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Seasonal variation of phytoplankton community composition in coastal waters off Rushikulya Estuary, East Coast of India

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A total of 149 phytoplankton species were identified during the study period wherein diatoms contributed 109, dinoflagellates 28, green algae 6, cyanobacteria 4 and cocolithophores 2. A striking feature of the study is the new record of 26 species from coastal waters vicinity off Rushikulya estuary (coastal and estuarine waters extending from Rushikulya to Bahuda) and 15 species from entire coastal waters of Odisha. A contrast in phytoplankton species composition was noticed in all seasons. Diatoms found as the dominant prevailing phytoplankton group in all seasons in terms of number of species and abundance. Diatom species *viz. Thalassiothix longissima, Skeletonema costatum, Coscinodiscus eccentricus* were ubiquitous off Rushikulya estuary throughout the year. River and monsoon influence coastal waters in supplying macronutrients for phytoplankton growth. Nitrogenous nutrients were found to be controlling factor for phytoplankton growth. A linear relationship between phytoplankton abundance and chlorophyll-*a* was observed during three seasons. Despite the highest species abundance during premonsoon, species diversity index showed maximum for postmonsoon and monsoon periods due to preponderance of few diatom species. Species were found to be more evenly distributed during monsoon as indicated from the Pielou's evenness (J') index. Non-metric multidimensional scaling (MDS) ordinations based on Bray-Curtis similarities indicated that phytoplankton communities prevailed in March and April were the least similar to those on other sampling occasions.

[**Keywords:** Phytoplankton, Taxonomic composition, Diversity index, Correlation, Chlorophyll-*a*, Monsoon]

Introduction

Diversity of phytoplankton, outburst and removal of some species, can be regarded as indication of change of water quality[1,2]. The distribution of phytoplankton is associated with nutrient variability, bio-physical processes *viz.* light environment, water column stratification / turbulence, temperature, removal by zooplankton and river discharge[3,4,5,6]. Species succession of phytoplankton is also associated with these environmental variables[7]. Composition and distribution of phytoplankton vary from coast to coast according to respective hydro-biological environments.

Variations in phytoplankton biomass and productivity influenced significantly by change in surface salinity due to freshwater influx in coastal waters of western and northern Bay of Bengal[8]. Physical oceanographic processes, river discharge and cyclones also proved to be controlling factors in the distribution of phytoplankton biomass i.e. Chlorophyll-*a* (Chl-*a*) in Bay of Bengal[9]. In the backdrop of the foregoing discussions, the long term monitoring of phytoplankton species composition and their relationships with seasonal changes of environmental conditions is required. The change in phytoplankton assemblages during different seasons was observed to be regulated by the change in water characteristics associated with monsoon[2]. The parameters salinity and nitrate have shown that the phytoplankton community shift was directly related to the environmental factors[10]. Relatively higher nutrient concentrations along the western Bay of Bengal than the central Bay appeared to contribute to higher phytoplankton abundance. The predominance of diatoms in the Bay could be attributed to rapid utilization of available nutrients. Among diatoms, pennales were significantly regulated by nutrients. While, apart from nutrients, physical stratification, light and eddies also seem to influence the distribution and abundance of centrales[11]. Though diatoms are the dominants, bloom forming dinoflagellate species are also reported from Bay of Bengal[12].

There are some sporadic reports limited to Rushikulya estuary on the distribution of phytoplankton, Chl-*a* and physico-chemical parameters [13-19]. However, there has been much less information available on this aspect towards offshore region of the estuary[20]. The present study of one year (March 2010 - February 2011) focuses on qualitative and quantitative analysis of extensive data on phytoplankton and associated physico-chemical parameters with an aim to (i) determine their distribution in seasonal scale, and (ii) identify the impact of physico-chemical parameters on distribution of phytoplankton.

Materials and Methods

Sampling site

The current study was conducted along southern coast of Odisha off Rushikulya estuary at five selected time series stations (19˚10ˊ0" N to 19˚ 30ˊ0" N & 85˚ 00ˊ 0" E to 85˚10ˊ0" E) as shown in Fig. 1. Study area experiences three different seasons, *viz*. [premonsoon: PRM (March-June), monsoon: MON (July-October) and postmonsoon: POM (November-February)]. Above seasons were classified according to the onset and termination of southwest monsoon which is the climatic factor of the study area[21]. Rainfall in this area mainly occurs during the MON seasons with peak in July; however, rain due to tropical cyclones, storm surges and deep depressions are common. Annual average rainfall is 1,210 mm[22]. Tide is semi-diurnal ranged between 0.85 m (neap tide) and 2.39 m (spring tide)[15,23]. The circulation pattern of the study area is governed by seasonal East India Coastal Current (EICC)[24], surface current driven by monsoon winds[25], cyclonic circulation[26]and river discharge[27].

