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Phytoplankton and nutrient dynamics of shallow coastal stations at Bay of Bengal, Eastern Indian coast

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Abstract Phytoplankton dynamics of Eastern Indian coast was studied from surface water for a period of 24 months (April 2005–March 2007) in relation to environmental variables like, temperature, pH, dissolved oxygen, biochemical oxygen demand (BOD), salinity and nutrient contents—including nitrate, phosphate and silicate. Total 43 taxa were recorded during the study period. Phytoplankton density ranged from approximately 350–3,000 cells/ml and showed complete dominance of diatom genera namely, *Asterionella japonica* in winter and *Odontella rhombus* in summer. Other frequently occurring diatoms were *Coscinodiscus perforatus*, *Actinocyclus normanii* f. *subsala*, *Thalassiothrix fraunfeldii*, *Ditylum brightwelli*, *Stephanodiscus hantzschoides*, *Cyclotella meneghiniana*, *Thalassionema nitzschoides* etc. Seasonal changes in abundance and diversity of phytoplankton significantly differed showing maximum diversity in autumn with high diversity index (2.76-Oct, 05) and minimum in winter (0.326-January, 06). The species evenness varied from 0.137 (January 06) to 0.991 (August 06), which signifies minimum variation in percentage contribution of individual species to total phytoplankton population in monsoon and maximum in winter. Correlation studies of total cell count to physicochemical variables indicated significant positive relation with dissolved oxygen, salinity and pH but negative relation with nitrate, silicate and BOD of the water body. Multivariate procedures like ordination by principal component analysis and multi dimensional scaling of phytoplankton population based on their occurrence data and magnitude of abundance indicated that some genera (*Biddulphia heteroceros*, *B. dubia*, *Odontella aurita*, *Gyrosigma acuminatum*, *Coscinodiscus granii*, *Paralia sulcata*, etc.) have specific preference for water temperature and salinity and flourished maximally in particular season(s). While other genera (*A. japonica*, *C. meneghiniana*, *C. perforatus*, *D. brightwelli*, *S. hantzschoides*, etc.) appeared in wide range of temperature and salinity gradient.

Keywords Phytoplankton diversity · Nutrients · Seasonality · Principal component analysis (PCA) · Multi dimensional scaling (MDS)

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Introduction

Phytoplankton dynamics or the time dependent changes in phytoplankton biomass are the result of a complex interplay of physical, chemical and biological processes. It is an established fact that nutrient availability largely determines the diversity of phytoplankton. Over the last few decades, there has been much interest to study different factors influencing the development of phytoplankton communities, primarily in relation to physico-chemical factors (Nielsen et al. 2002; Grenz et al. 2000; Elliot et al. 2002). Overall the successional pattern of phytoplankton communities in relation to nutrient variation will help to understand the ecosystem functioning (Magurran 1988; Barnese and Schelske 1994). In a lotic system, the irregular dynamics of inflow and variable flushing rates of freshwater markedly alter environmental conditions for biotic communities. Anthropogenic activities also increase the nutrient level of estuarine and coastal areas resulting in alteration of plankton population and biomass production (Cederwall and Elmgren 1990; Kahru 1994; Escaravage et al. 1996; Schöllhorn and Granéli 1996). Therefore climatic changes and anthropogenic effects on the coastal ecosystem have sent a sense of urgency in understanding the role of biodiversity and productivity in ecosystem dynamics. Many of these issues have not been sufficiently studied for Indian coastal waters; rather the studies on the taxonomic diversity of marine phytoplankton have had a long tradition.

From south and west coast of India, several reports are available on marine plankton diversity which primarily focussed on the taxonomic identification of the different phytoplankton genera (Venkataraman 1939; Subrahmanyan 1946). Venkataraman (1939) reported 98 forms, whereas Subrahmanyan (1946) gave a systematic account of 171 forms of planktonic diatom from Madras coast and south Indian coast, respectively. Kannan and Vasantha (1992) primarily worked on the species composition and population density of micro phytoplankton from Pitchavaram mangals of south east coast of India and recorded high species richness. Sasamal et al. (2005) recorded diatom bloom formation along the Orissa coast.

Distributions of phytoplankton in relation to environmental factors like upwelling and altered wind direction have also been studied in Indian Coast by few authors (Dehadrai and Bhargava 1972; Saravanane et al. 2000; Madhupratap et al. 2001). Dehadrai and Bhargava (1972) reported a clear succession of species where changes in hydrographical factors and biological processes of the nearshore waters of the central west coast of India were influenced by patterns of upwelling. Saravanane et al. (2000) studied the change in plankton population in response to altered wind direction at Kalapakkam coast of south India. They observed that changes in wind direction caused different ocean currents to influence the salinity and nutrient content of the habitat waters resulting in appearance of different phytoplankton genera. Madhupratap et al. (2001) worked on oceanography and fisheries of the Arabian Sea and reported that upwelling during the summer monsoon and cooling in the northern Arabian Sea during winter are the major attributes that contribute to phytoplankton productivity in this area.

Phytoplankton productivity can be predicted based on the three basic variables: phytoplankton biomass, biomass specific carbon assimilation rate and light availability (Cole and Cloern 1984). Several studies have revealed that primary productivity fluctuates seasonally in response to changes in environmental conditions. A study on primary productivity at Mandovi-Zuari estuaries in Goa revealed that productivity was maximum in the premonsoon period at two stations but in postmonsoon period it was maximum at the third station (Krishna Kumari et al. 2002). Madhupratap et al. (2003) reported that the Bay of Bengal is less productive than the Arabian Sea along the western coast of India. A work on phytoplankton composition and productivity at Ariyankuppam estuary and Verampattinam coast of Pondicherry revealed that Gross Primary Productivity was minimum in monsoon and maximum in summer (Ananthan et al. 2008).

Floristic pattern of planktons are generally represented by several biotic indices and Multivariate analysis. Diversity indices are mostly simple statistical methods generally implemented to simplify the comparative analysis of biotic communities when the number of individuals is high, belonging to different species. Thus, a study on plankton diversity using biotic indices is an important aspect to understand the system dynamics (Figueredo and Giani 2001). Use of multivariate procedures (PCA, MDS, CCA etc.) are increasingly being used to analyze water chemistry and phytoplankton characteristics in coastal aquatic habitats(Karentz and Smayda 1984; Philippart et al. 2000; Nasrollahzadeh 2008).

Indian coastline extending 7,500 km is bordered by Arabian Sea on the west and Bay of Bengal in the east. Though this area is ecologically important for fishery and other marine product harvesting, extensive studies in relation to phytoplankton dynamics are still lacking. In the present communication, an attempt has been taken to understand the seasonal changes in phytoplankton community and the primary productivity in relation to environmental variables at two coastal stations viz: Digha and Junput, (21°37′N and 87°31′30′E) along the Bay of Bengal. The floristic pattern has also been studied using Shannon and Weaver's index (1949), Pielou's evenness index (Pielou 1984) and species richness. To analyze the data computerized statistical package was used to calculate correlation co-efficient between phytoplankton density and physicochemical factors. Multivariate procedures were also included in this study to better understand the behaviour of the ecosystem. Accordingly, ordination of species by principal component analysis (Orlocci 1966) along with multi dimensional scaling (MDS) on a seasonal basis was also included in the present study.

