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Indian Contributions in the Field of Palaeoceanography (2006-2012)

ANIL KUMAR GUPTA[1], DEVESH K SINHA[2], ASHUTOSH K SINGH[2], P DIWAKAR NAIDU[3], RAJEEV SARASWAT[3] and A K RAI[4]

[1]*Wadia Institute of Himalayan Geology, Dehra Dun, India*

[2]*Department of Geology, Centre of Advanced Studies, University of Delhi, Delhi 110 007, India*

[3]*National Institute of Oceanography, Dona Paula, Goa, India*

[4]*Department of Earth and Planetary Sciences, Allahabad University, Allahabad, India*

Excellent studies have been carried by Indian scientists to understand paleoceanographic changes in the Indian Ocean including the Arabian Sea and Bay of Bengal using Ocean Drilling Program cores. These studies revealed both short-term and long-term changes in the Indian Ocean circulation and Indian monsoon system. In general, summer monsoon was intense during warm intervals and weaker during cold intervals. Changes in deep-sea were also observed. The above studies were based on planktic and benthic foraminiferal faunal and geochemical data. Changes in deep sea oxygenation, oxygen minimum zone and surface productivity in the Indian Ocean including the Arabian Sea and Bay of Bengal during the Neogene and Quaternay were driven by the Indian summer monsoon. These changes in nutrient and oxygen levels drove major changes in the fauna and flora of the Indian Ocean. Indian monsoon variability has been suggested as contemporaneous with the southeast Monsoon variability during the last glacial and the Holocene.

Key Words: Palaeoceanography; Indian Ocean; Indian Monsoon; Oxygen Minimum Zone

Introduction

Palaeoceanography, one of the youngest branches of Earth Science, owes its existence and subsequent exponential development to researches carried out on sediments collected from the oceans under Deep Sea Drilling Project (DSDP) which started in 1968 and its successors, the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program (IODP) which will be eventually launched in 2013 as International Ocean Discovery Program (IODP). These programs provided ample opportunities to recover long cores representing undisturbed and continuous archives of paleoceanographic changes at various time scales. The combined effort in the form of collaborative work by scientists from many parts of the world on same set of cores led to a multi proxy approach to paleoceanographic studies. Recently, India joined the IODP as an associate member country resulting in the participation of several of Indian Scientists in the IODP cruises that led to excellent research publications and contributions to man power development in the activities of the IODP.

The science of paleoceanography essentially concerns with the evolution of the ocean system through geological time essentially studied through ocean sediments which are generally not older than the Cretaceous as a result of ongoing subduction. This has resulted in most paleoceanographic studies limited to the Cenozoic Time Interval. The major contributions to the science of paleoceanography by the Indian scientists can be grouped under

1. Studies on short time scale
2. Studies on long time intervals
3. Studies related to verifying / establishing new proxies

Each of the above groups has importance of its own due to marked difference in their objective. The three groups contribute to each other in a definite domain. Several of these studies also contribute towards our understanding of the paleoclimate.

Studies on Short Time Scale (High Resolution Sampling)

This concerns with the study of last few kilo years based on high resolution sampling intervals in deep sea cores. The most extensively studied area has been the Arabian Sea owing to excellent preservation of pelagic sedimentary record from its western, central and eastern parts. Another reason for this attention has been the fact that the both

**Author for Correspondence: E.mail: anilg@wihg.res.in*

western and eastern sectors of the Arabian Sea provide a robust proxy record of summer and winter monsoons, respectively.

