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PALAEOCEANOGRAPHIC CHANGES IN THE BAY OF BENGAL DURING THE HOLOCENE

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ABSTRACT

The palaeoceanographic changes in the Bay of Bengal are driven by monsoonal variability. The present study was pursued on benthic foraminifera obtained from the NGHP Hole 3B (15°53.8919′ N, 81°53.9678′ E, water depth 1076m), Bay of Bengal to understand Holocene palaeoceonographic turnovers. A total of 21 species from 30 samples have been considered for multivariate analysis. Four biofacies are identified based on Q-mode cluster and R-mode factor analyses. Biofacies Be-Up (*Bulimina exilis* and *Uvigerina peregrina*), Ck-Ba (*Cibicides kullenbergi*, *Bulimina alazanensis*, *Bulimina striata*, *Vulvulina pennatula* and *Chilostomella oolina*) and Oc-Ou (*Osangularia culter*, *Oridorsalis umbonatus*, *Chilostomella oolina* and *Bolivina alata*) dominate during 8226 to 6248, 4815 to 2462 and 1896 to 1262 calibrated years before the present, respectively indicating intervals of high productivity with better aerated bottom water. The other biofacies Hb-Gp (*Hyalinea balthica*, *Globobulimina pupoides*, *Pullenia subcarinata*, *Bulimina marginata*, *Bulimina striata, Bolivinita quadrilatera* and *Rotaliatinopsis semiinvoluta*) dominates from 6070 to 5007 and 2300 to 1896 cal yrs BP indicating presence of cold and oxygen deficient environment. Better aerated condition was developed as a result of intense SW monsoon which was responsible for huge precipitation, supply of more freshwater and nutrients. Besides, during the climatic cold, weak SW monsoon may play an important role for development of oxygen deficient environment. A weak SW monsoon during cold climate causes less input of fresh water in the Bay of Bengal. However, upwelling driven by the intense NE monsoon may be another potential cause for such oxygen deficiency.

Keywords: Krishna-Godavari Basin, Bay of Bengal, Benthic foraminifera, Monsoon, Productivity.

INTRODUCTION

Upliftment of the Himalayan Mountainas as well as intense SW monsoon (Indian Summer monsoon) are the two major events responsible for increased sedimentation with more terrigenous input within the Bay of Bengal (Gupta *et al.*, 2004; Clift *et al*., 2008; Dewangan *et al*., 2010). The major rivers which contribute huge amount of sediments to the Bay of Bengal are the Brahmaputra (402 to 710 $\times 10^6$ tonnes/year), Ganga (403 to 660 $\times$ 10^6 tonnes/year), Mahanadi (5.08-20.39 mm/yr), Krishnaand Godavari (67.72 $\times$ 10^6 tonnes/year) and Cauvery (0.4-4mm/yr)(Ramesh and Subramanian, 1988; Chakrapani and Subramaniam, 1993; Ramanathan *et al.*, 1996; Subramanian and Ramanathan, 1996). Accordingly, this thick pile of sediments facilitate recording of various paleoclimatic and paleoceanographic signals in this region. Monsoonal variations in India are typically influenced by the two reverse wind circulation patterns. These opposite wind flows are the south west monsoonal winds (strong in summer) and the northeast monsoonal winds (variable but stronger in winter) (Tchernia, 1980; Gupta *et al*., 2006, 2008). The summer or southwest monsoonal winds carry moisture to the Indian land mass causing intense rainfall. Upwelling and related high surface productivity during the strong summer monsoon is pronounced in the Arabian Sea (Banse and English,1994; Gupta *et al.*, 2003, 2005; Caley *et al.*, 2011). Biological productivity is decreased during the winter season in the Central Indian Ocean when dry north-easterly winds blow from land to sea (Krey, 1973; Shetye *et al*., 1993; Gupta *et al.,* 2006).

Benthic foraminifera are reliable proxy used to understand paleaoceanographic settings of any ocean basin owing to the sensitivity to particular environment. Benthic foraminiferal distribution depends on the food, oxygen, salinity, temperature and deep-ocean currents (Streeter, 1973; Schnitker, 1974; Miller and Lohmann, 1982; Caralp, 1988; Gupta and Srinivasan, 1990; Mackensen *et al*., 1995; Miao and Thunell, 1993; Jian and Wang, 1997; Schmiedl and Mackensen, 1997; Sen Gupta and Machine-Castilo, 1993; Gupta, 1999; Schönfeld, 2002).

The present investigation was pursued using benthic foraminiferal proxies from sediment core samples collected from the Krishna-Godavari Basin, to understand Holocene Paleoceanograhic changes driven by monsoonal variability.

LOCATION AND OCEANOGRAPHIC SETTINGS

Unconsolidated sediment samples for the present study were collected from National Gas Hydrate Program (NGHP) Hole 3B, Krishna-Godavari Basin (hereafter designated by K-G basin). Hole 3B (15°53.8919′N, 81°53.9678′E) is situated 40 km off the coast line at a water depth 1076m (Fig. 1, Collett *et al*., 2007). Higher sedimentation rate during the Neogene period is recorded caused by the upliftment as well as erosion of the Himalaya (Dewangan *et al*., 2010). Accumulated sediments thickness in the offshore K-G basin may exceed 8 km in some places (Prabhakar and Zutski, 1993). The topmost Holocene nannofossils rich clay sequence of the K-G basin is the part of the Godavari Clay formation (Rao, 2001) in which the present study is confined.

The K-G basin is located at the western coast of Bay of Bengal influenced by coastal upwelling during south-west monsoon (June-October) as well as huge freshwater influx brought by the rivers Irrawaddy, Brahmaputra, Ganges, Mahanadi and Godavari (Shetye *et al.*, 1991; Kantha *et al.*, 2008). This part of the Indian Ocean (Bay of Bengal) receives excess precipitation than evaporation leading to comparatively fresh surface layers (Kantha *et al*., 2008).

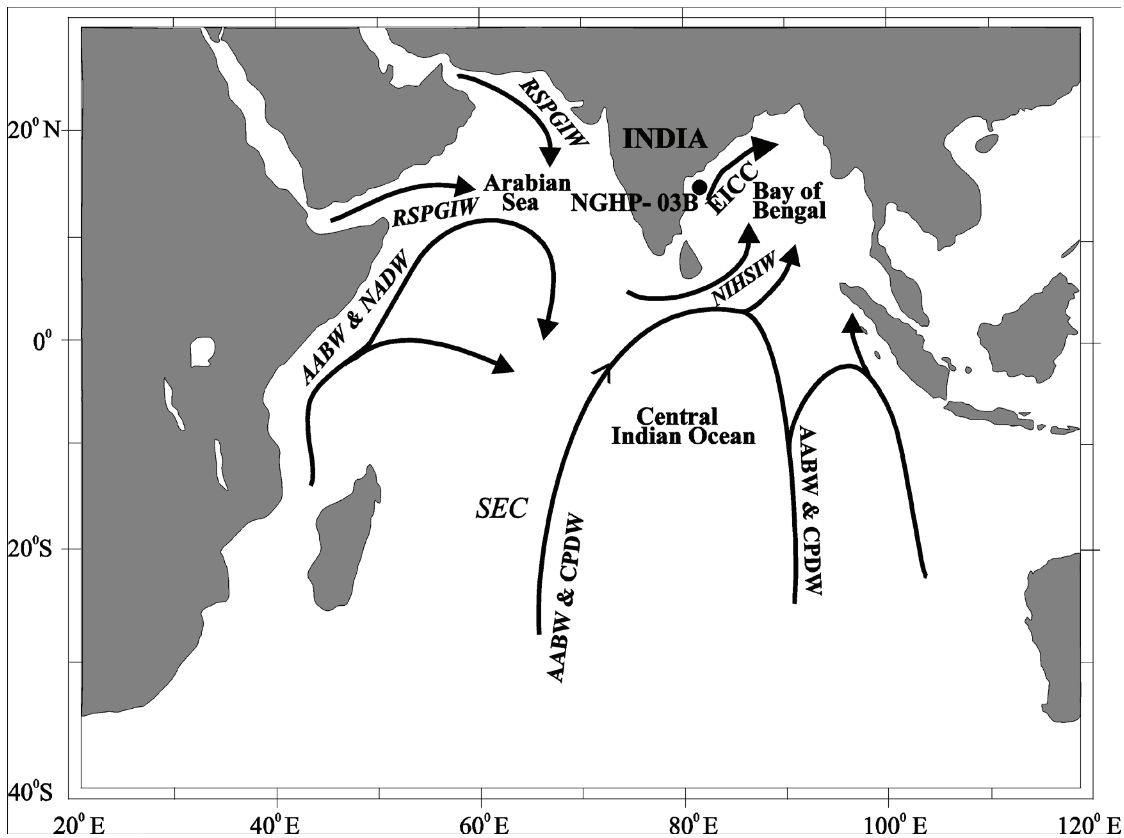

Fig. 1. Location map of National Gas Hydrate Program (NGHP) Hole 3B (15°53.8919′N, 81°53.9678′E, water depth 1076m), Krishna-Godavari Basin, Bay of Bengal (Collett *et al.*, 2007) with the ocean circulation pattern. Solid lines indicate deep ocean currents whereas dotted line indicates surface ocean currents. RSPGIW = Red Sea - Persian Gulf Intermediate water, AABW = Antarctic Bottom Water, NADW = North Atlantic Deep Water, CPDW = Circumpolar Deep Water, NIHSIW = North Indian High-salinity Intermediate Water, EICC = East Indian Coastal Current.