Sampling site

Digha and Junput (21°37′N and 87°31′30′E) are situated at the bank of Bay of Bengal located at the south eastern coast of India at a distance of approximately 100 km (Fig. 1). The habitat water is marine with mixing of freshwater due to monsoon rains and freshwater rivers' runoffs. The entire area is with a prolonged summer (April–May–June) and monsoon (July–August–September) with a short post-monsoon period showing variation of temperature from 15 to 30°C. Post-monsoon period (October–November) is followed by winter (December–January–February) with an average temperature of 15 ± 2°C and pre-summer periods (March).

Materials and methods

Water analyses

Water samples were collected at an interval of 15 days in every month for 2 years (April 2005–March 2007) in replicates of three. Composite samples were prepared by collecting equal volumes of samples from ten spots along an arbitrary transect at a distance of 5 m offshore and a depth of 0.5 m. This procedure was repeated at both the sites approximately at the same time during the entire study period and were pooled together to obtain the water sample for analyses, since in an earlier study it was observed that both sites represented almost similar phytoplankton populations with a narrow range of variation among the environmental variables. Water samples were filtered and the physicochemical parameters were analyzed in relation to water temperature, pH, nitrate, phosphate, silicate and salinity following the methods of APHA (1998). Water samples collected in 1 l PVC bottles were cooled to minimize the changes in water quality in thermostatically insulated ice buckets and were transported back to field laboratory for determination of nutrient concentrations within half an hour of sampling. Water temperature and salinity were recorded immediately after sampling with centigrade thermometer and refractometer, (ERMA, Tokyo) respectively. DO content was determined in situ following Winkler's Iodometric titration method (Winkler 1888). Gross primary productivity (GPP) and net primary productivity (NPP) were also measured in situ by light and dark bottle method after 3 h of incubation (Winkler's method). Productivity rates (GPP and NPP) were determined by converting oxygen fluxes to carbon equivalents using a photosynthetic quotient of 1.2 and a respiration quotient of 1.0.

Phytoplankton analysis

From each spot along the transect as mentioned earlier, about 50 l of sample water was passed through a tow phytoplankton net (mesh size 20 μ) and the residual phytoplankton biomasses in the collecting chamber of the phytoplankton net were pooled together to obtain the phytoplankton sample for study. [Sedimentation technique could not be implemented, since the habitat water had a high suspended load where the rate of settlement of silt component was almost similar to that of diatoms. This caused difficulties in proper taxonomic identification and so phytoplankton net was used for sampling]. Phytoplankton samples were fixed with neutralized formaldehyde (0.8–1.6% final concentration). From the composite samples phytoplankton counts were performed using Sedgewick-Rafter cell counter to determine the cell count per liter of sample

Fig. 1 Site map showing the study area (*arrows/lines* not to scale)

water using an inverted microscope (Carl Zeiss). Microscopic slides of samples were prepared using Naphrax as mounting medium. For taxonomic identifications, prism drawings were performed and microphotographs were taken with magnification powers of ×400 and ×1000 using Carl Zeiss Axiostar phase-contrast microscope. Taxonomic identification of the micro phytoplankton was done using appropriate monographs (Venkataraman 1939; Cupp 1943; Subrahmanyan 1946, 1958) and a floristic list was prepared (Table 1).

Numerical and statistical procedures

Shannon Weaver's (SW) Species diversity index (H′), species richness and species evenness index were estimated. Correlation analyses between biotic (cell count) and abiotic variables were performed using STATISTICA 6.0 software where $n = 24$ at $P < 0.05$(Stat Soft Inc. 1994–1995).

For the multivariate analysis, excessively rare species were removed from the original dataset as the inclusion of very rare species weakens correlations analysis. Ordination of species by principal component analysis (PCA) was performed by raw data of each species in different months. For MDS analysis, correlation matrix data of different species was plotted in accordance with the data applied for PCA. PCA and MDS analysis for the entire study period were performed on the seasonal basis. Eigenvector values and Eigenvalues were considered for analysis of PCA.

Results

Eastern Indian coast is densely populated area causing localized eutrophication, which directly influence nutrient level of coastal water and phytoplankton abundance. Moreover, the monsoon rain causes major changes in salinity level for 3 months (July–September). The silt and sandy coast along with rough waves resulted in turbid water, therefore reducing phytoplankton growth.

Physico chemical parameter analysis

The temperature and pH value of the coastal water of the study area ranged from, 15–30°C to 7–7.6, respectively (Fig. 2a, b). Minimum temperature was observed in winter and minimum pH value in monsoon.

As evident from Fig. 3a, nitrate content was maximum in October 2006 (24.193 µM) with minimum value in December 2005 (11.129 µM), in summer months also low level of nitrate was recorded. But maximum phosphate concentration was estimated in August 2005 (9.413 µM) and minimum in December 2005 and January 2006 (2.232 µM; Fig. 3b). Therefore in the study area nutrient concentration was maximum in monsoon period. Silicate concentration was quite high in comparison to nitrate and phosphate levels throughout the year, ranging from 19.971 to 127.319 µM with highest value in August, 2005 and lowest in January, 2006 (Fig. 3c) favouring the diatom growth. Maximum salinity level was recorded in winter (January 2006 and 2007—36‰), which dropped in monsoon period (September 2005—26‰; Fig. 3d).

Correlation matrix (Table 2) and 2-D scatter plots were performed based on Pearsonian r values, which showed that cell count had significant negative correlation with nitrate ($r = -0.5233$, $P = 0.0087$) silicate($r = -0.4805$, $P = 0.0175$) and non significant with phosphate ($r = -0.3648$, $P = 0.0797$) and temperature ($r = -0.342$, $P = 0.1019$) but positive significant correlation with salinity ($r = 0.5418$, $P = 0.0062$), and pH ($r = 0.5665$, $P = 0.0039$) at $n = 24$ and $P < 0.05$.

