Chapter 1

Introduction

Paleoclimatology of the northern Indian Ocean is very closely related to the phenomenon of monsoon. India in particular is very sensitive to fluctuations in monsoon as its economy largely depends on agriculture and a poor monsoon affects millions of lives. Similarly devastating floods and untimely intense precipitation due to an above normal monsoon episode would destroy crops and property. Moreover global warming due to increased greenhouse gases in the atmosphere with the accompanying global changes is now a reality (Houghton et al, 2001). It has been estimated that the average surface temperature of the earth has increased by 0.6^0C over the twentieth century (Mann et al, 1998) that has possibly led to the reduction of snow cover and an increase in the sea level. It is estimated that during the past century the precipitation has increased by 0.5% to 1% per decade for most of the mid- and high latitudes of the northern hemisphere continents and 0.2% to 0.3% for the tropical (10^0S to 10^0N) land areas. It was observed that in parts of Asia and Africa, the frequency and intensity of droughts increased (Houghton et al, 2001) in the period from 1900 to 1995 AD. Potential impact of global change on water resources include enhanced evaporation due to warming, geographical changes in precipitation intensity, duration and frequency affecting the average runoff, soil moisture and the frequency and severity of droughts and floods. Future projections using climate models point to an increase in the monsoon rainfall in most parts of India with increasing greenhouse gases and sulphate aerosols (Rupa Kumar et al, 2002). Many north Indian rivers such as the Ganga, Yamuna etc. have shown a sharp decline in the summer discharge in the recent past, possibly due the shrinking of the Himalayan glaciers that feed them (Gosain and Rao, 2003). These observations lead us to an important question whether this is a consequence of global warming or only a part of the low frequency climate variability inherent in the system. To answer this would require reliably dated, high-resolution records of the past monsoonal precipitation. Monsoon is known to exhibit variance over a range of periods such as annual, decadal and centennial to millennial time scales. Annual to decadal scale variations can be studied using the recorded meteorological data, which date back to the past 150 years. But even this is available for the big cities only, where weather stations are located. For studying the low frequency variations on centennial to millennial timescales, we have to take recourse to various paleoclimatic proxies such as sediments deposited in the Indian Ocean and various lakes, ice deposited in Tibetan/ Himalayan glaciers, speleothems etc. If suitable cores from appropriate regions (such as continental margins) are available, we can explore paleomonsoon variations on centennial to decadal time scales (comparable to human lifetime).

1.1. Monsoon and the associated oceanographic effects:

Monsoon is the one of the most important planetary scale phenomena involving atmosphere-ocean-terrestrial vegetation/albedo systems. It envelops large parts of the globe from 25^0S to 35^0N and 30^0W to 170^0E (Ramage, 1971) covering western and eastern Africa, Indian subcontinent, Southeast Asia, northern Australia and even some parts of southwestern USA. There is a lack of precise definition of monsoon as differences prevail among various workers whether it should be defined according to precipitation or wind. But broadly monsoon is described as system of winds confined to the tropics that exhibits marked seasonal shifts in the their direction that persist for a long time and commence due to the differential heating of land and the sea (Webster, 1987) and the solar induced seasonal shifting of the intertropical convergence zone (ITCZ, Charney,1969; Gadgil, 2003). Infact the word monsoon is derived from the Arabic word “Mausam”, which stands for season and was first experienced by Arab sailors traversing the Arabian Sea who noted a persistent reversal of the wind at the same time every year. The most pronounced monsoon occurs over the Indian subcontinent and is the lifeline of the countries influenced by it. The Indian monsoon is further divided into two parts:

