

# Assessing the suitability of benthic foraminiferal morpho-groups to reconstruct paleomonsoon from Bay of Bengal

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Temporal changes in benthic foraminiferal morpho-groups were suggested as an effective proxy to reconstruct past monsoon intensity from the Arabian Sea. Here, in order to test the applicability of temporal variation in morpho-groups to reconstruct past monsoon intensity from the Bay of Bengal, we have documented recent benthic foraminiferal distribution from the continental shelf region of the north-western Bay of Bengal. Based on the external morphology, benthic foraminifera were categorized into rounded symmetrical (RSBF) and angular asymmetrical benthic foraminifera (AABF). Additionally, a few other dominant groups were also identified based on test composition (agglutinated, calcareous) and abundance (Asterorotalids and Nonions). The relative abundance of each group was compared with the ambient physico-chemical conditions, including dissolved oxygen, organic matter, salinity and temperature. We report that the RSBF are abundant in comparatively warm and well oxygenated waters of low salinity, suggesting a preference for high energy environment, whereas AABF dominate relatively cold, hypersaline deeper waters with low dissolved oxygen, indicating a low energy environment. The agglutinated foraminifera, Asterorotalids and Nonions dominate shallow water, low salinity regions, whereas the calcareous benthic foraminiferal abundance increases away from the riverine influx regions. Food availability, as estimated from organic carbon abundance in sediments, has comparatively less influence on faunal distribution in the northwestern Bay of Bengal, as compared to dissolved oxygen, temperature and salinity. We conclude that the factors associated with freshwater influx affect the distribution of benthic foraminiferal morpho-groups in the northwestern Bay of Bengal and thus it can be used to reconstruct past monsoon intensity from the Bay of Bengal.

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## 1. Introduction

Temporal changes in benthic foraminiferal morpho-groups, in cores collected from shallow marine regions influenced by riverine influx, were suggested as an efficient proxy to reconstruct past monsoon intensity (Nigam *et al.* 1992, 1995; Nigam and Khare 1999). The characteristic benthic

foraminiferal assemblages in river dominated ocean margins are the result of the timing and extent of unique biogeochemical processes in both the water column as well as sediment. The unique biogeochemical processes in the ocean margins where rivers join the sea are influenced by the huge riverine influx of dissolved and particulate terrestrial matter (Hedges *et al.* 1997). The fluvial input is the

**Keywords.** Benthic foraminifera; Bay of Bengal; morpho-groups; Corg; agglutinated; calcareous foraminifera; paleomonsoon.

major source of nutrients in such marginal environment and results in localized enhanced primary production (Lohrenz *et al.* 1997). This enhanced primary productivity may eventually increase the biomass and density of benthic organisms. The enhanced productivity can, however, also create hypoxic/anoxic conditions at the sediment–water interface, which can substantially reduce benthic faunal population (Kemp and Boynton 1992). Therefore, the terrigenous material brought by the rivers along with the freshwater and consequent change in energy conditions in front of the river mouths, leads to a peculiar sedimentary environment. Different colonization stages can be observed in these unique micro-environments wherein foraminifera respond with an opportunistic strategy (Fontanier *et al.* 2002, 2008; Mojtahid 2009; Goineau *et al.* 2011, 2012). The unique environmental conditions with a combination of enhanced productivity combined with low oxygen conditions in the riverine influx region thus result in reduced species diversity and predominance of a single species or a morpho-group (Severin 1983; Nigam *et al.* 1992, 2000; Nigam and Khare 1994, 1999; Jayaraju and Reddy 1997; Rana and Nigam 2009). Utilizing the presence of characteristic fauna in river-dominated marginal marine regions, the ratio of angular asymmetrical to rounded symmetrical benthic foraminifera, was suggested as a tool to reconstruct past monsoon intensity (Nigam *et al.* 1992). The method has the advantage of circumventing the need to identify all the benthic foraminifera up to species level, which is required when benthic foraminiferal species assemblages are used to reconstruct past monsoon.

The application of benthic foraminiferal morpho-groups to reconstruct past monsoon from the Arabian Sea is, however, complicated by the presence of both seasonal coastal hypoxia and perennial intermediate water depth oxygen minimum zone (OMZ) (Naqvi *et al.* 2003). The high abundance of angular asymmetrical benthic foraminifera reported from such low dissolved oxygen zones, complicates the application of relative changes in angular asymmetrical benthic foraminifera to reconstruct past monsoon (Nigam *et al.* 2007, 2009; Nagy *et al.* 2009; Mazumder and Nigam 2014). Therefore, it is necessary to further test the relationship between riverine influx and relative abundance of benthic foraminiferal morpho-groups. The heavy freshwater influx along with huge sediment load from the Ganga–Brahmaputra–Mahanadi river system controls the physico-chemical parameters of the seawater in the northwestern Bay of Bengal, which ultimately affects the benthic fauna. Therefore, the northwestern Bay of Bengal is an ideal region to test the applicability of benthic foraminiferal morpho-groups to reconstruct past monsoon.

The previous work on foraminiferal distribution along the beaches and the estuaries adjoining the Bay of Bengal was initiated by Ghosh (1966) and followed by various researchers (Bhalla 1968; Ghosh and Bhattacharjee 1993; see Khare *et al.* 2007 for a comprehensive review). Foraminifera from the Bay of Bengal have also been used to reconstruct paleomonsoon (Cullen and Duplessy 1979; Cullen 1981; Duplessy 1982; Saraswat *et al.* 2005; Rana and Nigam 2009; Panchang and Nigam 2012). Even though, extensive studies to document benthic foraminiferal distribution have been carried out along the east coast of India, no detailed study has yet been carried out to document recent benthic foraminiferal distribution and their ecological preferences from continental shelf region off Ganga–Brahmaputra–Mahanadi region. Therefore, here, we document recent benthic foraminiferal distribution from the shelf region, off the Ganga–Brahmaputra–Mahanadi river system, one of the largest freshwater influx regions. We compare the benthic foraminiferal distribution with the ambient physico-chemical conditions, to understand and test the relationship between benthic foraminiferal morpho-groups and riverine influx. Other than the rounded symmetrical and angular asymmetrical benthic foraminifera, we have also studied the factors that control spatial distribution of total, calcareous, agglutinated and a few dominant benthic foraminiferal taxa in the northwestern Bay of Bengal.