The study area signifies itself as a fragile environment due to variability in phytoplankton concentration because of unstable concentration of nutrients, especially silicate and nitrate[13,14]. Mohapatra and Padhy (2001)[28] reported that the study area receives high amount of dissolved chemical inputs from several sources as a result of river runoff and localized phenomena of sea. The study area is under threat due to overfishing, activities of Gopalpur Port, and effluent discharge by nearby industries[29]. The data presented in this paper obtained on regular monthly sampling for a period of one year (March, 2010 to February, 2011) from five fixed time series stations on the platform of a fishing trawler.

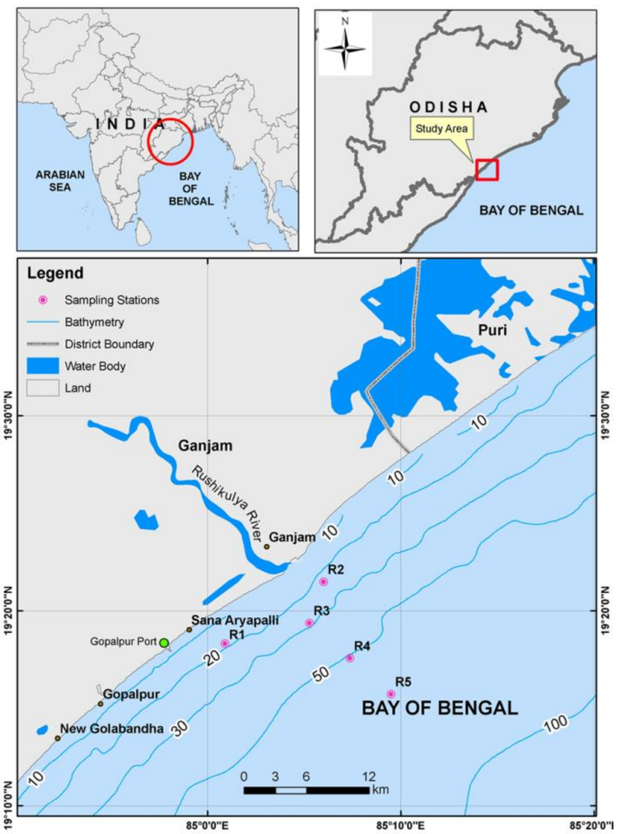

Fig. 1—sampling locations in the study area (R1-R5) with depth contours in meters

Field surveys were carried out on a monthly basis during the study period. During each survey, water samples were collected from different time series stations between 10.30 am to 3.30 pm. A mechanized fishing trawler was utilized as sampling platform.

Several physico-chemical parameters *viz.* salinity, dissolved oxygen (DO), sea surface temperature (SST) and nutrients [(Nitrite (NO_2), Nitrate (NO_3), Phosphate (PO_4), Silicate (SiO_4), and Ammonia (NH_4)] were measured from the surface water samples collected by means of a plastic bucket. Salinity was estimated following Knudsen's argentometric method. Temperature and pH were recorded by portable mercury filled thermometer & pH meter (Make: EUTECH) respectively. Transparency was determined using a Secchi Disk. Total Suspended Matter (TSM) was measured by gravimetric techniques[30]. Nutrients were analyzed as per the methods of Grasshoff et al. (1999)[31].

For quantitative analysis, 1 L of water samples were immediately filtered with 47 mm glass fiber filters (Whatman GF/F) under mild vacuum for measuring Chl-*a* concentration was taken as the measure of viable phytoplankton biomass. Filters were extracted into 90% acetone under cold and dark conditions. The extracts were analyzed using a UV-Visible Spectrophotometer (Make: JASCO Model: V-650) in order to determine Chl-*a*[30].

Phytoplankton samples (1 L) were collected from surface in clean plastic bottles. After collection, the samples were immediately preserved with Lugol's iodine and 3% neutralized formaldehyde. Investigation on phytoplankton involved determining the species composition, contribution to biomass and numbers. The fixed water samples were finally concentrated to 80 ml by sedimentation. In the laboratory, phytoplankton identification was made with the aid of an inverted fluorescence microscope (Make: Cippon; Model No.21033) in different magnifications *viz.* 40X, 100X, 400X from the plankton concentrate. A Sedgwick Rafter counting chamber was used as a platform for qualitative and quantitative estimation of phytoplankton. The phytoplankton abundance was represented as cell numbers per liter (Nos./l). Standard taxonomic identification keys were referred for the identification of species[32-38].