Phytoplankton composition

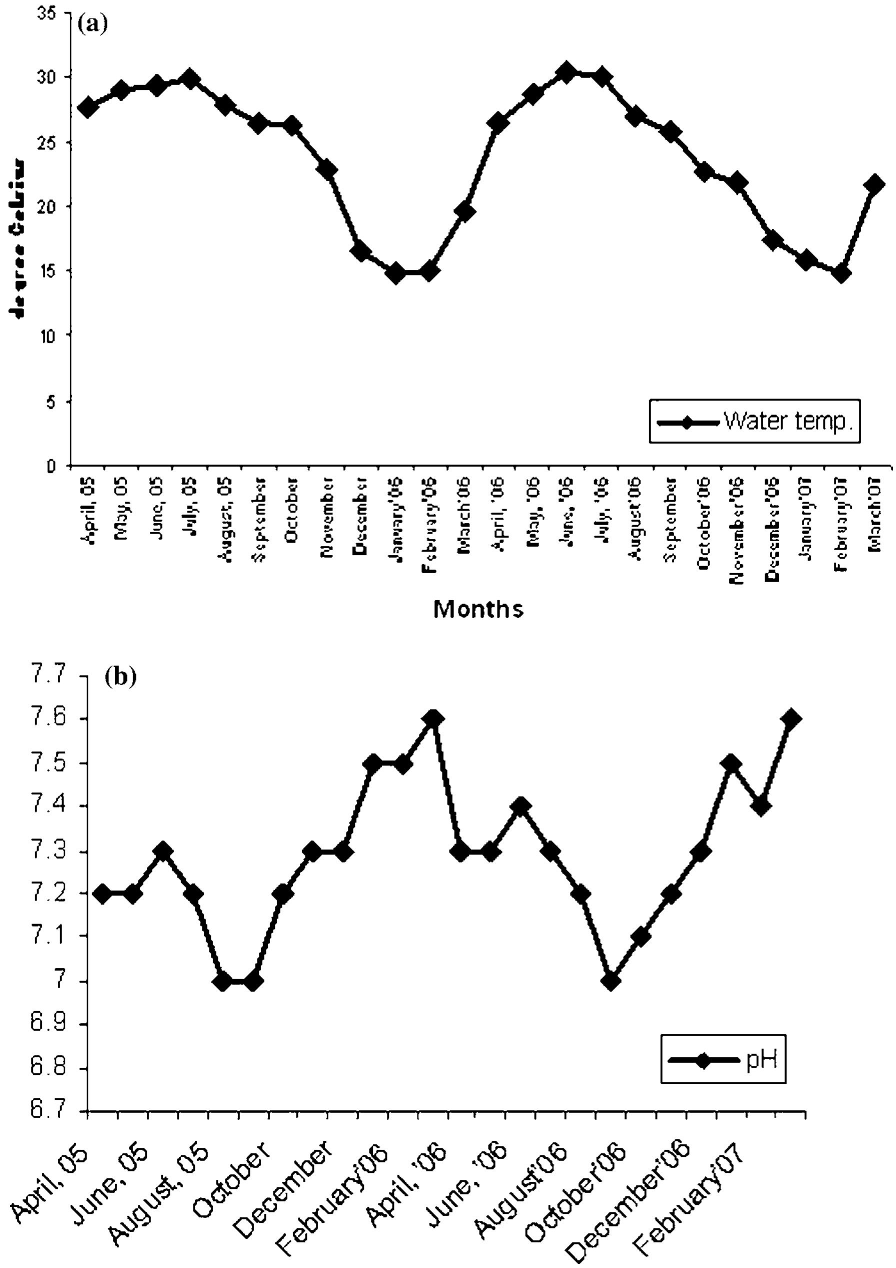
A total of 43 taxa belonging to 22 genera were recorded that flourished in different seasons (Table 1). The plankton flora was represented mainly by Diatoms, only two genera of Dinophyta, namely *Dinophysis* and *Gymnodinium* were recorded during the study period. Single species abundance of *Asterionella japonica* was observed from autumn to winter with a maximum growth of 94.46% in January 2006 (Fig. 4b). *Odontella rhombus* appeared as the most abundant species in June 2005, with a maximum growth of 47.97% of the total population (Fig. 4b). Among the other genera sudden appearance of *Skeletonema costatum* was remarkable in the summer month of June 2006 contributing 50.31% of total population, whereas *Cocconeis* sp. appeared as 25% of the flora in the month of May 2005.

Table 1 Floristic list of phytoplankton genera recorded during the study period

Division	Name of genera	Period of availability	Abundance
Bacillariophyta	*Asterionella japonica* Cleve (AJ)	Almost throughout the year	++++
	Odontella rhombus (Ehrenb.) Kütz. (OR)	Apr to Oct	+++
	O. mobilensis (J. W. Bailey) Grunow (OM)	Mar to Oct	++
	Odontella aurita (Lyngb.) C. Agardh (OAu)	Oct to Mar	++
	Biddulphia alternans (Bailey) Van Heurck (BA)	Aug to Jan	++
	B. dubia (Brightwell) Cleve (BD)	Oct to Mar	++
	B. heteroceros Grunow (BH)	Oct, Nov	+
	Gyrosigma obtusatum (Sull. & Wormley) Boyer (GOb)	Mar to July	+
	Gyrosigma acuminatum (Kütz.) Rabenh. (GAcu)	Feb to Apr	+
	Pleurosigma normanii Ralfs (PN)	Dec to Mar	+
	Cyclotella meneghiniana Kutz (CM)	Almost throughout the year	++
	Coscinodiscus perforatus Ehrenberg (CP)	Almost throughout the year	++
	C. centralis Ehrenberg (CC)	Nov to Apr	++
	C. excentricus Ehrenberg (CE)	Apr to July	++
	Actinocyclus normanii f. *subsala* (Juhl.-Dannf.) Hust. (AN)	June to Oct	++
	Coscinodiscus granii Gough (CG)	Oct, Nov	+
	Paralia sulcata (Ehrenberg) Cleve (PS)	Apr to July	+
	Nitzschia delicatissima Cleve (ND)	Apr to July	++
	Nitzschia sigmoidea Ehrenberg (NS)	Apr	+
	Cyclotella striata (Kutzing) Grunow (CS)	May to Sept, Nov (2006); Mar (2007)	+
	Stephanodiscus hantzschoides Grunow (SH)	Aug to Mar	++
	Thalassiosira decipiens (Grunow) Jorgensen (TD)	May, June	+
	Cocconeis sp.	May (2005)	Rare
	Ditylum brightwellii (West) Grunow (DB)	Almost throughout the year	++
	Chaetoceros curvisetus Cleve	June, July (2005)	Rare
	Surirella fastuosa (A. Schmidt) Cleve (SF)	June, Oct, Mar	+
	Bacteriastrum varians Lauder (BV)	July to Sept	+
	Chaetoceros diversus Cleve (CD)	July to Nov	++
	Diploneis interrupta (Kutz.) Cleve (DI)	Oct, Nov	+
	Diploneis weissflogii (A. Schmidt) Cleve (DW)	July to Nov	+
	Aulacoseira granulata (Ehrenb.) Simonsen (AuG)	July to Oct	+
	Chaetoceros wighami Brightwell (CW)	July to Oct	+
	Chaetoceros messanensis Castracane (ChM)	Aug to Oct	++
	Thalassiothrix frauenfeldii Grunow (TF)	Aug to Feb	++
	Thalassionema nitzschioides Grunow (TN)	Nov to Jan	++
	Bacillaria paxillifer (O. F. Müll.) Hendy (BPax)	Mar, Oct	++
	Nitzschia pacifica n. sp. (Npac)	Oct, Nov	+
	Amphiprora gigantea Ehrenberg (AG)	Oct, Nov	+
	Eucampia zoodiacus Ehrenberg	June (2006)	Rare
	Skeletonema costatum (Greville)	March (2006)	Rare (high count)
	Aulacodiscus johnsonii var. *amherstii*	May (2005)	Rare
Dinophyta	*Gymnodinium* sp.	May (2005)	Rare
	Dinophysis sp.	May (2005)	Rare

Abbreviations in parentheses represent different species in our figures of PCA and MDS analysis

Fig. 2 Monthly variation in physical parameters **a** water temperature and **b** pH



Rest of the diatom genera contributed 5–25% of the total phytoplankton population and appeared seasonally. A few genera like *Bacillaria paxillifer*, *Nitzschia pacifica*, *Amphiprora gigantea*, *Biddulphia heterocer-os*, *Aulacoseira granulata*, *Coscinodiscus granii*, *Surirella fastuosa*, *Chaetoceros curvisetus*, *Eucampia zoodiacus* and *Aulacodiscus johnsonii* occurred rarely in the study area (Table 1). The seasonal phytoplankton abundance is further supported by multivariate procedures like PCA and MDS (discussed later).