## 2. Environmental settings

The northwestern Bay of Bengal receives immense volume of fresh water and sediment from three major river systems, viz., Ganga, Brahmaputra and Mahanadi. The total annual freshwater influx into the entire Bay is 2950 km<sup>3</sup> (Sengupta *et al.* 2006), out of which Ganga and Brahmaputra rivers annually discharge  $\sim 10^{12}$  m<sup>3</sup> of fresh water into the Bay of Bengal at its northern end (Shetye 1993). More than 72% of this discharge occurs between June and September, the southwest monsoon period (Unger *et al.* 2003) and carries heavy sediment load ( $1670 \times 10^6$  t/yr) with it. A major part of the riverine terrigenous input is deposited within the continental shelf region close to the river outlet, thus forming a delta, viz., Sunderbans (Milliman and Meade 1983). The delta is about 360 km wide, along the Bay of Bengal (Islam and Gnauck 2008). The fluvial input is the major source of nutrients to the Bay of Bengal. The annual supply of nutrients by Ganga and Brahmaputra rivers to the Bay of Bengal is  $133 \times 10^9$  mol/year, which is  $\sim 2\%$  of the riverine input to the world ocean (Sarin *et al.* 1989). As a result of this heavy

freshwater influx, salinity of the surface water is 3–7 psu lower in the Bay of Bengal throughout the year as compared to that in the Arabian Sea (Varkey *et al.* 1996). The heavy freshwater influx also causes strong water column stratification (Shetye *et al.* 1991; Shetye 1993). The Bay is considered to be a region of low biological productivity due to various reasons including narrow shelf, cloud cover during summer monsoon, turbidity resulting from sediment influx (Prasanna Kumar *et al.* 2010) and freshwater-induced water column stratification (Qasim 1977; Gomes *et al.* 2000). The sea surface salinity varies from 26 to 31 psu in summer and between 27 and 31 psu in winter. The bottom water salinity ranges from 32.87 (at 28 m water depth) to 34.87 psu (at 120 m water depth). The sea surface temperature (SST) in the northwestern Bay of Bengal varies from 28.5° to 29.0°C during summer monsoon and from 26° to 28°C during the winter monsoon. The bottom temperature ranges from 18° (at 120 m water depth) to 27.54°C (at 28 m water depth). The annual mean bottom water dissolved oxygen concentration varies from 0.43 (at 120 m water depth) to 3.9 ml/l (at 29 m water depth).

Latitudinal and seasonal variations are noted in the northwestern Bay of Bengal OMZ, which varies from ~100 to 800 m water depth (Wyrтки 1971; Naqvi *et al.* 1979; Rao *et al.* 1994).

### 3. Materials and methodology

The top 0–1 cm section of 22 box cores (SC 01–SC 22), collected from the northwestern Bay of Bengal (BoB), from a depth of 28–120 m, during the 35th cruise of *RV Sindhu Sankalp* (SSK 35), have been used (figure 1, table 1). The standard procedure was followed for the processing of sediment samples for foraminiferal studies. An appropriate amount (5–10 g) of sediment sample was collected in pre-weighed and properly labelled petri-dish. The petri-dish was covered by aluminum foil and frozen for 24 hours at –30°C. The frozen samples were transferred to freeze drier. The dried sediment samples were weighed and transferred to 1000 ml beakers. The samples were soaked in distilled water. After 24 hr, the overlying water was decanted to remove fine colloidal suspended

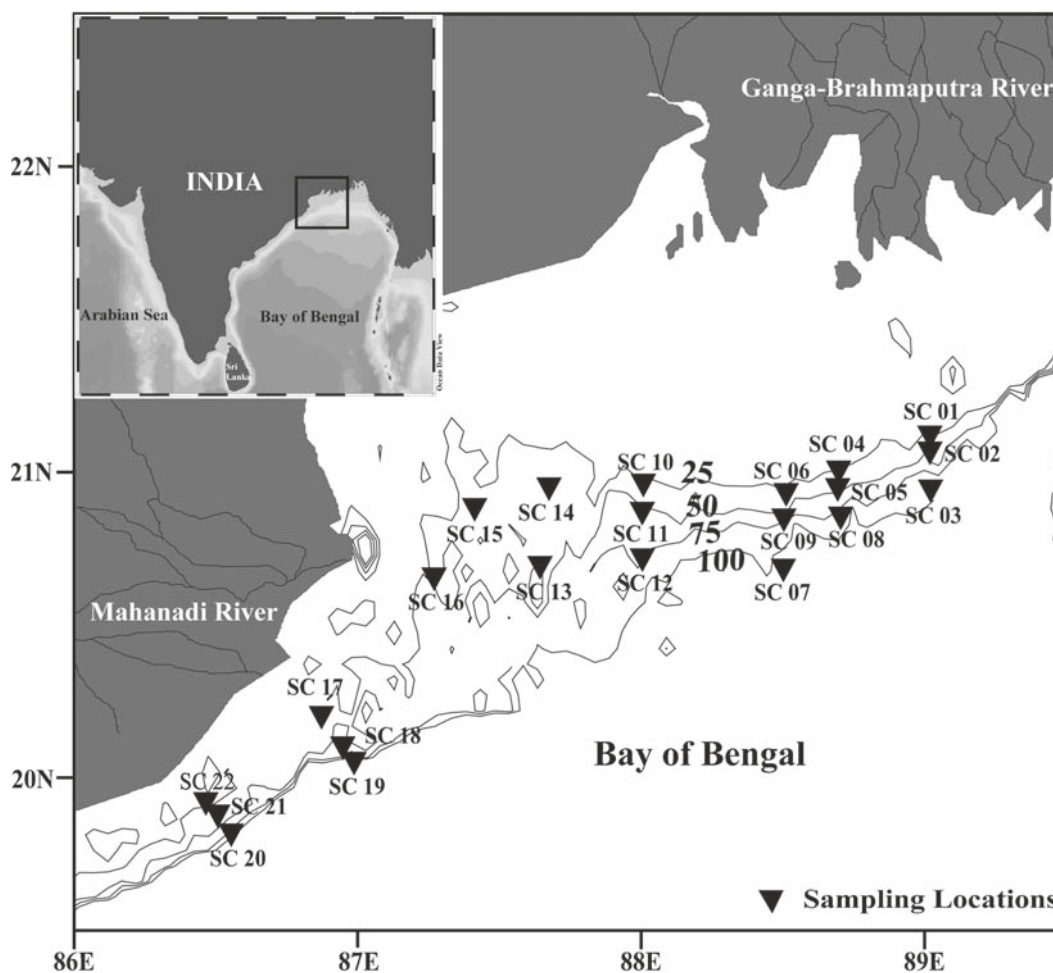


Figure 1. Map showing the sampling locations and bathymetry of the study area.

Table 1. Details of the sample locations and environmental parameters in the study area.

