CHAPTER 1

INTRODUCTION

1.1 Paleoclimate and proxy records

Paleoclimatological methods depend upon proxies and analogy. It is presumed that the past climatic changes have left their imprints in the geological and paleontological records of the Earth. For better understanding of the paleoclimatic changes that extend beyond the paltry human time scale and historic record, it is necessary to gain a fundamental knowledge about the climate system that can be solely attained by modern studies and keen observations. Thus geological record becomes the major contributor to evaluate the temporal and spatial scale paleoclimatic changes, enabling to model future climate dynamics.

Paleoclimatology, as a discipline has gained its importance in the last two decades, the impetus being partly of social concerns. The ongoing debate of anthropogenic activity and its adverse effects on global climate aroused a necessity to understand the historical range of climate variability that will permit interpretations of global climate data. Thus intense research and significant developments over the last few decades have enabled better understanding of climate change scenario. The knowledge of paleoclimatology is valuable in its own sense and is essential in evaluating the forcing factors and driving mechanisms of the environment causing evolutionary and ecological changes.

Various proxies are manifested for determining past climatic changes that are preserved in tree rings, soils, ice, lacustrine, speleothems and marine deposits. Another key component of this emerging field of science is Paleontology, since fossils and their preservational environments are the repository of paleoclimatic data. Paleobiology and paleoecology of organisms serve as important climate proxies, which are vital in understanding the evolution of species through ages. Foraminifera, the major contributor to the marine biotic community, are largely employed as an important tool for paleoclimatic reconstruction for their high fossilization potential and wide geographical distribution. Benthic foraminifera are potentially used as proxies in two ways: chemical and biological. The chemical pathway is when an element is incorporated into a shell in proportion to a parameter and it operates over a whole range of that parameter (e.g. stable isotopes, nutrient proxies Cd and Ba, physical proxies Mg, Sr, etc.). For example, calcium carbonate tests of foraminifera are secreted in isotopic equilibrium with the ambient seawater. The oxygen isotopic composition of the test includes both ^{16}O and ^{18}O, the fractionation of which is temperature dependent. Thus this ratio can be used to identify cool (glacial) and warm (interglacial) climate phases. Such proxies require only enough tests for analytical precision and are not dependent on the abundance of tests. The biological pathway involves a correlation between the abundance of the organism or the composition of an assemblage and a given environmental parameter. Relative abundances of benthic foraminifera have been correlated to the temperature, salinity, oxygen content, nutrients and carbonate saturation of the water masses and sometimes to substrate characteristics.

In recent years, the emphasis is laid upon environmental interpretations to quantify certain parameters like understanding organic flux and oxygenation of deep waters using benthic foraminifera (Den Dulk et al., 2000; Gooday, 2003; Gupta et al., 2004, Suhr and Pond, 2006). For example, in areas of high organic flux, faunas are typically dominated by calcareous taxa with infaunal microhabitat and are tolerant of persistent oxygen depletion resulting from the oxidation of organic carbon. Common genera of such environmental settings are *Bolivina, Bulimina, Cassidulina, Chilostomella, Globobulimina, Fursenkoina, Nonionella* and *Uvigerina* (Lutze and Coulbourne, 1984; Corliss and Emerson, 1990; Bernhard et. al., 1997; Schmiedl et. al., 1997; Gupta and Thomas, 2003; Gupta et al., 2004; Schumacher et al., 2007, Larkin and Gooday, 2008). The oxygen sensitive benthic foraminifera help to reconstruct the biogeochemical cycles of the ocean, to understand the ocean circulation history and to estimate the preservation potential of the organic matter. Similarly, the study of organic flux reveals the bioproduction and hydrocarbon generation of the ocean. The planktic foraminifera, on the other hand, are an important indicator of surface upwelling and productivity. For example, *Globigerina bulloides* – a subpolar species, dominates planktic foraminiferal assemblages in the tropical coastal upwelling settings like the western and northwestern (NW) Arabian Sea (Prell and Curry, 1981; Anderson and Prell, 1993; Reichart et al., 1998; Gupta et al., 2003, Larkin and Gooday, 2008) and in the Atlantic Ocean (Peterson et.al., 1991). Changes in the relative abundances and fluxes of *G. bulloides* have been associated with the Indian summer monsoon driven upwelling intensity in the Arabian Sea (Gupta et al., 2003; Ivanova et al., 2003; Ishikawa and Oda, 2007).