1.1.1 Southwest (SW) Monsoon: The continents surrounding the Arabian Sea receive a large amount of heat during the summer in Northern hemisphere, as sun is directly overhead (summer solstice). Because of this a low-pressure system develops over Arabia, northwest Indian subcontinent and the Tibetan plateau with pressures as low as 994 mb. On the other hand, high atmospheric pressure exists over the relatively cold southern subtropical Indian Ocean (~25^0S) with pressures upto 1020 mb (Rao, 1976) with a maximum pressure of 1026 mb observed around the so-called “Mascerene High” off the southeast coast of Madagascar. This causes the SE trade winds to rush into the low-pressure region, which become southwesterly after crossing the equator resulting in the "summer or SW monsoon". The major part of the rushing winds follow what is known as the "Findlater Jet", which is a low level jet stream at a height of 1 – 1.5 km with wind speeds upto 15 m/s (Hastenrath and Lamb, 1979). This jet originates around Mauritius and Northern Madagascar and strikes the Kenyan coast at 3^0S after which it traverses the plains of Kenya, Ethiopia, Somalia and emerges out of the Somalian coast at ~9^0N. Thereafter it splits into two branches at ~55^0E with one striking the western coast and the other going around the southern tip of India and over southern Sri Lanka (Findlater, 1981). These moisture-laden winds cause abundant precipitation over India from June to September and release latent heat in the troposphere, which further intensifies it (Webster, 1987). As most of the rainfall (~70 %) over India occurs during the summer months, the word monsoon in India usually refers to the Southwest monsoon precipitation.

1.1.2 Northeast (NE) Monsoon: During the northern hemisphere winter an intense surface high pressure system develops in the east Asian continent south of the Lake Baikal with pressures upto 1035 mb, whereas low pressure (~1110 mb) exists over the southern subtropical Indian Ocean due to the radiation it receives from the sun directly overhead (winter solstice). Due to the pressure difference air rushes towards the south of the equator causing intense precipitation over southeastern India, Sri Lanka, Malaysia and Indonesia. In the Indian context "winter or NE monsoon", which extends from mid-October to January is important as it the major rainy season for the southeastern India and accounts for ~50 % of the annual rainfall over the coastal Tamilnadu (Das, 2002). Unlike the summer monsoon, which occurs more or less continuously, the NE monsoon occurs in spells of 3-4 days of heavy rains interrupted by long dry periods with little or no rain. Sometimes big cyclones form in the Bay of Bengal and cause intense precipitation/floods in peninsular India.

During the summer and winter monsoons the surface oceanic circulation in the Northern Indian Ocean including the Arabian Sea and the Bay of Bengal experiences drastic changes in direction in consonance with the changing overlying wind patterns (Wyrtki, 1973) as shown in Figs. 1.1 and 1.2. The circulation patterns for the eastern, equatorial and western Arabian Sea are further discussed in detail in sections 3.3, 4.3 and 5.3 respectively.