Sl. no.	Sample	Longitude (°E)	Latitude (°N)	Depth (m)	Dissolved Oxygen (ml/l)	T (bottom) (°C)	Salinity (bottom) (psu)	TIC (%)	C <sub>org</sub> (%)	Dry sediment (g)	Coarse fraction (%)	Split CF taken for picking (g)
1	SC-01	89.0186	21.1137	31.0	3.81	27.44	33.086	0.24	0.79	4.0838	2.35	0.0960
2	SC-02	89.0185	21.0612	49.0	3.44	26.10	33.986	0.31	0.75	4.7845	6.54	0.2524
3	SC-03	89.0212	20.9372	104.0	0.62	19.96	34.801	0.32	0.56	5.2131	0.25	0.0097
4	SC-04	88.6967	20.9990	29.0	3.87	27.51	33.023	0.31	0.66	7.3753	6.35	0.3512
5	SC-05	88.6935	20.9415	44.0	3.56	26.48	33.743	0.26	0.76	5.4017	7.85	0.2012
6	SC-06	88.5113	20.9255	35.5	3.73	27.11	33.366	0.29	0.68	8.1249	5.53	0.4293
7	SC-07	88.5018	20.6781	120.0	0.43	18.56	34.874	0.29	1.04	3.9665	0.59	0.0169
8	SC-08	88.7039	20.8484	94.0	1.29	21.04	34.739	0.21	0.88	5.2613	0.33	0.0119
9	SC-09	88.5035	20.8425	78.5	1.59	23.05	34.594	0.35	0.61	8.3943	1.53	0.1219
10	SC-10	88.0078	20.9563	31.0	3.81	27.44	33.086	0.43	0.48	8.8336	19.39	1.6938
11	SC-11	88.0040	20.8640	59.5	2.79	25.06	34.237	0.30	0.74	7.1454	1.95	0.0366
12	SC-12	88.0044	20.7117	83.0	1.37	22.44	34.636	1.25	0.16	5.7570	84.02	1.5043
13	SC-13	87.6433	20.6870	54.0	3.17	25.63	34.105	2.61	0.54	9.9958	43.79	0.0313
14	SC-14	87.6750	20.9441	42.0	3.62	26.63	33.630	0.72	0.19	13.732	85.34	3.9125
15	SC-15	87.4127	20.8765	36.0	3.72	27.07	33.379	0.42	0.74	7.6086	97.59	0.9222
16	SC-16	87.2698	20.6493	28.0	3.9	27.54	32.874	0.28	0.75	3.8805	6.30	0.0583
17	SC-17	86.8725	20.1959	34.0	3.75	27.22	33.278	0.43	0.62	9.9958	28.04	0.2684
18	SC-18	86.9475	20.0964	54.0	3.17	25.63	34.105	0.37	0.75	8.3690	3.76	0.0339
19	SC-19	86.9875	20.0461	96.0	0.81	20.78	34.751	0.21	1.14	4.9492	0.49	0.0184
20	SC-20	86.5541	19.8114	107.0	0.57	19.68	34.82	0.16	1.15	4.7757	1.17	0.0217
21	SC-21	86.5067	19.8733	47.0	3.49	26.25	33.933	0.15	0.87	6.2861	1.69	0.1218
22	SC-22	86.4645	19.9140	36.0	3.72	27.07	33.379	0.16	1.10	7.8100	2.66	0.2077

organic matter. The beakers were re-filled with distilled water and the procedure was repeated until the overlying water was clear. The water from the beakers was finally decanted. The wet sediment samples were sieved through a 63  $\mu\text{m}$  mesh with very low water pressure to prevent foraminiferal test breakage. The >63  $\mu\text{m}$  fraction (coarse fraction) was transferred to a glass beaker and dried overnight. The dried coarse fraction was weighed and stored in plastic vials.

Foraminifera were picked from a representative fraction taken out of the total coarse fraction by coning and quartering, by using Olympus SZX 12 stereozoom microscope. A minimum of 300 benthic foraminifera were picked from each sample. In case of lack of specimens, the total coarse fraction was used to pick all the available benthic foraminifera, which at times yielded less than 300 specimens. Based on the external morphology and test composition, benthic foraminifera were classified into several groups, viz., rounded symmetrical forms, angular asymmetrical forms, agglutinated, calcareous and a few abundant genera, namely Asterorotalids and Nonions. The morpho-group assemblage was analyzed by hierarchical agglomerative clustering on the square root transformed abundance data. Similarity percentage program (SIMPER) was then used to identify the morpho-group contributing to the similarity within the cluster and

those morpho-groups responsible for dissimilarity between clusters. Indicator and discriminating groups were identified based on average similarity (dissimilarity)/standard deviation ratio and percentage similarity/dissimilarity contribution. A group with large similarity/dissimilarity percentage and small SD value will have large similarity (dissimilarity)/standard deviation ratio and hence are considered to be significant indicator/discriminating group (Clarke and Warwick 2001). A reliable indicator group will have high abundance across the stations (high percentage similarity) and consistent abundance (high SIM/SD ratio), while a reliable discriminating group will have the highest abundance (highest percentage dissimilarity) in one cluster, but will be rare in the other cluster. The environmental variables (salinity, temperature and dissolved oxygen) for each sampling location are the annual means downloaded from the World Ocean Atlas 2009 by using the Ocean Data View website (Schlitzer 2015) (table 1). The total inorganic carbon (TIC) was measured by UIC CM 5014 coulometer after acidification of the sample with 1N HCl and measuring the CO<sub>2</sub>. The analytical accuracy is  $\pm 0.43\%$  and precision for total inorganic carbon analysis is  $\pm 0.95\%$ . Total carbon (TC) was measured with a CE NCS 2500 elemental analyzer.

In order to identify the relationship between various morpho-groups and environmental parameters, a canonical correspondence analysis (CCA) was performed. In ecological studies, multivariate statistical methods are widely used to characterize community structures and to quantify the relationship between communities and environmental parameters (Ramette 2007). By using multivariate analysis such as CCA, faunal data can be directly related to environmental parameters, thus allowing a more comprehensive analysis of foraminiferal ecology. The CCA is a direct gradient analysis, which generates axes that maximize the dispersion of the species scores and that are constrained to be a linear combination of the measured environmental variables (ter Braak 1986). The CCA analysis was carried out by using MVSP program, version 3.22.

## 4. Results

### 4.1 Coarse fraction ( $>63 \mu\text{m}$ )

The coarse fraction ( $>63 \mu\text{m}$ ) percentage is high in the region in-between Ganga–Brahmaputra and Mahanadi rivers (figure 2a). The coarse fraction percentage decreases away from the river mouth, with increasing water depth in front of Mahanadi River. The lowest coarse fraction percentage is at station 3 (SC 03, at 104 m water depth) ( $\sim 0.2\%$ ) while the highest abundance ( $\sim 98\%$ ) is at the relatively shallow water station 15 (SC 15, 37 m water depth).

