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Monsoon-Related Flux in Inter-tidal Foraminiferal Diversity in the West Coast of India

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ABSTRACT

Studies on paleomonsoons rely on fossil foraminifera (forams) of sea bed core samples. While the stable isotopes of carbon and oxygen of foram shells are predominantly analysed, fluxes in foraminiferal assemblage in response to monsoons are not well recorded. To asses such fluxes at the level of the taxon as well as individual species, a study of inter-tidal foraminiferal diversity was undertaken over a period of 18 months, from October 2004 to March 2006, at an estuarine and a non- estuarine site on the west coast of India. Well-defined seasonality was seen both in live (LFN) and total foraminiferal number (TFN). The LFN and TFN reached a peak after SW monsoons with a lag of about three months. Population density, species richness and Shannon diversity indices of forams decline during summer and are lowest during monsoon. Several dominant species show seasonal fluxes with decrease in density during monsoon and peaks following post-monsoon. The density of angular, asymmetric forams increases during post-monsoon period. Fluxes in foram diversity correlate significantly with hydrological and sediment characteristics affected by monsoon. Forams showed significant (0.01 level) positive correlation with calcium and pH levels. It is likely that organic matter and phosphate enrichment due to monsoon and ocean upwelling increases foram density. These observations are useful in proxy validation of core sample data aimed at deducing paleomonsoons and paleoclimate.

Key Words: Diversity Flux, Biodiversity Indices, Morphogroups, Species Assemblage, Sediment, Hydrology.

INTRODUCTION

The Indian monsoon system is believed to have evolved about 10 million years ago. The Indian sub continent receives most of its rainfall during the south west monsoon. During summer, the moisture-laden winds blow from the southwest bringing the southwest (summer) monsoons during June - September. This is also associated with upwelling of the sea that brings nutrients to the surface. Understanding the phenomenon of monsoon and forecasting it are important as agriculture and global economy are directly dependent on monsoon. Paleomonsoons are studied to understand the past patterns of monsoon. To study paleomonsoon variability and to understand the forces that shape the Asian summer monsoons, numerous proxies like corals, speleothems, tree rings, rock magnetic data and palynology have been used (Naidu and Malmgren 1996, Schulz et al. 1998, Gupta et al. 2003). Fossil foraminifera from deep sea core samples are one such proxy that is often used in interpreting paleomonsoons (Weldeab et al. 2007). Stable isotope levels of oxygen and carbon vary in the environment depending on temperature. Foraminifera (forams) are shell secreting Protists and incorporate stable isotopes in their shells. These shells can be investigated for their stable isotopic contents. Thus deductions can be made about past temperature and associated environmental conditions. Present day seasonal studies on $\delta^{18}O$ and $\delta^{13}C$ in living benthic foraminifera from Swedish fjords (Filipsson et al. 2004) reveal correlation of isotopic contents with temperature and monsoonal rainfall.

Morphogroups of benthic foraminifera are often utilized for deducing paleomonsoons as river discharge and concomitant changes in salinity exert pronounced effect on test morphology of foraminifera (Nigam et al. 1992, Nigam and Khare 1994). During higher rainfall, rounded-symmetrical forms occur in larger proportions, whereas abundance of angular-asymmetrical forms increase during dry periods. Hence the density of morphogroups is used in quantifying past monsoonal precipitation. The size of the proloculus- the first chamber in the shell of foram have also been used as proxy for determining the strength and duration of paleomonsoons (Saraswat et al. 2005) as it indicates the input of organic matter associated with monsoon. Variation in deep sea benthic foraminiferal assemblages obtained from sea bed core samples has been used to assess palaeoceanographic changes and past monsoonal activity off Oman (Rai et al. 2007). Various environmental factors such as salinity, temperature, organic matter, phytodetritus, dissolved oxygen and calcium content influence the density and diversity of foraminiferal species. While core samples have been assessed for changes in foram assemblage (Rai et al. 2007), a study of their assemblage in terms of diversity and density of individuals in relation to South west monsoons is not well recorded. Information on the correlation of present day monsoons with foraminiferal diversity and distribution is scanty. Seasonal flux in planktonic foraminifera of the Ryukyu Islands (Xu et al. 2005) has been reported. There is a need to study fluxes in density and diversity of forams in relation to monsoon in India. The present study therefore was conducted on the west coast of India that experiences robust and clearly defined monsoonal rainfall. An annual average rainfall of about 3000 mm is received along the west coast. The gradient of Western Ghat escarpment and a narrow coastal region cause rapid changes in the marine environment of Arabian Sea coupled with the onset of monsoon as compared to Bay of Bengal where the changes are gradual. The present study records fluxes in intertidal foraminiferal diversity, including live and total numbers, species specific responses, sedimentological and hydrological characteristics over a period of eighteen months. Such observations help us to analyse the biology of forams with reference to their density and diversity. This data may be utilised to analyse fossil foraminiferal assemblage and assist proxy validation. Dominant forms and the species that are more sensitive to seasonal variations can be identified.

STUDY AREA

Coastal wetlands of Goa cover 130 sq. km, out of which estuaries account for 13.15 sq. km. As estuarine and non-estuarine systems differ in their dynamics of physicochemical properties, diversity, abundance and test morphology of intertidal foraminifera were studied from River Sal estuary (estuarine site) and Utorda (Non estuarine site) of Goa Coast in the present investigation. The River Sal is about 35 km long. The catchment area is 301 sq. km. The tidal influx is felt inwards up to 21 km. The site (Sal estuary) where the River Sal merges into the sea was chosen as estuarine site for the present study. The shore of the estuary is rocky in nature and the area is subjected to considerable anthropogenic pressures. Utorda, a non estuarine site, is a part of 30 km long stretch of uninterrupted beach of South Goa from Velsao to Cavelossim. It is located at 15° 19' N latitude and 73° 54' E longitude (Figure 1).

METHODS

Intertidal sediment and surface water samples were collected between October 2004 and March 2006 at monthly intervals from five stations at estuarine (Sal estuary) and five stations at non-estuarine (Utorda) coastal sites of Goa. Time of collection was between 12.00 and 14.00 hr. The sediment samples were washed through 63 µm sieve (230 ASTM) to retain foraminifera along with the sand fraction. The >63 µm fractions were stained overnight with Rose Bengal to distinguish live foraminifera from dead ones (Walton 1952). To avoid excess staining, the samples were washed with water thoroughly and oven dried at 60°C. A minimum of 300 specimens were picked with a 000 sable hair moist brush from pre weighed samples, using Olympus SZ 11 stereomicroscope. The Total Foraminiferal Number (TFN) and Live Foraminiferal Number (LFN) in each sample were computed and standardized to 1g dry sediment. The species were identified and classified by following Loeblich and Tappan (1987). A scanning electron micrograph illustrated catalogue prepared recently by us (Devi and Rajashekhar 2009) was used for confirming taxonomic identification. Apart from foraminiferal investigation, the physicochemical parameters of sediment and water were estimated following standard methods (Lindholm 1987, Loring and Rantala 1992, Trivedy and Goel 1986).