The Indian Ocean is bathed by three types of water masses. Shallower depth (up to ~ 1200 m) is influenced by the Antarctic Intermediate Water or AAIW (Tchernia, 1980). Depths between 1200 and 2000 m are mostly dominated by a mixture of the well oxygenated North Atlantic Deep Water (NADW) and North Indian Deep Water or NIDW (Fig.1, Wyrtki, 1971; Tchernia, 1980; Bhaumik *et al.*, 2014). The deeper part (> 3000 m) is bathed by nutrient rich, cold water of Antarctic origin – the Antarctic Bottom Water or AABW (Tchernia, 1980; Bhaumik *et al.,* 2014). Between 2000 and 3000 m, the water mass has the characteristic of both NADW and AABW due to mixing. The shallow part of the Indian Ocean adjacent to Andaman is presently bathed by the Equatorial Water Mass (De and Gupta, 2010; Bhaumik *et al.*, 2014). The East Indian Coastal Current (EICC) flows towards NE along the eastern cost of the Indian Ocean during the boreal summer whereas this current (EICC) moves opposite towards SW during the boreal winter (Schott and McCreary, 2001; Kantha *et al.*, 2008).

MATERIALS AND METHODS

A total of 30 unconsolidated core samples with 10cc volume each were collected to pursue the present study. Each sediment samples was soaked with normal water for about 12 hours for separation of foraminifera. Soaked samples then washed over 63μm (230 mesh) sieve. Finer clay particles were washed away and the coarser residual part (>63μm) transferred into the beaker and placed into oven todry at 60 °C. All the oven-dried samples were sieved over 125μm to remove the juvenile and dwarf forms prior to microscopic observation. Then the residual part (>125 μm) of each sample was split into suitable aliquot to get 250 to 300 individuals from each samples. Species level identification of benthic foraminifera were done under stereo-zoommicroscope. The age of the sediments of this hole is not available. Therefore, radiocarbon AMS ^{14}C dates of planktonic foraminifera from the nearby Hole MD161/11 are taken up to a depth of 13.55m. Hole 3B is situated at a distance of only 7.5 km from Hole MD161/11 towards east of southeast in similar water depth. Hence, it is considered that sediment ages of Hole 3B will be similar to that of Hole MD161/11. The sediments of Hole 3B show an age of 8226.3 year at a depth of 13.23 mbsf.

Species having abundance more than 5% in a sample and present at least in 15 samples were considered for multivariate (cluster and factor) analysis to reconstruct the paleoenvironments. A total of 21 species (Table1) were chosen as per the above mentioned criteria to perform the multivariate analyses. R-mode Principal Component Analysis (PCA) using SAS software is performed on the correlation matrix followed by an orthogonal VARIMAX rotation to maximize the variance. Four factors have been retained, based on the scree (x–y) plot of Eigen values versus the number of species (variables) and screening of factor scores, that account for 74.74% of the total variance (Table 2). Zero values used during the analysis are designated as missing values for each species against each observation number in PCA analysis. The Q-mode cluster analysis using Ward's Minimum Variance method is also performed. Prior

Table 1. List of species having abundance greater than 5% atleast in one sample and present in 15 samples used in multivariate analysis

1) *Bolivina alata* = *Bolivina alata* Sequenza, 1862
2) *Bolivinita quadrilatera* = *Textilaria quadrilatera* Schwager, 1866
3) *Bulimina alazanensis* = *Bulimina alazanensis* Cushman, 1927
4) *Bulimina arabiensis* = *Bulimina Arabiensis* Bharti and Singh, 2013
5) *Bulimina exilis* = *Bulimina exilis* Brady, 1884
6) *Bulimina gibba* = *Bulimina gibba* Fomasini, 1901
7) *Bulimina marginata* = *Bulimina marginata* d'Orbigny, 1826
8) *Bulimina striata* = *Bulimina striata* d'Orbigny, 1826
9) *Cassidulina carinata* = *Cassidulina laevigata* d'Orbigny var. *carinata* Silvestri, 1896
10) *Chilostomella oolina* = *Chilostomella oolina* Schwager, 1878
11) *Cibicides kullenbergi* = *Cibicides kullenbergi* Parker, 1953
12) *Fursenkoinia bradyi* = *Virgulina bradyi* Cushman, 1922
13) *Globobulimina pacifica* = *Globobulimina pacifica* Cushman, 1927
14) *Globobulimia pupoides* = *Bulimina pupoides* Cushman and Parker, 1947
15) *Hyalinea balthica* = *Nautilus balthicus* Schroeter, 1783
16) *Oridorsalis umbonatus* = *Rotalina umbonata* Reuss, 1851
17) *Osangularia culter* = *Planorbulina culter* Parker and Jones, 1865
18) *Pullenia subcarinata*= *Nonionina subcarinata* d'Orbigny, 1839
19) *Rotaliatinopsis semiinvoluta* = *Pulleniatina semiinvoluta* Germeraady, 1946
20) *Uvigerina peregrina*= *Uvigerina peregrina* Cushman, 1923
21) *Vulvulina pennatula* = *Nautilus* (Orthoceras) *pennatula* Batsch, 1791

to cluster analysis, a PCA was performed on the covariance matrix of the 21 highest ranked species from the dataset. Based on the plot of semi-partial R-squared values versus the number of clusters, four clusters were identified (Fig. 2). VARIMAX-rotated factors that show high factor scores with well-established species associations were used to identify biofacies. We identified 4 biofacies, and interpreted their paleoenvironments based on present day ecological preferences of the most abundant species in the biofacies (Table 2; Figs. 3-6).

RESULTS AND DISCUSSIONS

Four biofacies (Table 2, Figs. 3-6) are identified based on four clusters (Fig. 2), Eigen values, factors and species associations obtained through cluster and factor analyses. Each biofacies is described below with its species associations and environmental preferences.

Be-Up biofacies is dominated by two species i.e. *Bulimina exilis* and *Uvigerina peregrina* (Fig.3). Jonkers (1984) documented the *Bulimina exilis* in low oxygen and high food condition. It is abundant in areas of high organic flux which is fresh in nature. So, the presence of this species indicate huge amount of fresh or slightly altered organic influx (Caralp, 1989; Jonkers, 1984; Polyak *et al*., 2002). *Bulimina exilis* has sustained in oxygen depleted environment (Lutze and Coulbourn, 1984; Sen Gupta and Machine-Castilo, 1993; Rathburn and Corliss, 1994). The other major species *Uvigerina peregrina* prefers shallow to intermediate infaunal habitat, independent of oxygen but lives in the low to moderate oxygen concentration and high organic flux (Lutze and Coulbourn, 1984; Hermelin and Shimmield, 1990; Dingle and Nelson, 1993; Rathburn *et al*., 1996). Schmiedl *et al*. (1997) reported *U. peregrina* at the lower continental slope with high organic matter carried by the Cunene River. The distribution of this species depends on organic matter influxes in the North Atlantic and Northwest Indian Ocean (Miller and Lohmann, 1982; Lutze and Coulboum, 1984; Hermelin and Shimmield, 1990). The biofacies occupies an interval between 8226-6248 cal yr BP and species association shows high productivity interval (Table 2).