### 4.2 Total foraminiferal number (TFN)

Foraminiferal abundance varies from  $\sim 25$  to  $\sim 5100/\text{g}$  dry sediment (figure 2b). The TFN is

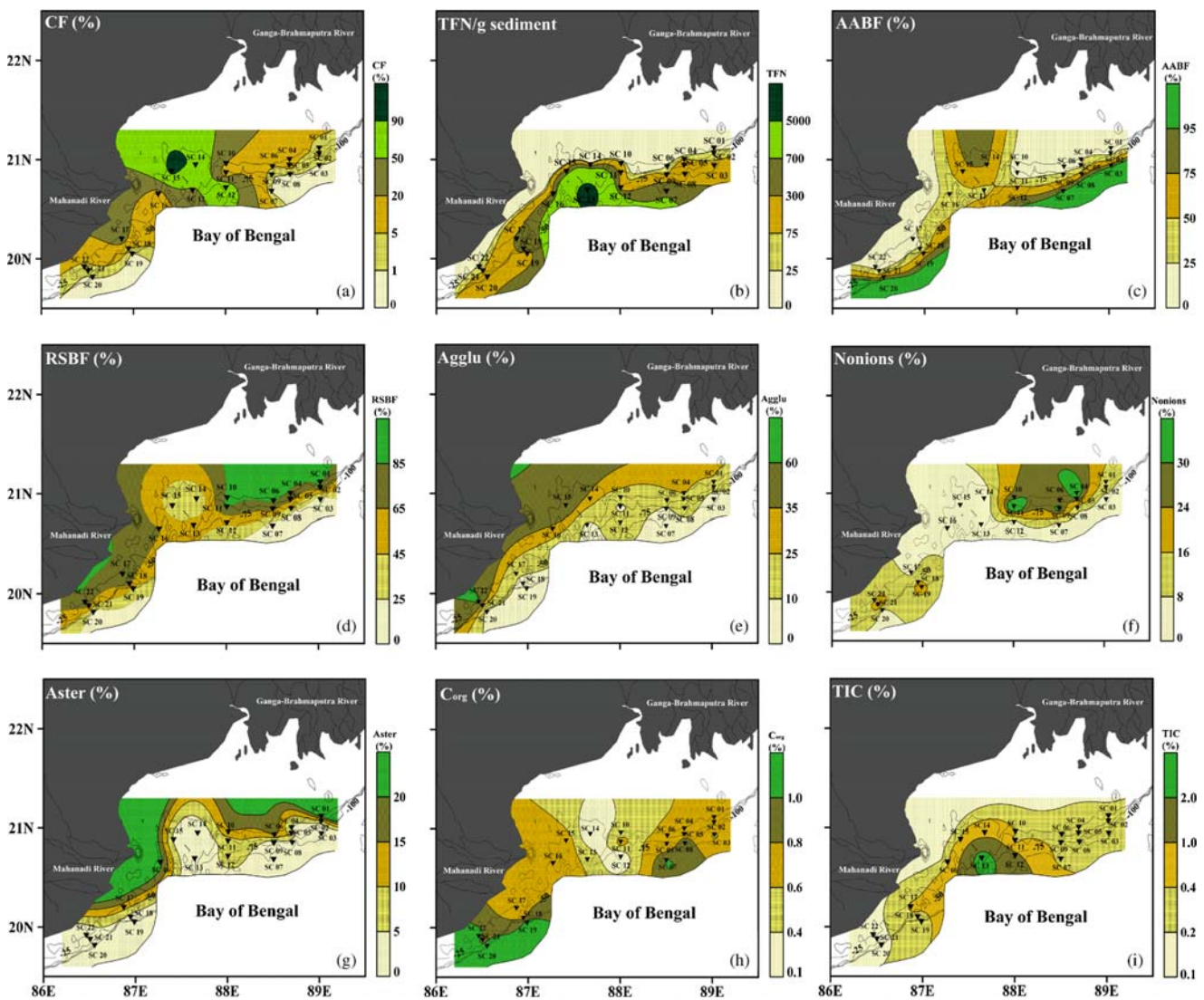


Figure 2. Distribution of (a) the coarse fraction, (b) total foraminiferal number (TFN), (c) angular asymmetrical benthic foraminifera (AABF), (d) rounded symmetrical benthic foraminifera (RSBF), (e) agglutinated foraminifera, (f) Nonions, (g) Asterorotalids, (h) organic carbon ( $C_{org}$ ), and (i) total inorganic carbon (TIC) in the continental shelf region of northwestern Bay of Bengal.

highest at station 13 (SC 13, 54 m water depth) (~5100/g sediment), located in-between the two river outlets, and the lowest at station 01 (SC 01, 31 m water depth), which is located in the north-western part of the study area, right in front of the Ganga–Brahmaputra river mouth. Relict benthic foraminifera were found at two stations, SC 12 and SC 16 at a water depth of 83 and 28 m, respectively. The relict benthic foraminifera are rare at both the stations and have not been included to calculate total foraminiferal abundance. The relict foraminifera, usually devoid of ornamentation, dull in luster and filled with secondary material, represent past low sea-stand and somehow escaped burial and remained exposed for a very long-time (Rana et al. 2007; Panchang et al. 2008).

#### 4.3 Angular asymmetrical benthic foraminifera

Angular asymmetrical benthic foraminifera (AABF) are elongate uni-, bi- and tri-serial flattened rectilinear forms. The group included genera like *Bolivina*, *Brizalina*, *Bulimina*, *Uvigerina*, and *Stainforthia*. The abundance of angular asymmetrical foraminifera varies from ~12 to ~96% (figure 2c), with the highest abundance (~96%) observed at station SC 03 (104 m water depth). The AABF abundance is also high at stations SC 07 (at 120 m water depth), and SC 20 (107 m water depth) (table 2). The AABF abundance is very low in front of the rivers and increases towards the southern

part of the study area, away from the riverine outlets with increasing water depth and decreasing dissolved oxygen level.

#### 4.4 Rounded symmetrical benthic foraminifera

The abundance of rounded symmetrical benthic foraminifera (RSBF) is comparatively lower than that of angular asymmetrical benthic foraminifera. It varies from ~4% to ~88%, with the highest abundance observed at station SC 10 (at 31 m water depth). The RSBF abundance is >80% in SC 01 (at 31 m water depth), SC 02 (at 49 m water depth), SC 06 (at 35.5 m water depth), SC 11 (at 59.5 m water depth), and SC 22 (at 36 m water depth) (table 2). The RSBF abundance is very high in the shallow water regions in front of river outlets (figure 2d). These stations are in turn highly influenced by the freshwater discharge. The RSBF abundance decreases with an increase in distance from the coast or the distance from the river outlet with increasing water depth and decrease in dissolved oxygen level. This group included genera like *Elphidium*, *Ammonia*, *Asterorotalia*, *Cancris*, *Nonion*, *Nonionella*, and *Lenticulina*.

