

Influence of river influx on phytoplankton community during fall inter – monsoon in the coastal waters off Kakinada, east coast of India

P. M. Sooria, P. D. Reny, L Jagadeesan & M. Nair*

CSIR-National institute of Oceanography, Regional centre, P. B. No.1913, Kochi 682018, India

*[e-mail: maheswari@nio.org]

Received 5 October 2010; revised 26 November 2011

Significant changes in phytoplankton community structure were observed in the coastal waters off Kakinada (Bay of Bengal) during fall intermonsoon (October) of 2006 and 2007. River influx was more in October 2007 compared to those in October 2006. Phytoplankton showed marked changes in composition and abundance between the two periods of observation. Abundance was considerably higher in October 2007 (av. $150.9 \pm 54.8 \times 10^3$ cells l^{-1}) compared to that of October 2006 (av. $7.9 \pm 4.8 \times 10^3$ cells l^{-1}). Phytoplankton community was formed by larger diatoms in October 2007, dominated by *Hemidiscus hardmannianus* and *Ditylum brightwellii* (300-500 μm in diameter) whereas in October 2006 smaller diatoms such as *Lioloma elongatum* (2 - 4 μm), *Thalassiosira subtilis* (15 - 32 μm) and *T. favus* (60 - 140 μm) dominated. Both *H. hardmannianus* and *D. brightwellii* occurred in bloom density throughout the study area (av. $> 50 \times 10^3$ cells l^{-1}). Agglomerative hierarchical cluster analysis of phytoplankton species abundance showed two well separated clusters (similarity $\leq 10\%$) for 2006 and 2007. It reveals the variation in community structure between the two periods of observation. Multidimensional scaling of species abundance superimposed on scaled values of salinity and nitrate has shown that the community shift was directly related to environmental factors. Coastal waters of western Bay of Bengal receive high freshwater inputs, particularly during the southwest monsoon and the internal variations observed in the Coastal waters of Kakinada could as well be relevant to the entire east coast of India.

[Keywords: phytoplankton community, size variation, river influx, salinity, nitrate, coastal water off Kakinada, Bay of Bengal]

Introduction

Coastal water receive massive riverine input which contains large volume of freshwater, suspended particulate matter, sediments and nutrients¹. In such regions, the fresh water helps in stabilizing the water column through salinity stratification². Thus, the coastal ecosystems exhibit definite patterns of phytoplankton variability depending on the environmental fluctuations. Coastal waters of the Bay of Bengal (BoB) on the east coast of India, have been reported to be highly dynamic and characterized by low surface salinity regions due to the immense freshwater inputs through excessive precipitation over evaporation and river discharge³. According to recent estimates, the annual total continental run off into BoB is about 2950 km³, which is more than half that is received in the entire tropical Indian ocean⁴. This large freshwater influx shows considerable seasonal variability and brings along with it seasonally varying sediment load and nutrients to the upper layer⁵. Although the hydrography of this region has been fairly well studied^{6,7,8}, the seasonality in the phytoplankton community has received little

attention^{9,10} and interannual variations in phytoplankton community in response to freshwater input has not been studied. Gomes et al¹⁰ have stated that changing surface salinity, due to freshwater discharge from rivers, has tremendous influence on phytoplankton biomass and productivity. Present study is an attempt to assess the interannual variations in phytoplankton community in the coastal waters off Kakinada in the BoB during the fall inter monsoon (FIM)) of two successive years (October 2006 and October 2007).

Materials and Methods

As part of a regular environmental monitoring programme in the coastal waters off Kakinada, situated in the Krishna-Godavari (KG) basin, five stations in a transect perpendicular to the coast were sampled (Fig. 1) during October 2006 and October 2007. KG basin covers an area of 45,000 km² in the south-east coast of India, The study region experiences both the northeast (mid November-February) and the southwest (June-mid September) monsoons. These seasons are separated by the intervening spring (April-May) and

fall (mid September- mid November) intermonsoons Coast of India. Water samples from near-surface (1 m below surface) and near-bottom (1 m above bottom) were collected using 5 L Niskin samplers (Hydrobios). Both biotic and abiotic components were analyzed from all stations. Transparency of water column was estimated using Secchi disc and attenuation coefficient was calculated for each station. Water temperature was measured using a centigrade thermometer (0-50°C) and pH was measured using a pH meter (ELICO LI610, precision ±0.01). Salinity was measured with an electrodeless induction type Salinometer (DIGI AUTO model 3G, precision ±0.01×10⁻³). Water samples (500 mL) were prefiltered and analyzed for macro nutrients (nitrate, phosphate and silicate), using a spectrophotometer (Shimadzu 1650PC), following standard procedures¹¹. Phytoplankton abundance and composition were determined from 500 mL water samples. Samples were fixed with Lugol’s Iodine, kept for settling in a cool dark place and later concentrated to 20 mL by siphoning. Phytoplankton cells were counted from