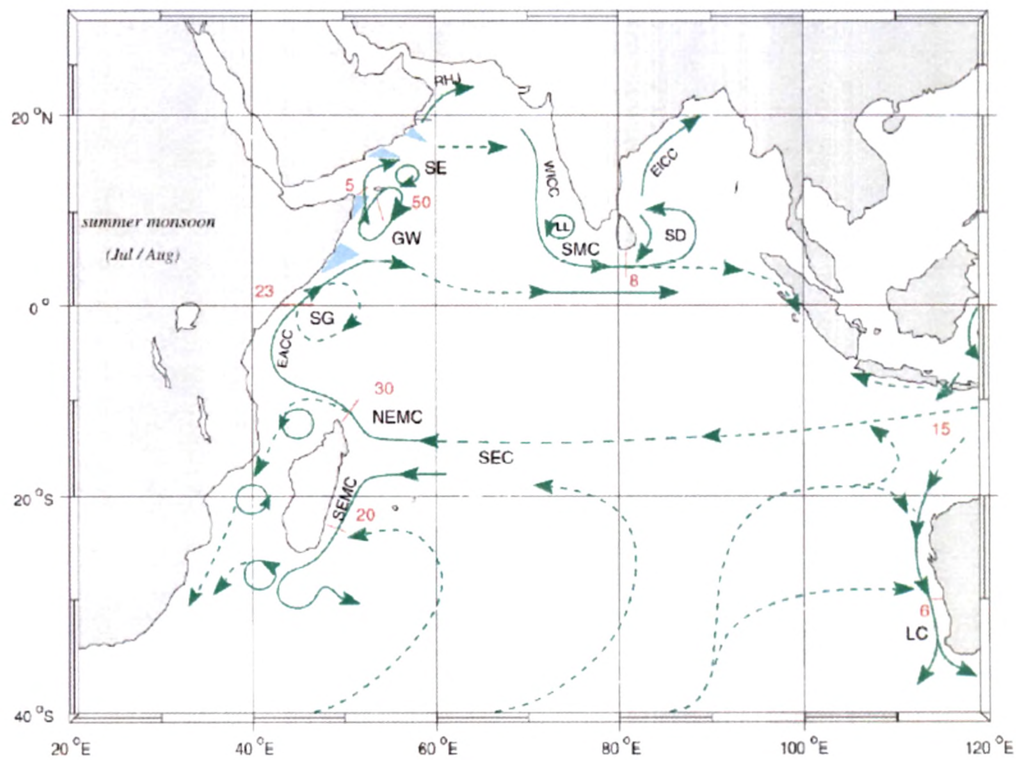

Fig. 1.1. A schematic representation of identified current branches during the Southwest monsoon, including some choke point transport numbers (Sv = 10^6 m^3s^{-1}). Current branches indicated (see also Fig. 1.2, next page) are the South Equatorial Current (SEC), South Equatorial Countercurrent (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), East African Coast Current (EACC), Somali Current (SC), Southern Gyre (SG) and Great Whirl (GW) and associated upwelling wedges, Socotra Eddy (SE), Ras al Hadd Jet (RHJ) and upwelling wedges off Oman, West Indian Coast Current (WICC), Laccadive High and Low (LH and LL), East Indian Coast Current (EICC), Southwest and Northeast Monsoon Current (SMC and NMC), South Java Current (JC) and Leeuwin Current (LC) (from Schott and McCreary, 2001). Shaded regions (blue) along the Somalia and Oman margins represent upwelling centers.