Biofacies Hb-Gp is defined by the dominance of *Hyalineabalthica*, *Globobulimina pupoides*, *Pulleniasubcarinata*, *Bulimina marginata*, *Bolivinita quadrilatera*, *Buliminastriata* and *Rotaliatinopsis semiinvoluta* (Fig. 4). Both *Hyalinea balthica* and *Pullenia subcarinata* are bathed by the cold watermass (Bock, 1970; Collen, 1974; Ross, 1984; Murray, 1991; Mackensen *et al.*, 1995). Gvirtzman *et al.*(1997) considered the *H. balthica* as an "Early Pleistocene

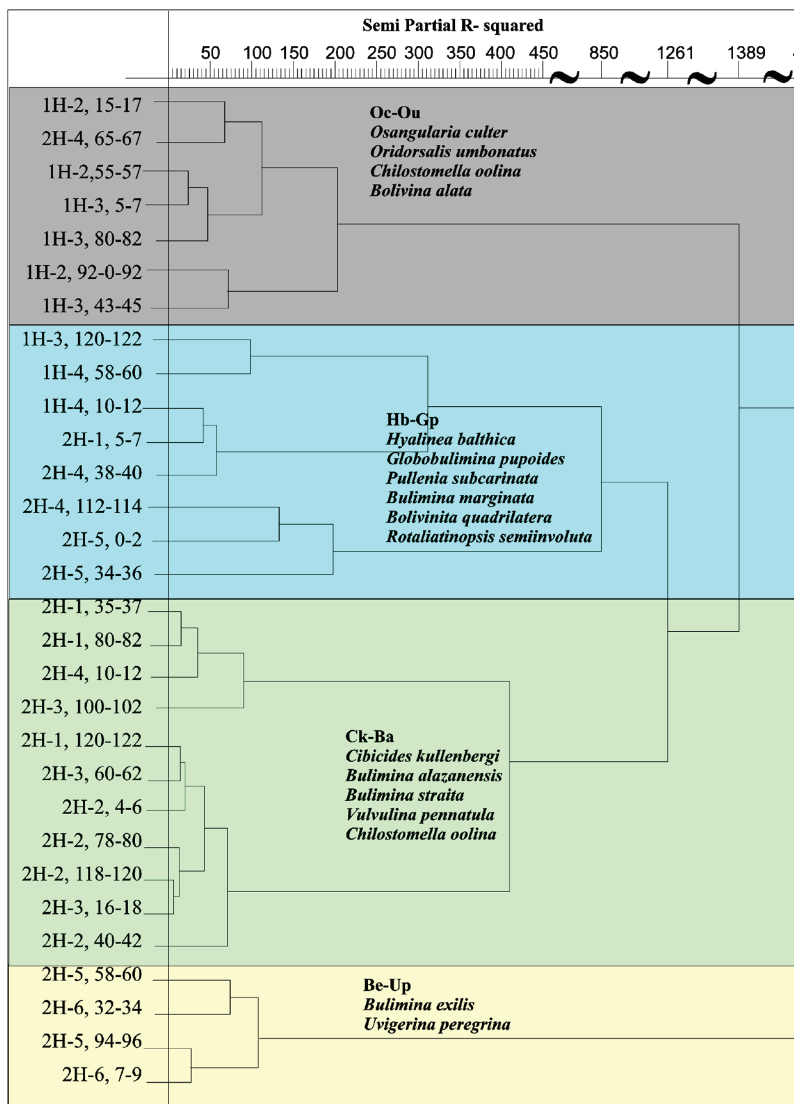

Fig. 2. Dendrogram based on Q-mode cluster analysis of 30 Holocene samples from NGHP Hole 3B using Ward's Minimum Variance method. Four clusters have been identified on the basis of the number of clusters versus semi-partial R^2. Each cluster corresponds to a biofacies named after the most dominant species within each cluster.

Table 2. Benthic foraminiferal biofacies with their preferred environment.

Biofacies	Variance (%)	Factor	Environment
Hb-Gp (Factor 1 +ve)	21.29		
Hyalinea balthica		0.814	Oxygen deficient
Globobulimina pupoides		0.785	cold to temperate
Pullenia subcarinata		0.705	climate
Bulimina marginata		0.415	
Bolivinita quadrilatera		0.362	
Bulimina striata		0.313	
Rotaliatinopsis semiinvoluta		0.305	
Ck-Ba (Factor 2 +ve)	20.25		
Cibicides kullenbergi		0.878	High organic
Bulmina alazanensis		0.768	carbon with
Bulimina striata		0.595	moderate oxic
Vulvulina pennatula		0.528	environment
Chilostomella oolina		0.437	
Oc-Ou (Factor 3 +ve)	18.26		
Osangularia culter		0.766	Relatively better
Oridorsalis umbonatus		0.719	ventilated-low
Chilostomella oolina		0.482	organic carbon rich
Bolivina alata		0.319	bottom water
Be-Up (Factor 4 –ve)	14.94		High productiv-
Bulimina exilis		-0.531	ity, independent
Uvigerina peregrina		-0.736	of bottom water oxygenation

cold water nordic guest". *Hyalinea balthica* is most profuse in cooler waters of the North Atlantic during the late Pliocene (van Morkhoven *et al.*, 1986). It also prefers to live in epifaunal to shallow infaunal habitat, neritic to upper bathyal zone, muddy sand area with oxygen level of 0.3 ml/l (Hermelin and Shimmield, 1990; Murray, 1991; Jannink, 1998; Rosenthal *et al.*, 2011).This species is reported from the core of OMZ (oxygen minimum zone) in the Arabian Sea (Hermelin and Shimmield, 1990). According to Rathburn *et al*. (1996) *B. marginata* is a shallow infaunal species which lives in low oxygen with high organic conditions (SenGupta and Machine-Castilo, 1993). *Bulimina striata* lives in an infaunal microhabitat and indicates high surface productivity (Rathburn and Corliss, 1994; Gupta, 1997). Warm water, shallow infaunal species *Bolivinita quadrilatera* indicates low oxygen concentration and high productivity (Poli *et al.*, 2010). Jannink *et al.* (1998) documented *Rotaliatinopsis semiinvoluta* as an oxygen minimum zone species from the Arabian Sea. This biofacies occurs during 6070-5007 and 2300-1896 cal yr BP and is suggested Oxygen deficient cold to temperate climate (Table 2).

The biofacies Ck-Ba is characterised by *Cibicides kullenbergi*, *Bulimina alazanensis*, *Bulimina striata*, *Vulvulina pennatula* and *Chilostomella oolina* and ranges between 4815-2462cal yr BP (Fig. 5). *Cibicides kullenbergi* lives in a variety of environmental settings. The occurrence of this species is also indicative of intermediate to low organic flux, warm deep water, NADW, high oxygen (Gooday, 2003; Lutze and Coulbourn, 1984; Woodruff, 1985; Gupta and Srinivasan, 1990; Lohmann, 1978; Bhaumik *et al.*, 2007). It has been considered as an epifaunal spices and oxic indicator (>2 ml/l O_2) (Kaiho, 1999). Lutze and Coulbourn (1984) and Gupta and Thomas (1999) documented this species in low organic carbon flux in north-western Africa as well as associated with the high organic flux and warm water species. *Cibicides kullenbergi* prefers to live on the middle and lower slope and the abyssal plain, deep infaunally(van Morkhoven *et al.*, 1986; Holbourn and Henderson, 2002; Jorrisen *et al.*, 1998). *Bulimina alazanensis* suggests low temperature, high oxygen (2.5-3.3 ml/l), intermediate PO_4, NO_2/food (De and Gupta, 2010). It has been associated with the species of oxygen rich and saline core of North Atlantic Deep Water (NADW) (Schmiedl *et al*., 1997). *Bulimina alazanensis* also prefers to live an infaunal microhabitat in low-oxygen, organic carbon rich environment with high and continuous food supply (Corliss and Chen, 1988; Gupta and Thomas, 1999; Gupta *et al*., 2006). *Bulimina striata* lives in an infaunal microhabitat and indicates high surface productivity (Gupta, 1997; Rathburn and Corliss, 1994). Elevated epibenthic species *Vulvulina pennatula* is an active suspension feeder (Lutze and Theil, 1989; Schönfeld, 1997, 2002). This biofacies is inferred to reflect high organic carbon with moderate oxic environment (Table 2).

Biofacies Oc-Ou consists of *Osangularia culter*, *Oridorsalis umbonatus*, C*hilostomella oolina* and *Bolivina alata* (Fig. 6). This biofacies is dominantly present during 1896 to 1262 cal yr BP. *Osangularia culter* is documented as middle to lower bathyal taxon with other forms usually found in the Holocene sediments of the eastern Indian Ocean and is associated with relatively well oxygenated Indian Deep Water and the Indian Bottom Water (Corliss, 1979; Peterson, 1984). Schmiedl *et al.* (1997) suggested this species as an indicator of high oxygen and low food level in the Indian Ocean. This species is also recorded with higher numbers in oligotrophic, oxygen rich,

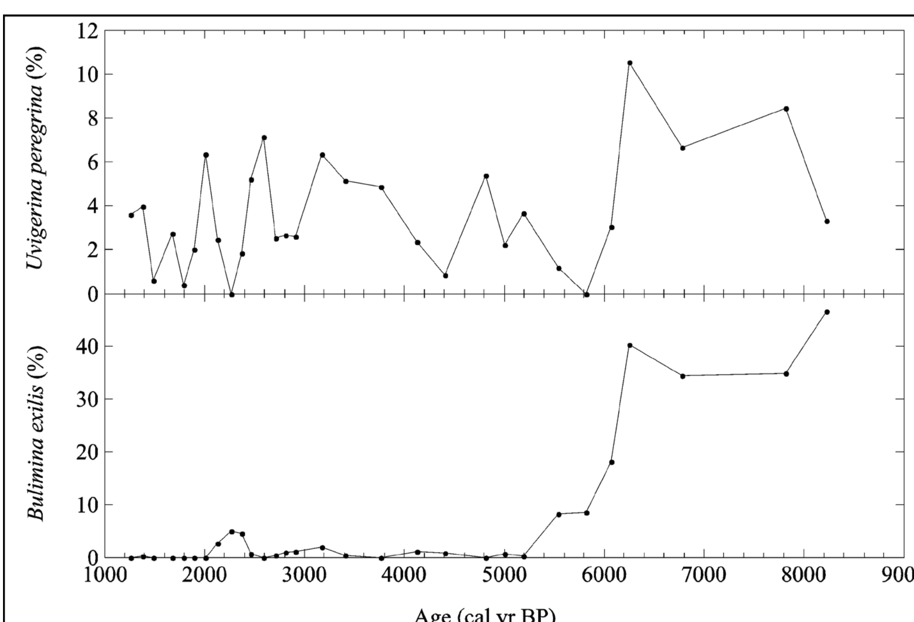

Fig. 3. Relative abundances of the dominant species in biofacies Be-Up.