1 mL of the concentrated sample in a Sedgewick Rafter under an inverted microscope (OLYMPUS, C.K-30) according to JGOFS protocols¹².

Statistical analysis

Community indices

To determine the dominance of species, the following formula was used¹³:

$$Y_i = (N_i/N) * f_i$$

where, Y_i is the dominance of species i , N_i is the number of individuals of species i , at all stations, N is the number of individuals of all species at all stations, and f_i is the frequency of stations at which species i occurs. Species with a Y value of ≥ 0.02 were defined as dominant species.

Cluster analysis

Agglomerative hierarchical cluster analysis (AHCA) on station versus phytoplankton abundance (standardized square root transformed) through Bray–Curtis similarity and group-average linking were chosen to classify the assemblages/clusters^{14,15}. To explain divergence of salinity and nitrate Multi-dimensional scaling (MDS) was created based on the Bray-Curtis similarity matrix.

Results

Physico-chemical parameters

Light attenuation coefficient (k) was higher during FIM of 2007 (range, 0.13-0.34) compared to that of 2006 (range, 0.10-0.18), indicating relatively high turbidity in water column during the former period. Near-surface water temperature showed marginal variation during both periods of sampling (28.5-30°C in Oct. 2007 and 29-32°C in Oct. 2006), but near-bottom water temperature was relatively low (25.0-29.0°C) in Oct.2007 compared to Oct.2006 (28.5-30°C) (Table 1). MDS analysis (Fig. 4) showed

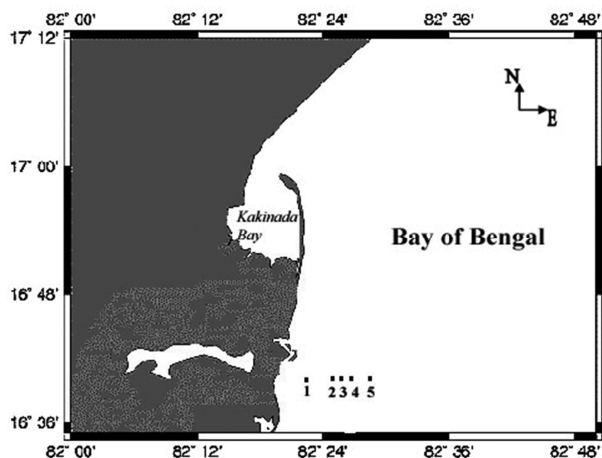


Fig. 1—Study area showing station location in Kakinada coast

Table 1 — Temperature and salinity distribution in near - surface and near - bottom waters

Stations	Near-surface		Near-bottom	
	Temperature (°C)	Salinity	Temperature (°C)	Salinity
Oct.2006	1	29.0	26.9	28.6
	2	31.0	26.9	30.5
	3	32.0	27.2	31.0
	4	30.0	25.0	31.2
	5	30.0	25.0	31.2
Oct.2007	1	29.0	22.3	22.1
	2	29.0	23.4	31.4
	3	30.0	22.3	33.8
	4	28.5	18.6	34.5
	5	30.0	20.7	35.7

discrete segregation of salinity values of both sampling periods. The distance between the stations was less for near-bottom values than that of near-surface. Thus salinity showed significant difference, particularly in the near-bottom layers between the two periods of observation. In Oct.2006, the near-surface salinity ranged from 25.0 (Stn. 4) to 27.2 (Stn. 3) while in Oct.2007, the respective values were 18.6 (Stn. 4) and 23.4 (Stn. 2). Salinity of near-bottom layer, however, showed a reversal, having relatively high values in Oct.2007 (31.4 to 35.7) except at Stn. 1 (22.1) and low values in Oct.2006 (28.6 to 31.0) (Table 1), thus indicating that a strong vertical stratification in salinity prevailed during the former period.