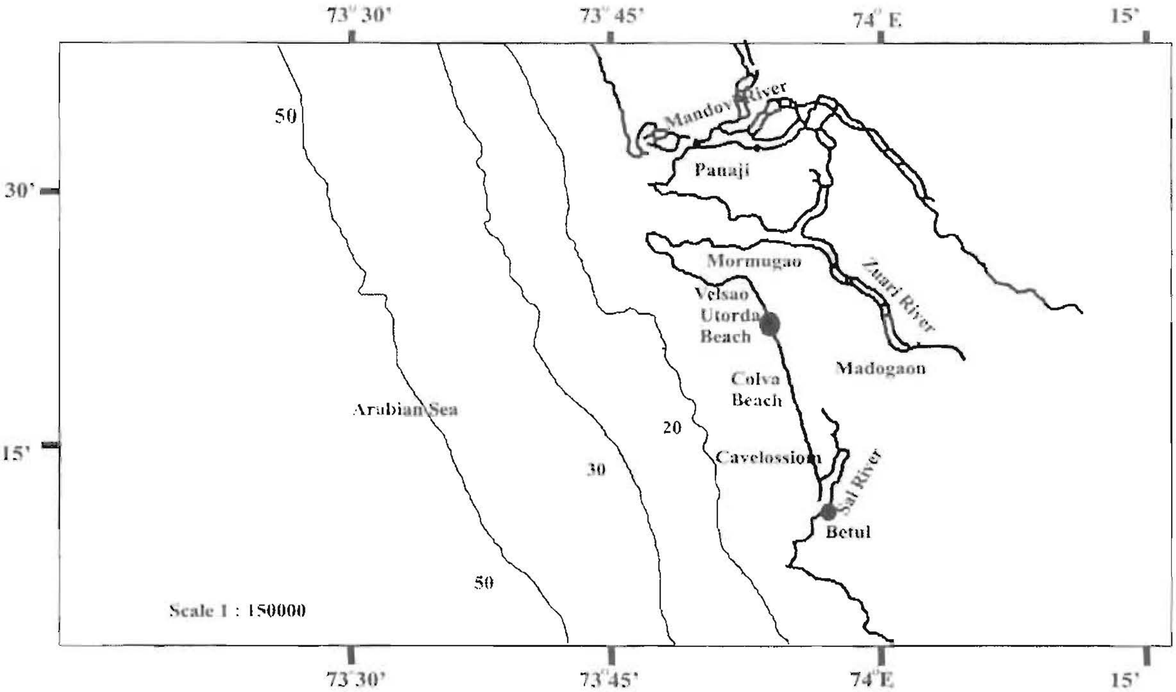

Figure 1. Location map of sudy area showing estuarine (Sal Estuary) and non-estuarine (Utorda beach) sites

RESULTS

Foraminiferal Number

Lowest densities and diversities of foraminifera were observed during monsoon and highest densities and diversities of foraminiferal species were found during post-monsoon at both estuarine and non-estuarine sites. Tables 1 and 2 show the fluctuations in the density of some of the dominant species of foraminifera found at estuarine and non-estuarine sites. Total Foraminiferal Number (TFN) varied from 37 to 121 and 1105 to 2040 per gram sediment at estuarine and non-estuarine sites respectively (Table 3; Figure 2a). Clear seasonality was observed in Live Foraminiferal Number (LFN)/g sediment. LFN varied from 14 to 49/g and 368 to 729/g at estuarine and non-estuarine sites respectively (Table 4; Figure 2b). Similar to TFN, the abundance of total and live foraminiferal population was less during southwest monsoon (June to September 2005) and high during post monsoon period at both sites. There is significant difference in total foraminiferal population for pooled samples between estuarine and non-estuarine sites (Mann-Whitney U test: $U = 369.5$, $P = 0.003$).

Species Richness

The lowest number of species was observed during the southwest monsoon at both the estuarine and non-estuarine sites. There was a significant increase in the number of species following monsoon. The number of species (total = live plus dead) varied from 6 to 25 and 20 to 59 at estuarine and non-estuarine sites respectively (Table 3). The number of live foraminiferal species ranged from 6 to 25 and 20 to 56 at estuarine and non-estuarine sites respectively (Table 4). At the estuary (Sal estuary), lesser diversity of foraminifera represented by 25 species (23 benthic and 2 planktonic species) belonging to 15 genera, 9 families and 3 sub-orders were found. In contrast, 59 foraminiferal species (55 benthic and 4 planktonic species) were recorded at non-estuarine site (Utorda). They belong to 27 genera, 15 families and 4 sub-orders. Significant difference in the richness of species was observed between the two sites ($T=5.962$, $P=0.0001$, $df = 22$).

Spiroloculina tricarinata, Quinqueloculina vulgaris, Rotallidium annectans, Rotallinoides papillosus, Ammonia beccarii, A.dentata, Elphidium discoidale, Amphistegina radiata, and *Poroeponides lateralis* were found in abundance at both the locations but their density was higher