Studies from the Arabian Sea

Gupta *et al.* (2010) reported evidence of the mid-Brunhes climatic event for the first time from the equatorial Indian Ocean, and established a link between long-term Indian Ocean Dipole (IOD) dynamics and climate of the Indian Ocean region in the geological record. Coincidence of increased equatorial East African precipitation and drying of Australasia across the middle Brunhes indicated that the Indian Ocean Dipole and Indian Ocean Equatorial Westerlies (IEW) were major forcing factors driving significant climatic changes in the Indian Ocean region during the late Quaternary. These interpretations are found important in linking IOD with the rainfall in the East African and Australasian (Indonesian) regions. Recent studies (Gupta *et al.*2008) from the northern Arabian Sea suggested high-amplitude climate shifts in the early and middle Holocene based on faunal and benthic isotopic proxy records. In another study Gupta *et al.* (2011) observed that although the surface response to monsoon variability was more or less similar in the western and northeastern Arabian Sea, the deep-sea conditions show a marked contrast in the two regions during the past 21 Kyr. In a study from the northeastern Arabian Sea. Nigam *et al.* (2009) observed a strong correlation between the present-day abundance of rectilinear bi- and triserial benthic foraminifera (RBF) and low dissolved oxygen conditions. Persistently relative high abundance of RBF, large proportion of amorphous organic matter and protoperidinioid dinocysts throughout the time-span covered by the core that goes well beyond the beginning of human intervention, indicated that the eutrophication of coastal water and subsequent development of low dissolved oxygen conditions was a natural phenomenon that has been in existence even before the advent of anthropogenic influence. In the western Arabian Sea (WAS), the highest seasonal sea surface temperature (SST) difference occurs between May and August. In order to gain an understanding on how monsoonal upwelling modulates the SST difference between these two months, Godad *et al.* (2011) computed SST for the months of May and August based on census counts of planktic foraminifera by using the artificial neural network (ANN) technique. The SST difference between May and August exhibits three distinct phases: i) a moderate SST difference in the late Holocene (0–3.5 ka) is attributable to intense upwelling during August, ii) a minimum SST difference from 4 to 12 ka is due to weak upwelling during the month of August, and iii) the highest SST difference during the last glacial interval (19 to 22 ka) with high *Globigerina bulloides* percentage could have been caused by the occurrence of a prolonged upwelling season (from May through July) and maximum difference in the incoming solar radiation between May and August.

Variations in the sea-surface temperature (SST), $\delta^{18}O$ of sea water and salinity were reconstructed for the past 68 ka using a sediment core (AAS9/21) from the eastern Arabian Sea (EAS) by Govil and Naidu (2010) in order to understand changes in the evaporation and precipitation associated with the monsoon system. The Mg/Ca-derived SST record varies by ~ 4°C; it shows that marine isotope stage (MIS) 4 was warmer than (MIS) 3, that the Last Glacial Maximum (LGM) was 4°C cooler than the present, and that there was a 2°C increase within the Holocene.

Singh and Conan (2008) estimated Aragonite export fluxes of pteropods (4250, 150-250 and 125-150 mm) in the Somali Basin using a 9-month time-series sediment trap (MST9-E) from June 1992 to February 1993. The trap with 23 time-series sediment collectors placed at 1032m water depth collected settling particles over a total of 249 days. Pteropods showed large seasonal variations in both the numerical and mass fluxes (4125 mm) with their maxima at the end of the SW Monsoon during September and early October.

Anand *et al.* (2008) estimated past sea surface temperatures (SST) and seawater $\delta^{18}O$ ($\delta^{18}Ow$) variations for the past 35 ka. These authors interpreted the consistent presence of the seasonal temperature contrast to reflect a combination of seasonal summer upwelling (SW monsoon) and winter convective mixing (NE monsoon) in the western Arabian Sea. They observed that a large seasonal temperature contrast occurred during the LGM which favors the assumption that strong NE monsoon winds forced winter upwelling or convective mixing off shore Goa.

Singh *et al.* (2011) presented paleoproductivity records from a composite sediment core at the millennial scale during the last 80 kyr B.P. from the eastern Arabian Sea. They observed that the eastern Arabian Sea upwelling-induced productivity was higher in the glacial period than in the Holocene, but it fell repeatedly on millennial time scales. In correlating the new results from the eastern and western Arabian Sea these authors inferred that the entire biological factory severely diminished during the North Atlantic Heinrich events and the seasonal productivity change in the Arabian Sea monsoon system was reduced with year-round low productivity.

Using the Pteropod assemblages from ODP Hole 728A, Rai *et al.* (2007) studied the variations in the Northwestern Arabian Sea Oxygen Minimum Zone (OMZ) during the last 175 ka. They observed pteropod spikes at the transition of MIS 6 and 5; MIS 2 and 1 and during glacial stages MIS 6 and MIS 2 reflect deepening of the

Aragonite Compensation Depth and relatively shallow OMZ in this region possibly due to deep sea mixing and thermocline ventilation and the relative decline in surface productivity during the winter monsoon. Rai and Das (2011) observed changes in the abundance of selected planktic foraminiferal species and some sedimentological parameters at ODP site 728A and suggested surface productivity and deep sea oxygenation.