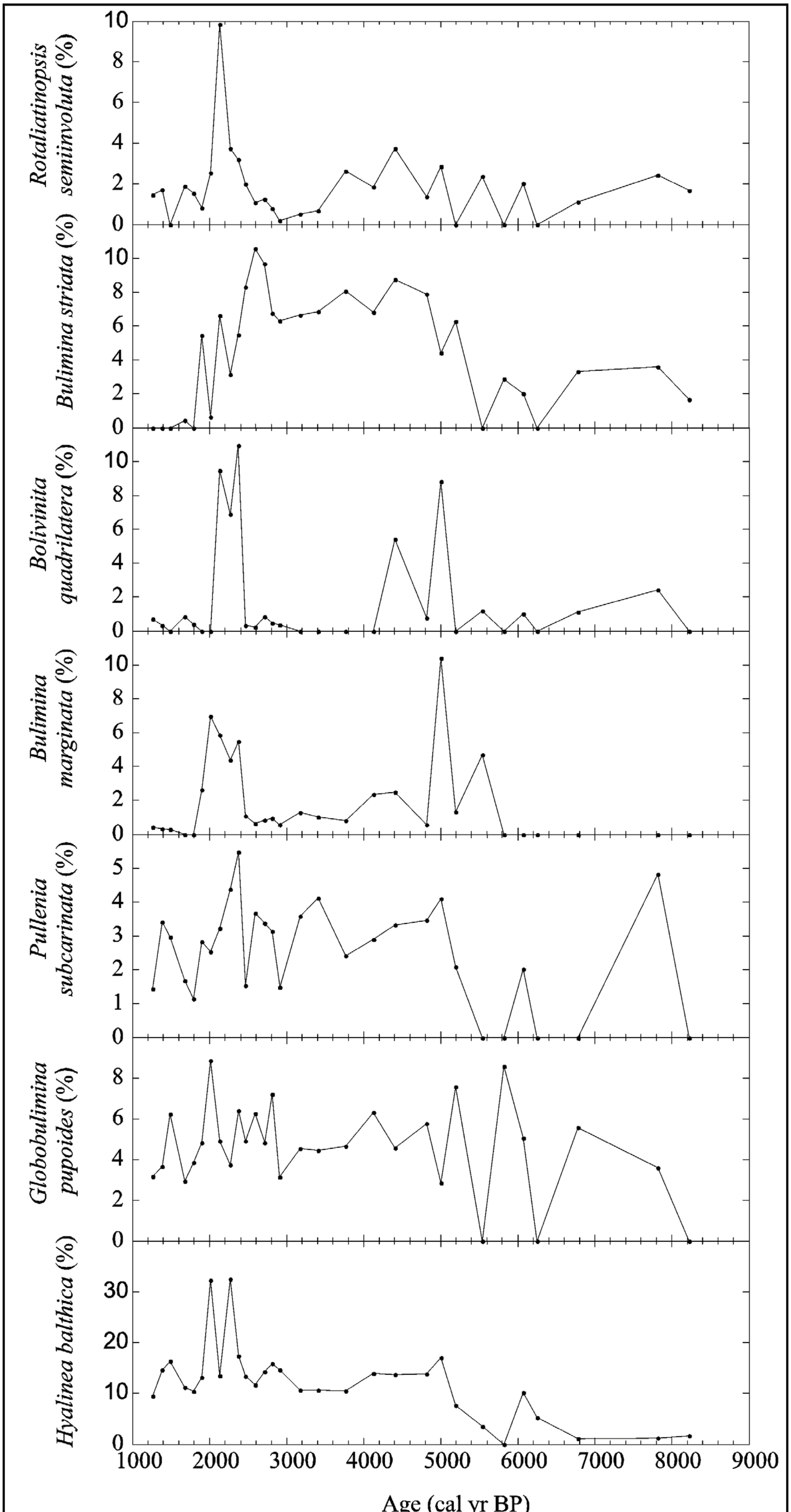

Fig. 4. Relative abundances of the dominant species in biofacies Hb-Gp.

saline NADW (Murray, 2006). Gupta (1999) linked this species with high energy, well oxygenated and probably low organic carbon environment in the Indian Ocean. However, Jannink *et al.* (1998) described this as a dysoxic (O_2 level 0.3ml/l) species. *Oridorsalis umbonatus* is reported from various environmental settings and is commonly known as a cosmopolitan taxon preferring wide range of oxygen and food levels (Miao and Thunell, 1993; Schmiedl and Mackensen, 1997; Gupta and Thomas, 1999). Study of Jannink *et al.* (1998) described this species as dysoxic (O_2 level 0.4ml/l). Also this species is considered as an indicator of well oxygenated, low organic carbon environment by numerous workers (Den Dulk *et al*., 2000; Jorissen *et al*., 1998; Jayaraju *et al*., 2010; Rai and Srinivasan, 2000; Mackensen *et al*., 1985; Corliss and Chen, 1988). Both *Chilostomella oolina* and *Bolivina alata* are mostly described as low oxygen species by several workers (Rathburn *et al*., 1996; Murray, 1991; Schmiedl *et al*., 2003; Sen Gupta and Machine-Castilo, 1993; Kaiho, 1999). However, *C.oolina* is reported as associated species of *Anomalinoides* sp. in well ventilated condition in the Red Sea (Badawi *et al*., 2005). Shallow infaunal species *Bolivina alata* is dominant in the dysoxic environment (Stefanelli, 2004; Stefanelli *et al*., 2005; Drinia *et al*., 2008). Thus, biofacies Oc-Ouis considered as an indicative of relatively better ventilated (dysoxic or better)-low organic carbon rich environment (Table 2).

The Indian monsoonal system directly affects the ocean water properties including nutrient levels, production of organic carbon, oxygen level, and sedimentation rates as well as variations in population of benthic foraminifera (Singh and Gupta, 2004). Also, the Holocene climatic condition is assumed to be relatively stable and warm (Bond *et al*., 1997; Gupta *et al.,* 2008).The benthic foraminiferal biofacies pattern in the present study suggests prominent climatic variations during the last 8226 years. The present investigation shows presence of high productive and relatively better oxygenated conditions during 8226 to 6248 cal yr BP (biofacies Be-Up), 4815-2462 cal yr BP (biofacies Ck-Ba) and 1896- 1262 cal yr BP (biofacies Oc-Ou) (Table 2, Fig. 7). However, dominance