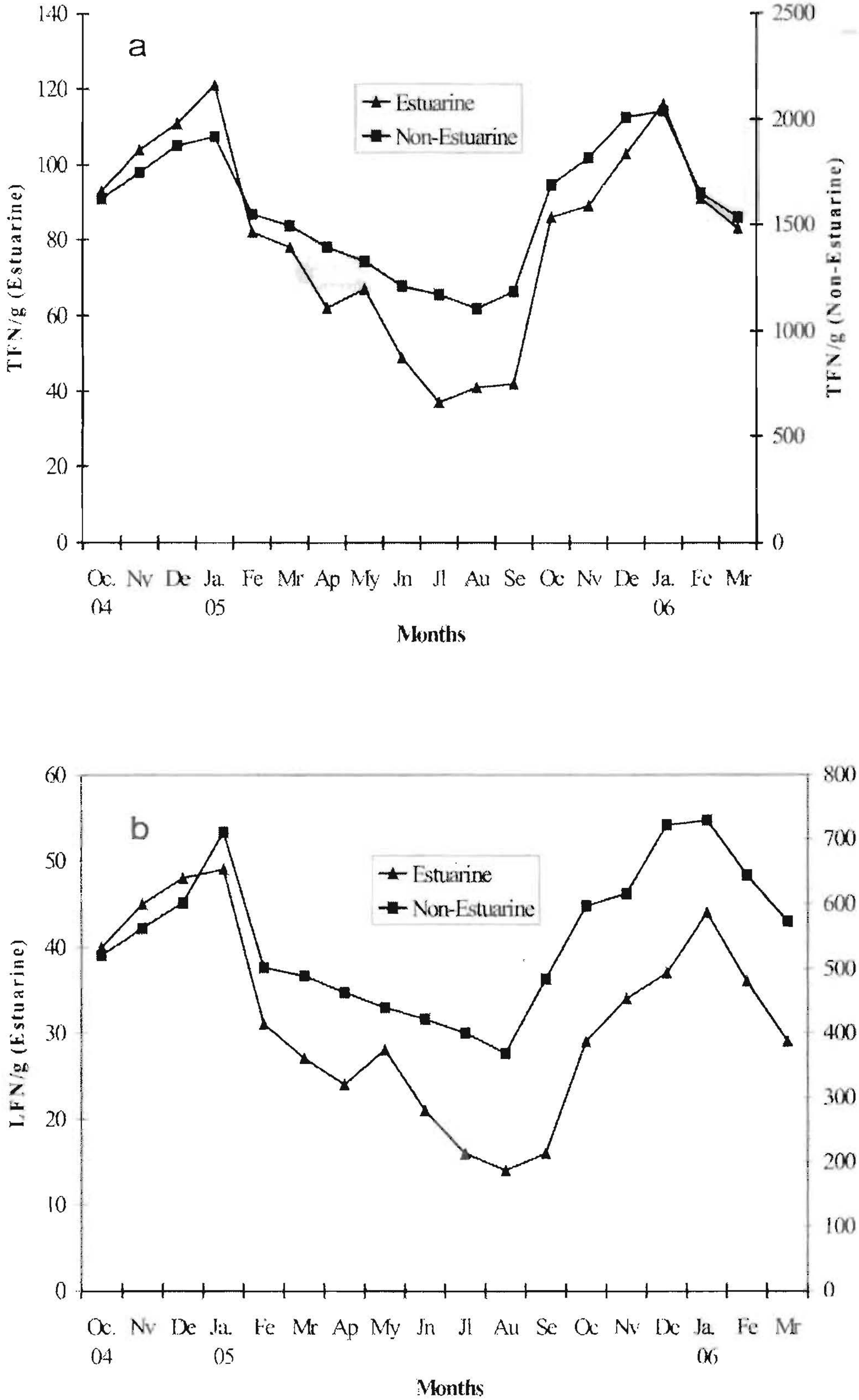

Figure 2. Monthly variation in bio-diversity characteristics of intertidal foraminifera at estuarine and non-estuarine sites (October 2004 – March 2006). a. Total Foraminiferal Number, b. Live Foraminiferal Number.

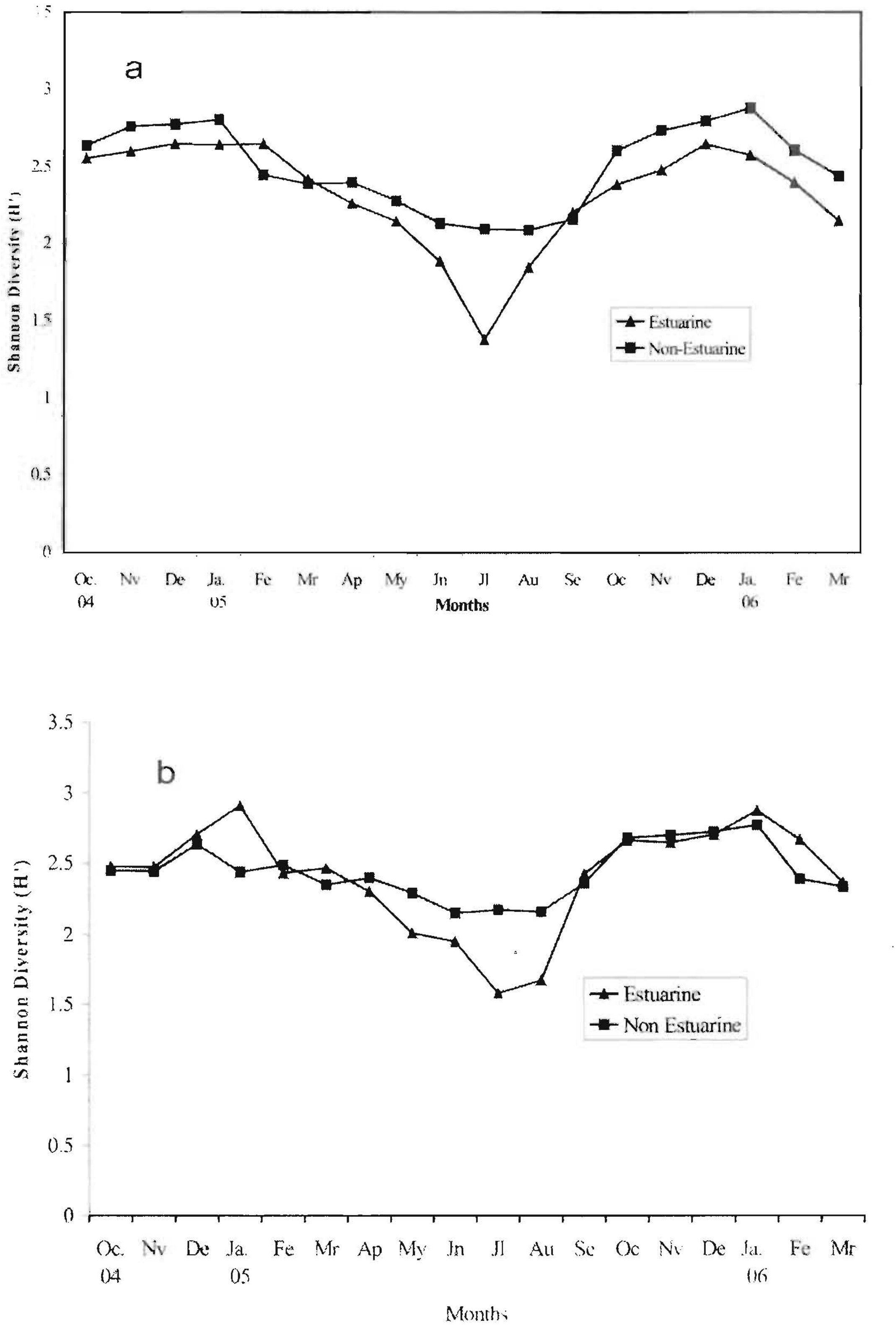

Figure 3. Monthly variation in biodiversity characteristics of intertidal foraminifera at estuarine and non-estuarine sites (October 2004 - March 2006). a. Shannon diversity (H') of total foraminiferal populations b. Shannon diversity (H') of live Foramiiferal populations.