Primary productivity

Maximum productivity [Gross Primary Productivity or GPP] was recorded in June, 2006 (1,330 mgC/m^3/h) when phytoplankton count was as high as 31.58 $\times$ 10^5 cells/l and minimum productivity was recorded in July, 2006 (77.78 mgC/m^3/h; Fig. 4c). On a seasonal basis, highest productivity was recorded in winter, followed by summer with the lowest productivity in monsoon. Maximum plankton productivity

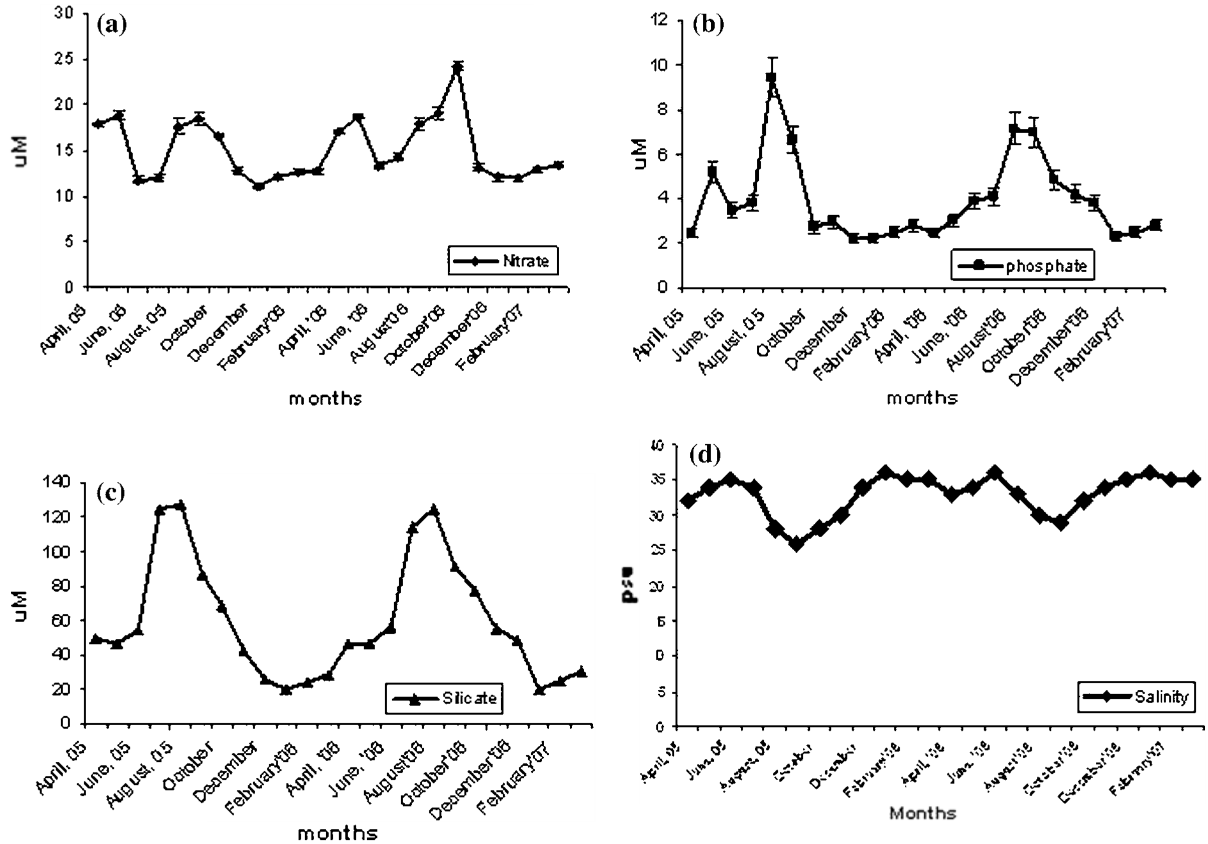


Fig. 3 Monthly variation in chemical parameters **a** nitrate, **b** phosphate, **c** silicate and **d** salinity

Table 2 Correlation matrix of cell count vs. environmental variables

	Cell count in lacks	Nitrate	Phosphate	Si	Salinity	GPP	NPP	BOD	DO	Water temperature	pH
Cell count in lacks		−0.52	−0.36	−0.48	0.54	0.91	0.56	−0.49	0.58	−0.34	0.57
Nitrate	−0.52		0.52	0.42	−0.58	−0.54	−0.57	0.55	−0.47	0.45	−0.58
Phosphate	−0.36	0.52		0.77	−0.65	−0.37	−0.48	0.78	−0.50	0.44	−0.75
Si	−0.48	0.42	0.77		−0.61	−0.56	−0.67	0.91	−0.77	0.67	−0.85
Salinity	0.54	−0.58	−0.65	−0.61		0.52	0.42	−0.78	0.45	−0.39	0.78
GPP	0.91	−0.54	−0.37	−0.56	0.52		0.71	−0.58	0.73	−0.58	0.58
NPP	0.56	−0.57	−0.48	−0.67	0.42	0.71		−0.65	0.86	−0.87	0.53
BOD	−0.49	0.55	0.78	0.91	−0.78	−0.58	−0.65		−0.74	0.64	−0.85
DO	0.58	−0.47	−0.50	−0.77	0.45	0.73	0.86	−0.74		−0.85	0.55
Water temperature	−0.34	0.45	0.44	0.67	−0.39	−0.58	−0.87	0.64	−0.85		−0.51
pH	0.57	−0.58	−0.75	−0.85	0.78	0.58	0.53	−0.85	0.55	−0.51	

was recorded in winter months (1,611 cells/ml), while in monsoon, it was minimum (494 cells/ml; Fig. 4a). Thus, it can be conclusively said that phytoplankton productivity was highly correlated with the total phytoplankton cell count which was further evidenced from the 2-d scatter plot ($r = 0.91$,