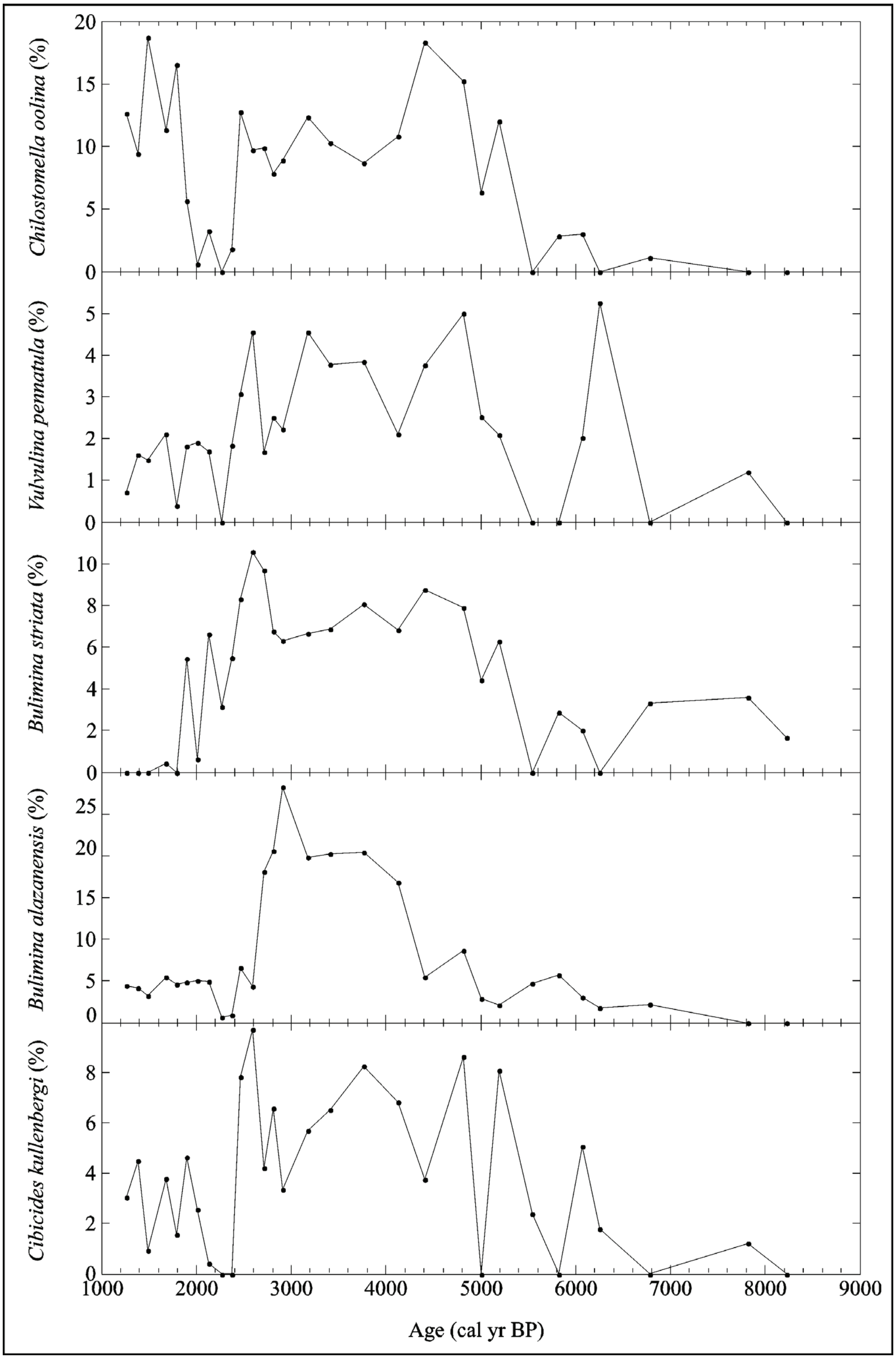

Fig. 5. Relative abundances of the dominant species in biofacies Ck-Ba.

of biofacies Hb-Gp in two intervals (6070-5007 and 2300-1896cal yr BP) indicates presence of cold to temperate climate environment with reducing oxygen levels (Table 2, Fig. 7).

It is believed that the early Holocene climate was highly variable and relatively warmer and the SW monsoon was intense between 11 to 8 kyrs time period (Flightmen *et al*., 2003; Gupta *et al*., 2003. Also Rasid *et al.* (2011) documented intensified Indian monsoon as well as monsoonal precipitation during ~7-6 ka within the western Bay of Bengal. Several earlier studies also confirm existence of warmer condition since last 8000 years and warm phase became stronger during 7200 and 6000cal yr BP in the Bay of Bengal (An *et al*., 2000; Sun and Li, 2011). Also, high precipitation in southern China and maximum monsoon in East Asia occurred during the last 3000 years (An *et al*., 2000). Similarly, India experienced wet phase since 1500-1000 cal yr BP due to increase in SW monsoon strength (Yadava and Ramesh,1999).

Our data supports the studied site shows increased production of organic carbon during intervals of intense monsoon. We assume that the SW monsoonal wind became strong during all these climatic warm phases which carried vast moisture and precipitated it over the Indian subcontinent. Thus, intense rainfall carried nutrients to the Bay of Bengal which ultimately led high productivity.

On the contrary, a minor shift of environment is observed during 6070-5007 and 2300-1896cal yr BP. Both the intervals are dominated by biofacies Hb-Gp which indicates cold to temperate climate with low oxygen conditions prevailing in the Bay of Bengal. Study of Gupta *et al.* (2003) documented cold spells with weaker monsoon from 6100 to 5400 and 1700 to 1900 cal yr BP in the Arabian Sea. Also scientists correlated disappearance of Indus valley civilization (5-4 ka) and decreased riverine influx of sediments in the Arabian Sea as a consequence of strengthening of dry phase in the Indian monsoon (Staubwasser *et al*., 2003).The cold and dry phase indicating a weak SW monsoon is also documented in the proxy records from the western China and northern India during ~ 1600 - 1670 year BP (Jones and Bradley, 1992; Jacoby *et al*., 1996; Sharma and Chauhan, 2001). Our data set also documented these two cold phases with slight age deviation. It is presumed that the SW monsoon weakened and related precipitation decreased during these cold periods. Thus the supply of nutrients to the ocean became low as well as stagnancy in ocean water column intensified due to less influx of fresh water. However, study of Vinayachandran and Mathew

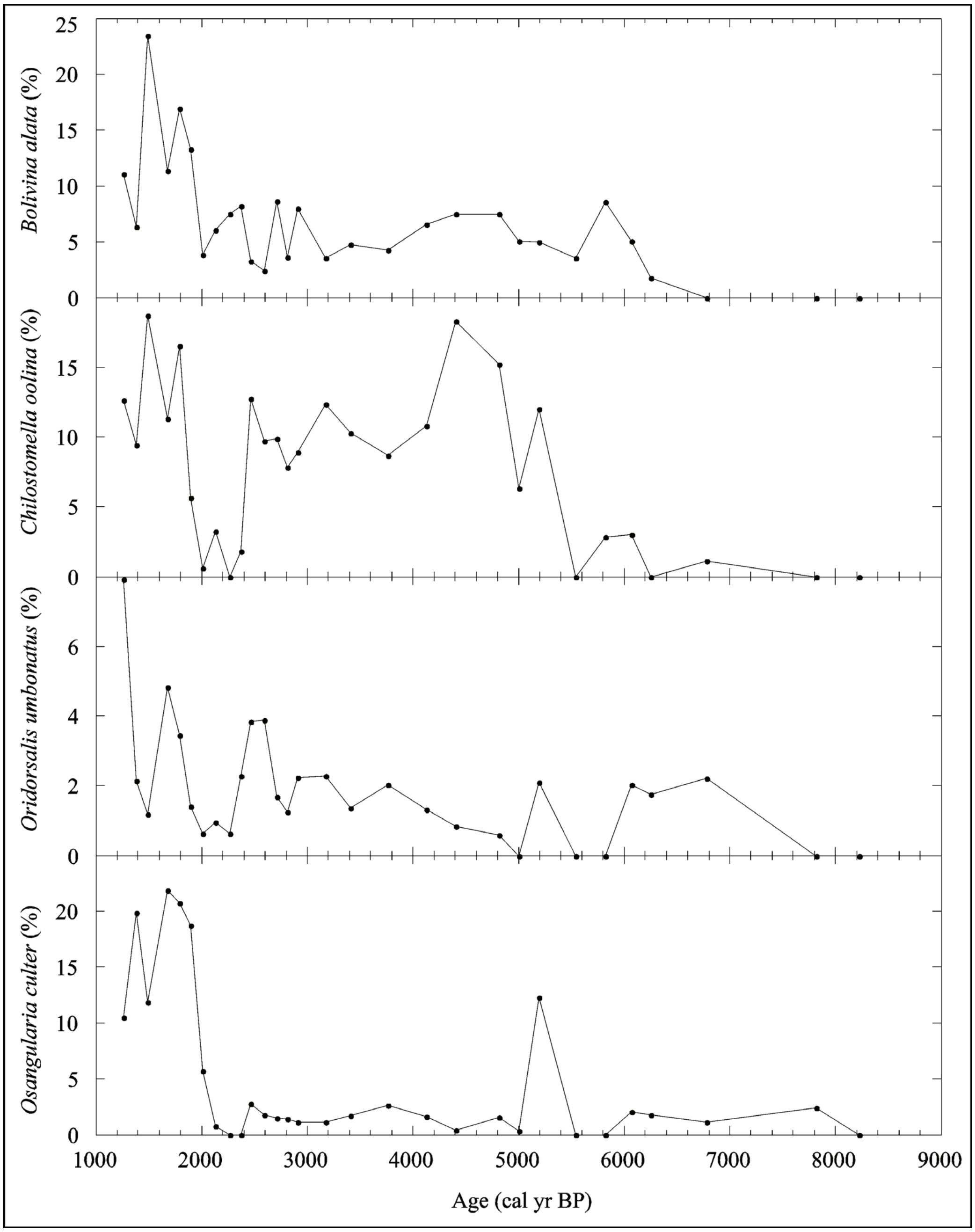

Fig. 6. Relative abundances of the dominant species in biofacies Oc-Ou.