Table 1. Density of five dominant species of Inter Tidal-Foraminifera at Estuarine Region.

Species	Oct 04	Nov	Dec	Jan 05	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan 06	Feb	Mar
Nonion boueanum	7	11	12	7	5	3	4	6	5	5	6	7	6	9	11	6	6	3
(d'Orbigny)	(3)	(4)	(4)	(4)	(1)	(1)	(1)	(3)	(5)	(5)	(4)	(2)	(2)	(2)	(3)	(3)	(3)	(2)
Ammonia beccarii	10	14	17	19	12	14	12	13	10	9	6	6	13	14	14	18	14	16
Linne	(6)	(5)	(4)	(6)	(5)	(4)	(4)	(6)	(3)	(5)	(3)	(1)	(4)	(5)	(5)	(4)	(4)	(5)
Ammonia tepida	6	9	11	11	9	11	10	12	8	_	4	2	4	8	6	10	7	9
Cushman	(1)	(3)	(4)	(2)	(2)	(3)	(2)	(5)	(4)	(-)	(1)	(1)	(2)	(2)	(2)	(2)	(3)	(3)
Ammonia dentate	6	6	8	9	8	7	7	6	4	_	_	_	4	6	4	7	9	8
(Parker & Jones)	(2)	(3)	(2)	(2)	(2)	(2)	(3)	(2)	(1)	(-)	(-)	(-)	(1)	(2)	(10)	(2)	(2)	(2)
Rotalidium annectans	26	23	20	26	20	20	14	16	14	18	14	12	27	21	23	28	24	26
(Parker &Jones)	(9)	(10)	(9)	(9)	(7)	(5)	(5)	(6)	(2)	(2)	(3)	(3)	(5)	(7)	(6)	(7)	(6)	(7)

Number in parentheses refer to live foraminiferal populations

Table 2 Density of five dominant species of Inter Tidal-Foraminifera at Non-Estuarine Region.

Species	Oct 04	Nov	Dec	Jan 05	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan 06	Feb	Mar
Nonion asterizens	41	47	51	55	41	44	39	_	_	_	_	3	43	48	49	52	36	41
(Fichtel and Moll)	(12)	(7)	(14)	(16)	(13)	(13)	(12)	(-)	(-)	(-)	(-)	(1)	(14)	(8)	(17)	(21)	(11)	(13)
Nonion boueanum	50	54	74	70	66	74	76	81	86	91	88	76	52	61	59	64	71	68
(d'Orbigny)	(16)	(18)	(19)	(22)	(21)	(24)	(24)	(27)	(32)	(41)	(37)	(39)	(23)	(24)	(20)	(24)	(24)	(21)
Ammonia beccarii	113	89	98	110	102	106	90	87	82	71	65	73	119	96	105	126	106	110
(Linne)	(18)	(27)	(30)	(49)	(27)	(30)	(29)	(28)	(33)	(25)	(24)	(42)	(39)	(23)	(42)	(47)	(32)	(35)
Rotalidium annectans	482	508	558	575	535	523	495	485	466	420	399	449	502	523	601	605	544	537
(Parker & Jones)	(189)	(216)	(199)	(265)	(164)	(179)	(171)	(162)	(145)	(133)	(123)	(149)	(169)	(181)	(213)	(228)	(254)	(198)
Rotaliniodes papillosus	301	323	328	315	295	275	244	229	213	233	220	200	311	330	342	319	299	279
(Brady)	(105)	(112)	(117)	(136)	(89)	(91)	(81)	(74)	(77)	(74)	(68)	(65)	(104)	(121)	(129)	(119)	(130)	(141)

Number in parentheses refer to live foraminiferal populations

Table 3. Diversity characteristics of total Inter-tidal Foraminiferal populations (E - Estuarine, NE - Non-estuarine).

Species		Oct 04	Nov	Dec	Jan 05	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan 06	Feb	Mar
TFN (No g^{-1})	E	93	104	111	121	82	78	62	67	49	37	41	42	86	89	103	116	91	83
	NE	1625	1750	1878	1920	1550	1495	1392	1325	1210	1170	1105	1184	1690	1820	2010	2040	1650	1535
Species richness	E	20	19	22	25	18	16	12	10	8	6	9	13	19	18	21	23	17	14
	NE		46	47	50	52	41	38	39	30	25	21	20	28	39	42	49	59	5042
Shannon Diversty (H')	E	2.554	2.600	2.649	2.644	2.648	2.417	2.261	2.142	1.881	1.378	1.842	2.204	2.386	2.480	2.648	2.576	2.396	2.145
	NE	2.638	2.760	2.755	2.805	2.446	2.388	2.398	2.277	2.129	2.093	2.086	2.157	2.606	2.736	2.797	2.879	2.606	2.439
Simpson's Dominance	E	0.119	0.102	0.095	0.103	0.121	0.141	0.143	0.154	0.177	0.321	0.164	0.149	0.145	0.115	0.100	0.124	0.127	0.166
	NE	0.147	0.132	0.133	0.131	0.170	0.173	0.174	0.183	0.200	0.192	0.193	0.194	0.140	0.130	0.132	0.126	0.156	0.171
Eveness	E	0.853	0.883	0.857	0.821	0.836	0.815	0.862	0.884	0.905	0.769	0.886	0.859	0.810	0.858	0.840	0.822	0.846	0.813
	NE	0.689	0.717	0.709	0.780	0.659	0.656	0.655	0.670	0.661	0.688	0.696	0.647	0.711	0.732	0.719	0.706	0.666	0.653

Table 4. Diversity characteristics of Inter-tidal Foraminifera (Live Foraminiferal populations).