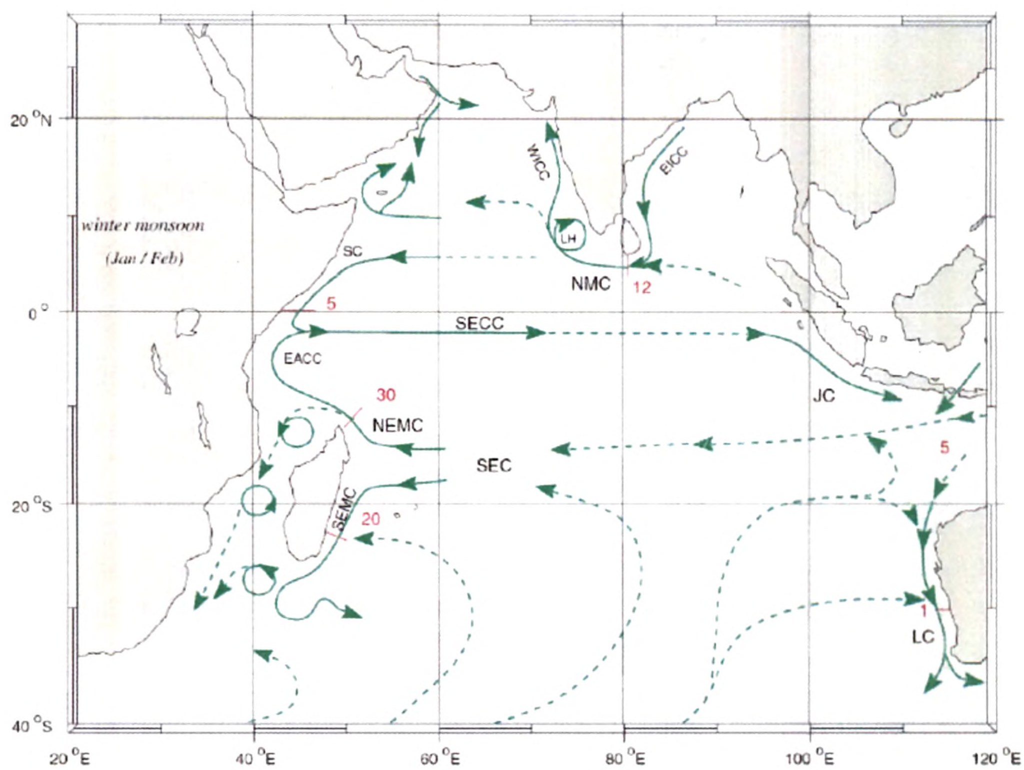

Fig.1.2. Schematic representation of surface circulation in the Indian Ocean during the NE monsoon (from Schott and McCreary, 2001). The captions for various current branches are the same as in the Fig 1.1 (see previous page).

One of the major features of the SW monsoonal circulation is the occurrence of an upwelling zone along the Somalian and Oman coasts, which causes intense biological and geochemical changes in this region with SST falling by ~4^0C as nutrient rich deeper water surfaces that enhances the sea surface biological productivity considerably (Wyrtki, 1973; Nair et al, 1989; Haake et al, 1993 b). Weak upwelling also occurs along coastal southwest India (Wyrtki, 1973; Shetye, 1984). During the Northeast monsoon the surface circulation reverses completely with minor upwelling observed in the northeastern Arabian Sea (Wyrtki, 1973). The cold and dry NE monsoon winds causes the deepening of the mixed layer to a depth of 100 – 125 m due to convective mixing in the northern Arabian Sea, which leads to nutrient injection and hence high productivity during winter monsoon in this region (Banse and McClain, 1986; Madhupratap et al, 1996). The typical productivity values for the western Arabian Sea are 2.0, 1.0 and 0.5 g $C/m^2/day$ for the SW monsoon, NE monsoon and the intermonsoon periods respectively (Codispotti, 1991; Barber et al, 2001). Similarly for the eastern Arabian Sea the typical productivity values are 0.6, 0.3 and 0.2 g $C/m^2/day$ for the SW monsoon, NE monsoon and the intermonsoon periods respectively (Bhattathiri et al, 1996). Along the west coast of India lies a chain of hills (with a typical altitude of 1000 – 2000 m) known as the Western Ghats. The moisture laden SW monsoon winds approach the Ghats from the west and are forced to ascend in the process of which they shed copious amounts of precipitation over the Western Ghats. All this fresh water gets into the coastal Arabian Sea, which reduces the sea surface salinities considerably during the SW monsoon season (Sarkar et al, 2000). Another phenomenon of importance is denitrification that takes place due to the very low concentration of oxygen in the entire Arabian Sea from 250 m to 1250 m water depths (Naqvi, 1987, Wyrtki, 1971; Deuser et al, 1978, Olson et al, 1993). This oxygen minimum zone (OMZ) is due to the high oxygen consumption below the thermocline for the oxidation of organic matter supplied by the high overhead surface productivity. Furthermore the sluggish flow of the oxygen poor intermediate water (Olson et al, 1993; You and Tomczak, 1993) along with a strong tropical thermocline (due to relatively high SST that prevents mixing of the oxygen rich surface waters with the deeper waters) maintains the OMZ (Spencer et al, 1982; Qasim, 1982). Although the OMZ and denitrification are not directly affected by the monsoon winds but the ensuing productivity along with other climate controlled factors such as ocean ventilation rate (Reichart et al, 1997, 1998, 2002 a; Schulz et al, 1998; Altabet et al, 2002) affect them.

Such pronounced changes in the seawater characteristics make the Arabian Sea ideal for deciphering the past changes in monsoon intensity. The surface productivity that manifests itself in many forms such as organic, calcareous and siliceous productivity, also affects the carbon isotopic composition of the seawater, which is preserved in the calcitic shells of various foraminifera. Similarly the SST and sea surface salinity alter the oxygen isotopic composition of these shells and they get preserved in the sea sediments. The nitrogen isotopic composition of sedimentary organic matter can indicate the denitrification intensity relatable to productivity variations. Thus the downcore variations of such proxies could help document the past variations in monsoon intensity and the related climatic changes. The suitability of these proxies for paleoclimatic reconstruction is further discussed in section 2.4.