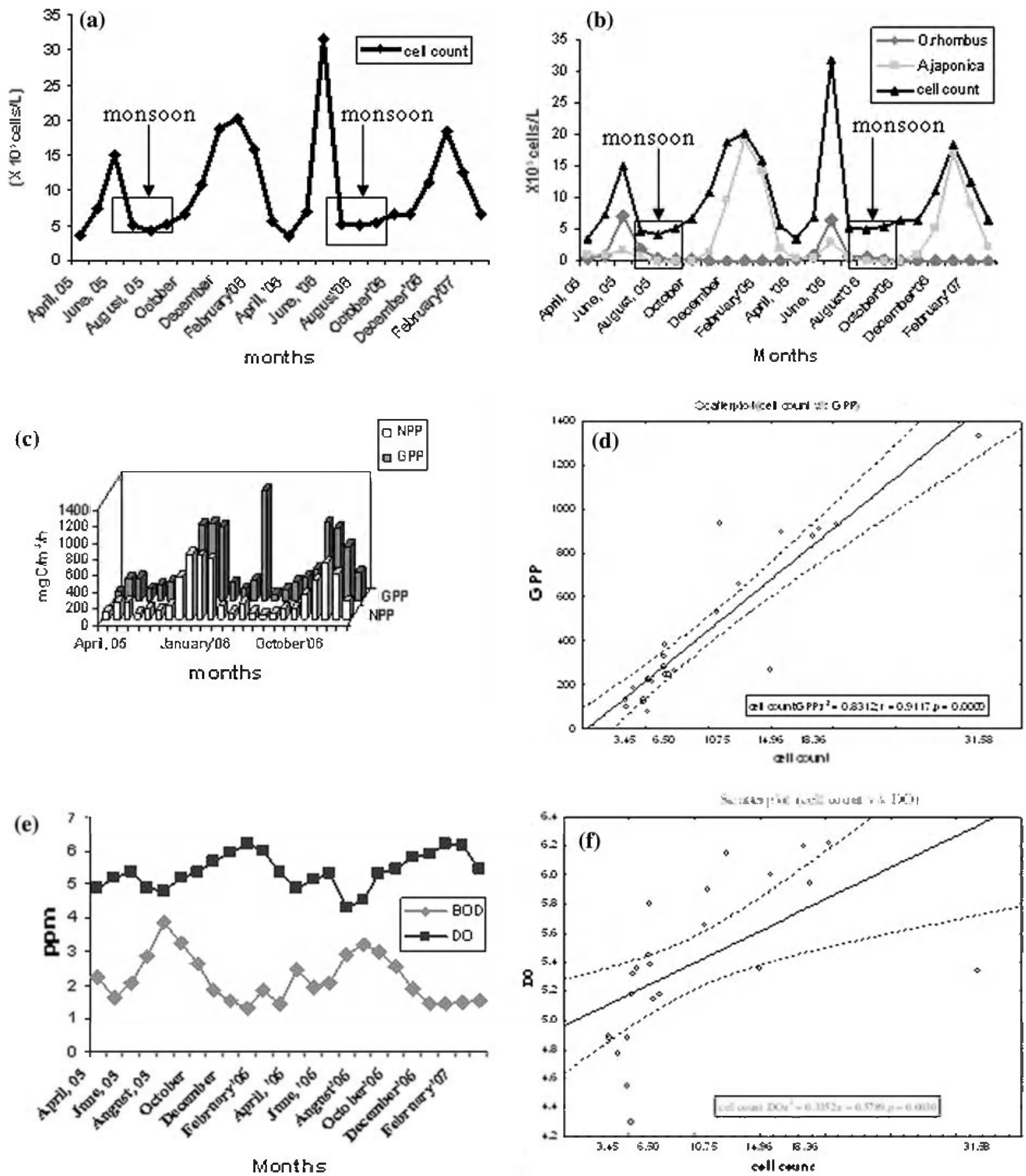


Fig. 4 Monthly variation in **a** phytoplankton cell count, **b** monthly variation in total vs. two major species viz. *Odontella rhombus* and *Asterionella japonica*, **c** productivity (GPP and NPP), **d** 2-d scatter plot between cell count and GPP, **e** BOD and DO contents and **f** 2-d scatter plot of cell count vs. DO

$P = 0.000$; Fig. 4d). On the other hand, Net Community Primary Productivity (NPP) was maximum in December, 2005 (788.88 mgC/m^3/h) and minimum in July, 2006 (44.44 mgC/m^3/h) with a significant positive correlation with total phytoplankton cell count as evidenced from Table 2 ($r = 0.56$, $P = 0.0046$).

Oxygen concentrations

Dissolved oxygen content is a reflection of the photosynthetic activity of the phytoplankton biomass. Accordingly DO values were higher in those months where plankton count was high, with a maximum of 6.22 mg/l in January 2006 and minimum of 4.3 mg/l in July 2006 (Fig. 4e). BOD value ranged from 1 to 4 mg/l, with highest value in monsoon (August, 2005) and lowest in winter (January, 2006) when DO content was high. From the correlation matrix plot (Table 2) there was a positive correlation between cell count and dissolved oxygen content ($r = 0.5789$, $P = 0.0030$; Fig. 4f) and negative correlation with BOD($r = -0.4932$, $P = 0.0143$).

Species diversity, richness and evenness

Species diversity index ranged from 0.328 to 2.76 in 2005–2006 and 0.413–2.716 in 2006–2007 (Fig. 5a) during the entire study period. A gradual increase in SW Index was recorded from July onwards reaching maximum in October (2.76 in 2005 and 2.72 in 2006) followed by November (2.67 in 2005 and 2.53 in 2006). In winter months, SW Index dropped drastically showing minimum value in January 2006 (0.328).

Species richness varied from 9 to 28 in 2005–2006 and 9 to 18 in 2006–2007 (Fig. 5b). Like SW index, maximum species richness was also observed in the month of October (28 in 2005 and 18 in 2006). Gradual decrease in species richness recorded from November onwards with minimum value in summer (June, 2006).

Like diversity index and species richness, species evenness dropped in the winter months being as low as 0.137(January, 2007), though phytoplankton count was significantly high. This was due to single species abundance caused by a high density of *A. japonica* (90% of total population). Species evenness varied from 0.13 to 0.99 bits/individual signifying the variation in contribution of different species to the total phytoplankton population in different months (Fig. 5c).

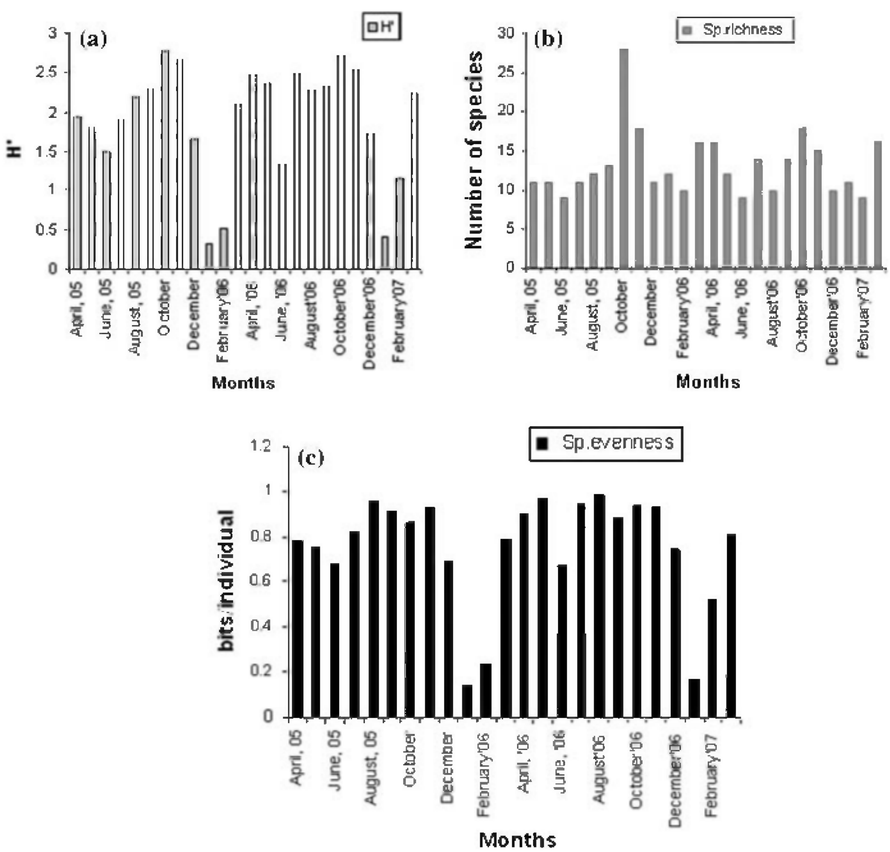


Fig. 5 Monthly variation in biotic indices **a** Shannon–Weiner index, **b** species richness and **c** species evenness

Principal component analysis

In our principal component analysis (PCA) study, the factor loading matrix indicates the correlation between each principal component to each of the species. In our study, species that appeared only once in the total sampling period were not considered. Out of 36 species considered, 11 had their strongest correlation with highest factor loading with the first two principal components (PC1 and PC2; Table 3). Accordingly the PCA plot was done considering PC1 and PC2. These two components explained 37.43% of the variation within the species data. The co-variates in the PCA plot were grouped together based on their factor loading values along PC1/PC2. Covariability between the species plotted along PC1 and PC2 was relatively high because the explained variance by the first two principal components is about 6.5 times higher than it would have been if the time series of the 36 algal species were not correlated at all. Thus, more than one-third of the variation in the 36 algal species during the study period is accounted for by the 1st and 2nd principal components in our plot. On plotting PC1 against PC2, the variability in individual species occurrence becomes evident, where the distance between the plotted species points provide a relative measure of the degree of similarity/dissimilarity between species with respect to both their seasonal occurrence and magnitude of abundance. The temporal pattern of occurrences of each individual species was also accounted by plotting PC1 vs. PC2.