#### 4.5 Agglutinated and calcareous foraminifera

A significant number of agglutinated foraminifera are also found in the northwestern BoB. Agglutinated benthic foraminiferal abundance varies from

Table 2. Relative abundances of morpho-groups in the northwestern BoB.

Sl. no.	Sample no.	Specimens picked	TFN/g sediment	AABF (%)	RSBF (%)	Asterorotalids (%)	Nonions (%)	Agglutinated foraminifera (%)	Calcareous foraminifera (%)
1	SC-01	104	25	13	87	24	11	23	77
2	SC-02	128	33	18	82	7	14	14	86
3	SC-03	401	102	96	4	0	2	2	98
4	SC-04	415	75	22	78	5	36	26	74
5	SC-05	412	161	22	78	10	28	16	84
6	SC-06	421	54	13	87	15	21	19	81
7	SC-07	1860	655	93	7	0	1	3	97
8	SC-08	392	107	69	31	0	10	17	83
9	SC-09	406	51	29	71	0	36	7	93
10	SC-10	1208	138	12	88	14	26	20	80
11	SC-11	379	201	13	87	7	46	4	96
12	SC-12	278	155	54	46	8	1	24	76
13	SC-13	370	5177	47	53	0	5	6	94
14	SC-14	393	86	75	25	1	1	31	69
15	SC-15	388	411	67	33	4	1	49	51
16	SC-16	313	338	34	66	22	6	32	68
17	SC-17	332	347	23	77	13	6	13	87
18	SC-18	385	427	27	73	3	17	5	95
19	SC-19	327	87	65	35	0	18	7	93
20	SC-20	379	204	88	12	0	5	4	96
21	SC-21	455	63	29	71	2	30	25	75
22	SC-22	329	42	20	80	0	13	63	37

~2 to ~63% (figure 2e) with the highest (63%) at location SC 22 (at 36 m water depth). A relatively high agglutinated foraminiferal abundance is also recorded at locations 14, 15 and 16 (SC 14, SC 15 and SC 16). The abundance of the agglutinated foraminifera is more in the shallower part of the northwestern Bay of Bengal, near the river mouths. The calcareous foraminifera, on the other hand, show an opposite trend to that of agglutinated foraminifera. The abundance varies from ~37% to ~98%, and is comparatively higher in the deeper locations.

#### 4.6 Nonions

Nonions abundance varies from 1 to 46% (figure 2f). Nonions are abundant at location number 4, 9 and 21 (SC 04, water depth 29 m; SC 09, water depth 78 m; and SC 21, water depth 47 m), right in front of the river mouths. The relative abundance of Nonions is relatively high in front of Ganga–Brahmaputra river mouth as compared to that in front of Mahanadi River.

#### 4.7 Asterorotalids

Asterorotalids are found in 14 out of the total 22 samples. The abundance of Asterorotalids varies from 0 to 24% (figure 2g). The highest abundance of Asterorotalids is at location 01 (SC-01) (at 31 m water depth) (table 2), again right in front of the river mouth, while the abundance is very low in the deeper parts of the northwestern Bay of Bengal. Asterorotalids abundance is relatively high in front of Ganga–Brahmaputra river mouth as compared to that in front of Mahanadi River.

The relative abundance of Asterorotalids is low in the region in-between Ganga–Brahmaputra and Mahanadi river outlets. A few specimens of *Asterorotalia* in the northwestern Bay of Bengal have less than three or at times more spines. Ghosh (1966) also recorded *Asterorotalia* with one to four spines and considered them to be aberrant forms.

#### 4.8 Total organic carbon ( $C_{org}$ ) and total inorganic carbon (TIC)

The % $C_{org}$  varies from 0.15 to 1.2% (dry weight) (figure 2h). The lower % $C_{org}$  is observed in relatively coarse grained sediments in-between the Ganga–Brahmaputra and Mahanadi river mouths (SC 12 and SC 14), while the high % $C_{org}$  is reported at relatively deeper locations dominated by fine-grained sediments (SC 07, SC 19, SC 20 and SC 22). TIC, includes both the *in-situ* biogenic carbonate as well as that brought from the land by the rivers. The TIC is very low in large part of the northwestern Bay of Bengal. The TIC in the northwestern Bay of Bengal varies from 0.1 to 2.6% (dry weight) (figure 2i) and is the highest at location 13 and 12. The lowest %TIC is reported in front of the river mouths. As the larger fraction of TIC comprise of benthic foraminiferal calcareous shells, it is clear that low TIC indicates less abundance of calcareous benthic foraminifera. In the discussion section, TIC distribution is further compared and discussed with the total foraminiferal abundance.

#### 4.9 Cluster analysis

The cluster analysis produced a dendrogram with four clusters at 75% similarity level (figure 3). The

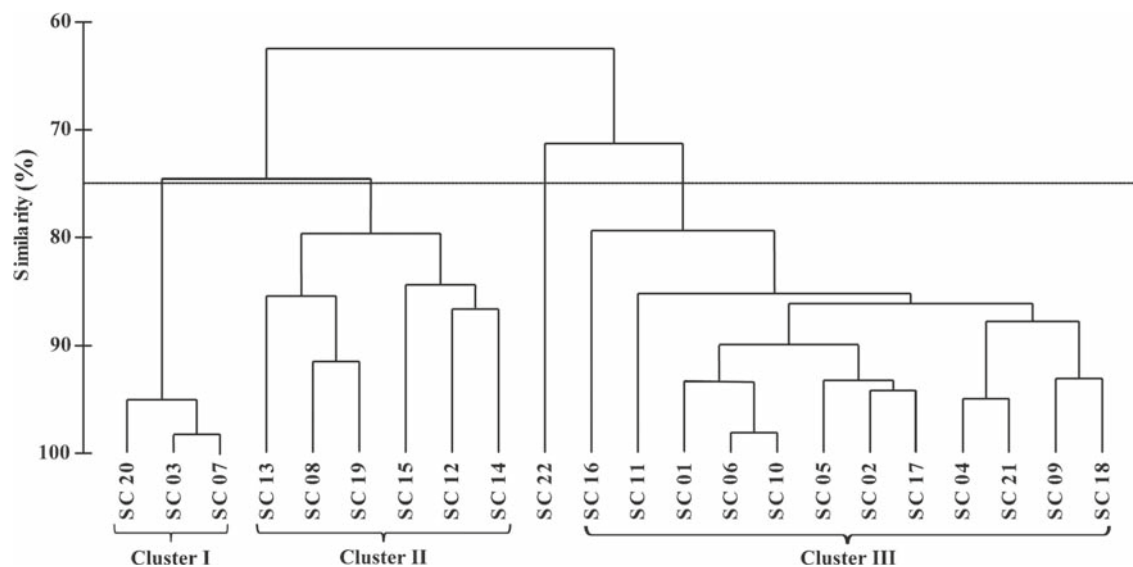


Figure 3. The cluster analysis dendrogram of sample stations. The arbitrary value of 75% similarity that represents a statistically significant cluster is marked by horizontal dark black line.