1.2. A brief review of the earlier work on past monsoon variations:

1.2.1. Western/Northern Arabian Sea:

The western Arabian Sea has received maximum scientific attention for deciphering the past monsoon fluctuations as it experiences the most intense biogeochemical changes during the monsoon season. The earliest and very comprehensive studies were carried out by Prell et al (1980), Prell (1984), Prell and Van Campo (1986) in which they found that SW monsoon was weaker during the glacial periods and stronger during interglacials. They further asserted that much of the 10^3 to 10^5 year variability in the monsoon is due to the changes in solar radiative forcing and the associated feedback effects. Prell and Kutzbach (1987) proposed that glacial boundary conditions such as SST, earth's albedo, sea level, extent and elevation of large ice masses play equally important roles in modifying monsoon patterns. Later Clemens et al (1991), Clemens and Prell (1991) argued that monsoon is mainly governed by the precession induced insolation changes and not by the changing glacial boundary conditions. Several authors such as Gasse et al (1991), Anderson and Prell (1992), Sirocko et al (1993), Van campo and Gasse (1993), Overpeck et al (1996) refuted this hypothesis and maintained that glacial boundary conditions indeed are instrumental in modifying monsoon intensities. Sirocko et al (1993) carried out a high resolution, centennial scale study on a core off the Oman coast and reported that monsoonal climate changed in abrupt steps and not in a gradual manner with increase in its intensity observed at ~15.5 ka BP and a maximum at ~8.5 ka BP, which they attributed to albedo changes during the periods of deglaciation. Sirocko et al (1996) proposed that SW monsoon intensified at 11.4 ka BP that coincides with the climate transition as observed in polar ice cores and hence proposed that monsoon exhibits correlation with the high latitude climatic changes. Naidu and Malmgren (1996) analyzed the cores from the western Arabian Sea upwelling regions and concluded that SW monsoon was relatively stronger during 22 – 18 ka BP than ~18 – 13.8 ka BP with a major intensification at 13 ka BP and a maximum between 10 and 5 ka BP, after which it declined with the weakest phase at 3.5 ka BP. Naidu and Malmgren (1995) also observed a sub-Milankovitch periodicity of 2,200 years exhibited by the SW monsoon induced upwelling indices from which they inferred that SW monsoon is influenced by oceanic circulation changes that controls the ~2,300 year periodicity, observed in atmospheric ^{14}C. They also extensively measured $CaCO_3$ and stable isotopes of carbon and oxygen in foraminifera and concluded that lower $CaCO_3$ in the western Arabian Sea during interglacials along with higher $\delta^{13}C$ is due to higher non-carbonate productivity and higher dissolution of $CaCO_3$ due to enhanced Antarctic Bottom Water ventilation in the equatorial Indian Ocean (Naidu et al, 1993; Naidu and Malmgren, 1999). Altabet et al (1995) and Ganeshram et al (2000) have shown that in the western Arabian Sea denitrification intensity is controlled by SW monsoon induced productivity changes, which was weaker during the glacials and stronger during interglacial periods.