The data were classified into three seasons such as PRM, MON and POM. One-way analysis of variance (ANOVA) was applied to hydrographic and biological datasets to see if there is any significant variation among seasons as well as stations. Correlation and regression analyses were carried out using MS-Excel (2007). Univariate measures [Shannon-Wiener diversity index (H'), Margalef's species richness (d) and Pielou's evenness (J'), Simpson dominance (D)] were determined using PRIMER (Plymouth Routines in Multivariate Ecological Research) software Version 5. Phytoplankton species composition and abundance at five sites over the period from March 2010-February 2011 were clustered using nonparametric multidimensional methods in PRIMER v5[39,40].

Species Richness [d] = $(S - 1)/\ln N$[41]

S = number of taxa

N = number of individuals.

Species Diversity: Shannon Diversity Index [H'][42]

$$H' = \sum_{i=1}^{s} - (P_i * \ln P_i)$$

H = the Shannon diversity index

P_i = fraction of the entire population made up of species i

S = numbers of species encountered

$\sum$ = sum from species 1 to species S

Species Evenness [J'][43]

$$J' = H' / \ln S$$

H' = Shannon diversity index

S = total number of species in the sample

Species Dominance: Simpson's Dominance Index [D][44]

$$D = \sum (pi)^2$$

D= Simpson's Dominance Index

P_i = fraction of the entire population made up of species i

Results

Hydrographic parameters

The results obtained for all the physicochemical parameters are presented in Fig. 2. Sea surface temperature (SST), salinity and pH showed temporal variations. SST ranged between 24.70^{0}C and 30.03^{0}C. Highest SST was recorded in PRM whereas lowest in POM. Salinity was found highest in PRM period (34.83 PSU) but lowest in MON (26.94 PSU). Highest (8.3, at station R5) and lowest values (7.51 at station R1) values of pH were associated with MON. Maximum (8.46 mg/l) and minimum (7.29 mg/l) values of DO were observed during POM. NO_2 was found maximum in MON (0.49 µg/l) while minimum in PRM (0.27 µg/l). Highest and lowest values for NO_3 were associated with PRM (2.06 µg/l) and MON (0.93 µg/l) respectively. Similarly, the NH_4 content was maximum in POM (5.06 µg/l) and minimum in MON (1.35µg/l). The concentration of PO_4 was found highest in POM (2.98 µg/l) and lowest in MON (0.77 µg/l). The highest value for SiO_4 was recorded during POM (9.23 µg/l) and lowest during MON (3.11 µg/l). Chl-*a* showed its maximum in PRM (5.67 mg/m^3) and minimum in MON (1.29 mg/m^3) (Fig. 2).

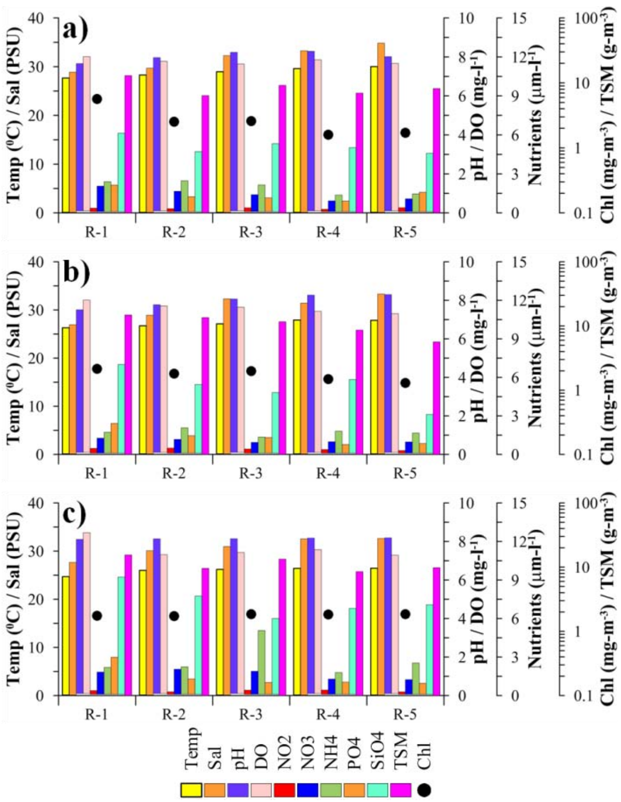

Fig. 2—variability of water quality parameters at sampling stations during a) pre-monsoon, b) monsoon and c) post monsoon season

Phytoplankton Community

Taxonomic identification reveals that the community contained 149 species of phytoplankton in the shallow coastal water off Rushikulya estuary during the observation period. Of total, 109 species are of diatoms, 28 species of dinoflagellates, 6 species of green algae, 4 species of cyanobacteria (blue green algae) and 2 species of cocolithophore (Table 1). According to the number of species under different groups a sequence diatom > dinoflagellate > green algae > cyanobacteria > cocolithophore was noticed during PRM and MON periods (Table 2). But during POM, number of species under different groups followed the sequence diatom > dinoflagellate > green algae > cocolithophore > cyanobacteria (Table 2).