LFN (No./g)	E	521	563	602	711	502	489	463	439	421	399	368	484	597	616	722	729	644	573
	NE																		
Species richness	E	42	44	47	48	39	38	37	30	23	21	20	24	38	39	45	56	47	40
	NE	16																	
Shannon Diversty (H')	E	2.479	2.473	2.704	2.908	2.430	2.465	2.301	2.011	1.951	1.581	1.673	2.425	2.660	2.644	2.700	2.872	2.664	2.363
	NE	2.449	2.442	2.634	2.438	2.487	2.349	2.397	2.291	2.151	2.173	2.161	2.360	2.678	2.697	2.720	2.769	2.387	2.332
Simpson's Dominance	E	0.180	0.104	0.083	0.076	0.116	0.100	0.118	0.153	0.156	0.242	0.204	0.107	0.084	0.093	0.087	0.068	0.082	0.122
	NE	0.183	0.194	0.158	0.188	0.164	0.191	0.179	0.184	0.183	0.174	0.175	0.145	0.130	0.137	0.134	0.139	0.205	0.191
Eveness	E	0.894	0.913	0.919	0.903	0.897	0.934	0.926	0.915	0.938	0.882	0.934	0.946	0.939	0.915	0.934	0.943	[illegible]	0.895
	NE	0.655	0.684	0.684	0.630	0.677	0.646	0.664	0.673	0.686	0.714	0.721	0.743	0.736	0.736	0.715	0.688	0.618	0.682

Table 5. Correlation between foraminiferal diversity and sedimentary characteristics at Estuarine site.

	Total Sand	Coarse Sand	Medium Sand	Fine Sand	Organic Matter	Calcium Carbonate	Abundance	Species Richness
Abundance	-0.697**	-0.875**	-0.743**	0.848**	0.220	0.822**	1.000	
Species Richness	-0.595*	-0.805**	-0.771**	0.879**	0.375	0 .830**	0.721**	1

** Correlation is significant at the 0.01 level (two-tail) * Correlation is significant at the 0.05 level (two-tail)

Table 6. Correlation between foraminiferal diversity and hydrological characteristics at Estuarine site.

	Rainfall	Air Temp.	Water Temp.	Dissolved O_2	pH	Salinity	Calcium	Phosphate	Silicate	Abundance	Species Richness
Abundance	-0.755**	0.169	-0.230	0.552*	0.714**	0.138	0.562*	-0.758**	-0.816**	1.000	
Species Richness	-0.715**	0.079	-0.300	0.441	0.728**	0.020	0.634*	-0.659**	-0.770**	0.721**	1.000

** Correlation is significant at the 0.01 level (two-tail)
* Correlation is significant at the 0.05 level (two-tail)

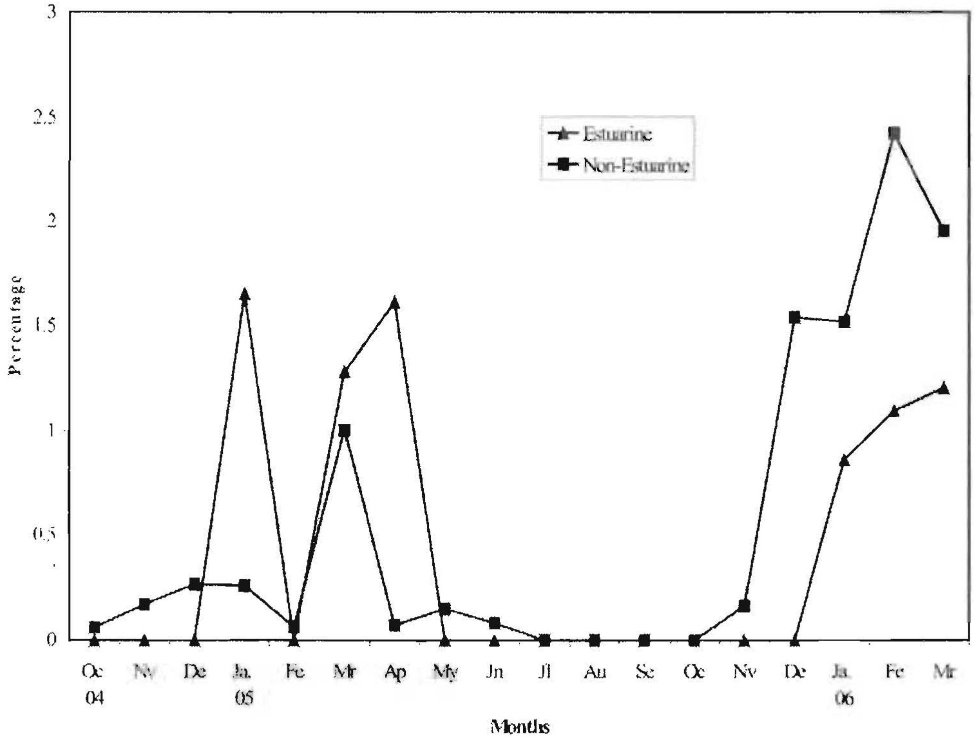

Figure 4. Monthly variation in percentage of Angular and Asymmetrical Foraminifera at estuarine and non-estuarine sites.

at non estuarine site. *Lagena leavis, Cancris auriculus* and *Rosalina sp.* were found only at non estuarine site. Planktonic forms-*Globigerina bulloides* and *Globigerinoides ruber* were found at both the sites. Out of the 59 taxa at non-estuarine site, 4 species viz. *Globigerina bulloides, Globigerinoides ruber, Globigerinodies sacculifer* and *Orbulina universa* were planktonic, while the rest were benthic. The suborder Rotaliina was more abundant than Miliolina, Lagenina and Globigerinina.

Biodiversity Indices

Biodiversity indices of total and live foraminiferal populations indicated striking similarities between the two (Tables 3, 4). Shannon diversity (H') values of total foraminiferal populations varied from 1.378 to 2.649 at estuarine and 2.086 to 2.879 at non estuarine sites (Figure 3a). Shannon diversity (H') values of live foraminiferal populations varied from 1.581 to 2.908 at estuarine and 2.173 to 2.769 at non estuarine sites (Figure 3b). Simpson's dominance index of total foraminiferal populations varied from 0.095 to 0.321 at estuarine and 0.126 to 2.00 at non estuarine sites (Tables 3). Simpson's dominance index of live foraminiferal populations varied from 0.068 to 0.242 at estuarine and 0.130 to 0.205 at non estuarine sites (Tables 4). At both the sites when Shannon diversity was high, low Simpson's Dominance was observed. It shows clearly that the number of dominant species was reduced with an increase in diversity of species. The species uniformity or Evenness Index (E) of total foraminiferal populations varied from 0.769 to 0.905 and 0.647 to0.780 at estuarine and non-estuarine sites respectively (Table 3). Evenness Index (E) of live foraminiferal populations varied from 0.882 to 0.946 and 0.618 to 0.743 at estuarine and non-estuarine sites respectively (Table 4).