The concentrations of nutrients, particularly nitrate varied significantly inter-annually (Table 2). During 2006 FIM, it varied from 0.02 (Stn. 5) to 0.16 $\mu\text{mol.l}^{-1}$ (Stn. 2) in near-surface waters while the respective values for 2007 FIM were 1.38 $\mu\text{mol.l}^{-1}$ (Stn.1) and 14.30 $\mu\text{mol.l}^{-1}$ (Stn. 5). In near-bottom waters, the minimum concentration of 0.04 $\mu\text{mol.l}^{-1}$ was observed at Stns. 4 and 5 and the maximum of 0.12 $\mu\text{mol.l}^{-1}$ at Stn. 1 during 2006 FIM. During 2007 FIM, the values recorded were generally higher (range, 1.16 at Stn.1 - 7.76 $\mu\text{mol.l}^{-1}$ at Stn.5). Phosphate concentration of near-surface waters varied from non-detectable level (Stn.5) to 1.13 $\mu\text{mol.l}^{-1}$ (Stn.3) during Oct.2006, whereas it ranged from 0.10 $\mu\text{mol.l}^{-1}$ (Stn.2) to 0.58 $\mu\text{mol.l}^{-1}$ (Stn.5) during Oct.2007. In the near-bottom waters, the concentration was non-detectable, except at Stns. 2 and 3 during Oct.2006. But, during Oct. 2007, it ranged from 0.15 (Stn. 1) to 1.55 $\mu\text{mol.l}^{-1}$ (Stn.5). Silicate content during both

periods showed higher values in near-surface waters (14.53-37.09 $\mu\text{mol.l}^{-1}$ during Oct.2006 and 11.50-30.46 $\mu\text{mol.l}^{-1}$ during Oct.2007). During both periods Stns. 4 and 5 recorded relatively higher values. In the near-bottom waters, silicate concentration varied from 6.01 (Stn.3) to 18.77 $\mu\text{mol.l}^{-1}$ (Stn.2) and 2.95 (Stn. 1) to 10.17 $\mu\text{mol.l}^{-1}$ (Stn.5) during Oct.2006 and 2007, respectively.

Phytoplankton composition

A total of 38 phytoplankton species were encountered during Oct.2007 (Table 4), as against 24 species during Oct.2006 (Table 3). Diatoms such as *Ditylum brightwellii* and *Hemidiscus hardmannianus* showed maximum density during Oct. 2007. The average cell count of both species was higher at near-surface (53.5×10^3 cells l^{-1} and 56×10^3 cells l^{-1} , respectively) than at near-bottom (48.6×10^3 cells l^{-1} and 52.4×10^3 cells l^{-1} , respectively). The highest cell count (100×10^3 l^{-1}) of *H. hardmannianus* was recorded at Stn.2 near-bottom and Stn. 5 near-surface and the lowest count (15×10^3 l^{-1}) at Stn. 3 near-bottom (Tables 4). Incidentally, the highest cell density of *D. brightwellii* during Oct.2007 was also 100×10^3 l^{-1} and recorded at Stn. 4 near-surface layer. The lowest density was 20×10^3 l^{-1} at Stn. 5 near-bottom. The other diatoms species present at most of the stations, though in low numbers, were *Leptocylindrus danicus* and *Thalassiosira subtilis*. The dinoflagellates common to most of the stations were *Protoperdinium depressum*, *Ceratium inflatum* and *Prorocentrum micans*. The interesting observation, during Oct.2006 was that both *H. hardmannianus* and *D. brightwellii* were totally absent at all the stations sampled during

Table 2—Nutrient distribution in near-surface and near-bottom waters

Station s	Near-surface			Near-bottom			
	NO_3^- ($\mu\text{mol.l}^{-1}$)	PO_4^- ($\mu\text{mol.l}^{-1}$)	SiO_4^- ($\mu\text{mol.l}^{-1}$)	NO_3^- ($\mu\text{mol.l}^{-1}$)	PO_4^- ($\mu\text{mol.l}^{-1}$)	SiO_4^- ($\mu\text{mol.l}^{-1}$)	
Oct.2006	1	0.10	1.07	19.40	0.12	Nd	11.6
	2	0.16	Nd	18.67	0.06	0.09	18.77
	3	0.08	1.13	14.53	0.08	1.73	6.01
	4	0.06	Nd	37.09	0.04	Nd	7.29
	5	0.02	Nd	37.09	0.04	Nd	7.29
Oct.2007	1	1.38	0.44	13.36	1.16	0.15	2.95
	2	10.82	0.10	11.50	3.16	0.73	8.06
	3	2.86	0.19	17.93	3.55	0.24	7.47
	4	5.42	0.34	28.54	2.47	0.68	4.18
	5	14.30	0.58	30.46	7.76	1.55	10.17