As evident from our PCA plot, (Fig. 6) a negative temperature gradient was established along PC1. Accordingly, genera with a high positive factor loading along PC1 flourished in the cooler months with comparatively low water temperature. Thus genera with positive factor loadings on PC1 are more abundant in the post monsoon and winter months when the average temperature is about 12–18°C. On the contrary, genera with negative factor loading along PC1 had a preference to flourish in the summer months when the average water temperature is comparatively higher (30–36°C).

PC2 axis represents the relative degree of variation in temporal occurrence with low to high gradient of species availability during an annual cycle. As evident from the plot PC2 also represent a salinity gradient from top to

Table 3 Factor loading matrix, eigenvalue (λ) and cumulative proportion of total variance explained by each vector of the principal components' analysis

Species	Acr	1	2
Asterionella japonica	AJ	0.017	−0.254
Odontella rhombus	OR	−0.179	0.011
O. mobiliensis	OM	−0.193	0.218
B. alternans	BA	0.290	0.005
O. aurita	OAu	0.272	−0.168
B. dubia	BD	0.192	−0.202
B. heteroceros	BH	0.218	0.187
Gyrosigma obtusatum	GOb	−0.121	0.044
G. acuminatum	GAcu	−0.018	−0.118
Pleurosigma normanii	PN	0.212	−0.096
Cyclotella meneghiniana	CM	−0.176	0.163
Coscinodiscus proforatus	CP	−0.106	−0.129
C. centralis	CC	0.168	−0.285
Paralia sulcata	PS	−0.119	−0.072
Nitzschia delicatissima	ND	−0.120	−0.035
N. sigmoidea	NS	−0.049	−0.076
Cyclotella striata	CS	−0.112	0.139
Stephanodiscus hantzschoides	SH	0.0997	−0.067
Thalassiosira decipiens	TD	−0.123	-0.048
Ditylum brightwelli	DB	−0.084	0.103
Coscinodiscus excentricus	CE	−0.181	0.019
Surirella fastuosa	SF	−0.016	0.079
Actinocyclus normanii f. *subsala*	AN	−0.144	0.268
Bacteriastrum varians	BV	−0.057	0.214
Chaetoceros diversus	CD	0.134	0.349
Diploneis interrupta	DI	0.112	0.106
D. weissflogii	DW	0.219	0.046
Aulacoseira granulata	AuG	0.267	0.111
Chaetoceros wighamii	CW	0.071	0.329
C. massenensis	ChM	0.108	0.322
Thalassiothrix fraunfeldii	TF	0.230	0.187
Thalassionema nitzschoides	TN	0.212	0.078
Coscinodiscus granii	CG	0.274	0.0998
Bacillaria paxillifer	BPax	0.177	−0.184
N. pacifica	NPac	0.041	−0.002
Amphiprora gigantea	AG	0.231	0.131
Eigenvalue	λ	7.971	5.503
Cumulative variance	%	22.14	37.43

For each species, the loading with the highest absolute value is underlined. Acronyms (Acr) for Figs. 6 and 7 are indicated for each species

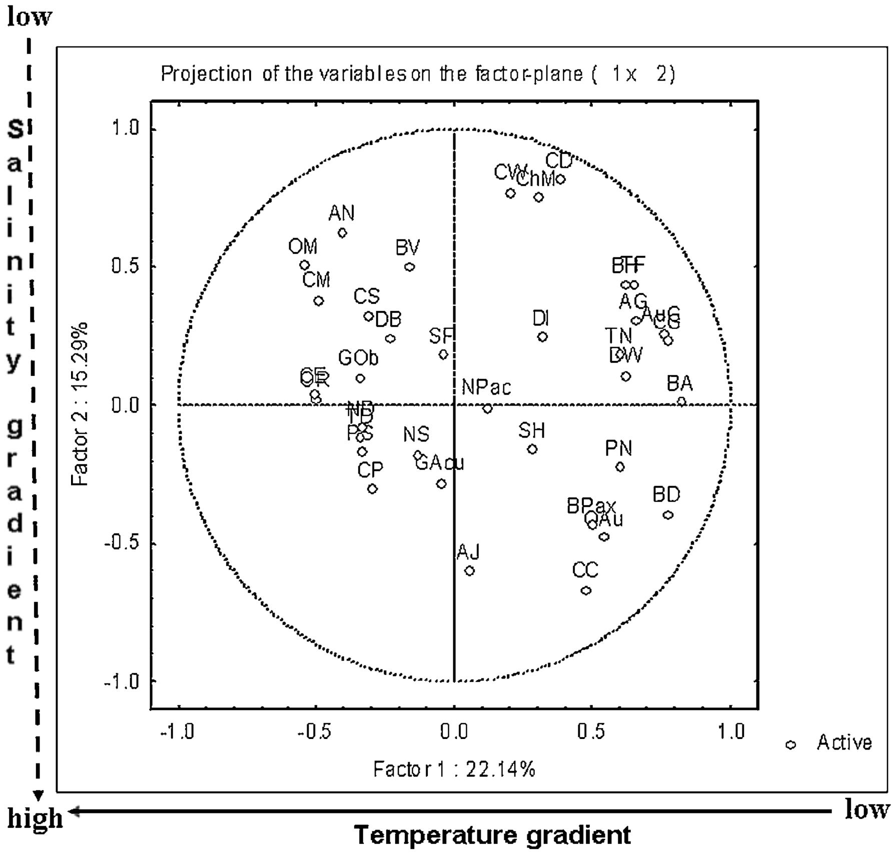


Fig. 6 PCA plot of PC1 vs. PC2 showing the pattern of species orientation based on environmental variables and magnitude of abundance

bottom in which the species align as per their salinity requirement. Species having a high positive correlation with this vector generally exhibited a specific seasonal occurrence where salinity requirement was low (as the gradient is from low to high).

Accordingly, from the PCA plot (1st quadrant) it was evident that *Biddulphia alternans* (BA) along with other genera like *Thalassionema nitzschoides* (TN), *Diploneis interrupta* (DI) and *Diploneis weissflogii* (DW) are more abundant in the post monsoon and winter months. Taxa like *C. granii* (CG), *A. gigantea* (AG) and *Aulacoseira granlata* (AuG) have intermediate positive factor loading on PC1 which are the representative of only the particular post-monsoon period with low or no availability in other seasons. Genera like *Chaetoceros wighamii* (CW), *C. massenensis* (ChM) and *C. diversus* (CD) had a very high positive loading along PC2 with intermediate factor loading along PC1 which can be clearly explained by the fact that their availability was restricted to the monsoon season (water temperature 28–32°C) and they never flourished in any other season.

Genera with a positive factor loading on PC1 but negative loading on PC2 (2nd quadrant) were mostly available in the late post-monsoon to winter months with a high abundance. This is because during this period average water temperature is low, but with a decrease in both seasonal and riverine precipitation there is a rise in salinity. Accordingly, genera like *Biddulphia dubia* (BD), *Odontella aurita* (OAu) and *Coscinodiscus centralis* (CC) attained their peak growth in this period with high abundance which culminated with a very high cell count of *A. japonica*.