During the study period phytoplankton abundance varied between 1.5 x 10^4 cells L^{-1} (in POM month December) and 7.0 x 10^4 cells L^{-1} (PRM month April). Averaged phytoplankton abundance observed a trend as PRM (4.2 x 10^4 cells L^{-1}) > MON (3.6 x 10^4 cells L^{-1}) > POM (2.4 x 10^4 cells L^{-1}) (Table 1). During PRM, the phytoplankton population varied from 1.8 x 10^4 to 7.0 x 10^4 cells L^{-1} (avg 4.2 x 10^4 cells L^{-1}) (Table 1, Fig.3). Of total 83 phytoplankton species, 54 species of diatoms, 17 species of dinoflagellates, 6 species of green algae, 4 species of cyanobacteria (blue green algae) and 2 species of cocolithophore were noticed during the study period (Table 2) Diatoms dominated the phytoplankton community followed by the dinoflagellates (Fig.3). The other groups found were green algae, cyanobacteria and cocolithophore. As compared to other seasons, PRM had shown high population density.

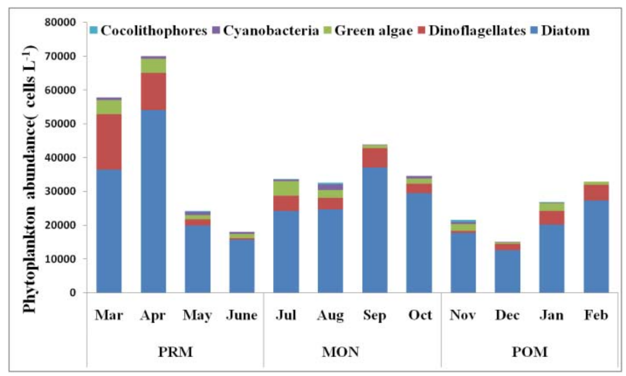

Fig. 3—phytoplankton group density in different months during 2010-11

Station-wise diatom and dinoflagellate abundance were higher in R-1 in comparison to other stations (Fig. 4). This might be attributed to the river influence and terrestrial runoff as this station is close to both estuary and coast. Station-wise population density of different groups under phytoplankton showed the sequence diatoms > dinoflagellates > green algae > others in four stations *i.e* R-1, R-2, R-4 and R-5 except in R-3 where the pattern followed diatoms > green algae > dinoflagellates > others (Fig. 4).

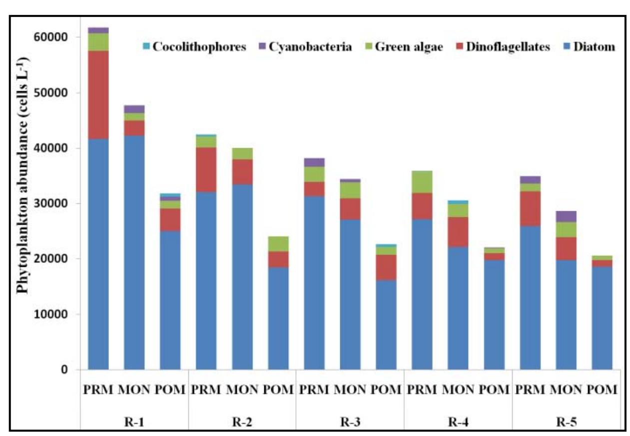

Fig. 4—station-wise phytoplankton density in different seasons during 2010-11

Table 1—Phytoplankton species composition (cells L^{-1}) and their percentage during Premonsoon (PRM), Monsoon (MON) and Postmonsoon (POM). *denotes first report of phytoplankton species from vicinity off Rushikulya estuary; *#denotes first report of phytoplankton species from entire coastal waters of Odisha