Table 3. SIMPER analysis based on groups obtained from Bray–Curtis cluster.

Species	Av. abund.	Av. sim.	Sim/SD	Contrib.%	Cum.%
Cluster I					
Average similarity: 86.58					
Calcareous forms	90.04	40.89	5.62	47.23	47.23
AABF	87.95	40.63	9.88	46.93	94.16
Cluster II					
Average similarity: 82.09					
Calcareous forms	79.26	33.32	4.35	40.59	40.59
AABF	60.28	26.28	7.25	32.02	72.6
RSBF	37.66	15.9	14.26	19.37	91.97
Cluster III					
Average similarity: 86.49					
Calcareous forms	83.05	33.43	11.54	38.65	38.65
RSBF	78.47	31.68	11.66	36.63	75.28
AABF	21.26	7.28	3.06	8.42	83.7
Nonions	23.09	6.58	1.76	7.6	91.3

Cluster I consists of locations SC 20, SC 03 and SC 07 and is dominated by AABF and calcareous foraminifera. Cluster II consists of SC 13, SC 08, SC 19, SC 15, SC 12 and SC 14. Calcareous and AABF contributed to the similarity of this cluster as well, but the substantial abundance of RSBF distinguishes this cluster from Cluster I. The third cluster which includes stations SC 16, SC 11, SC 01, SC 02, SC 04, SC 05, SC 06, SC 08, SC 09, SC 10, SC 17 and SC 21, is although again dominated by calcareous foraminifera, also has large abundance of both the RSBF and AABF, along with Nonions, which are the better discriminators in Cluster III (table 3). Cluster IV comprising of only one station, viz., SC 22 is an outlier due to the highest abundance of agglutinated foraminifera (63.22%).

#### 4.10 Correlation with environmental factors (CCA plot)

A canonical correspondence analysis was performed to evaluate how well the environmental variables explain the distribution of identified morpho-groups. The length of the environmental arrow indicates the influence of the variable on the two axes. The significant environmental variables therefore tend to be represented by longer arrows than less important environmental variables which are represented by smaller arrow length (ter Braak 1986). The angle between the arrows and the axes is inversely proportional to the correlation between the environmental variable and the axes. On the biplot, the position of morpho-group is projected perpendicularly on to the environmental arrows to understand their weighed average optima along each environmental variable. The environmental conditions responsible for the development

of a characteristic morpho-group/assemblage can be identified by this method. The first two axes explained 89% of the relationship between environment variable and foraminiferal distribution (figure 4). Temperature, dissolved oxygen and salinity were the most important environmental variables influencing the distribution as compared to the CF% and %C<sub>org</sub>. Total inorganic carbon although included in the CCA, is not depicted in the biplot as its length is less than one-tenth of the either axis (one of the optional criteria for displaying environmental variables), suggesting that it is not one of the important environmental variables influencing the benthic foraminiferal morpho-group distribution, in the study area. AABF showed a preference for higher salinity, lower temperature and low dissolved oxygen. Contrary to that, RSBF are positively correlated with both the temperature and dissolved oxygen and negatively correlated with salinity. Agglutinated foraminifera prefer warmer water, high dissolved oxygen and also higher percentage of coarse fraction but low salinity. Even though, the calcareous foraminifera showed a preference towards higher %C<sub>org</sub> and salinity, it is difficult to state the preference of this group with confidence, as it falls near the center of the biplot. Nonions are positively correlated with temperature, dissolved oxygen and negatively correlated with salinity. Asterorotalids prefer warmer temperature and high dissolved oxygen and low saline waters.

## 5. Discussion

The spatial distribution and population density of benthic foraminifera is controlled by numerous physico-chemical parameters such as organic matter