Genera in the 3rd quadrant had intermediate negative factor loading for both PC1 and PC2. Hence, these genera flourished in the relatively warmer months when salinity was about 32–35 psu but with a low cell count. *Nitzschia sigmoidea* (NS) and *Gyrosigma acuminatum* (GAcu) were available only in the months of March and April. *Nitzschia delicatissima* (ND) and *Paralia sulcata* (PS) were exclusively available only in the months of April to July during the entire study period. Thus the findings clearly suggested that these genera represented the

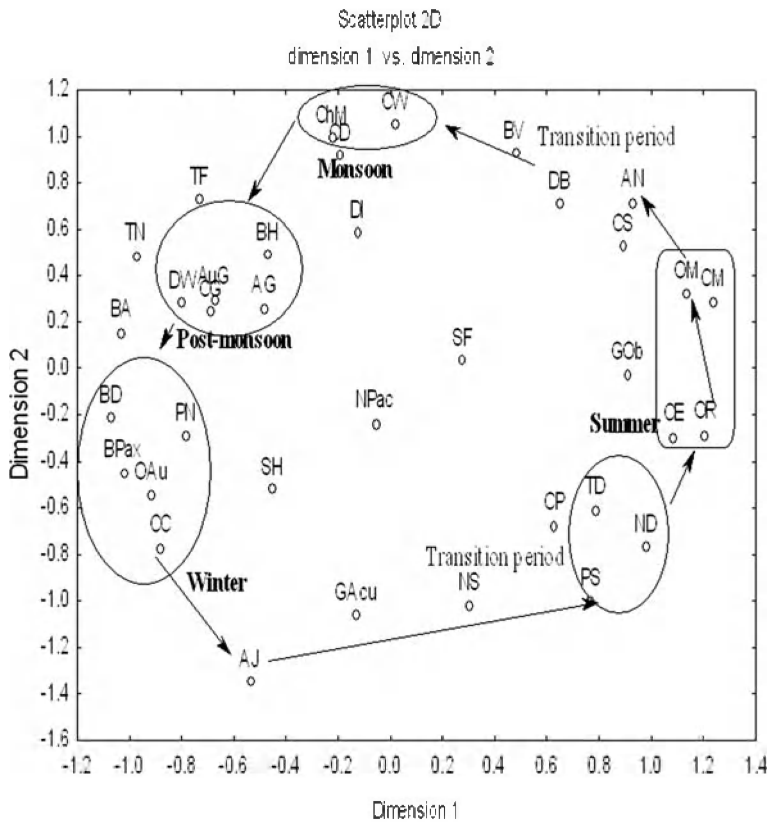


Fig. 7 Multidimensional scaling of different species considering dimension 1 and dimension 2

population of the transitory period from winter to summer months.

Finally, the 4th quadrant comprised of those genera which were abundant in the warmer months but were significantly less in the winter months of December and January with a relatively high cell count of individual species. Along with genera like *O. rhombus* (OR) and *C. excentricus* (CE) genera like *Odontella mobiliensis* (OM), *Cyclotella meneghiniana* (CM) and *Actinocyclus normanii* f. *subsala* (AN) had negative loading on PC1 but intermediate positive loading along PC2, suggesting their relatively even abundance with high density in the summer and monsoon periods.

Multidimensional scaling

For further confirmation of this seasonal pattern of species based upon their abundance data and preference for temperature and salinity, multidimensional scaling (MDS) was performed (Fig. 7). The MDS configuration plot of all genera (Dimension 1 vs. Dimension 2) clearly demarcates distinct groups based upon the seasonal preference of the individual species. In the MDS plot 5 distinct groups were configured. Starting from an anticlockwise direction from summer months (Group 1), the genera *O. rhombus* (OR), *Coscinodiscus excentricus* (CE) and *O. mobiliensis* (OM) appeared together as the dominant genera of the summer months along with *C. meneghiniana* (CM) that was available in other seasons as well but had a preference for the summer months. Genera like *Ditylum brightwelli* (DB), *Cyclotella striata* (CS) and *A. normanii* f. *subsala* (AN) began to flourish in the summer months and continued to increase in population to the monsoon period and accordingly they are representative of the transition from a summer to a monsoon season.

With the advent of the monsoon months there is significant alteration of the available nutrient concentration and accordingly the population fluctuates with the abundance of representative genera (Group 2) like *Chaetoceros wighamii* (CW), *C. massenensis* (ChM) and *C. diversus* (CD). As monsoon is prolonged there is significant enhancement of nutrient input but reduction in mean salinity. Accordingly, phytoplankton population is highly specific which is evident from the fact that the different species of *Chaetoceros* do not flourish at any other season of our sampling period except monsoon.

In the post monsoon period phytoplankton population changes with the appearance of representative genera like *B. heteroceros* (BH), *A. granulata* (AuG), *A. gigantea* (AG), *C. granii* (CG) and *D. weissflogii* (DW) (Group 3) which were available only in the months of October and November with intermittent presence in the late monsoon months.

In winter season a different population flourished which was represented by genera like *Biddulphia dubia* (BD), *O. aurita* (OAu) *Pleurosigma normanii* (PN), *B. paxillifer* (BPax) and *Coscinodiscus centralis* (CC) (Group 4). These genera appeared mostly in the late post-monsoon period of November and flourished in the winter months and gradually diminished with the approach of the summer months. This winter population finally culminated with the abrupt rise in *A. japonica* (AJ) population where only a very few individuals of other species developed. Genera like *G. acuminatum* (GAcu) appeared in the late winter months of February and flourished in March till the early summer months of April. Likewise *Nitzschia sigmoidea* (NS) and *N. delicatissima* (ND) (Group 5) appeared in the early summer month of April and accordingly they are considered as representatives of the transitory population between a winter and summer phytoplankton population.

Surirella fustuosa (SF) and *N. pacifica* (NPac) appeared irregularly with very low cell count. On the contrary, *Stephanodiscus hantzschoides* (SH) appeared all throughout the year and did not show any seasonal preference. Accordingly, these genera appeared in the middle of the MDS configuration in a scattered manner and did not belong to any particular Group.

Discussion

Physicochemical parameters of coastal water changes due to various factors that significantly influence the phytoplankton population. In the present study, the multiparameter regression analysis showed significant negative correlation of phytoplankton population with nutrient concentration like nitrate and silicate. As both the nutrients are essential for development and growth of the diatoms population, accordingly, as and when diatom population flourished there was significant drop of these nutrients in the surface waters. The fluctuation in nutrient concentration was mainly due to influx of fresh water from perennial rivers and monsoon rainfall and anthropogenic factors. Silicate level may have controlled the diatom abundance but the diatom population never disappeared and did not shift to non-siliceous plankton pulse. In the present study area the nutrient levels maintained an optimum condition, helping in maintenance of phytoplankton population. Therefore none of N or P appeared as limiting factor as they never reached below detection limit. On the other hand, significant positive correlation of the phytoplankton cell count was established with salinity. This suggests a relationship between cell number and salinity (Cl^- uptake) of the phytoplankton population. This environmental variable was mainly responsible for the establishment of a salinity gradient along which each species was differently correlated thereby playing an important role in the seasonal succession pattern. In a natural system, pH is primarily determined by the concentration of alkali metals in the ionic forms (Na^+, Ka^+, Cl^-) with higher concentrations resulting in higher pH (Hinga 2002). As salinity was considerably higher in winter and freshwater influx was low as compared to monsoon period, hence due to greater concentration of available alkali metals in their ionic forms pH in winter was higher than in monsoon months.