Reichart and coworkers have carried out extensive work regarding the monsoon and oxygen minima zone (OMZ) variability for the late Quaternary (covering the past ~225 ka) in the northern Arabian Sea. Reichart et al (1997) studied productivity and dust input records in a core from Murray Ridge (Northern Arabian Sea) and concluded that productivity in this region is mainly controlled by the SW monsoon and the intensity of OMZ is governed by the sea surface productivity, which was lower during the weak SW monsoon that occurred during glacial periods. Reichart et al (1998, 2002 a) showed that OMZ and SW monsoon strength varied in synchronicity with polar ice records. The stadials as deciphered by the polar records are characterized by light colored, bioturbated sediments with low C_{org} implying weak OMZ due to reduced productivity that in turn is because of weaker SW monsoon. Reichart et al (1998, 2002b) showed that during stadials the OMZ was destroyed because of deep convective overturning due to intensified cool and dry winter monsoon winds that led to surface water cooling and enhanced the salinity due to evaporation. Reichart et al (2004) further showed that just after strong stadials at stadial-interstadial boundaries, a brief episode of hyperstratification takes place due to weakened winter monsoon (and hence less cooling due to evaporation) that facilitates the formation of strong OMZ during interstadials. Schulz et al (1998) and Altabet et al (2002) studied the monsoon induced OMZ variability by analyzing the C_{org} content in cores from the northern Arabian Sea and denitrification intensity in cores from the Oman margin. They showed that monsoon intensity is closely related with the GISP2 ice core record even on short centennial timescales with reduced monsoon during the cooler periods and concluded that high latitude and tropical climates are most probably linked via rapid atmospheric forcing. Leuschner and Sirocko (2000) studied three cores from the northern Arabian Sea analyzing the aeolian dust content that represents humid/arid continental climate and found that it exhibits good correlation with the GISP2 and Vostok ice records with humid periods coinciding with the temperature maxima. Zonneveld et al (1997) obtained a core from the Somalian upwelling region and studied the relative dominance of dinoflagellates cysts of the (SW) monsoon-induced upwelling and non-upwelling species. They found that broadly, monsoon follows the insolation forcing, which is nonlinear due to the effect of snow cover over the central Asia and Tibetan plateau. Other forcing factors, which they identified, are the changing glacial – interglacial boundary conditions (due to varying thermohaline circulation) and tropical land cover forcing (that influences the albedo). Von Rad et al (1999) and Luckge et al (2001) analyzed varve sequences in cores from the northern Arabian Sea raised from OMZ and studied monsoon variations for the past 5000 years. They deduced that precipitation decreased after ~4 ka BP with minima centered at ~2 ka BP and ~500 a BP with higher precipitation during the intervening periods. Burns et al (1998) studied the speleothems from northern Oman covering the past 125 ka and concluded that early Holocene (~10 – 6 ka BP) was a wetter period than the modern times and the last interglacial was even wetter than the early Holocene. They further asserted that precipitation records from the continents do not always match with the sedimentary productivity records, as the latter are essentially wind strength indicators and not precipitation proxies. Neff et al (2001) studied $\delta^{18}O$ in stalagmites from northern Oman and compared with the $\Delta^{14}C$ record from tree rings that reflects changes in solar activity. They found an excellent correlation that led them to conclude that monsoon is controlled by the solar activity on a decadal to centennial scale. Fleitmann et al (2003, 2004) reconstructed the history of SW monsoon from speleothem records from southern Oman for the past

~10 ka and proposed that early monsoon variations are controlled by glacial boundary conditions and monsoon decreased after ~8 ka with the solar induced forcing controlling the decadal to multi-decadal variations. Recently Anderson et al (2002) and Gupta et al (2003) determined the abundance of *G.bulloides* in cores from the Oman upwelling margin and found excellent correlation with the North Atlantic sedimentary records and concluded that SW monsoon exhibits excellent correlation with the high latitude climate on centennial timescales (weak summer monsoon coincides with cold periods). They showed that monsoon broadly follows the insolation curve at 65^0N with a monsoon maximum at ~8.5 ka BP and declining since then upto ~1.5 ka BP. They further proposed that monsoon strength has been increasing for the past 400 years due to northern hemisphere warming and will continue to do so as the greenhouse gases concentration increases.