Well-marked seasonal variations of foraminifera in relation to monsoon were observed at both estuarine and non-estuarine sites. Abundance (Figures 2a, 2b), Species Richness and Shannon Diversity (Figures 3a, 3b) of total and live foraminiferal populations were found to be highest during post monsoon and lowest during the monsoon season at both estuarine and non-estuarine sites. Simpson's dominance index values fot total foraminiferal populations were highest during the monsoon and lowest during the post-monsoon at both estuarine and non-estuarine sites (Table 3). Live foraminiferal populations at estuarine site also exhibited similar variations in Simpson's dominance index values.

At non- estuarine site, Simpson's dominance index value of live foraminfera was highest during pre monsoon and lowest during post monsoon (Table 4). Evenness index of total foraminiferal population was highest during monsoon at estuarine and post monsoon at non-estuarine sites. At both the regions, the observed values of Evenness index were lowest during pre monsoon (Table 3). Evenness index values of live foraminifera at both estuarine and non-estuarine sites were highest during monsoon and lowest during pre monsoon (Table 4).

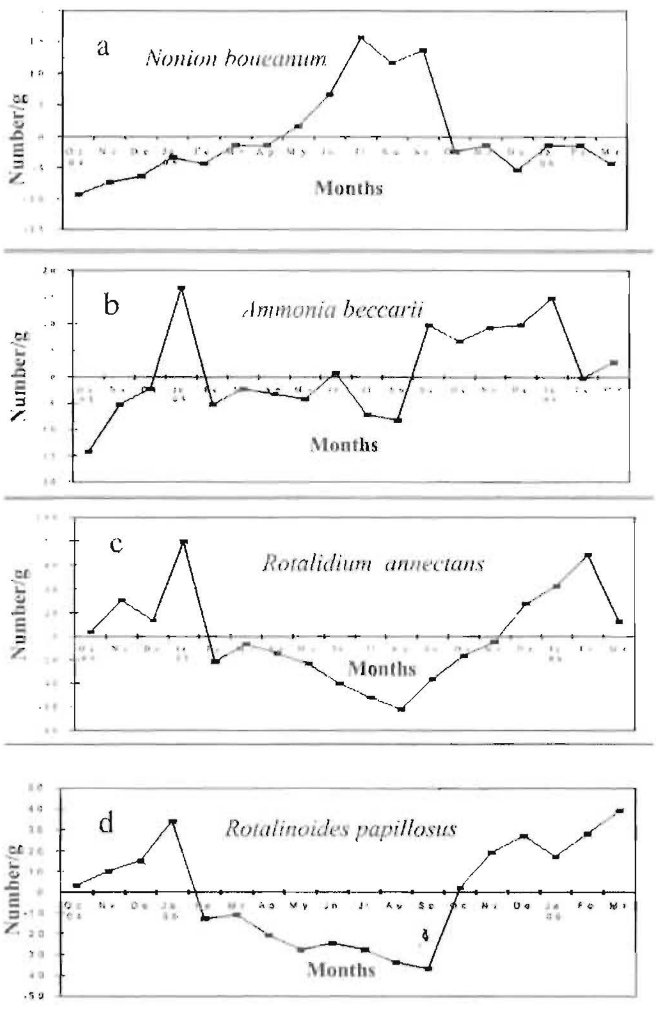

Figure 5. Species specific responses of foraminiferal number at non-estuarine site in relation to Monsoon. The graphs indicate variations from mean numbers (zero line) found during the study period. Positive values indicate an increase and negative values indicate a decrease from mean values.

The Morisita-Horn similarity index for samples over the months at estuarine and non-estuarine regions shows that the species composition is not very different. Morisita-Horn similarity for pooled samples of total foraminiferal populations, between estuarine and non-estuarine sites is 0.834. Morisita-Horn similarity for pooled samples of live foraminiferal populations, between estuarine and non-estuarine sites is 0.802.

Morphogroups

The population of angular asymmetrical foraminifera decreased during monsoon and later, their proportion increased during the post-monsoon. These form varied from 0.862 to 1.653 and 0.062 to 2.424% at estuarine and non-estuarine sites, respectively. No angular asymmetrical forms were found at both the sites during southwest monsoon from July to October 2005 (Figure 4). The angular asymmetrical forms observed at estuarine and non-estuarine sites were *Lagena leavis, Bolivina striatula, Bolivina kuriani, Bolivina limbata, Bulimina marginata* and *Siphouvigerina porrecta*. Species- specific responses were observed in relation to rainfall. The population of *Nonion boueanum* increased whereas those of *Ammonia beccarii*, *Rotalidium annectans* and *Rotalinoides papillosus* decreased during the monsoon (Figure 5).

Sediment Characteristics

Intertidal sediment samples were examined for texture, organic matter and calcium carbonate. The percentage of total sand varied from 93.0% to 96.0 and 64.1% to 69.0% at estuarine and non-estuarine sites respectively. The observed percentage of coarse sand varied from 4.9% to 8.7% and 4.0% to 6.8% at estuarine and non-estuarine sites respectively. Medium textured sand varied from 53.9% to 58.1% at estuarine and 11.4% to 23.1% at non-estuarine sites. Fine textured sand ranged from 29.0% to 34.4% and 39.0% to and 49.2% at estuarine and non-estuarine sites respectively. An increase in fine sand was observed during post monsoon period. Organic matter in sediment ranged from 0.25% to 0.48% at estuarine site and 0.65% to 0.90% at non-estuarine site. Monthly variation in calcium carbonate in sediment ranged from 2.9mg L^{-1} to 4.4 mg L^{-1} and 26.4 to 34.0 mg L^{-1} at estuarine and non-estuarine sites respectively. Direct relationship was observed between abundance and diversity of foraminifera and the calcium carbonate content of the sediment.