(Nd = Non-detectable)

Table 3—Phytoplankton species composition in October 2006 (No.×10³ l⁻¹)

Diatoms	Stn.1		Stn.2		Stn.3		Stn.4		Stn.5	
	S	B	S	B	S	B	S	B	S	B
<i>Asteromphalus fabellatus</i>	-	-	-	-	-	-	2	-	-	-
<i>Bacteriastrium hyalinum</i>	-	-	-	0.2	-	-	-	-	-	-
<i>Biddulphia mobiliensis</i>	1	-	-	0.5	-	0.2	-	6.6	-	5
<i>Chaetoceros affinis</i>	-	-	-	1	-	-	-	-	0.5	-
<i>Fragilaria striatula</i>	-	-	-	-	1	1	-	-	-	-
<i>Grammatophora marina</i>	-	-	-	1	-	-	-	-	-	-
<i>Haslea</i>	-	-	-	0.1	-	-	1	-	-	0.1
<i>Leptocylindrus minimus</i>	-	-	-	-	-	1	-	-	3	0.5
<i>Lioloma elongatum</i>	0.5	-	-	-	-	-	0.1	-	4.5	-
<i>Navicula directa</i>	-	1	-	-	3	-	-	-	-	-
<i>Nitzschia longissima</i>	-	1.7	-	-	-	-	-	-	-	-
<i>Nitzschia sigma</i>	-	0.2	-	-	1	-	-	-	0.1	-
<i>Pseudonitzschia fraudulenta.</i>	-	-	-	-	-	-	-	-	0.5	-
<i>Rhizosolenia robusta</i>	-	-	1	-	-	-	-	-	1	0.5
<i>Thalassionema oestrupii</i>	0.5	-	-	-	-	-	-	-	1	-
<i>Thalassiosira subtilis</i>	0.5	-	0.9	4	-	0.1	0.3	0.6	-	-
<i>Triceratium favus</i>	1	-	1	-	2	-	-	-	-	-
Dinoflagellates										
<i>Alexandrium insuetum</i>	-	0.1	-	-	1	-	-	0.3	-	-
<i>Ceratium furca</i>	-	-	-	-	-	-	-	-	-	-
<i>Corythodinium tessellatum</i>	-	-	-	-	1	-	-	-	-	-
<i>Dinophysis caudata</i>	-	-	-	-	1	-	-	3	0.5	-
<i>Gonyaulax spinifera</i>	-	-	-	-	-	-	1	-	-	-
<i>Gymnodinium brevi</i>	0.5	0.1	-	0.1	3	0.1	0.1	0.3	0.5	-
<i>Oxytoxum scolopax</i>	-	-	-	-	0.1	-	-	-	-	-
<i>Prorocentrum micans</i>	-	-	-	-	3	-	-	3.3	-	-
<i>Protoperdinium conicum</i>	-	-	-	-	1	5	-	-	-	0.2
<i>P. depressum</i>	-	-	0.4	-	-	-	-	-	-	-
<i>Scropsiella trochoidea</i>	-	-	-	-	-	0.6	-	-	-	-
Total density (No.×10³l⁻¹)	4	3.1	3.3	6.9	17.1	8	4.5	14.1	11.6	6.3

October 2006 (Table 3). The common species of diatoms and dinoflagellates present, though in small numbers, were *T. subtilis*, *Lioloma elongatum*, *Triceratium favus*, *Gymnodinium brevi* and *Gonyaulax spinifera*. The total phytoplankton counts were 1 to 2 orders of magnitude lower in Oct. 2006 compared to Oct. 2007.

Relationship between abiotic and biotic variables

Salinity showed a significant negative correlation ($r=-0.96$, $p<0.001$) with density of *D. brightwellii* (Fig. 2a). Nitrate content showed a significant positive correlation with the cell density of *H. hardmannianus*

($r=0.92$, $p\leq 0.01$) (Fig. 2c) while the cell density of *D. brightwellii* showed a significant positive correlation with silicate concentration ($r=0.93$, $p\leq 0.01$) (Fig. 2b), indicating the influence of these macro-nutrient in the bloom formation of these two diatom species.