1.2.2. Eastern Arabian Sea:

One of the earliest studies involving the cores from the northern Indian Ocean was carried out by Duplessy (1982) who reconstructed the Holocene and LGM sea surface conditions such as salinity and temperature based on oxygen isotopic analysis of the surface dwelling foraminifera *G.ruber* from the cores spread all over the Bay of Bengal and the Arabian Sea. He concluded that SW monsoon was weaker during the LGM and NE monsoon was stronger than present with more precipitation south of 10^0N. Sarkar et al (1990) analyzed a core from the eastern Arabian Sea and proposed that winter monsoon was stronger during LGM as evident by enhanced NE monsoon current during that time. They based their conclusion on the negative excursion shown by oxygen isotope in four different species of foraminifera, which they attributed to influx of enhanced low salinity water via the NE monsoon current and SST increase due to vanishing of SW monsoon induced mixed layer deepening. Sarkar et al (1993) inferred that anoxic conditions prevailed in the deep Arabian Sea during the last glacial period based on enhanced preservation of organic matter and simultaneous removal of uranium in seawater in a core from eastern Arabian Sea. Sarkar et al (2000) carried out oxygen and carbon isotopic analysis on the planktonic foraminifera *G.sacculifer* and *G.menardii* in cores off the west coast of India. They inferred that excess of evaporation over precipitation (E-P) has decreased steadily form the 10 ka BP to ~2 ka BP implying a steady increase in the SW monsoon precipitation during the Holocene. Thamban et al (2001) measured the oxygen and carbon isotopes in planktonic and benthic foraminifera along with $CaCO_3$ and C_{org} content from the eastern Arabian Sea near Cochin. They concluded that major increase in SW monsoon precipitation occurred after ~9 ka BP and in contrast to western Arabian Sea records the productivity in this region was lower during 13 - 6 ka BP and was maximum between ~18 – 15 ka BP, which they attributed to increased strength of winter monsoon that led to greater nutrient injection due to enhanced convective mixing. Agnihotri et al (2003 a) studied various sedimentary proxies regarding productivity such as $CaCO_3$, C_{org}, nitrogen, Sr and Ba etc. in the cores from eastern Arabian Sea and concluded that surface productivity was lower during the last glacial-interglacial transition and higher during the Holocene. Agnihotri et al (2003 b) found increasing denitrification intensity in a core from the eastern Arabian Sea from ~10 – 2 ka BP that implies an increasing SW monsoon intensity during Holocene. Bhushan et al (2001) calculated the paleoproductivity in the same core mentioned above using the burial flux of $CaCO_3$ and C_{org} and inferred that SW monsoon intensity increased from ~10 ka to ~2 ka BP. Agnihotri et al (2002) measured the monsoon proxies such as C_{org}, N and Al in a core off the Saurashtra coast for the past millennium and compared with the past variations in the total solar irradiance (TSI) reconstructed from the production rate of cosmogenic ^{14}C and ^{10}Be. They found that SW monsoon exhibits good correlation with the solar activity with reduced monsoon during the periods of solar minima. Yadava and Ramesh (2005) analyzed speleothems samples with very high resolution (~14 years) from Orissa, eastern India, that covers the past ~3500 years and found that SW monsoon was stronger between 3400 and 3000 years with arid periods at ~2000 and 1730 a BP and an enhanced monsoon at ~600 a BP.

1.2.3. Equatorial Arabian Sea:

Studies from the equatorial Arabian Sea are very sparse compared to other parts of the Arabian Sea. A giant piston core MD900963 has been obtained east of the Maldives covering the past 910 ka. Rostek et al (1993) measured the oxygen isotopes in the *G.ruber* in this core and inferred that glacial stages were characterized by increased evaporation and/or decreased precipitation, which they attributed to enhanced dry NE monsoon and/or reduced SW monsoon. Various other studies such as Beaufort et al (1997), Rostek et al (1997), Schulte et al (1999), Pailler et al (2002) were carried out on the core MD900963. They inferred that primary productivity in this region was enhanced during the glacial periods and was lower during the interglacial periods in contrast to other productivity records from the Arabian Sea. They attributed it to increased convective overturning due to stronger NE monsoon winds that led to nutrient injection in the surface layer and hence increasing the productivity. In all the studies, the productivity proxies exhibit a ~23 kyr precession cyclicity induced by insolation variations. Furthermore they maintain that deep water at this site remained oxygenated for the past 350 ka.