Hydrological Characteristics

Rainfall in the study site occurs mostly during the southwest monsoon (June to September). Rainfall regime varied from 24.0 to1223.7mm and 24.0 to 1096.9mm at estuarine and non-estuarine sites respectively. During the study period, the rainfall was higher than the annual average for coastal areas of Goa (2800 mm). Atmospheric temperature varied from 25^0 to 33^0 C and 24^0 to 35^0 C at estuarine and non-estuarine sites respectively. Surface water temperature showed cyclical fluctuations, ranging from 26^0 to 33^0 C at both estuarine and non-estuarine sites. Monthly variation in dissolved oxygen was inconsistent. The dissolved oxygen content at estuarine site varied between 4.22ml L^{-1} and 6.84ml L^{-1} whereas it ranged from 2.41ml L^{-1} to 5.22ml L^{-1} at the non-estuarine site. The pH values ranged from 6.30 to 8.06 and 7.42 to 8.61 at the estuarine and non-estuarine site, respectively. The salinity of water varied from 22.06‰ to 31.96‰ at estuarine site, and from 26.65‰ to 36.60‰ at the non-estuarine site. The calcium content ranged from 279.8 to 689.4 mg L^{-1} and from 496.1 to 1079.3 mg L^{-1} at the estuarine and non-estuarines sites, respectively. Whereas at the estuarine site the phosphate content varied from 0.25μg to 3.82μg L^{-1}, it ranged from 0.49 to 8.07 μg L^{-1} at the non-estuarine site (Figure 6).The silicate concentration at the estuarine site ranged from 22.24 to 120.84μg L^{-1} and 13.4 to 98.06 mg L^{-1} at the non-estuarine site.

DISCUSSION

Environmental factors cause several changes in the biology and behaviour of organisms. When such structural and/or chemical changes are preserved, they can be interpreted to deduce past environment. The monsoon has left traces of its past in many forms. Fossilised Foraminifera (forams) are among the most favoured organisms for interpreting palaeomonsoons. The southwest monsoon is an annual climatic event that hydrological changes due to upwelling and river discharge. Studying its effect on forams of the west coast can provide clear results due to well defined temporal pattern of the river discharges into the Arabian Sea along the west coast of India. For example, the west-flowing Kali River has one peak of discharge during monsoon, whereas the east-flowing Cauvery has three peaks of discharge during an annual cycle (http:/www.sage.wisc.edu/.riverdata/). Such a bi- or polyphasic input of organic and inorganic materials is likely to provide an ambiguous picture during investigations. The present study was therefore conducted at estuarine and non- estuarine sites on the west coast. These sites are less influenced by the north eastern monsoons.

Monsoon brings about annual changes in sedimentological and hydrological characteristics in marine environment surrounding the Indian peninsula (Sikka and Raghavan 1976, Pati 1980, de Sousa et al. 1996; Ittekkot et al. 2000, Kumar et al. 2002, Naidu 2006).

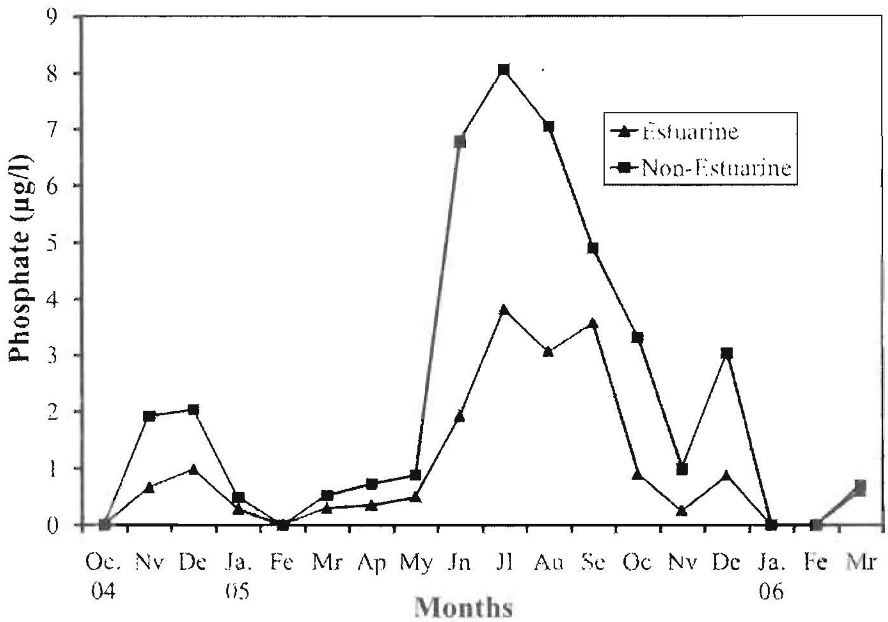

Figure 6. Monthly variation in phosphates at estuarine and non-estuarine sites (October 2004 – March 2006).

The total rainfall (3326 mm) due to SW monsoon during the study period was above the annual average (3000 mm). Changes in physico-chemical parameters are brought about by discharge of rivers or due to Arabian Sea upwelling during monsoon. The parameters of significance are texture of sand, sediment composition and organic and inorganic inputs during monsoon. The level of fine sand enhanced during post-monsoon period. Forams occurred in higher density in fine sand-rich sediments. Increase in organic matter content and calcium carbonate of sediment was elevated during post monsoon period. These conditions are favourable for forams. Among the important physico-chemical properties of water, the parameters that were low during monsoon but increased following monsoon were dissolved oxygen and calcium. Dissolved phosphate and silicate contents increased during monsoon. This may be largely due to ocean upwelling. These nutrients are expected to contribute to productivity following monsoon as phosphate and silicate support productivity. Salinity change would be largely due to river discharge and is a factor that influences foram density. Salinity decreased during monsoon and was highest before the onset of monsoon. Thus a clear annual oscillation in factors influencing foram density is brought about by high atmospheric temperatures prior to monsoon, ocean upwelling and river discharge during monsoon. Paleontological studies pertaining to foram assemblage and sediment granulometry have been carried out to analyse paleomonsoons near the mouth of Kali River (Khare et al, 2008). However, present day seasonal analysis of forams on the west coast of India is lacking.

Foram Assemblage

The prime question addressed in the present study is whether foram assemblage in terms of density and diversity is influenced in relation to the sedimentological and hydrological characteristics mentioned above. Fossil foram assemblage in sea bed core samples do show changes and such changes have been interpreted to deduce past climatic conditions (Rai et al. 2007). Present day environmental condi-tions are known to influence forminiferal assemblages and their diversity (Scott and Medioli 1980, Jorissen et al 1995, Gustafsson and Nodberg 2001, Panchang et al. 2006). Monsoons are also known to influence foram diversity and the isotopic composition of the shell (Xu et al. 2005, Fontanier et al. 2006). In the present study clear periodicity was seen in the number of total as well as live foraminifera, with foraminiferal density increa-sing during post monsoon period at both estuarine and non-estuarine regions. The peak increase showed a latency of two months following monsoon. TFN and LFN decreased during monsoon but subsequently increased following monsoon (Figures 2a, 2b). Similar depletions in live foraminiferal populations have been reported during monsoon (Majumdar et al 1999, Buzas et al. 2002). As LFN and TFN oscillate with a clear annual periodicity, it is likely that a majority of the species have a one-year life cycle. Such of the species which do not show a clear periodicity may have life cycle of two years or longer. Ohga and Kitazato (1997) have found similar seasonal fluxes in bathyal foraminifera populations related to seasonal organic matter input in Sagami Bay, Japan, and attribute one-year life cycle to be the reason for clear annual periodicity. The duration of life cycle of many of the foram species is not known. Post-monsoon sampling also yielded some of the minor species. An increase in their density may render them assessable during this period. For similar reasons, higher species diversity is recorded following monsoon.