Sl.No	Taxon	Mar 2010	April 2010	May 2010	June 2010	PRM	July 2010	Aug 2010	Sep 2010	Oct 2010	MON	Nov 2010	Dec 2010	Jan 2011	Feb 2011	POM
	DIATOMS															
1	*Actinoptychus* sp.	0	0	0	0	0	0	0	558	0	140	0	0	0	0	0
2	*Actinoptychus undulatus*	0	0	0	300	75	0	0	0	476	119	0	0	0	0	0
3	**Amphora coastatum*	0	0	494	0	124	952	0	0	646	400	0	88	0	0	22
4	*Amphora laevis*	0	0	0	0	0	0	0	0	0	0	0	64	0	0	16
5	*Asterionellopsis glacialis*	0	0	0	0	0	0	0	0	323	81	0	450	396	0	212
6	*Asterionellopsis* sp.	0	0	952	343	324	447	1572	918	425	841	998	96	610	0	426
7	*#*Aulacodiscus orbiculatus*	0	0	0	0	0	0	0	0	0	0	330	0	0	0	83
8	**Auliscus reticulatus*	0	0	0	0	0	736	0	0	0	184	0	0	0	0	0
9	*Bacillaria paxillifera*	0	0	480	214	174	808	480	0	0	322	308	236	0	0	136
10	*Bacteriastrum comosum*	0	0	0	0	0	0	0	0	0	0	0	120	612	0	183
11	*Bacteriastrum delicatulum*	570	576	224	151	380	0	900	0	0	225	0	160	0	0	40
12	*Bacteriastrum hyalinum*	0	0	416	0	104	954	0	0	306	315	0	72	612	378	266
13	*Bacteriastrum* sp.	0	0	0	0	0	0	0	0	0	0	0	152	0	0	38
14	*Bacteriastrum varians*	1867	1182	608	0	914	0	1102	882	306	573	756	0	0	810	392
15	*Caloneis elongata*	0	0	0	0	0	0	0	0	0	0	0	249	93	0	85
16	*Caloneis madraspatensis*	0	0	0	0	0	0	0	0	0	0	476	0	0	0	119
17	*Campylodiscus* sp.	0	0	182	1107	322	0	0	0	0	0	0	233	200	0	108
18	*#*Ceratualina pelagica*	0	0	0	0	0	0	0	0	306	77	0	144	0	0	36
19	*Chaetoceros affinis*	0	0	0	0	0	0	0	0	252	63	0	0	0	0	0
20	*Chaetoceros capense*	0	0	0	0	0	0	0	918	0	230	0	0	0	0	0
21	*Chaetoceros constrictus*	0	0	0	0	0	0	416	612	0	257	0	0	0	554	139
22	*Chaetoceros decipiens*	666	666	0	0	333	0	0	0	0	0	0	0	0	0	0
23	*Chaetoceros didymus*	0	0	0	0	0	0	0	0	0	0	0	192	0	0	48
24	*Chaetoceros lorenzianus*	0	0	0	0	0	608	0	0	442	263	540	537	0	0	269
25	*#*Chaetoceros messanensis*	0	0	0	0	0	0	0	0	0	0	0	120	0	0	30

26	*Chaetoceros peruvianus*	0	0	0	0	0	0	0	792	0	198	0	0	0	0	0
27	*Chaetoceros* sp.	0	0	0	0	0	0	0	1026	0	257	0	152	0	0	38
28	**Climacosphenia moniligera*	0	0	0	0	0	0	0	0	0	0	0	48	0	0	12
29	**#Cocconeis litoralis*	0	0	0	0	0	432	0	0	0	108	0	0	0	0	0
30	*Corethron hystrix*	0	0	0	0	0	0	0	0	0	0	0	72	0	0	18
31	*Coscinodiscus centralis*	0	0	0	0	0	0	0	0	1151	288	0	384	93	0	119
32	*Coscinodiscus eccentricus*	0	0	254	240	124	1556	862	3222	1770	1853	749	0	955	3058	1190
33	*Coscinodiscus gigas*	3990	6462	1664	1909	3506	2390	1664	0	0	1014	0	555	1142	378	519
34	**Coscinodiscus hyalinum*	0	0	0	0	0	0	0	0	0	0	240	0	0	0	60
35	**Coscinodiscus radiatus*	0	0	0	0	0	0	0	0	0	0	0	0	1152	0	288
36	*Coscinodiscus* sp.	1046	1512	0	0	640	0	182	1638	0	455	0	0	0	1924	481
37	*Cyclotella meneghiniana*	0	0	256	0	64	0	446	0	0	112	0	0	0	0	0
38	*Cyclotella* sp.	0	0	0	0	0	0	208	504	0	178	0	0	0	82	21
39	*Cyclotella striata*	0	0	286	0	72	708	516	0	627	463	0	0	0	522	131
40	*Cylindrotheca closterium*	0	0	552	0	138	704	552	0	0	314	0	0	2043	1944	997
41	*Diploneis smithii*	0	0	0	321	80	0	0	0	324	81	0	0	0	0	0
42	*Diploneis weissflogii*	1086	576	456	0	530	0	460	90	0	138	150	48	0	0	50
43	*Ditylum brightwelli*	598	1206	300	0	526	174	440	270	1169	513	392	218	0	0	153
44	*Ditylum sol*	0	0	416	171	147	416	416	0	0	208	0	166	113	0	70
45	**Eucampia cornuta*	0	0	0	0	0	0	0	0	0	0	224	0	0	0	56
46	*Eucampia* sp.	522	522	0	0	261	0	0	0	0	0	0	0	0	0	0
47	*Eucampia zoodiacus*	0	0	0	0	0	0	206	864	0	268	0	48	0	180	57
48	*Fragilariopsis oceanica*	0	0	608	0	152	0	0	0	0	0	0	0	0	0	0
49	*Fragillariopsis* sp.	0	0	0	0	0	0	0	90	0	23	0	96	0	0	24
50	*Grammatophora marina*	0	0	0	0	0	0	0	0	0	0	0	208	42	0	63
51	**#Guinardia delicatula*	1706	1944	0	0	913	0	0	378	289	167	0	120	0	0	30
52	*Guinardia flaccida*	0	0	0	0	0	0	0	0	476	119	0	0	0	0	0
53	*Guinardia* sp.	0	0	0	0	0	0	0	0	0	0	0	0	792	0	198
54	*Gyrosigma balticum*	558	558	538	0	413	0	1062	0	0	266	578	72	279	378	327