Thus the broad picture regarding the paleomonsoon variation that emerges out of the above discussion is that SW monsoon was stronger during interglacials and weaker during glacial periods with the NE monsoon exhibiting the opposite behaviour. The intensity of monsoon is basically controlled by the sun-earth geometry and the consequent insolation changes. The monsoons are mainly governed by precessional cycle of the earth. It has been verified using the paleoclimate models that the tropical climate is affected more by the precession of the earth's perihelion, while high latitudes are more affected by the changes in earth's obliquity (Kutzbach, 1981; Jagadheesha et al, 1999). A crude understanding is that snow cover increased over the Tibetan plateau/ central Asia during LGM that reduced the land – ocean temperature contrast during summer and enhanced it during winter that led to weakened SW monsoon and strengthened winter monsoon. The monsoon system is further affected by high latitude cooling shown by proxies for North Atlantic Deep Water formation, ice rafting etc. and surface feedbacks such as vegetation (through changes in Albedo, surface friction and evapotranspiration). During the early Holocene, the SW monsoon intensified with a maximum at ~8 – 9 ka BP and declined since then in accordance with the decreasing summer insolation as inferred from the productivity proxies, which are manifestation of SW monsoon wind alone. On the contrary, precipitation proxies indicate that SW monsoon has consistently increased from 10 ka BP to ~2 ka BP. Thus more well dated, high-resolution cores are needed to answer the question that how good is the correlation between the wind and rain proxies from the western and eastern Arabian Sea on different timescales and whether increasing wind intensity in the west (sea) always favours enhanced precipitation in the east (land) or not.

1.3. Aims of the present study:

My study area is the Arabian Sea, which forms a major and 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; Overpeck et al, 1996). The Arabian Sea can be divided into three distinct regimes as far as paleomonsoon reconstruction is concerned: (i) Western Arabian Sea, off the Somalian coast(near the mouth of the Gulf of Aden): it experiences intense upwelling during southwest monsoon resulting in increased organic/inorganic productivity (Nair et al, 1989) and negligible fresh water run off due to meager precipitation over adjoining landmass. (ii) 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). And finally (iii) 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).

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 be relatively inaccurate. Recently with the advent of AMS (Accelerator Mass Spectrometry) we can obtain highly accurate chronologies because, here, instead of dating bulk sediments, planktonic foraminifera are dated (no contamination from detrital carbonate material). As evident from the discussion in the section 1.2, majority 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. Hence I would be able to study various processes that are manifestations of SW monsoon at different locations to delineate local versus regional responses. The cores were strategically chosen from the locations where sedimentation is fast enough to provide a high time resolution (centennial to sub-centennial). They were radiocarbon dated employing the AMS technique that yield highly accurate ages, which provided better age control. 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 run-off to the ocean, surface salinity etc. It also looks at changes during intermonsoon periods, by the study of the equatorial core.

The specific objectives of this study are:

1. To obtain accurate Radiocarbon chronologies on planktonic foraminiferal separates in sediment cores and to determine the past monsoon variations for the Late Quaternary period (~35,000 a BP to present) on millennial to centennial scales by high-resolution sampling using stable isotopic and chemical tracers.

2. It has been proposed that during the 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.

3. 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.

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 a; 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 signal as inferred from the oxygen isotopes of planktonic 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; Schott and McCreary Jr., 2001; Hastenrath et al, 1993). 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, 2003). This study aims to check that how the SW monsoon is affected by the changes in solar activity on a centennial scale by comparing the high-resolution data from the eastern Arabian Sea core with the reconstructed Total Solar Irradiance (Bard et al, 2000).

7. Lastly, to carry spectral analysis on various SW monsoon proxies to detect the underlying periodicities that might help in detecting the various factors forcing the SW monsoon from centennial to Milankovitch timescales.

1.4. Thesis outline:

In addition to this chapter, this thesis has been divided into five other chapters. **Chapter 2** deals with the materials used, the suitability of various proxies employed in this study and the experimental techniques used. **Chapter 3** deals with the results from the core from the coastal eastern Arabian Sea covering the past ~3 ka and sampled at a sub-centennial scale. **Chapter 4** presents the results of the core from the southern/equatorial Arabian Sea covering the past ~35 ka BP with a resolution of ~350 years. **Chapter 5** deals with the results from the western Arabian Sea covering the past ~19 ka BP with a resolution of ~300 years. This core records the productivity variations due to the intense SW monsoon winds in that region. **Chapter 6** highlights the conclusions reached in this study and presents the scope for future work.