In a study from the western Arabian Sea, Tiwari *et al*. (2010) inferred decreasing trend in foraminiferal abundance – due to favouring of silicate rather than carbonate productivity by the increased Indian summer monsoon (ISM) wind strength. These authors suggested that there is no evidence to conclude that Southwest Monsoon declined during the Holocene. A comparison with East Asian summer monsoon (EASM) records suggests that both ISM and EASM varied in unison, implying common forcing factors on such longer timescales. Ramesh *et al.* (2007) reported nitrogen isotope variations of organic carbon, in a precisely dated core from the equatorial Indian Ocean. These authors observed that peaks in the $\delta^{15}N$ of organic carbon lagged those in $\delta^{13}C$ of *Globigerinoides sacculifer* by 2-3 ka. Nitrogen loss from the oceans by intense productivity (seen as peaks in $\delta^{13}C$) on the surface and consequent de-nitrification in the intermediate waters of the northern Indian Ocean led to an ensuing period of low oceanic nitrogen and high $\delta^{15}N$. Their results also indicate that even in sub-millennial timescales, ocean productivity and nitrogen budget appear to be tightly coupled.

Tiwari *et al*. (2006a) based on their study on the high-resolution stable oxygen isotope variations, of two different species of planktic foraminifera, namely, *Gs. sacculifer* and *Gs. ruber*, in an AMS ^{14}C dated sediment core from the monsoon-runoff-dominated eastern Arabian Sea inferred that during the past ~1800 years (and perhaps up to ~2800 years) reductions in monsoon wind strength in the western Arabian Sea appear to be persistently accompanied by aridity over India. Their study clarifies that past fluctuations in South West Monsoon (SWM) precipitation over the Indian subcontinent followed the wind intensity records from the western Arabian Sea on centennial time scales. Tiwari *et al.* (2006b) based on ä^{18}O record of three planktic foraminiferal species from a core from Equatorial Indian Ocean, inferred that minimum precipitation occurred during Last Glacial Maximum (LGM) with a subsequent increase at Termination 1A. They also deduced that abrupt cooling and warming events are related to sudden reduction and enhancement of southwest Monsoon respectively.

Studies from Bay of Bengal

Besides Arabian Sea, important contribution from the Bay of Bengal (BoB) came from Govil and Naidu (2011) using paired measurements of $\delta^{18}O$ and Mg/Ca ratio in a planktic foraminifer species *Globigerinoides ruber* from core SK218/1 in the western BoB in order to understand rainfall variability associated with the SWM over the past 32 kyr. Their SST reconstructions reveal that the Bay of Bengal was 3.2ºC cooler during the LGM as compared to present day temperature and a 3.5ºC rise in SST is documented from 17 to 10 ka. Both SST and $\delta^{18}O$sw exhibit greater amplitude fluctuations during MIS 2 which is attributable to the variability of NE monsoon rainfall and associated river discharge into the BoB in association with strong seasonal temperature contrast. Onset of strengthening phase of the SWM started during Bølling-Allerød as evidenced by the low $\delta^{18}O$sw values 14.7 ka. $\delta^{18}O$sw shows consistently lower values during the Holocene (with an exception around 5 ka), which suggests that the freshening of the BoB due to heavy precipitation and river discharge caused by strong SWM. Results of this study signify that the maximum fluctuations of the NE monsoon rainfall during MIS 2 appear to be controlled by the strong seasonality and boundary conditions.

Teleconnections

The interval since the LGM till present is one of the most important intervals for studying relative influence of natural and anthropogenic factors on climate. The transition from the LGM to the Holocene was an internal of climate variability that was characterized by large spatial and temporal variations. Naidu and Govil (2010) showed that deglaciation warming in the northern Indian Ocean was initiated ca. 19 ka, which is contemporary with deglaciation warming in the Antarctica and Southern Ocean. A gradual warming occurred during the glacial/Holocene transition in the northern Indian Ocean, unlike the two-step warming seen in Greenland and the North Atlantic. Synchronous deglacial warming ca. 19 ka in Antarctica and the northern Indian Ocean suggests a strong connection in the propagation of climate signals between Antarctica and the Indian Ocean, probably through the Indonesian Throughflow and/or Subantarctic Mode Water. This study has an important bearing on the summer monsoon intensity and provides additional data that it's the southern hemisphere which influences our monsoon system and Indian ocean climate more than the changes occurring in far north Atlantic.