55	*Gyrosigma* sp.	0	0	0	0	0	0	130	486	442	265	0	0	0	162	41
56	**Hemidiscus hardmanianus*	0	450	0	0	113	0	0	0	0	0	0	0	0	0	0
57	*Lauderia annulata*	0	0	0	300	75	0	0	252	1149	350	300	144	0	0	111
58	*Leptocylindrus danicus*	0	0	130	846	244	0	0	0	595	149	1030	351	555	0	484
59	*Leptocylindrus minimus*	0	0	0	200	50	0	0	810	1155	491	0	184	0	0	46
60	*Licmophora abbreviata*	0	0	0	0	0	330	0	0	0	83	0	0	0	0	0
61	*Mediopyxis helysia*	0	0	0	0	0	0	0	288	0	72	0	0	0	0	0
62	*Melosira sulcata*	1544	1944	505	0	998	0	609	756	1139	626	1482	754	0	144	595
63	*Navicula clavata*	0	0	0	0	0	0	0	0	0	0	499	0	0	0	125
64	*Navicula longa*	950	990	448	0	597	448	448	756	955	652	280	249	0	0	132
65	*Navicula* sp.	0	0	0	0	0	0	476	0	0	119	0	0	0	342	86
66	*Nitzschia longissima*	0	0	0	0	0	0	0	684	0	171	0	0	0	0	0
67	*Nitzschia penduriformis*	0	0	0	0	0	0	0	0	0	0	593	0	0	0	148
68	*Nitzschia seriata*	0	1098	218	0	329	0	916	0	0	229	0	0	0	0	0
69	*Nitzschia sigma*	0	0	0	0	0	0	972	252	288	378	0	0	0	1134	284
70	**Odontella alternans*	0	0	0	0	0	0	0	0		0	0	128	0	0	32
71	*Odontella heteroceros*	0	0	1141	429	392	486	458	1134	1232	827	0	554	1379	0	483
72	*Odontella mobiliensis*	0	0	0	0	0	1344	694	1458	0	874	616	192	721	908	609
73	*Odontella sinensis*	0	0	0	0	0	0	0	0	0	0	532	0	0	0	133
74	*Paralia* sp.	4800	7848	0	0	3162	0	0	0	0	0	0	0	0	0	0
75	*Paralia sulcata*	0	0	0	0	0	0	0	0	0	0	0	0	0	396	99
76	*Pinnularia alpina*	0	0	256	389	161	0	500	0	1369	467	300	0	0	0	75
77	*Pinnularia* sp.	486	486	0	0	243	0	0	0	0	0	0	0	0	0	0
78	*Planktoniella sol*	854	486	0	171	378	0	0	0	0	0	0	0	0	0	0
79	*Pleurosigma angulatum*	0	0	0	0	0	0	0	0	408	102	448	0	0	0	112
80	*Pleurosigma carinatum*	0	0	0	300	75	0	0	0	0	0	0	0	0	0	0
81	*Pleurosigma directum*	0	0	0	0	0	0	0	522	544	267	0	0	0	0	0
82	*Pleurosigma elongatum*	2214	630	0	257	775	256	0	0	0	64	570	399	0	0	242
83	*Pleurosigma normanii*	0	0	0	0	0	0	0	0	0	0	330	0	0	0	83