Dominant species and similarity indices

Level of dominance of each species was calculated (Table 5) according to the formula derived by Yang *et al.*¹³. During 2007 FIM, 3 species were found to dominate (*D. brightwellii*, *H. hardmannianus* and *Protoperdinium leonis*.) in near-surface waters, but only *D. brightwellii* and *H. hardmannianus* showed

Table 4—Phytoplankton species composition in October 2007 (No.×10³ l⁻¹)

Diatoms	Stn.1		Stn.2		Stn.3		Stn.4		Stn.5	
	S	B	S	B	S	B	S	B	S	B
<i>Aulacodiscus orbiculatus</i>	-	3	-	-	-	-	-	-	-	-
<i>Bacteriastrum hyalinum</i>	-	-	-	-	5	-	3	10	-	-
<i>Biddulphia rhombus</i>	-	-	-	2	-	-	1	-	1	-
<i>Coscinodiscus centralis</i>	-	3	3.3	2	-	-	-	-	-	1.9
<i>Chaetoceros affinis</i>	3	-	-	2	-	-	11	15	2	-
<i>C. holstaticus</i>	-	-	6.7	-	-	-	-	-	-	-
<i>Ditylum brightwellii</i>	33	66	30	66	35	25	100	85	82	20
<i>Fragillariopsis cylindrus</i>	-	-	-	-	-	-	1	-	-	-
<i>Grammatophora kerguelensis</i>	3	-	-	2	-	-	4	-	-	-
<i>Hemidiscus hardmannianus</i>	40	36	66.67	100	30	15	31	60	100	32
<i>Leptocylindrus danicus</i>	6.7	-	-	1	10	5	17	-	1	5.8
<i>Laudaria annulata</i>	-	-	3.3	-	-	-	2	-	-	-
<i>Navicula directa</i>	-	-	-	-	-	5	-	-	-	-
<i>Navicula distans</i>	-	-	-	-	10	-	1	5	3	5.8
<i>Nitzschia fasciculata</i>	-	-	-	-	-	10	2	15	1	-
<i>Pseudonitzschia fraudulenta</i>	-	-	-	-	-	-	5	-	1	-
<i>Pleurosigma fomosum</i>	-	-	-	3	-	-	-	-	-	-
<i>Rhizosolenia robusta</i>	-	-	-	-	-	-	3	-	-	-
<i>Skeletonema costatum</i>	-	-	-	-	-	-	1	-	-	-
<i>Thalassiosira subtilis</i>	10	6.7	-	9	5	5	2	15	1	-
<i>Thalassiothrix longissima</i>	-	3	10	4	-	-	-	-	-	15.4
<i>Thalassionema nitzschioides</i>	3	6.7	-	-	-	-	5	-	1	-
<i>Triceratium favus</i>	10	13	-	-	-	-	-	-	-	-
Dinoflagellates										
<i>Alexandrium insuetum</i>	-	3	6.7	-	-	-	1	-	-	-
<i>Ceratium inflatum</i>	-	-	3.3	-	5	-	3	10	2	-
<i>Ceratocorex horrida</i>	-	3	-	-	-	-	-	-	-	-
<i>Corythodinium tessellatum</i>	-	6.7	-	-	-	-	-	-	-	-
<i>Gymnodinium abbreviatum</i>	-	-	3.3	-	5	-	2	-	-	-
<i>Prorocentrum micans</i>	-	-	-	-	5	-	4	5	7	1.9
<i>Protoperidinium leonis</i>	-	-	-	1	-	-	1	-	-	-
<i>P. depressum</i>	-	-	13.3	-	5	-	5	5	5	3.8
<i>Scripsiella trochoidea</i>	-	-	3.3	-	-	5	-	-	-	-
Total Density (No. ×10³ l⁻¹)	108.7	150	150	192	115	70	205	225	207	86.6

(S= Near-surface; B= Near-bottom)

Table 5—Dominant species, level of dominance and frequency of distribution in surface and bottom waters