Saraswat (2011) compiled equatorial SSTs of the last 150,000 years BP as estimated from. Mg/Ca ratio of the foraminiferal shells in order to get an update of the past SST changes in the equatorial region. They inferred that the average cooling during the LGM (the interval dated from ~ 23–19 kyr BP during the last glacial period, when the ice-sheets covered maximum area) was ~ 2.3°C as compared to the Holocene.

Paleoceanographic Studies on Longer Time Scale

From their study of deep-sea benthic foraminifera from Ocean Drilling Program Hole 757B , Singh and Gupta (2010), observed around 11.5 Ma substantial transport of deep Pacific water to the Indian Ocean through the Indonesian seaway. Mohan *et al.* (2011) studied the evolution of deep-sea benthic foraminifera from the Blake Ridge during the late Neogene. They observed that during the late Miocene there was an increased influence of Southern Component Waters in the Blake Ridge region. Bhaumik *et al*. (2011), documented variability in the relative volume of Southern Component (SCW) and Northern Component Waters (NCW) over the last 7 Ma from Blake Outer Ridge. SCW was dominant before ~5.0 Ma, at ~3.6–2.4 Ma, and 1.2–0.8 Ma, whereas NCW dominated in the warm early Pliocene (5.0–3.6 Ma), and at 2.4–1.2 Ma. The relative volume of NCW and SCW fluctuated strongly over the last 0.8 Ma, with strong glacial–interglacial variability.

Karas *et al.* (2009) concluded that the tectonically driven closure of tropical seaways during the Pliocene epoch (5–2 million years (Myr) ago) altered ocean circulation and affected the evolution of climate. Gupta *et al*. (2006) observed a significant change in benthic foraminiferal e assemblages at DSDP site 238 which shows a major shift at 0.7 to 0.6 Ma, marked by major turnovers in the relative abundances of species, coinciding with an increased amplitude of glacial cycles .These cycles appear to have influenced low latitude monsoonal climate as well as deep-sea conditions in the Central Indian Ocean Basin. In another study from the Indian Ocean Gupta *et al.* (2010) concluded that the tropical Indian Ocean is an important component of the largest warm pool, marked by changes in sea surface temperatures and depths of thermocline and mixed layer in its western and eastern extremities leading to the development of a dipole mode. Rai *et al.* (2007) concluded that in most of the past 5 Ma (i.e. 5-4.2 Ma, 2.8-1.8 Ma, and 1.2 Ma to Recent) the dominant occurrence of *Cibicides wullestorfi-Oridorsalis umbonatus* assemblages represent active bottom water currents with more ventilation and relatively low trophic levels reflecting the influence of NADW at abbysal depths in the central Indian Ocean.

In another paper Rai and Maurya (2007) analyzed the late Oligocene to latest Miocene deep sea benthic foraminifera from ODP site 760A and 761B on wombat plateau in eastern Indian Ocean. The concluded that distinctly low values of diversity indices across the Oligocene Miocene transition correspond well with the higher values of benthic $\delta^{18}O$ and $\delta^{18}O$ reflecting relatively cold nutrient depleted young bottom waters which possibly indicate the influence of Antarctic circum polar current (ACC) in this region.

Oceanic biostratigraphy has been an important component for scaling the paleoceanographic events. Though benthic foraminifera are not considered important for this purpose, yet several attempts have been made to divide the benthic foraminifera species deep sea sections based on ranges of selected species. Rai and Maurya (2008) attempted to establish a biostratigraphic subdivision of ODP site 754 A on the Broken Ridge. Singh and Rai (2011) studied variation in the surface productivity in the eastern Indian Ocean during Pleistocene based on benthic foraminifera. They concluded that between 2.4 and 2.0 Ma along with low percentages of total infaunal taxa and higher benthic foraminiferal diversity reflect low organic carbon flux rates possibly due to decreased surface water productivity and better deep sea ventilation. Between 2.0 and 0.5 Ma, *Uvigerina proboscidea* assemblages was the most dominant which also coincided with the higher percentages of total infaunal taxa and relatively less diverse fauna representing higher rates of surface water productivity with some oscillations. Rai and Maurya (2009) studied Miocene deep sea benthic foraminiferal diversity at ODP site 754A in the southeastern Indian Ocean. They observed good correlation between species diversity and benthic $\delta^{13}C$ suggesting changing trophic level has much influence on the faunal diversity. Das *et al.* (2008) inferred influence of sediment source and monsoonal variations in the late Quaternary clay mineral assemblages from Northwestern Arabian sea and inferred that interglacial stages are marked by high biogeneic productivity and carbonate content due to intense monsoon.