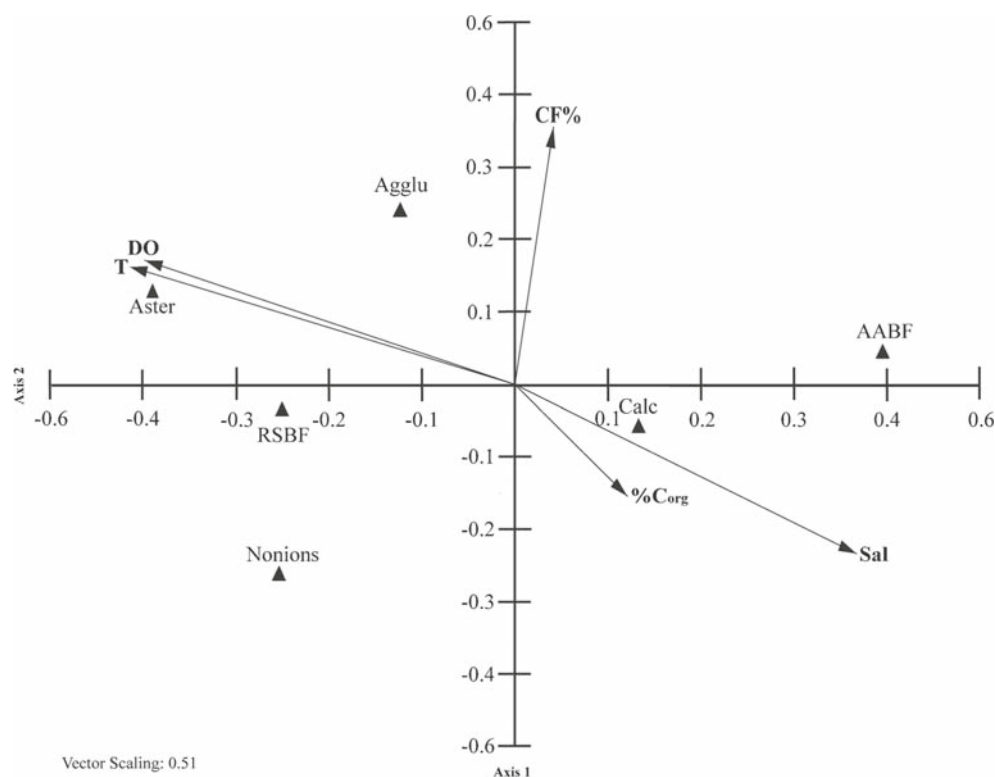


Figure 4. CCA biplot of benthic foraminiferal morpho-groups (inverted triangle) and environmental variables (arrow). Environmental abbreviations: Sal=Salinity, CF%=Coarse fraction percentage, T=Temperature, DO=Dissolved Oxygen, %C<sub>org</sub>=Organic Carbon. Morpho-group abbreviations: AABF=Angular Asymmetrical Benthic Foraminifera, Agglu=Agglutinated Foraminifera, Calc=Calcareous forms, RSBF=Rounded Symmetrical Benthic Foraminifera, Aster=Asterorotalids, Nonion=Nonions.

flux, oxygen availability, sea-water temperature, salinity, distance from the river mouth, extent of bioturbation, substrate, water depth and other related factors (Corliss and Fois 1990; Gooday 2003; Murray 2006; Jorissen *et al.* 2007). The relative effect of any of these factors, however, varies from location to location. In the northwestern Bay of Bengal, at comparable water depths, TFN is relatively higher in the region in-between the Ganga–Brahmaputra and Mahanadi influx regions as compared to the region right in front of these rivers. The increase in TFN away from the river mouth, suggests that the less turbid and low energy environment is conducive for foraminifera. As the distance from the river mouth increases, the salinity also increases, which is also responsible for the high foraminiferal abundance. The salinity in the study area depends on the freshwater discharge from the three river systems, viz., Ganga–Brahmaputra–Mahanadi. Foraminiferal abundance in the riverine influx dominated continental shelf region of the northwestern Bay of Bengal deviates from the widely accepted, generalized TROX model (Jorissen *et al.* 1995). We suggest that TROX model may not be able to explain benthic foraminiferal abundance in river-dominated very shallow continental shelf regions.

The oxygen deficiency is another factor, which controls benthic foraminiferal distribution in the northwestern Bay of Bengal. The locations marked by low dissolved oxygen have high C<sub>org</sub> and increased abundance of fine-grained sediments. Although, such locations are in line of the river discharge they are towards the deeper side. The high benthic foraminiferal abundance at these locations can thus be explained with a combination of physico-chemical and biological factors. The freshwater influx from the river brings enormous quantity of nutrients, which enhances the productivity in the area and increases the food availability for foraminifera. A close relationship exists between abundance of benthic foraminifera and organic matter flux (Gooday 1993; Jorissen *et al.* 1992; Wahyudi and Minagawa 1997; Jorissen 1999). According to Setty and Nigam (1982), low organic carbon content is attributed to low input of organic matter, rapid decay, low sedimentation rate, arid conditions, sparse vegetation and lack of inflow from the surrounding terrains. All or a few of these factors can lead to low %C<sub>org</sub>. Therefore, the high %C<sub>org</sub> in front of the river mouths is attributed to better preservation in fine-grained sediments with high sedimentation rate. The highest %C<sub>org</sub> in the deeper part of the study area

probably indicates high surface water productivity in less turbid regions (Prasanna Kumar *et al.* 2010). The high productivity with freshwater influx induced stratification, at deeper locations, results in low dissolved oxygen concentration (Sarma *et al.* 2013). Very high organic-matter flux in these areas induces severe oxygen depletion and only low oxygen tolerant taxa are able to survive in such low oxygen environment, resulting in increased abundance of a few opportunistic species (Sen Gupta and Machain-Castillo 1993; Jorissen *et al.* 1995; den Dulk *et al.* 1998; Jannink *et al.* 1998; Bernhard and Sen Gupta 1999; Kitazato *et al.* 2000; Schumacher *et al.* 2007; Glock *et al.* 2013; Caille *et al.* 2013, 2015). Additionally, low dissolved oxygen is detrimental to large benthic organisms resulting in low bioturbation (Diaz and Rosenberg 2008; Sturdivant *et al.* 2012). The low bioturbation and increased amount of food will result in increased benthic foraminiferal population. The foraminiferal number is well correlated with TIC. However, the highest foraminiferal abundance is in a coarse fraction dominated station where TIC is also high. Here we would like to state that at few stations, benthic foraminiferal population is large enough to substantially influence the inorganic carbon content of the sediments.

From the plot (figure 2c), it is clear that the abundance of angular forms increases with distance from the river mouth as well as increase in organic carbon content and decreasing dissolved oxygen concentration. The CCA biplot confirms the high salinity (an indicator of distance from the riverine influx which brings freshwaters and thus lowers the salinity) and low dissolved oxygen preference of AABF (Buzas *et al.* 1993). Previously, relatively higher abundance of AABF has been reported from oxygen-depleted environments (Sen Gupta and Machain-Castillo 1993; Nigam *et al.* 2007; Schumacher *et al.* 2007; Nagy *et al.* 2009; Caille *et al.* 2014). Additionally, we observe that the relative abundance of AABF also increases with decreasing sea-water temperature. But, the AABF abundance in the northwestern Bay of Bengal does not uniformly increase with increasing water depth, especially in the region falling in-between the riverine influx area. Therefore, it is difficult to say whether the AABF abundance has a clear relationship with water depth. Therefore, based on the spatial distribution and the CCA plot, we conclude that the abundance of AABF is inversely related to the amount of freshwater influx in the northwestern Bay of Bengal. A huge amount of freshwater input from the rivers creates high energy environment in front of the river mouths, which adversely affects the abundance of angular asymmetrical foraminifera. A similar relationship between angular asymmetrical forms and the

freshwater influx has also been reported from the northern Indian Ocean (Nigam 1993; Nigam and Khare 1994 (from west coast); Jayaraju and Reddy 1997; Rana and Nigam 2009 (from east coast)). Based on the CCA plot of the available data, we report that in the northwestern Bay of Bengal, low dissolved oxygen and sea-water temperature exert a dominant control on the relative abundance of AABF, as compared to the freshwater influx.