The seasonally reversing wind system, popularly known as the Indian monsoon or the South Asian monsoon has a pronounced affect on the fauna and flora of the Indian subcontinent between 30^0 N and 20^0 S. Thermal contrast between the land and sea drive changes in the monsoon circulation. During summer months, the landmass is warmer than the sea, causing formation of a low pressure zone over the landmass. Thus, wet, moisture-laden, intense winds blow from the southwest (Ocean) towards the landmass, called as the southwest (SW) or summer monsoon. This causes widespread upwelling and high surface productivity in different parts of the Arabian Sea. During the winter months, the thermal contrast reverses causing reversal of pressure cells and thus dry and variable winds blow from the land (northeast) to the ocean – the so-called northeast or winter monsoon. During winter monsoon months, the upwelling is weak and surface productivity is low.

Globigerina bulloides – thrives in upwelled waters and is a well tested monsoon proxy, which has been widely used to understanding centennial to millennial changes in monsoon intensity through time slices (Anderson and Prell, 1992; Overpeck et al., 1996; Naidu and Malmgren, 1996; Gupta et al., 2003, Murray, 2006). Besides, the difference in δ^{18}O values of *Globigerina bulloides* and *Globigerinoides ruber* can be used in the reconstruction of sea surface temperature as the former calcifies during SW monsoon season whereas the latter calcifies throughout the year (Saher et al., 2007). In addition, the ratio of benthic to planktic foraminifera often called as B/P ratio (Berger and Diester-Hass, 1988; Almogi-Labin et al., 2000), Benthic Foraminiferal Accumulation rates (BFAR) (Herguera and Berger, 1991; Hergeura, 1992) and changes in planktic foraminifer species composition (Prell and Curry, 1981; Ishikawa and Oda, 2007) have been employed to interpret paleoproductivity and paleoclimatic changes.

An important aspect that has to be taken into consideration is that proxy reconstructions are indirect inferences of rainfall, upwelling, sea surface temperature and tend to have uncertainties. For example, employing faunal assemblages for paleoclimatic reconstruction largely depends on the degree of preservation. Typically dissolution will preferentially affect fragile, thinly walled species and thus can lead to biased data distribution. Similarly, study relying on elemental ratio like Mg/Ca of foraminiferal test which increases exponentially with temperature, has an accuracy of temperature estimation of about 1-1.6 °C. Calcite dissolution, which increases with water depth, affects Mg/Ca ratios in foraminiferal test by preferential removal of Mg. This preservation bias leads to an underestimation of water mass temperatures (Henderiks, 2005). In general proxy records are averaged and data is reduced using statistical data reduction techniques like Principal Component Analysis (PCA) to understand fluctuations over a range of time interval to compare it with global record. This averaging of years of variability in a single sample provides us major changes in the trend of monsoonal variability over decadal to centennial time scale rather than year to year variability. This renders us invaluable insight into the long-term climate variability but the year to year changes are aliased.

It is important to establish the reliability of the proxy before applying it for paleoclimatic studies. The reliability of various planktic forminiferal species for Monsoonal strength has been mainly established by JOINT GLOBAL OCEAN FLUX STUDIES (JGOFS), an international and multi-disciplinary program under the auspices of the Scientific Committee of Ocean Research (SCOR). The program includes coring recovery, benthic and planktic studies, detailed examination of paleoceanographic proxies within the context of a comprehensive biogeochemical study. The cores are archived, evaluated and made available to studies supported by other funding agencies.

1.2 Aims and Objectives

The primary aims and objectives of this study are:

a) to understand the high resolution multi-decadal to century scale variability in the southwest (SW) monsoon during the last 16 Kyr
b) to comprehend the causes of small scale changes in the SW monsoon
c) to understand the impact of monsoon intensification and deep-sea circulation on the Oxygen Minimum Zone (OMZ) and its effect on benthic fauna
d) to understand a relation between the SW monsoon and North Atlantic variability
e) to estimate the preservation potential of the organic matter produced by enhanced surface productivity within the OMZ
f) the other aspect of my work will be taxonomic descriptions of benthic foraminifera using scanning electron micrographs (SEM)

1.3 Previous studies

The Arabian Sea has been an area of keen research interest to paleoceanographers worldwide as it is marked by strong southwest monsoon circulation which causes intense upwelling and enhanced biological productivity leading to the formation of extensive Oxygen Minimum Zone at depths 200-1200 m. Off the continental margin of Oman, NW Arabian Sea, the summer monsoon winds are strongest and biogenic sedimentation rate is highest, providing one of the best archives of monsoon-driven centennial to millennial changes. Pioneering studies conducted on Indian Ocean and Arabian Sea foraminifera are included in Table 1.1.

Table 1.1: List of major studies conducted on Indian Ocean and Arabian Sea foraminifera.