Species	Near-surface		Near-bottom		
	Dominance (Y)	F %	Species	Dominance (Y)	F %
2006					
<i>Lioloma elongatum</i>	0.126	60	<i>Biddulphia mobiliensis</i>	0.319	80
<i>Thalassiosira subtilis</i>	0.042	60	<i>Thalassiosira subtilis</i>	0.122	60
<i>Triceratium favus</i>	0.099	60	<i>Protoperidinium conicum</i>	0.135	40
<i>Gymnodinium brevis</i>	0.101	80			
2007					
<i>Ditylum brightwellii</i>	0.372	100	<i>Ditylum brightwellii</i>	0.364	100
<i>Hemidiscus hardmannianus</i>	0.356	100	<i>Hemidiscus hardmannianus</i>	0.337	100
<i>Protoperidinium leonis</i>	0.038	80	<i>Thalassiosira subtilis</i>	0.049	80

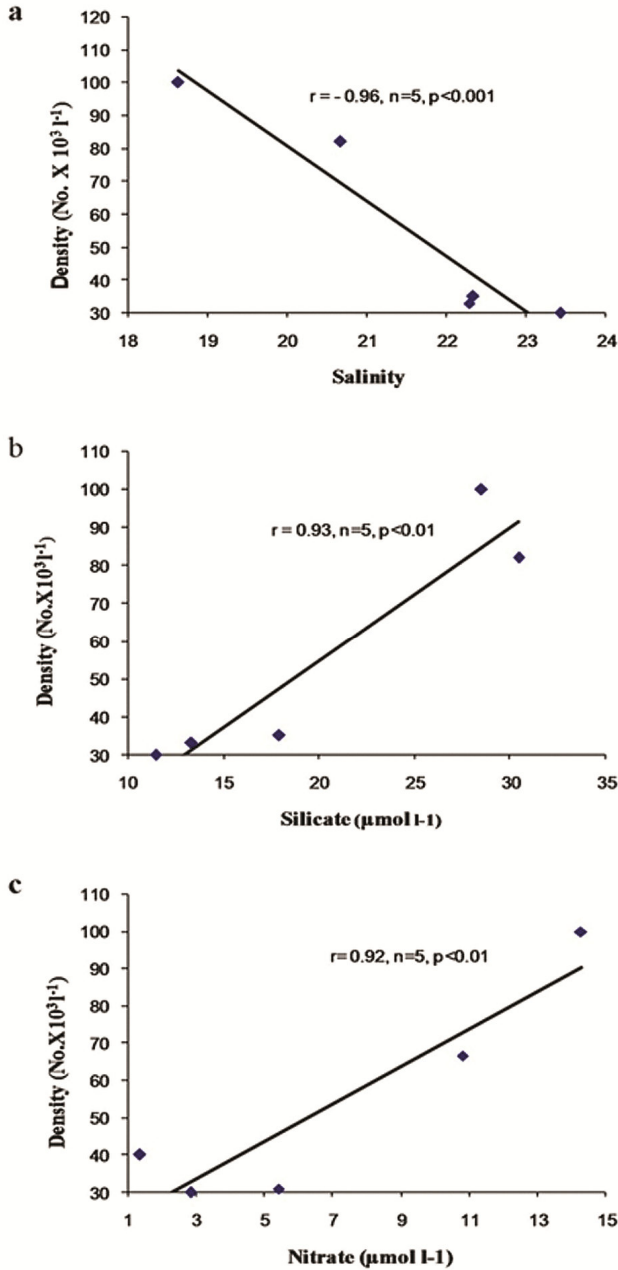


Fig. 2—Correlation between *D. brightwellii* cell density and salinity (a) and silicate (b); *H. hardmannianus* cell density and nitrate (c) in surface water

maximum Y value (0.372 and 0.356, respectively). During 2006 FIM, *T. subtilis*, *L. elongatum*, *T. favus* and *G. brevis* showed dominance in near-surface waters, but Y values were very low. In near-bottom layer, *Biddulphia mobiliensis*, *T. subtilis* and *Protoperdinium conicum* showed dominance during 2006 FIM with a high Y value of 0.319 for *B. mobiliensis*. During 2007 FIM, both *D. brightwellii*