(2003) shows event of upwelling in the Bay of Bengal during the retreating NE monsoon which may be of another cause for the existence of cold and oxygen deficient condition.

CONCLUSIONS

Changes in benthic foraminiferal biofacies indicate climatic variations within the relatively stable warm Holocene epoch. Dominance of biofacies Be-Up, Ck-Ba and Oc-Ou during 8226-6248, 4815 to 2462 and 1896 to 1262 cal yr BP respectively indicates intervals of intensified SW monsoon during warm conditions. Strong and moisture-rich SW monsoonal wind contributed huge freshwater and nutrient to the Bay of Bengal leading to high productivity. On the other hand, the intervals within 6070 to 5007 and 2300 to 1896 cal yr BP are dominated by biofacies Hb-Gp which indicate, cold and oxygen deficient condition. Thus, it may indicate weakening of the SW monsoon, less rainfall as well less contribution of fresh water and nutrient to the Bay of Bengal leading to the development of oxygen deficient condition.

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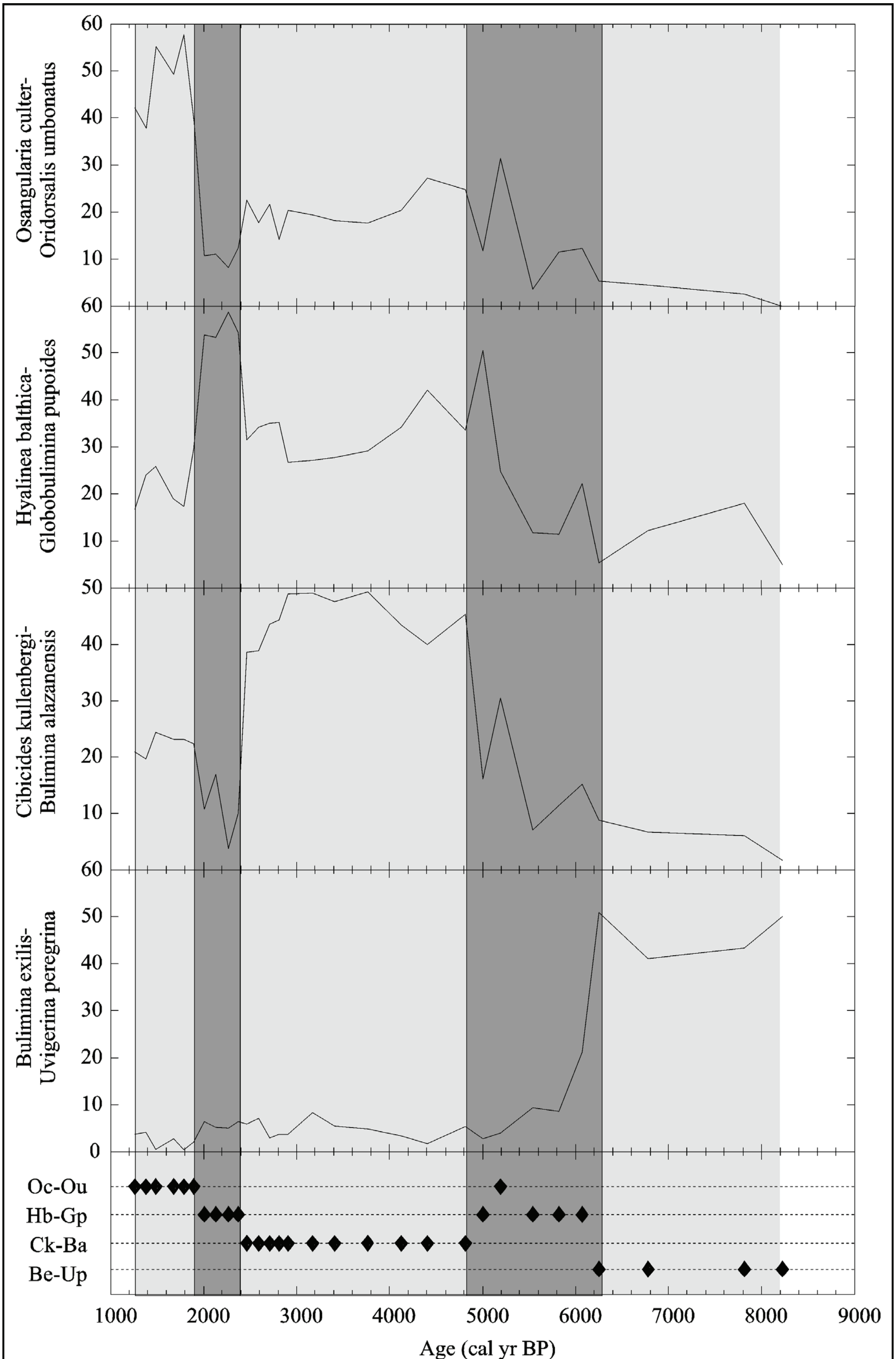

Fig. 7. Distribution of clusters with respect to time. Also cumulative sum of all the members of each biofacies (in terms of %) are plotted against clusters. Light grey bars indicate intervals of high productive, better aerated SW monsoon dominated environments whereas dark grey bars indicate cold, oxygen deficient weak monsoonal periods.

REFERENCES

Ali, S., Hathorne, E. C., Frank, M., Gebregiorgis, D., Stattegger, K., Stumpf, R. and Giosan, L. 2015. South Asian monsoon history over the past 60 kyr recorded by radiogenic isotopes and clay mineral assemblages in the Andaman Sea. *Geochemistry, Geophysics, Geosystems*, **16**(2): 505-521.

An, Z., Porter, S. C., Kutzbach, J. E., Xihao, W., Suming, W., Xiaodong, L. and Weijian, Z. 2000. Asynchronous Holocene optimum of the East Asian monsoon. *Quaternary Science Reviews*, **19**(8): 743-762.

Badawi, A., Schmiedl, G. and Hemleben, C. 2005. Impact of late Quaternary environmental changes on deep-sea benthic foraminiferal faunas of the Red Sea. *Marine Micropaleontology*, **58**(1): 13-30.

Banse, K. and English, D. C. 1994. Seasonality of coastal zone color scanner phytoplankton pigment in the offshore oceans. *Journal of Geophysical Research: Oceans*, **99**(C4): 7323-7345.

Bhaumik, A. K., Gupta, A. K. and Ray, S. 2014. Surface and deep-water variability at the Blake Ridge, NW Atlantic during the Plio-Pleistocene is linked to the closing of the Central American Seaway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **399**: 345-351.

Bhaumik, A. K., Gupta, A. K., Raj, M. S., Mohan, K., De, S. and Sarkar, S. 2007. Paleoceanographic evolution of the northeastern Indian Ocean during the Miocene: Evidence from deep-sea benthic foraminifera (DSDP Hole 216A*). Indian Journal of Marine Sciences*, **36**(4): 332-341

Bock, W. D. 1970. *Hyalinea baltica* and the Plio-Pleistocene Boundary in the Caribbean Sea. *Science*, **170**(3960): 847-848.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., Priore, P. and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science*, **278**(5341): 1257-1266.

Caley, T., Malaizé, B., Revel, M., Ducassou, E., Wainer, K., Ibrahim, M.and Marieu, V. 2011. Orbital timing of the Indian, East Asian and African boreal monsoons and the concept of a 'global monsoon'. *Quaternary Science Reviews*, **30**(25): 3705-3715.

Caralp, M. H. 1988. Late glacial to recent deep-sea benthic foraminifera from the Northeastern Atlantic (Cadiz Gulf) and Western Mediterranean (Alboran Sea): paleooceanographic results. *Marine Micropaleontology*, **13**(3): 265-289.

Caralp, M. H. 1989. Abundance of*Bulimina exilis*and*Melonis barleeanum*: Relationship to the quality of marine organic matter. *Geo-Marine Letters*, **9**(1): 37-43.

Chakrapani, G. J. and Subramanian, V. 1993. Rates of erosion and sedimentation in the Mahanadi river basin, India. *Journal of hydrology*, **149**(1-4): 39-48.

Clift, P. D., Giosan, L., Blusztajn, J., Campbell, I. H., Allen, C., Pringle, M. and Carter, A. 2008. Holocene erosion of the Lesser Himalaya triggered by intensified summer monsoon. *Geology*, **36**(1): 79-82.

Collen, J. D. 1974. *Hyalinea* cf. *balthica* from Pliocene sediments, New Zealand. *New Zealand Journal of Geology and Geophysics*, **17**(4): 907-912.