Author(s)	Study site and published work
Fitchell and Moll, 1798	Arabian Sea and Red Sea; taxonomic classification of foraminifera from sea floor surface samples
D' Orbigny, 1826	Indian Ocean; taxonomic classification and detailed description of foraminiferal species from sea floor surface samples
Brady, 1884	Indian Ocean; generic description of foraminifera from sea floor surface samples
Boltovskoy, 1978	Ninetyeast Ridge; taxonomic classification of foraminifera from Holocene DSDP samples
Corliss, 1979a, b	Southeast Indian Ocean; taxonomic classification of foraminifera from sea floor surface sample
Corliss, 1983	Southwest Indian Ocean; taxonomic classification of foraminifera from sea floor surface sample
Prell et al., 1981, 1982, 1992	Arabian Sea; the *Globigerina bulloides* record was linked to monsoon strength through surface productivity driven by wind-induced upwelling; the biogenic opal record was similarly linked to monsoon strength through upwelling-induced production of diatoms and radiolarian
Gupta and Srinivasan, 1989, 1990, 1992, 1996	eastern Indian Ocean; preferential living environment of benthic foraminifera was linked to upwelling induced by monsoonal pattern studies conducted on Neogene DSDP samples to understand paleoclimatic changes
Hermelin and Shimmield, 1990, 1995	northwest Indian Ocean; relation of strong summer monsoon with enhance in productivity and formation of Oxygen Minimum Zone on late Quaternary ODP samples

Anderson, 1991	Arabian Sea; changes in upwelling and productivity due to change in monsoonal pattern on Quaternary ODP samples
Anderson and Prell, 1992, 1993	Arabian Sea; high abundances of *G. bulloides* in upwelling areas on Quaternary ODP samples
Hermelin, 1992	Arabian Sea; study conducted on ODP samples to understand sea level fluctuations leading to variation of water influx from Red Sea to Arabian Sea causing changes in upwelling
Mackensen et al., 1993	Southern Indian Ocean; study conducted on the ODP samples to understand the relation between C-isotope in benthic foraminifera and C-isotope in sea water in high productivity areas
Sirocko et al., 1993, 1996	Arabian Sea; The change in elemental values of sediment cores on Quaternary ODP samples was interpreted to be caused by decrease in upwelling productivity and large eolian dust influx
Naidu and Malmgren, 1995, 1996	Arabian Sea; study conducted on the Quaternary ODP samples showed test size of planktic foraminiferal species can be related to ecological factors like temperature
Overpeck et al., 1996	Arabian Sea; study conducted on Holocene ODP samples showing relationship of climatic variability with solar forcing
Schulz et al., 1998	Arabian Sea; study conducted on Quaternary ODP samples correlating climatic variations in Arabian Sea and Greenland oscillations
Gupta and Thomas, 1999	northwest Indian Ocean; study conducted on DSDP samples interpreting living environment of benthic foraminiferal biofacies and suggest changes in oxygenation are partially because of productivity and partially of deep-sea oxygenation
Almogi-Labin et al., 2000	Gulf of Aden, NW Arabian Sea ; study conducted on benthic, selected planktic foraminifera and stable isotope records to infer changes in the primary productivity over span of 530 kyr
Gulf Den Dulk et al., 1998, 2000	North Arabian Sea; study related to changes in calcium carbonate preservation due to post-depositional organic matter degradation under dysoxic conditions
Gupta et al., 1999, 2001, 2004	northeastern Indian Ocean; study conducted on ODP samples concluding Indian Ocean high-productivity event was caused by strengthened wind regimes resulting from global cooling and the increase in volume of the Antarctic ice sheets
Gupta and Satpathy, 2000	westcentral Indian Ocean; study conducted on DSDP samples demonstrating environmental preferences of benthic foraminifera
Anderson et al., 2002	NW Arabian Sea; study conducted on box core samples revealed possible link between Eurasian warmth/ snow cover