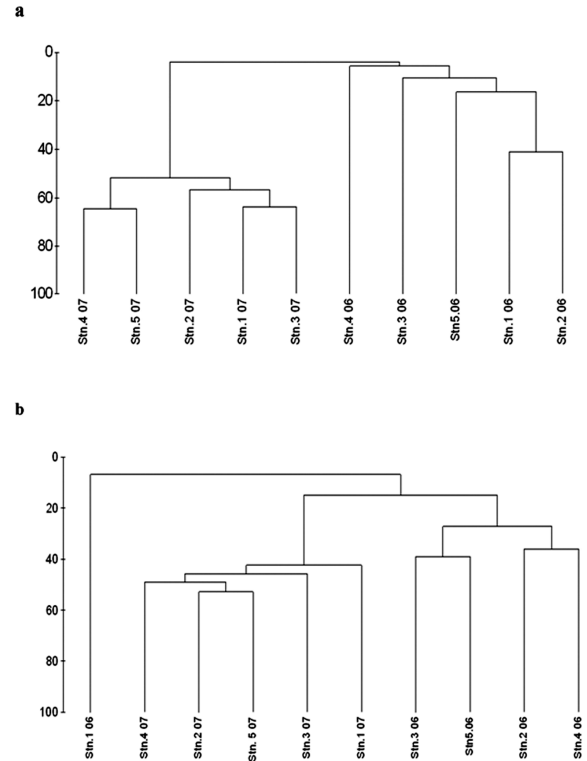


Fig. 3—Similarity between the station based on phytoplankton abundance in surface (a) and in bottom (b) during 2006 and 2007

and *H. hardmannianus* showed dominance (Y 0.364 and 0.337, respectively) and their frequency of occurrence (F %) was 100% in both depth strata.

AHCA grouping based on phytoplankton density showed two separate clusters for each sampling periods (Figs 3a & b) and the similarity between the clusters was <10%, indicating that the communities were distinctly different during both sampling periods. In the MDS plot of cell density with superimposed scaled values of salinity and nitrate, the stations of both sampling periods were shown to be clearly distinct at 0.07 stress level. For 2007 observation, all near-surface and near-bottom stations which recorded low salinity and high phytoplankton density were located close to each other (Figs 4a & b). Similarly, stations with high nitrate content and phytoplankton abundance also formed separate cluster (Figs .5a & b).

Discussion

Sengupta *et al.*, have reported that total annual precipitation and run off are very high in BoB from June to October. The low surface salinity values encountered during the present study also corro-

the only nitrogen source¹⁹. The nutrient contents in water of the study region did not show any unusual variation during October 2006, but an increase in nitrate concentration was seen during October 2007, most likely through terrestrial freshwater input.

An inverse relationship was found to exist between the two dominant diatom species, viz. *H. hardmannianus* and *D. brightwellii* (Table 4). This can be explained by the salinity preference of the latter species. According to Qasim *et al.*¹⁷, the optimum salinity requirement varies with species. When mixed phytoplankton populations were subjected to gradual salinity change, a rapid selection was observed in their assemblages. In the experiment conducted by Rijstenbil²⁰, *D. brightwellii* became dominant in a salinity medium of 18. In the present study, a significant negative correlation was observed between the cell density of *D. brightwellii* and salinity (Fig. 2a). At the station where *D. brightwellii* had the highest density (Stn. 4), the near-surface salinity was 18.6. Consequently, the stations where salinity was low, *D. brightwellii* dominated and outnumbered *H. hardmannianus*. Thus, the intrinsic factors that regulate the phytoplankton composition and community structure in the study area appear to be differential salinity tolerance and cell size of the species. It is also evident that composition of the phytoplankton community can undergo changes since the salinity and nutrient content of the Bay undergo drastic fluctuations on an interannual scale⁴. Similarity of the species composition of the successive FIM periods was found to be <10%, indicating a clear variation in the species composition in the community. Further, the MDS plot also confirmed a distinct community shift associated with salinity and nitrate.

Conclusion

Apart from regular seasonal fluctuations, the implications of inter-annual variability of different hydrographic parameters on the phytoplankton community structure are still unknown. According to earlier studies²¹, BoB harbors diverse diatom communities that seem to be syntrophic, non-competitive and co-habiting in the generally low nutrient, stratified surface waters. But, the present study provides a strong evidence of inter-annual variability in community structure influenced by the riverine input into the Bay. Further, species with adaptations like large size and low salinity tolerance have advantage over others to survive and flourish in the low saline nutrient rich conditions of the coastal

waters of the Bay of Bengal. Thus these effects can lead to a phytoplankton community shift in the ecosystems that undergo frequent environmental perturbations.

Acknowledgements

Authors thank Director, NIO and the Scientist-in-Charge of its Regional Centre at Kochi for the support extended for the study.