Collett, T., Riedel, M., Cochran, J., Boswell, R., Presley, J., Kumar, P., Sathe, A., Sethi, A., Lall, M. V. and Sibal, V. the NGHP Expedition 01 Scientists, 2007. Indian National Gas Hydrate Program Expedition 01 Initial Reports. Directorate General of Hydrocarbons, Ministry of Petroleum and Natural Gas (India), **10-13**: 1-150.

Corliss, B. H. 1979. Size variation in the deep-sea benthonic foraminifer *Globocassidulina subglobosa* (Brady) in the southeast Indian Ocean. *Journal of Foraminiferal Research*, **9**(1): 50-60.

Corliss, B. H. and Chen, C. 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology*, **16**(8): 716-719.

De, S. and Gupta, A. K. 2010. Deep-sea faunal provinces and their inferred environments in the Indian Ocean based on distribution of Recent benthic foraminifera. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **291**(3): 429-442.

Den Dulk, M., Reichart, G. J., Van Heyst, S., Zachariasse, W. J. and Van der Zwaan, G. J. 2000. Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **161**(3): 337-359.

Dewangan, P., Ramprasad, T., Ramana, M. V., Mazumdar, A., Desa, M. and Badesab, F. K. 2010. Seabed morphology and gas venting features in the continental slope region of Krishna–Godavari basin, Bay of Bengal: Implications in gas-hydrate exploration. *Marine and Petroleum Geology*, **27**(7): 1628-1641.

Dingle, R. V. and Nelson, G. 1993. Sea-bottom temperature, salinity and dissolved oxygen on the continental margin off south-western Africa. *South African Journal of Marine Science*, **13**(1): 33-49.

Drinia, H., Antonarakou, A. and Kontakiotis, G. 2008. On the occurrence of early Pliocene marine deposits in the Ierapetra Basin, eastern Crete, Greece. *Bull. Geosci*, **83**(1): 63-78.

Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A. and Matter, A. 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science*, **300**(5626): 1737-1739.

Gooday, A. J. 2003. Benthic foraminifera (Protista) as tools in deep-water palaeoceanography: environmental influences on faunal characteristics. *Advances in marine biology*, **46**: 1-90.

Gupta, A. K. 1997. Paleoceanographic and paleoclimatic history of the Somali Basin during the Pliocene-Pleistocene; multivariate analyses of benthic foraminifera from DSDP Site 241 (Leg 25). *Journal of Foraminiferal Research*, **27**(3): 196-208.

Gupta, A. K. 1999. Latest Pliocene through Holocene paleoceanography of the eastern Indian Ocean: benthic foraminiferal evidence. *Marine Geology*, **161**(1): 63-73.

Gupta, A. K. and Srinivasan, M. S. 1990. Response of northern Indian Ocean deep-sea benthic foraminifera to global climates during Pliocene-Pleistocene. *Marine Micropaleontology*, **16**(1-2): 77-91.

Gupta, A. K.and Thomas, E. 1999. Latest Miocene-Pleistocene Productivity and Deep-Sea Ventilation in the Northwestern Indian Ocean (Deep Sea Drilling Project Site 219). *Paleoceanography*, **14**(1): 62-73.

Gupta, A. K., Anderson, D. M. and Overpeck, J. T. 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature*, **421**: 354– 357.

Gupta, A. K., Das, M. and Anderson, D. M. 2005. Solar influence on the Indian summer monsoon during the Holocene. *Geophysical Research Letters*, **32**: L17703.

Gupta, A. K., Das, M. and Bhaskar, K. 2006. South Equatorial Current (SEC) driven changes at DSDP Site 237, Central Indian Ocean, during the Plio-Pleistocene: evidence from benthic foraminifera and stable isotopes. *Journal of Asian Earth Sciences*, **28**(4): 276-290.

Gupta, A. K., Das, M., Clemens, S. C. and Mukherjee, B. 2008. Benthic foraminiferal faunal and isotopic changes as recorded in Holocene sediments of the northwest Indian Ocean. *Paleoceanography*, **23**(2): PA2214 1-10.

Gupta, A. K., Sarkar, S. and Mukherjee, B. 2006. Paleoceanographic changes during the past 1.9 Myr at DSDP Site 238, Central Indian Ocean Basin: benthic foraminiferal proxies. *Marine Micropaleontology*, **60**(2): 157-166.

Gupta, A. K., Singh, R. K., Joseph, S. and Thomas, E. 2004. Indian Ocean high-productivity event (10–8 Ma): Linked to global cooling or to the initiation of the Indian monsoons?. *Geology*, **32**(9): 753-756.

Gupta, B. K. S. and Machain-Castillo, M. L. 1993. Benthic foraminifera in oxygen-poor habitats. *Marine Micropaleontology*, **20**(3-4): 183-201.

Gvirtzman, G., Martinotti, G.M. and Moshkovitz, S. 1997. Stratigraphy of the Plio-Pleistocene sequence of the Mediterranean coastal belt of Israel and its implications for the evolution of the Nile Cone. In: Van Couvering, J.A. (Ed.), The Pleistocene Boundary and the Beginning of the Quaternary. Cambridge University Press, Cambridge, pp. 156–168.

Hermelin, J. O. R.and Shimmield, G. B. 1990. The importance of the oxygen minimum zone and sediment geochemistry in the distribution of Recent benthic foraminifera in the northwest Indian Ocean. *Marine Geology*, **91**(1-2): 1-29.

Holbourn, A. E. and Henderson, A. S. 2002. Re-illustration and revised taxonomy for selected deep-sea benthic foraminifers. *Palaeontologia Electronica*, **4**(2): 34.

Jacoby, G. C., Arrigo, R. D. and Davaajamts, T. 1996. Mongolian tree rings and 20th-century warming. *Science*, **273**(5276): 771.

Jannink, N. T., Zachariasse, W. J. and Van der Zwaan, G. J. 1998. Living (Rose Bengal stained) benthic foraminifera from the Pakistan continental margin (northern Arabian Sea). *Deep Sea Research Part I: Oceanographic Research Papers*, **45**(9): 1483-1513.

Jayaraju, N., Reddy, B. C. S. R., Reddy, K. R. and Reddy, A. N. 2010. Deep-Sea Benthic Foraminiferal Distribution in South West Indian Ocean: Implications to Paleoecology. *International Journal of Geosciences*, **1**(02): 79.

Jian, Z. and Wang, L. 1997. Late Quaternary benthic foraminifera and deep-water paleoceanography in the South China Sea. *Marine Micropaleontology*, **32**(1-2):127-154.

Jones, P. D. and Bradley, R. S. 1992. 33 Climatic variations over the last 500 years. In: Bradley, R. S., Jones, P. D. (Eds.), Climatic since AD 1500. Routledge, London, pp. 649-665.

Jonkers, H.A. 1984. Pliocene benthonic foraminifera from homogeneous and laminated marls on Crete. *Utrecht Micropaleontological Bulletin*, **31**: 1–179.

Jorissen, F. J., Wittling, I., Peypouquet, J. P., Rabouille, C. and Relexans, J. C. 1998. Live benthic foraminiferal faunas off Cape Blanc, NW-Africa: community structure and microhabitats. *Deep Sea Research Part I: Oceanographic Research Papers*, **45**(12): 2157-2188.

Kaiho, K. 1999. Effect of organic carbon flux and dissolved oxygen on the benthic foraminiferal oxygen index (BFOI). *Marine micropaleontology*, **37**(1): 67-76.

Kantha, L., Rojsiraphisal, T. and Lopez, J. 2008. The North Indian Ocean circulation and its variability as seen in a numerical hindcast of the years 1993–2004. *Progress in Oceanography*, **76**(1): 111-147.

Krey, J. 1973. Primary production in the Indian Ocean I. In The biology of the Indian Ocean. Springer Berlin Heidelberg, pp. 115-126.

Lohmann, G. P. 1978. Abyssal benthonic foraminifera as hydrographic indicators in the western South Atlantic Ocean. *Journal of Foraminiferal Research*, **8**(1): 6-34.

Lutze, G. F. and Coulbourn, W. T. 1984. Recent benthic foraminifera from the continental margin of northwest Africa: community structure and distribution. *Marine Micropaleontology*, **8**(5): 361-401.

Lutze, G. F. and Thiel, H. 1989. Epibenthic foraminifera from elevated microhabitats; *Cibicidoides wuellerstorfi* and *Planulina ariminensis*. *Journal of Foraminiferal Research*, **19**(2): 153-158.

Mackensen, A., Schmiedl, G., Harloff, J. and Giese, M. 1995. Deep-sea foraminifera in the South Atlantic Ocean: ecology and assemblage generation. *Micropaleontology*, **4**: 342-358.

Mackensen, A., Sejrup, H. P. and Jansen, E. 1985. The distribution of living benthic foraminifera on the continental slope and rise off southwest Norway. *Marine Micropaleontology*, **9**(4): 275-306.