Sinha *et al.* (2006) based on planktic foraminiferal census counts and stable isotopic analysis of a surface dwelling planktic foraminifer, *Globigerinoides sacculifer*, showed five episodes of diminishing strength of the Leeuwin Current. From the same region off western Australia, Sinha and Singh (2008) studied the late Neogene section of ODP Hole 763A, Exmouth Plateau, and provided biochronology for the southeast Indian Ocean. These authors showed that in the Late Pliocene of eastern Indian ocean there is a major faunal turnover in planktic foraminifera and attributed this to Northern Hemisphere glaciations. Sinha and Singh (2007) provided a detailed summary of the surface circulation changes in eastern Indian Ocean during Plio-Plesitocene.

An edited book containing peer reviewed papers from authors from leading scientists from all over the world was published by Sinha (2007). The book contains several Indian contributions in the field of palaeoceanography.

Proxies in Paleoceanographic Studies

Important contributions have been made by the Indian scientists towards strengthening our understanding of additional proxies for paleoceanographic studies.

Nigam *et al.* (2008) carried out laboratory culture experiment on benthic foraminifer *Rosalina leei*. They concluded that *R. leei* reproduces at a very narrow range of temperature and salinity which is different from the temperature and salinity conditions in the present experiment. They further inferred that under the present set of temperature–salinity conditions, 25.8C temperature and 35‰ saline water is most suitable for the growth of *R. leei*. These results results are significant as the responses of benthic foraminifera to different temperatures and salinity are being used for palaeoclimatic reconstruction.

Saraswat and Khare (2010) made an important contribution towards understanding the modern calcification depth of *Globigerina bulloides* in the southwestern Indian Ocean. The study showed that irrespective of latitudinal region, the estimated seawater temperature matches well with the seawater temperature during the austral spring season suggesting that *G. bulloides* is abundant at that time. The findings are important in paleoclimatic reconstruction studies based on characteristics of *G. bulloides*.

Saraswat *et al.* (2011) carried out studies on the relationship between abundance and morphology of benthic foraminifer *Epistominella exigua*. They observed an opposite relationship between the abundance and size of *E. exigua* shells. The higher abundance correspondswith smaller *E. exigua* shells. The findings can be used to apply morphological characteristics of *E. exigua* as a proxy to infer past climatic conditions.

Naik *et al.* (2010) showed that shell weights of *Globigerinoides sacculifer* and the elemental concentration of magnesium and calcium (Mg/Ca) from *Globigerinoides ruber* measured from an Arabian Sea sediment core, AAS9/21, exhibit an inverse relationship with each other, which reveals that shell weights are mainly controlled by surface water [$CO_3^{=}$] rather than calcification temperature.

Saraswat *et al.* (2011) studied growth and reproduction in benthic foraminifera *Rosalina globularis* and its implications for paleoclimatic studies. It was observed that out of five different temperatures, optimum growth took place at 30°C. The growth in rest of the specimens subjected to either higher or lower temperatures was comparatively less. However, the highest percentage of reproduction was reported in the specimens subjected to 27°C temperature. The study further indicates that variation in morphology and abundance of benthic foraminifera, might reflect different climatic conditions.

Mergulaho *et al.* (2006) made an important contribution to the understanding of application of coccolithophores in palaeoceanographic studies. The higher fluxes were attributed to the enhancement of primary production in the central Arabian Sea due to southward extent of nutrients from the northeast Arabian Sea by the prevailing surface currents. Similarly, the occurrences of relatively lower coccolithophore fluxes during the spring intermonsoon and southwest (SW) monsoon were attributed to the low nutrients in the warm, shallow surface mixed layer and downwelling to the south of Findlater Jet respectively in the central Arabian Sea. Mohan *et al.* (2006) made an important study on the seasonal variation of pteropods from the western Arabian Sea sediment trap. The variation in fluxes of calcium carbonate, organic carbon and biogenic opal show positive correlations with fluxes of pteropods and planktic foraminifers.

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