84	*Pleurosigma* sp.	882	882	0	0	441	0	1512	0	0	378	0	0	0	2250	563
85	*Pseudonitzschia pungens*	522	522	0	0	261	0	0	306	306	153	0	0	0	0	0
86	**Rhabdonema mirficum*	486	486	0	0	243	0	0	0	0	0	0	0	0	0	0
87	*Rhabdonema* sp.	0	0	0	0	0	0	0	0	0	0	0	166	0	0	41
88	*Rhaphoneis amphiceros*	486	486	0	0	243	0	0	0	450	113	0	0	0	0	0
89	*Rhizosolenia alata*	1242	7614	844	1757	2864	0	1468	1296	816	895	0	469	929	2115	878
90	*Rhizosolenia castracanei*	0	0	552	86	159	0	680	0	0	170	0	144	0	0	36
91	*Rhizosolenia crassipina*	0	0	0	214	54	0	0	0	0	0	0	0	0	0	0
92	*Rhizosolenia cyclindrus*	0	0	130	629	190	450	0	0	0	113	0	0	859	0	215
93	*Rhizosolenia imbricata*	0	0	0	0	0	0	0	396	0	99	0	48	0	0	12
94	*Rhizosolenia robusta*	0	0	0	0	0	0	0	0	0	0	0	0	279	0	70
95	*Rhizosolenia setigera*	0	0	624	1114	435	850	0	126	1774	688	2531	663	457	792	1111
96	*Rhizosolenia stolterforthii*	0	0	0	0	0	574	0	0	0	144	0	543	0	862	351
97	*Rhizosolenia styliformis*	0	0	604	303	227	1286	440	162	425	578	0	224	2068	378	668
98	*Skeletonema costatum*	1884	3366	1058	300	1652	1813	1518	4212	1326	2217	1624	168	2248	1398	1359
99	*Stephanopyxis turris*	1210	1278	0	0	622	448	0	0	0	112	0	147	0	0	37
100	*Surirella eximia*	0	0	0	257	64	0	0	108	786	224	0	0	457	558	254
101	*Surirella fluminensis*	0	0	390	300	173	374	0	0	0	94	0	0	0	0	0
102	*Synedra formosa*	0	0	416	0	104	416	416	0	578	353	168	249	0	0	104
103	*Thalassionema nitzschioides*	0	0	0	0	0	1320	0	954	992	817	210	64	0	792	267
104	*Thalassiosira* sp.	0	0	0	0	0	0	0	0	0	0	0	96	0	0	24
105	*Thalassiosira subtilis*	0	0	0	0	0	450	0	3438	442	1083	0	0	0	0	0
106	*Thalassiothix longissima*	4660	9994	3930	3164	5437	2504	1974	5976	3043	3374	390	1641	336	4948	1829
107	*Thalassiothrix frauenfeldii*	0	0	0	0	0	0	0	0	0	0	0	0	918	0	230
108	*Trachyneis aspera*	0	0	0	0	0	0	0	0	0	0	180	0	0	0	45
109	*Triceratium* sp.	1742	342	0	0	521	0	0	0	0	0	0	0	0	0	0
	DINOFLAGELLATES															
110	*Amphisolenia bidentata*	288	288	0	0	144	0	0	0	0	0	196	0	0	0	49
111	**#Ceratium azoricum*	1980	1980	0	0	990	0	0	0	0	0	0	0	0	0	0