Miao, Q. and Thunell, R. C. 1993. Recent deep-sea benthic foraminiferal distributions in the South China and Sulu Seas. *Marine Micropaleontology*, **22**(1-2): 1-32.

Miller, K. G. and Lohmann, G. P. 1982. Environmental distribution of Recent benthic foraminifera on the northeast United States continental slope. *GSA Bulletin*, **93**(3):200-206.

Murray, J. W. 1991. Ecology and distribution of benthic foraminifera. In: Lee, J.J., Anderson, O.R. (Eds.), Biology of Foraminifera. Academic Press, New York, pp. 221– 253.

Murray, J. W. 2006. Ecology and applications of benthic foraminifera. Cambridge University Press, pp: 202

Peterson, L. C. 1984. Recent abyssal benthic foraminiferal biofacies of the eastern equatorial Indian Ocean. *Marine Micropaleontology*, **8**(6): 479-519.

Poli, M. S., Meyers, P. A. and Thunell, R. C. 2010. The western North Atlantic record of MIS 13 to 10: Changes in primary productivity, organic carbon accumulation and benthic foraminiferal assemblages in sediments from the Blake Outer Ridge (ODP Site 1058). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **295**(1): 89-101.

Polyak, L., Korsun, S., Febo, L. A., Stanovoy, V., Khusid, T., Hald, M. and Lubinski, D. J. 2002. Benthic foraminiferal assemblages from the southern Kara Sea, a river-influenced Arctic marine environment. *Journal of Foraminiferal Research*, **32**(3): 252-273.

Prabhakar, K. N. and Zutshi, P. L. 1993. Evolution of southern part of Indian east coast basins. *Geological Society of India*, **41**(3): 215-230.

Rai, A. K. and Srinivasan, M. S. 2000. Deep sea benthic foraminiferal response to the pliocenepalaeoenvironments of the northen Indian Ocean. *Geobios*, **33**(3): 301-308.

Ramanathan, A. L., Subramanian, V. and Das, B. K.1996. Sediment and heavy metal accumulation in the Cauvery basin. *Environmental Geology*, **27**(3): 155-163.

Ramesh, R. and Subramanian, V. 1988. Temporal, spatial and size variation in the sediment transport in the Krishna River basin, India. *Journal of Hydrology*, **98**(1-2): 53-65.

Ramprasad, T., Dewangan, P., Ramana, M. V., Mazumdar, A., Karisiddaiah, S. M., Ramya, E. R. and Sriram, G. 2011. Evidence of slumping/sliding in Krishna-Godavari offshore basin due to gas/fluid movements. *Marine and Petroleum Geology*, **28**: 1806-1816.

Rao, G. N. 2001. Sedimentation, stratigraphy, and petroleum potential of Krishna-Godavari basin, East Coast of India. *AAPG bulletin*, **85**(9): 1623-1643.

Rashid, H., England, E., Thompson, L. and Polyak, L. 2011. Late glacial to Holocene Indian summer monsoon variability based upon sediment. *Terr. Atmos. Ocean. Sci*, **22**(2): 215-228.

Rathburn, A. E. and Corliss, B. H. 1994. The ecology of living (stained) deep-sea benthic foraminifera from the Sulu Sea.*Paleoceanography*, **9**(1): 87-150.

Rathburn, A. E., Corliss, B. H., Tappa, K. D. and Lohmann, K. C. 1996. Comparisons of the ecology and stable isotopic compositions of living (stained) benthic foraminifera from the Sulu and South China Seas. *Deep Sea Research Part I: Oceanographic Research Papers*, **43**(10): 1617-1646.

Rosenthal, Y., Morley, A., Barras, C., Katz, M. E., Jorissen, F., Reichart, G. J. and Linsley, B. K. 2011. Temperature calibration of Mg/Ca ratios in the intermediate water benthic foraminifer *Hyalinea balthica*. *Geochemistry, Geophysics, Geosystems*, **12**(4): 1-17.

Ross, C. R. 1984. *Hyalinea balthica* and its late Quaternary paleoclimatic implications; Strait of Sicily. *Journal of Foraminiferal Research*, **14**(2): 134-139.

Schmiedl, G. and Mackensen, A. 1997. Late Quaternary paleoproductivity and deep water circulation in the eastern South Atlantic Ocean: Evidence from benthic foraminifera. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **130**(1): 43-80.

Schmiedl, G., Mackensen, A. and Müller, P. J. 1997. Recent benthic foraminifera from the eastern South Atlantic Ocean: dependence on food supply and water masses. *Marine Micropaleontology*, **32**(3): 249-287.

Schmiedl, G., Mitschele, A., Beck, S., Emeis, K. C., Hemleben, C., Schulz, H. and Weldeab, S. 2003. Benthic foraminiferal record of ecosystem variability in the eastern Mediterranean Sea during times of sapropel S 5 and S 6 deposition. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **190**: 139-164.

Schnitker, D. 1974. West Atlantic abyssal circulation during the past 120,000 years. *Nature*, **248**(5447):385-387.

Schönfeld, J. 1997. The impact of the Mediterranean Outflow Water (MOW) on benthic foraminiferal assemblages and surface sediments at the southern Portuguese continental margin. *Marine Micropaleontology*, **29**(3-4): 211-236.

Schönfeld, J. 2002. A new benthic foraminiferal proxy for near-bottom current velocities in the Gulf of Cadiz, northeastern Atlantic Ocean. *Deep Sea Research Part I: Oceanographic Research Papers*, **49**(10): 1853-1875.

Schott, F. A. and McCreary, J. P. 2001. The monsoon circulation of the Indian Ocean. *Progress in Oceanography*, **51**(1):1-123.

Schulz, H., von Rad, U. and Erlenkeuser, H. 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature*, **393**(6680): 54.

Sen Gupta, B. K. and Machain-Castillo, M. L. 1993. Benthic foraminifera in oxygen-poor habitats. *Marine Micropaleontology*,**20**:183– 201.

Sharma, C. and Chauhan, M. S. 2001. Late Holocene vegetation and climate of Kupup (Sikkim), Eastern Himalaya, India. *Journal of the Palaeontological Society of India*, **46**: 51-58.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S. and Nampoothiri, G. 1993. The western boundary current of the seasonal subtropical gyre in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, **98**(C1): 945-954.

Shetye, S. R., Shenoi, S. S. C., Gouveia, A. D., Michael, G. S., Sundar, D. and Nampoothiri, G. 1991. Wind-driven coastal upwelling along the western boundary of the Bay of Bengal during the southwest monsoon. *Continental Shelf Research*, **11**(11): 1397-1408.

Singh, R. K. and Gupta, A. K. 2004. Late Oligocene–Miocene paleoceanographic evolution of the southeastern Indian Ocean: evidence from deep-sea benthic foraminifera (ODP Site 757). *Marine Micropaleontology*, **51**(1): 153-170.

Staubwasser, M., Sirocko, F., Grootes, P. M. and Segl, M. 2003. Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. *Geophysical Research Letters*, **30**(8): 1425

Stefanelli, S. 2004. Cyclic changes in oxygenation based on foraminiferal microhabitats: Early–Middle Pleistocene, Lucania Basin (southern Italy). *Journal of Micropalaeontology*, **23**(1):81-95.

Stefanelli, S., Capotondi, L. and Ciaranfi, N. 2005. Foraminiferal record and environmental changes during the deposition of the Early–Middle Pleistocene sapropels in southern Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **216**(1): 27-52.

Streeter, S. S. 1973. Bottom water and benthonic foraminifera in the North Atlantic—glacial-interglacial contrasts. *Quaternary Research*, **3**(1): 131-141.

Subramanian, V. and Ramanathan, A. L. 1996. Nature of sediment load in the Ganges-Brahmaputra river systems in India. J.D. Milliman and B.U. Haq (eds.), Sea-Level Rise and Coastal Subsidence. Springer Netherlands, pp: 151-168.

Tchernia, P. 1980. Descriptive Regional Oceanography. Pergamon, New York, pp. 171-215

Van Morkhoven, F. P., Berggren, W. A., Edwards, A. S. and Oertli, H. J. 1986. Cenozoic cosmopolitan deep-water benthic foraminifera. *Elf Aquitaine*,**11.**

Vinayachandran, P. N. and Mathew, S. 2003. Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones. *Geophysical Research Letters*, **30**(11): 1572

Woodruff, F. 1985. Changes in Miocene deep-sea benthic foraminiferal distribution in the Pacific Ocean: relationship to paleoceanography. *Geological Society of America Memoirs*, **163**: 131-176.

Wyrtki, K. 1971. Oceanographic atlas of the international Indian Ocean expedition. National Science Foundation, pp: 531

Yadava, M. G. and Ramesh, R. 1999. Speleothems—useful proxies for past monsoon rainfall.*Journal of Scientific and Industrial Reseach*, **58**: 339-348

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