived from the peninsular Indian regions, whereas, the rest of the fan sediment have signatures of a Himalayan origin. The sediments on the Ninety East Ridge and in the deep southern areas beyond the reach of fan deposition result from the *in situ* alteration of volcanics (Kolla and Rao, 1990). The Ninety East Ridge acts as a barrier preventing the coalescence of two Bengal Fan lobes (Kolla and Biscaye, 1973).

The influence of continental inputs on the Bay of Bengal sediments is further illustrated by the Ti/Al and Fe/Al ratios. The higher ratios in samples from the east coast areas of India compared to the Bengal Fan sediments indicate the influence of material derived from the Deccan basalts and mafic rocks of the Indian Peninsula. The clay mineral assemblages of the upper Bengal Fan sediments show dominance of illite and chlorite suggesting a Himalayan source (Roonwal et al., 1997). It has been observed that the distribution of Al and Fe give a representative picture of the nature of distribution of sediment in the Bay of Bengal. The Al content varies considerably (up to 9%) with the highest values (>6.5%) are found in the terrigenous sediments off the east coast of India, west of Burma, the Java Trench, in the pelagic sediments of the Wharton Basin, and in a few isolated patches in the Central Indian Basin. The above variation is attributed to the varying continental sources. Fe also shows considerable variation with the high values (>5.5%), found proximal to the Indian subcontinent and in some pelagic sediments of the Wharton and the Central Indian Basins. The concentration however decreases off the east coast of India towards the central Bay of Bengal (Wijayananda and Cronan, 1994).

One of the major components of the tropical climate system is the Indian summer monsoon, which results in a differential land-sea sensible heating, producing seasonal reversals in wind direction and intense rainfall. Clemens et al. (1991) suggested that variations of the summer monsoon intensity are mainly forced by the contrast in insolation between the northern and the southern hemispheres. In addition, recent investigations of deep-sea sediment cores of the Arabian Sea (Sirocko et al., 1993, 1996; Heusser and Sirocko, 1997; Schulz, et al., 1998) indicate that the intensity of the Indian monsoon has also experienced changes that are independent from insolation variations. It has been suggested that these rapid changes should be related to the high-amplitude climatic changes, observed in the $\delta^{18}O$ records of the Greenland ice core GRIP (GRIP member, 1993; Dansgaard et al., 1993) and GISP2 (Grootes et al., 1993; Stuiver et al., 1995) and in the North Atlantic sediment cores (Heinrich, 1988; Bond et al., 1992; Bender et al., 1994; Bond and Lotti, 1995), via an atmospheric and/or oceanic tele-connection (Zonneveld et al., 1997). On a regional scale, the Indian summer monsoon represents an important factor driving weathering and erosion of the Himalayan and Burmese mountain ranges. On geological time scales, changes in the strength of the summer monsoon rainfall are likely to affect the chemical and physical weathering intensity of the Ganges-Brahmaputra and the Irrawaddy catchment and drainage areas. Sediments of the Bay of Bengal and the Andaman Sea thus provide a record of the variability of the intensity of erosion of the Himalayan and Burmese mountain ranges that in turn relate to palaeoclimatic and palaeoenvironmental variations that have affected the dynamics of the monsoon (Colin et al., 1998).

For example, using the magnetic grain size in the Bay of Bengal sediment core samples, Colin et al. (1998) have reconstructed a detailed record of monsoon variability during the last glacial period which they attributed to the rapid temperature variations in the northern latitude (Dansgaard–Oeschger cycles and Heinrich events). According to them, rapid cold events of the North Atlantic (Heinrich events) during the last glacial stages are characterized by a weaker summer monsoon rainfall over the Himalaya via an atmospheric tele-connection. During the Last Glacial Maximum (LGM), the high value and low gradient of $\delta^{18}O$ (Duplessy, 1982) has been interpreted as a decrease in the fresh water inflow from the Himalayas (Cullen, 1981). Based on SST and $\delta^{18}O$ record obtained from foraminifera, Chauhan (2003) suggested that between 20 and 15 kyr the Himalayas were extensively glaciated with a minimum fluvial discharge (until 15 kyr) reaching the Bay of Bengal. Rashid et al. (2007) have used the Mg/Ca and $\delta^{18}O$ data of the planktonic foraminifera from the Andaman Sea to reconstruct the SST and $\delta^{18}O$ of sea water during the last 25 kyr. According to them, SST was ~3^{0}C lower during the LGM than the late Holocene. The study suggests decreased evaporation–precipitation in the Andaman Sea with increased outflow of the Irrawaddy River during LGM. The above studies indicate that in strategically selected core samples, geochemical and isotopic proxies can be used to reconstruct the climate (monsoon intensity) and provenance variability over long as well as short time scales.