References

- 1 Cloern J E, Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California, *Rev. Geophys.*, 34 (1996) 127-168.
- 2 Simpson J H, Sharples I & Rippeth T P, A perspective model of stratification induced by freshwater runoff, *Estuar. Coast. Shelf Sci.*, 33 (1991) 23-35.
- 3 Yu Z & McCreary J P, Assessing precipitation products in the Indian Ocean using an ocean model. *J. Geophys. Res.*, 109 (2004) C05013 doi 10.1029/2003JC002106.
- 4 Sengupta D G, Bharath Raj N & Shenoi S S C, Surface freshwater from Bay of Bengal runoff and Indonesian Through flow in the tropical Indian Ocean, *Geophys. Res. Lett.*, 33 (2006), L22609, doi: 10.1029/2006GL027573.
- 5 Sardessai S, Ramaiah N, Prasanna Kumar S & de Sousa S N, Influence of environmental forcings on the seasonality of dissolved oxygen and nutrients in the Bay of Bengal, *J. Mar. Res.*, 65 (2007) 301-316
- 6 Murty C S & Varadachari V V R, Upwelling along the east coast of India. *Bull. Nat. Inst. Of Sci. India*, 36 (1968) 80-86
- 7 Gopalkrishna V V & Sastry J S, Surface circulation over the shelf off the coast of India during the southwest monsoon. *Ind. J. Mar. Sci.*, 14 (1985), 62-66
- 8 Shetye S R, Gouveia A D, Shankar D, Shenoi S. S. C, Vinayachandran P N, Sunder D, Michael G S & Nampoothiri G, Hydrography and circulation in the western Bay of Bengal during the northeast monsoon, *J. Geophys. Res.*, 101 (1996) 14011-14025
- 9 Madhu N V, Jyothibabu R, Maheswaran P A, VijayJohnGerson, Gopalakrishnan T C & Nair K K C, Lack of seasonality in phytoplankton standing stock(chlorophyll a) and production in the western Bay of Bengal, *Cont. Shelf. Res.* 26 (2006) 1868-1883
- 10 Helga R G, Joaquim I. G & Toshiro S, Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal, *Cont. Shelf. Res.* 20 (2000) 313-330
- 11 Grasshoff K, Erhardt, M & Kremiling K, Methods of Seawater analysis, (Verlag Chemie.,Weinheim)1983, 89-224
- 12 UNESCO, Protocols for the Joint Global Ocean Flux Study. In: *Manual and Guides*, 29. (1994) 190
- 13 Yang G M, He D H, Wang C S., Miao Y T & Yu H H, Study on the biological oceanography characteristics of planktonic copepods in the waters north of Taiwan, II.Community characteristics. *Acta Oceanol. Sin.* 21 (1999) 72-80

- 14 Clarke K R & Green R H, Statistical design and analysis for a 'biological effects' study. *Mar. Ecol. Prog. Ser.*, 92 (1988) 205-219
- 15 Clarke K. R & Warwick R. M., *Changes in marine communities: an approach to statistical analysis and interpretation* (Plymouth Marine Laboratory UK) 1994, 144
- 16 Prasanna Kumar S, Narvekar J, Nuncio M, Kumar A, Ramaiah N, S. Sardesai, Gauns M, Fernandes V & Paul J, Is the biological productivity of the Bay of Bengal light limited?, *Current Science.*, 98 (2010) 1331-1339.
- 17 Qasim S Z, Bhattathiri P M A & Devassy V P , The influence of salinity on the rate of photosynthesis and abundance of some tropical phytoplankton, *Mar. biol.* 12 (1972) 200-206.
- 18 Santhanam R, *Hydrobiological studies in Porto Novo waters. Ecology of phytoplankton in the different biotop.*, Ph.D. thesis, Annamalai. Univ. 1976
- 19 Stolte W & Riegman R, Effect of phytoplankton cell size on transient state nitrate and ammonium uptake kinetics, *Microbiology*.141 (1994) 1221-1229
- 20 Rijstenbil J. W, Phytoplankton composition of stagnant and tidal ecosystems in relation to salinity, nutrients, light and turbulence. *Nether. J. sea Res.* 21 (1987) 113-123
- 21 Paul, J T, Ramaiah N , Gauns M & Fernandes V, Preponderance of a few diatom species among the highly diverse microphytoplankton assemblages in the Bay of Bengal, *Mar. biol.*, 152 (2007) 63-75.