As compared to the AABF, RSBF are abundant in the shallow water regions, highly influenced by the three river systems and hence, are the indicators of turbulent environment, as observed in deeper mixed layer depths in the northwestern Bay of Bengal (Chamarthi and Rao 2007). The riverine influx also decreases the sea-water salinity of the northwestern Bay of Bengal (Sengupta *et al.* 2006; Durand *et al.* 2011) and hence the abundance of RSBF in the shallow water regions suggests that such forms can survive in the low salinity environment. In the northwestern Bay of Bengal, the river discharge is largely due to monsoon precipitation. The fluctuations in riverine influx are related to the changes in monsoon intensity in the adjacent areas (Durand *et al.* 2011). Therefore, we suggest that changes in relative abundance of AABF and RSBF can be effectively used for the paleomonsoon reconstruction and freshwater intensity reconstruction from the core collected from the northwestern Bay of Bengal, as previously applied in the Arabian Sea and central Bay of Bengal (Nigam *et al.* 1992; Nigam and Khare 1994; Rana and Nigam 2009).

Based on the CCA plot, we report that agglutinated benthic foraminifera prefer low saline, relatively warmer and well-oxygenated waters. Additionally, the relative abundance of agglutinated foraminifera increases with an increase in abundance of coarser fraction. The previous studies from different parts of the world also suggest that the agglutinated foraminifera are more abundant in low saline, sandy substrate (Hayward and Hollis 1994; Murray *et al.* 2003). The increased relative abundance of agglutinated foraminifera in shallow water regions marked by low salinity is attributed to carbonate undersaturated waters as well as carbonate dissolution prevalent in these regions (Murray and Alve 2011). The studies on agglutinated foraminifera have suggested that in general, agglutinated foraminifera are less tolerant to low-oxygen conditions than calcareous foraminifera (Moodley *et al.* 1997; Neira *et al.* 2001; Gooday *et al.* 2009). Present study also confirms the strong influence of dissolved oxygen and warmer water on the relative abundance of agglutinated benthic foraminifera in front of the Ganga–Brahmaputra–Mahanadi river system (figure 4). Based on the CCA plot, we report that calcareous foraminifera prefer high %C<sub>org</sub> and salinity but it is difficult to

state the preference of this group with confidence, as it falls near the center of the biplot. The spatial distribution, however, suggests that the calcareous foraminifera are more abundant in deeper regions away from the riverine influx. The higher salinity and relatively low energy environment, probably favours calcareous benthic foraminifera. Boltovskoy and Wright (1976) reported that the solubility of  $\text{CaCO}_3$  is proportional to salinity of the sea-water. Therefore, as the salinity decreases, the concentration of  $\text{CaCO}_3$  also decreases which in turn lowers the growth of foraminifera. Laboratory culture studies also confirm decreased growth and even reproduction in benthic foraminifera under hyposaline conditions (Nigam *et al.* 2006, 2008).

Nonions being round in shape, can survive in high energy environment as they are found in the inner shelf region (0–100 m water depth) (Murray 1991; Nigam *et al.* 1992; Nigam and Khare 1994). According to Murray (2006), the salinity preference of Nonions ranges from 32–35 psu. But in the north-western Bay of Bengal, the abundance of Nonions is more, near the river mouth where salinity is comparatively low (34.237 psu, at 59.5 m water depth) while the dissolved oxygen is high. The abundance decreases as the distance from the river mouth increases. Duijnsteet *et al.* (2004) reported that *Nonionella turgida* is negatively correlated with the bottom-water temperature and positively related to bottom water oxygenation. Contrary to this, Mojtahid *et al.* (2010) reported that maximum abundances of *Nonian scaphum* and *Nonionella turgida* found to occur in deep below in the sediment, below the limit of oxygen penetration. Gooday and Rathburn (1999) also stated that *Nonionella* have an ability to tolerate oxygen depletion resulting from the oxidation of organic carbon, in continental slope regions. According to Alve (2010), *Nonionella iridea* depends on seasonal supply of fresh phytodetritus to sustain its populations. *Nonionella iridea* have been recorded in sediments rich in organic carbon (Mackensen *et al.* 1985; Mackensen and Hald 1988). Based on the CCA plot, we suggest that the relative abundance of Nonions in the northwestern Bay of Bengal is strongly related with warmer, well oxygenated and low saline water.

Panchang and Nigam (2012) and Rao *et al.* (2013) studied the ecology of *Asterorotalia trispinosa*, in front of the Irrawaddy river delta and Muthupet Lagoon and concluded that *Asterorotalia* prefers low salinity and fine grained substrate. In the present study, based on CCA analysis, we report that Asterorotalids in the northwestern Bay of Bengal are affected not only by salinity, but also by temperature and dissolved oxygen concentration. Furthermore, CCA plot also showed that Asterorotalids prefer warmer, well oxygenated and

low saline water. The surface distribution of Asterorotalids in the northern Bay of Bengal in front of rivers Ganga–Brahmaputra and Mahanadi also confirms that Asterorotalids prefer low salinity environment. But Murray (1991), found *Asterorotalia* in the less oxygenated waters of inner shelf regions of Andaman Sea.

## 6. Conclusions

Based on the distribution of benthic foraminifera in the surface sediments, collected from the north-western Bay of Bengal in front of the Ganga–Brahmaputra–Mahanadi river systems, we report that TFN is relatively higher in the region in-between the Ganga–Brahmaputra and Mahanadi influx regions as compared to the region right in front of these rivers, suggesting the influence of high energy, as well as  $\%C_{\text{org}}$  and only at few stations grain-size. The high abundance of RSBF indicates highly oxygenated warmer low saline water, which conforms with high energy environment, whereas the increased abundance of AABF indicates relatively cold and more saline water with low dissolved oxygen and higher  $\%C_{\text{org}}$  suggesting a preference for low energy environment. We further conclude that Asterorotalids and Nonions prefer low salinity, warmer water with high dissolved oxygen, whereas agglutinated benthic foraminifera can survive in low saline warm water with high dissolved oxygen as well as in coarse-grained sediments, again suggesting preference for high energy environment. Thus, the different benthic foraminiferal morpho-groups show different ecological preferences, with abundance being controlled by energy condition, salinity, temperature, dissolved oxygen and total organic carbon. The findings of this study will help us to better understand paleomonsoon intensities and freshwater input reconstructions by using benthic foraminifera.

## Acknowledgements

We are thankful to the Director, National Institute of Oceanography, Goa for his kind permission to publish this work. We are thankful to the anonymous reviewers for their constructive comments and suggestions, that helped to significantly improve the earlier version of the manuscript. The financial support from the Ministry of Earth Sciences (MoES) (sanctioned to RN) and University Grant Commission (JRF/SRF to MM) are highly acknowledged. Dr C Prakash Babu and Dr V Ramaswamy are thanked for CN and Coulometer analysis. We thank Dr Sanitha K Sivasdas, NIO,

Goa and Dr Priya M D'Costa, Goa University, for their help in performing cluster and CCA analysis. We also thank Dr Nagender Nath for leading the cruise in which the samples were collected.

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