Due to influx of freshwater from perennial rivers and seasonal rainfall causing low salinity, abrupt decline in diatom population from summer to monsoon month was observed (Fig. 2a). A similar observation was made from the Pampulha reservoir, Brazil (Figueredo and Giani 2001). Upwelling is a major feature in any open ocean system regulating the fluctuation of phytoplankton population especially in shifting the species composition (Reynolds 1984). During our study, the seasonal phytoplankton dynamics showed appearance of the same taxa in the same season at regular time intervals of two consecutive years. Lack of intense upwelling of this coast is due to the equator ward flow of the freshwater plume which resulted in overwhelming the offshore Ekman transport in the coast of Bay of Bengal, maintaining similar seasonal plankton dynamics (Gopalakrishna and Sastry 1985). Sudden appearance of large number of *Skeletonema costatum* may be due to altered wind direction because of cyclonic weather in summer months.

Dissolved oxygen content is a measure of the photosynthetic activity of the phytoplankton biomass. Accordingly DO values were higher in months where plankton count was high. During the monsoon period, high suspended matters are carried over by the Hooghly River and other tributaries which resulted in a very turbid water column (Mukhopadhyay and Pal 2002) which was further supported by the low pH of habitat water. This resulted in a fall in the photic zone to the mixing depth ratio, so that despite the high incident irradiance, the average irradiance in the water column was relatively low which may have accounted for the drop in DO content. Our results also suggested that GPP was primarily regulated by the phytoplankton cell count as well, thereby suggesting that GPP is actually the phytoplankton productivity whereas NPP (NPP = GPP-R) is a measure of available photosynthetically fixed carbon after eliminating the catabolic loss of organic matter due to respiration (R). In our study, it was observed that NPP was considerably low in the late summer and monsoon months with a relatively high BOD values. As the month of July, 2006 was the end of summer and the beginning of the monsoon season with high freshwater runoffs and seasonal precipitation, it resulted in nutrient enrichment of the study area promoting a rise of heterotrophic population. Moreover, the late summer and monsoon months were the beginning of the fishing season in these coastal stations that further enhanced heterotrophic growth. Due to this high heterotrophic growth a relatively high community respiration rate was also observed in this month (1191.67 $mgC/m^3/h$), [data not represented in Fig. 4] thereby resulting in a significant drop in NPP as compared to GPP. A similar result was also obtained from the Mandovi River estuary (Verlencar and Qasim 1985) having highest productivity in the post-monsoon season with intermediate values in the pre-monsoon period and the lowest productivity in monsoon. High nutrient concentration but relatively low cell count and productivity was due to upwelling along with the roughness of the sea caused by cyclonic weather of the study area during the monsoon period of Indian coast. Such nutrient enrichment of surface waters due to episodic cyclonic events in the monsoon months have also been reported from the Arabian Sea as well (Madhupratap et al. 2003). A drop in primary productivity in the monsoon months and a rise of the same in the post-monsoon period was also reported from Lake Tana in Ethiopia (Wondie et al. 2007). Thus, a rise in DO content was indicative of the enhanced GPP whereas a rise in BOD was a measure of drop in NPP of the concerned ecosystem.

Diversity indices are calculated on the basis of total biomass data obtained from cell count method and the number of individuals, which indicate the community pattern of the particular ecosystem. Our study showed that in the month of July or in monsoon season nutrient concentration was high with well mixing due to seasonal precipitation and riverine influx of nutrient-rich water which appeared as a suitable condition for phytoplankton diversification that accounted for maximum SW Index in the post-monsoon period with stabilized nutrient pool. Thus, in the present study, post-monsoon period (October–November) appeared to be most conducive for phytoplankton diversity showing maximum species richness (number of individual species) and therefore the diversity index, though total phytoplankton count was less than summer and winter months. Observation of maximum diversity and species richness in post monsoon period agrees well with the earlier reports for Hugli estuary, north east coast of India (De et al. 1994) and Vellar estuary (Hangovan 1987). Decreasing tendency of SW Index indicates shifting of phytoplankton community from high species richness to bloom formation, (that is predominance of any particular genera) as reported by many authors in eutrophic and hypertrophic lakes and reservoirs (Jacobsen and Simonsen 1993; Padisak 1993; Calijuri and Santos 1996; Kyong and Joo 1998). With the advent of the cooler winter months, as seasonal precipitation stopped, sea surface temperature (SST) dropped which may have resulted in a more stable stratification of the sea surface allowing dominance of single species (*A. japonica*) with a drop of SW Index in winter as compared to other seasons (Fig. 5a). A rise in *A. japonica* population during the winter months was also reported from Orissa coast reaching as high as 99% of the total phytoplankton population (Sasamal et al. 2005). A similar finding was recorded for the summer months as well with the development of a different population (*O. rhombus*). On the contrary, in the monsoon period, as the water column was highly disturbed due to several factors like seasonal precipitation, riverine inflows, alternating air currents due to cyclonic weather, etc. a very high phytoplankton count was not recorded although the biotic indices were intermediate. Thus, at our study area, diversity of phytoplankton population decreased with a rise in productivity from the post-monsoon to the winter months. Margalef (1994) suggested that regions with seasonal climatic oscillations show an ecosystem diversity governed by cyclic modifications where periods of high diversity are followed by other presenting high dominance of few species. Our study area also exhibited a similar pattern with the post-monsoon and transition periods showing high diversity whereas the summer and winter months represented periods of high dominance and productivity of the genera *O. rhombus* and *A. japonica*, respectively, with low diversity. A similar situation was also observed by Elliot et al. (2000) who recorded a decrease in diversity under stable condition. In another study on winter phytoplankton assemblages of coastal Yellow Sea connected to Jiaozhou Bay, China, diatoms dominance was reported with low diversity index and high cell count (Wen et al. 2007).

Principal components' analysis increasingly has been increasingly used to group the species comprising phytoplankton communities into assemblages characterized by common spatial and/or temporal occurrences under given environmental conditions, water mass type or seasonally changing habitats (Margaleef 1969). Our findings suggest that the phytoplankton population of our study area were affected by the seasonal fluctuation nature of the environmental variables. As evident from the results of multivariate analysis, temperature and salinity seems to be best correlated to the seasonally changing pattern of phytoplankton population although other environmental variables (nutrients) also were important contributors for the temporal distribution of the phytoplankton population. On analyzing the data a distinct pattern in phytoplankton dynamics was recorded. As can be inferred from the MDS results, it was found that most of the genera had significant seasonal preferences of occurrence. But different species of *Coscinodiscus* viz,—*Coscinodiscus perforatus*, *A. normanii*, and genera like *D. brightwelli*, *C. meneghiniana*, *S. hantzschoides* flourished throughout the seasons with varied salinity indicating the euryhaline nature of these taxa. From the MDS plot it can be further concluded that the phytoplankton community in the sampling area gradually changed on a seasonal basis with distinct transitional zones between two relatively homogenous systems (seasonal phytoplankton population) as is expected from an ecotone (ecotones are classified as narrow ecological and spatial zones between two different and homogeneous community types; van der Maarel 1990; Kent et al. 1997) represented by presence of distinct transitional population of phytoplankton. These shifts in population were mostly dependent on riverine discharges and seasonal precipitation (summer to monsoon transition) and a lack of it (winter to summer transition) representing entirely different communities.

In conclusion it can be said that seasonality is the major factor in determining the plankton diversity and species succession in the open ocean system of Bay of Bengal at Indian coast associated with changes in temperature, salinity and nutrient concentration.

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