	and the SW monsoon persists on the centennial scale
Gupta et al., 2003	NW Arabian Sea ; study conducted on ODP samples shows intervals of weak summer monsoon that coincide with cold periods documented in the North Atlantic region, thus suggesting link between North Atlantic climate and the Asian monsoon is a persistent aspect of global climate
Naqvi et al., 2005	Arabian Sea ; study dealing with relationship of primary productivity with availability of micro-nutrients
Prabhu and Shankar, 2005	Eastern Arabian Sea; multiproxies investigations about paleoceanographic changes during Mid-Pliestocene transition
Erbacher and Nelskamp, 2006	NE Arabian Sea; study conducted on comparison of benthic foraminifera and sulphur oxidizing mat present in Oxygen Minimum Zone
Heinz and Hemleben, 2006	Western and Southern Arabian Sea; study conducted on preferential living environment of live benthic foraminifera
Schumacher et al., 2007	Arabian Sea; study conducted on live and dead benthic foraminifera from surface sediments of Pakistan continental margin to determine relationship of faunal composition and bottom water oxygenation
Ishikawa and Oda, 2007	NW Arabian Sea; dealing with reconstruction of paleomonsoonal activity based on planktic foraminiferal record
Saher et al., 2007	Western Arabian Sea; study concludes change in sea surface temperature occurs due to variations in upwelling intensity, influence of monsoon and influx of water in Arabian Sea
Murty et al., 2009	Pakistan Margin of the Arabian Sea; study conducted on megafaunal response to oxygen level and food availability
Brand and Griffiths, 2009	NW Arabian Sea; study concludes linkage between solar forcing and seasonal change in wind pattern thus affecting hydrography and biochemistry of sea water
Larkin and Gooday, 2009	NE Arabian Sea; study of foraminiferal faunal responses to oxygen level and primary productivity
Hughes et al., 2009	NE Arabian Sea; study dealing with response of macrofaunal communities to bottom water oxygenation and sediment organic carbon content
Gooday et al., 2009	Pakistan Margin, Arabian Sea; study dealing with response of microfauna, macrofauna and megafauna to changes in oxygenation level in water

The composition and the organic carbon content from the Arabian Sea also been studied previously are listed in Table 1.2.

Table 1.2: List of major studies conducted on organic carbon content in the sediments of Indian Ocean and Arabian Sea.

Author(s)	Study site and published work
Stackelberg, 1972	study conducted on the surface sediments of Eastern Arabian Sea revealed turbid-layer transport or episodic gravitational redeposition of the sediments affecting organic carbon preservation
Marchig, 1972	study conducted on the carbon and nitrogen ratio along the western slope of India leading to the conclusion that the organic matter is mostly marine in origin
Kolla et al., 1976, 1981	study conducted on the clay mineralogy of the surface sediments of Arabian Sea to understand the origin of the organic matter
Slater and Kroopnick, 1984	study conducted on the organic carbon content of sediments concluding high primary productivity and salinity stratification is responsible for formation, maintenance and extent of Oxygen Minimum Zone
Shimmield et al., 1990	study conducted on Ti/Al ratio and Barium mass accumulation rate to understand its relationship with summer monsoon
Pedersen et al., 1992	Box core samples ; study reveals lack of enhanced preservation of marine or non refractory organic carbon beneath Oxygen Minimum Zone
Paropkari et al., 1992	study conducted on the organic carbon type and content in surfacial sediments of Western slope of India indicating organic carbon enrichment in sediment does not reflect high primary productivity
Haake et al., 1993	sediment traps; study suggests organic matter enrichment in Arabian Sea is not only dependent on primary productivity but also on the supply of lithogenic material
Luckge et al., 1996	study conducted on ODP samples to understand the preservation potential of organic matter
Budziak et al., 2000	study conducted on ODP samples reveals relationship of organic carbon content with solar forcing, thus monsoon-primary

	productivity linkage
Banakar et al., 2005	sediment core, SK 117 – GC-8; study involves oxygen isotope, organic carbon and C/N ratio record from eastern Arabian Sea demonstrating telecommunications between high latitude climates and Indian monsoons
Prabhu and Shankar, 2005	gravity cores; study involves multiproxies approach to understand the paleoceonographic and paleoclimatic changes during Mid Pliestocene Transition
Lahajnar et al., 2005	sediment cores, German RV- Meteor; study involves dissolved organic carbon fluxes measurements in Arabian Sea
Cowie, 2005	study conducted on surface sediments of Pakistan continental margin demonstrating benthic biogeochemical responses to varying intensity of Oxygen Minimum Zone
Woulds et al., 2007	study suggests benthic communities abundances are dependent on the oxygenation level, which in turn control the bacterial abundance affecting the organic carbon decomposition
Cowie and Levin, 2009	study suggests benthic communities play a major role in the early cycling of sediment organic matter through differential feeding and bioturbation activities
Jeffreys et al., 2009	study addresses the pigment, lipid and amino acid compositions of surface sediments underneath Oxygen Minimum Zone and suggested that the marine organic matter are usually in advanced degraded state and more prone to decomposition
Hughes et al., 2009	study of surface sediments from Pakistan Margin involving microfaunal and sediment structure shows contrasting pattern as reported from the Oman margin, concluding that local factors like bioturbation also play a major role in the process