Higher Shannon diversity values observed following monsoon indicate increase in species diversity. Decrease in the values of the index during monsoon indicates low species diversity (Figures 3a, 3b). Higher Simpson's index (Tables 3, 4) during monsoon indicates an increase in number of dominant species. The dominant species thus occur in relatively larger numbers during adverse conditions and show an opportunistic increase during favourable conditions, following monsoons. As the number of individuals of a species, increases due to favourable conditions, the likelihood of their inclusion in the samples increases and for this reason the biodiversity indices in the data obtained increased following monsoon. Non-estuarine site was rich in terms of abundance and species diversity. At both the sites (estuarine and non-estuarine) when Shannon diversity was high, low Simpson's Dominance index was observed. It shows clearly that the relative number of dominant species was reduced with an increase in diversity of species. The analysis of biodiversity indices of both total tests and live foraminifera indicated striking similarities between the two categories. Thus the tests provide a comparable picture of live foraminiferal diversity. Tests can therefore be considered as appropriate represen-tation of foraminiferal diversity at a site.

Morphogroups

Intensity of monsoon is interpreted from the morphogroups of benthic foraminifera. Analysis of core samples has clearly established relation between angular-asymmetrical forms and rounded-symmetrical forms, corresponding to monsoonal rainfall. During higher rainfall rounded-symmetrical forms occur in larger proportions, whereas angular-asymmetrical forms tend to increase in abundance during dry periods (Nigam et al. 1992). Analogous variations were observed in the present study. Striking similarity to such a variation in proxy is observed in the present study. Following monsoon, angular asymmetric forms constitute 1.5%-2.5% of the TFN. Dominance of rounded-symmetrical forms was observed during monsoon whereas the percentage of angular and asymmetrical forms increased following Monsoon (figure 4). Species specific responses were also observed in relation to rainfall. While *Nonion boueanum* showed positive correlation with monsoon, *Ammonia beccarii, Rotalidium annectans*, and *Rotalinoides papillosus* showed decrease in abundance (Figures 5a b, c, d). Therefore increase in abundance of *Nonion boueanum* indicates low saline conditions of seawater.

Sediment Characteristics, Hydrology and Foram Assemblage

Abundance and species richness of foraminifera are significantly correlated with some of the sedimentological characteristics. At estuarine site, abundance and species richness of foraminifera were significantly and positively correlated with fine sand, calcium carbonate as indicated by correlation values (Table 5) and negatively and significantly correlated with total sand, coarse sand and medium sand (Table 5). At non-estuarine site abundance and species richness of foraminifera were significantly and positively correlated with fine sand, organic matter, calcium carbonate and negatively and significantly correlated with total sand, coarse sand, and medium sand.

Sal River is a short river and is likely to discharge lesser amount of sediments, compared to longer rivers. An increase in fine sand content was observed during post monsoon period which was also characterized by an increase in abundance and diversity of foraminifera, indicating a positive relationship with foraminiferal assemblages. Sediment, rich in fine sand and clay has higher density and abundance of foraminiferal species than the coarse grain sediments (Scott et al. 1979, Jennings and Nelson 1992). Similarly a positive relationship was observed between organic matter and diversity of species which is significant at non-estuarine site. Organic matter had greater influence over TFN than species diversity. Similar relationship was reported between foraminiferal assemblages and organic carbon in benthic marine ecosystem by Setty and Nigam (1982). Thus, sediment characteristics and foram assemblage can be good tools to assess palaeoclimate. Of the various hydrological variables considered for the present study some correlate significantly with abundance and species richness of foraminifera at estuarine (Table 6) and non-estuarine sites. Abundance and species richness of foraminifera at estuarine and non estuarine sites were significantly and positively correlated with pH of water. There was also significant and positive correlation between abundance and species richness of foraminifera and calcium content of water at estuarine (Table 6) and non estuarine sites. Abundance and species richness of foraminifera at estuarine and non estuarine sites were significantly and negatively correlated with rainfall (Table 6). There was significant negative correlation between abundance and species richness of foraminifera and phosphate and silicate content of water at estuarine (Table 6) and non-estuarine sites.

Several studies have been carried out to find out the relationship between dissolved oxygen and foraminiferal assemblages (Hohenegger et al. 1993, Bernhard and Sen Gupta 1999, Ernst et al. 2002). However, some have reported that the abundance and species richness are positively correlated with dissolved oxygen (Bernhard and Reimers 1991). In the present findings total foraminifera and dissolved oxygen showed a marginal direct relationship. Lowest values of pH were recorded at both the sites during the south-west monsoon due to increased discharge from the river that lowered the pH of water as well as abundance and diversity of foraminifera. The pH affects total foraminiferal number (TFN) and species diversity equally. Salinity is one of the important factors that govern distribution, abundance and diversity of foraminifera. At lower salinities, the foraminiferal abundance and diversity were low (Hayward and Hollis 1994, Reddy and Reddi 1994). Our study shows greater impact of salinity over species diversity than abundance.

Calcium is required for the formation of test in foraminifera. This may explain the increase in abundance and species richness of foraminifera with an increase in calcium carbonate content of the sediment and calcium content of water. Nutrient availability is an important regulating factor for foraminifera (Jorissen et al. 1995, De Casamajor and Debenay 1995, Rijk 1995). Nutrient enrichment (Phosphate, Figure 6) during monsoon might have enhanced the increase in TFN and LFN during post monsoon.

Decreased salinity, pH, calcium content and organic matter resulted into low species diversity, TFN and LFN during Monsoon. Optimal increase in the above mentioned physicochemical characteristics enhanced the diversity and abundance of species following Monsoon. Thus foraminiferal data of monsoon and non-monsoon periods had a profound correlation with sedimentological and hydrological data. The observed fluctuations in foraminiferal diversity during pre-monsoon, monsoon and post-monsoon permit better understanding in analyses of proxy data.

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