In the present study, the surface sections of sediment cores from the Bay of Bengal were analysed to understand the sediment distribution and provenance. Two cores, that were radiocarbon dated using Accelerated Mass

Spectrometry (AMS) were analysed to reconstruct the Late Quaternary climatic history spanning the last 50 kyr using geochemical and isotopic parameters. A highlight of the present study is the successful use of $^{87}Sr/^{86}Sr$ ratio and ε_{Nd} in the sediment core that enabled the recognition of the summer and winter monsoon variability and also helped ascertain the spatial and temporal changes in sediment provenance.

Scope of the Present Study

The unique biogeochemistry of the Arabian Sea and the Bay of Bengal areas of the northern Indian Ocean and their typical hydrological and geographic characteristics require special attention as it provides a unique opportunity to understand upwelling processes and rates, sediment provenance and climate changes. Recognizing the importance of the region in its role in influencing climate, particularly the well known monsoon systems of the Indian subcontinent, this investigation was initiated for detailed studies on the water column in the Arabian Sea, the sediments of the Bay of Bengal and representative samples from the estuaries of major rivers draining into the Bay of Bengal.

The Arabian Sea is known for its high productivity due to the wind associated seasonally reversing monsoon system and upwelling of nutrient rich deep waters to the surface. To understand these processes, the air-sea CO_2 exchange rate and the upwelling rate in the Arabian Sea have been estimated from measurements in the water column and atmospheric samples using radiocarbon as a tracer for the following:

- Bomb ^{14}C inventory of the water column in the Arabian Sea,
- Atmospheric inventory of the ^{14}C,
- Hydrological parameters in the water column at select depths,
- Nutrients, ΣCO_2 and Salinity in seawater,
- Pre-bomb concentrations of radiocarbon from archived shells.

To ascertain the provenance of sediments and to understand the climatic changes during the last 50 kyr in the region, various chemical and isotopic proxies were measured. Analyses of sediment cores distributed spatially in the Bay of Bengal included the following:

- Radiocarbon dating of cores based on select planktonic foraminifer species,
- Major and Trace element analysis on bulk sediments,
- $CaCO_3$, Carbon and Nitrogen measurements on bulk sediments
- Carbon ($\delta^{13}C$) and Nitrogen ($\delta^{15}N$) isotopic composition of the organic matter in the sediments from the central Bay of Bengal core.
- $^{87}Sr/^{86}Sr$ and ε_{Nd} in the silicate fraction of the sediments from the central Bay of Bengal core.
- ε_{Nd} in the silicate fraction of the sediments from the southern Bay of Bengal core.

These analyses were done to understand:

1) Provenance of sediments in the Bay of Bengal,
2) Variations in detrital flux and surface productivity during the past 50 kyr,
3) Source variation of the sediment deposited in the central and southern Bay of Bengal during the last 50 kyr.
4) Climatic implications of the detrital and productivity variations.

The present investigation has been carried out as part of this doctoral dissertation and has been presented in six chapters as:

Chapter-I presents the general introduction to the above two mentioned themes and the rationale for undertaking this study. Also highlighted here are salient observations made by previous workers that are relevant to the objectives of this study.

Chapter-II describes the sample details, sampling procedures and measurement techniques employed for various analyses.

Chapter-III addresses the procedures followed for obtaining the upwelling rates in the Arabian Sea.

Chapter-IV pertains to the sediment distribution pattern and provenance in the Bay of Bengal.

Chapter-V discusses the history of the climatic variation during the past 50 kyr.

Chapter-VI summarizes the results and discusses the understanding developed in respect of the objectives outlined.