112	**#Ceratium densus*	702	702	0	0	351	0	0	0	0	0	0	0	0	0	0
113	*Ceratium extensum*	0	0	46	0	11	46	46	0	0	23	0	0	0	0	0
114	*Ceratium furca*	0	0	0	0	0	0	296	0	0	74	0	72	0	1260	333
115	**Ceratium fusus*	0	0	0	0	0	0	0	0	0	0	0	48	0	0	12
116	*Ceratium* sp.	0	0	0	0	0	170	0	432	0	151	0	0	0	0	0
117	*Ceratium trichoceros*	0	0	0	0	0	0	0	0	0	0	0	64	0	0	16
118	*Ceratium tripos*	0	0	0	0	0	0	0	0	448	112	0	192	826	0	255
119	*Dinophysis caudata*	1946	1782	380	100	1052	456	448	522	799	556	240	0	396	0	159
120	**#Dinophysis hastata*	0	0	0	0	0	0	0	0	0	0	0	0	157	0	39
121	*Gonyaulax minima*	0	0	206	171	94	243	0	162	0	101	0	351	0	0	88
122	**#Gyrodinium* sp.	1582	1332	0	0	729	0	0	0	0	0	0	0	0	0	0
123	*Noctiluca miliaris*	1728	0	632	107	617	0	968	0	0	242	0	234	0	0	59
124	*Noctiluca scintillans*	6520	3240	0	0	2440	0	390	1782	0	543	0	128	371	756	314
125	**#Peridinium crassipes*	0	0	234	0	59	0	0	0	0	0	0	0	0	0	0
126	*Prorocentrum maximum*	0	0	192	0	48	1308	192	594	408	626	0	96	0	0	24
127	*Prorocentrum micans*	0	0	0	0	0	1241	0	1242	510	748	0	168	1194	414	444
128	*Prorocentrum rostratum*	540	540	0	0	270	0	0	0	0	0	0	0	0	0	0
129	*Prorocentrum* sp.	0	0	0	0	0	0	0	414	0	104	0	0	0	0	0
130	**#Protoperidinium ovatum*	0	0	0	171	43	0	0	0	0	0	0	0	0	0	0
131	**#Protoperidinium*	0	0	0	0	0	0	0	0	0	0	0	32	0	0	8
132	*Protoperidinium* sp.	512	684	0	0	299	0	770	522	255	387	0	144	288	1116	387
133	*Protoperidinium steinii*	0	0	0	0	0	0	292	0	0	73	0	168	0	558	182
134	*Pyrocystis fusiformis*	0	0	0	0	0	0	0	0	391	98	180	166	0	0	86
135	*Pyrocystis* sp.	0	0	184	0	46	1081	0	0	0	270	0	0	792	468	315
136	**#Pyrophacus horologicum*	558	558	0	0	279	0	0	126	0	32	0	82	0	0	21
137	*Pyrophacus steinii*	0	0	70	0	18	0	0	0	0	0	0	0	0	0	0
	GREEN ALGAE															
138	*Chlamydomonas marina*	396	396	96	107	249	424	798	0	162	346	366	160	414	270	303
139	**Chlorella marina*	696	342	684	86	452	212	672	288	306	370	240	0	0	216	114

140	*Chlorella salina*	1438	1314	84	593	857	2338	0	144	255	684	796	210	307	216	382
141	*Oocyctis* sp.	414	414	68	380	319	936	446	198	794	594	376	32	1209	0	404
142	*Pediastrum duplex*	296	702	272	0	318	468	510	162	0	285	250	0	378	360	247
143	*Pediastrum* sp.	900	900	0	0	450	0	0	0	0	0	0	0	0	0	0
	CYANOBACTERIA															
144	**#Calothrix crustacea*	306	306	0	0	153	0	0	0	0	0	0	0	0	0	0
145	*Oscillatoria* sp.	0	0	104	343	112	552	0	162	340	264	561.6	112	49	0	181
146	*Trichodesmium erythraeum.*	0	0	773	0	193	0	1664	90	416	543	0	0	0	0	0
147	*Trichodesmium* sp.	576	576	0	200	338	0	0	0	0	0	0	0	0	0	0
	COCOLITHOPHORE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
148	**#Discosphaera* sp.	0	0	296	0	74	0	0	0	0	0	437	0	0	0	109
149	*Phaeocystis* sp.	0	0	72	0	18	72	450	0	0	131	210	0	216	0	107
	Total	57949	70162	24325	18030	42617	33781	32637	43974	34586	36245	21676	15136	26939	33022	24194

The appearance of Cyanobacteria and Cocolithophores at different stations were irregular (Fig.4). Station-wise total phytoplankton diversity in terms of number of species during PRM varied from 29 (at station R-4) to 37 (at station R-1) (Table 3). The species *viz.* *Thalassiothrix longissima* (12.8%), *Coscinodiscus gigas* (8.2%), *Paralia* sp. (7.4%), *Rhizosolenia alata* (6.7%), *Noctiluca scintillans* (5.7%), *Skeletonema costatum* (3.9%) were found abundant. During MON, the phytoplankton population ranged from 3.2 x 10^4 to 4.3 x 10^4 cells L^{-1} (avg 3.6 x 10^4 cells L^{-1}) (Table 1, Fig. 3). Of total 95 species of phytoplankton, diatoms 71 species, dinoflagellates 16 species , green algae 5 species, cyanobacteria (blue green algae) 2 species and cocolithophore 1 species were encountered during the study period (Table 2). Diatoms dominated the community followed by dinoflagellate, green algae, cyanobacteria and cocolithophores (Fig. 3 & 4). Diatom, dinoflagellate population had shown clear variation among stations (Fig. 3). As compared to other seasons, the population was lower than PRM and higher than POM (Table 1). Similar to PRM, the density of diatoms were comparatively higher in R-1 than other stations (Fig. 4). Also in comparing different groups as well as among the stations in terms of population density, the diatoms, dinoflagellates and green algae took up the 1st, 2nd and 3rd order of dominancy in all the stations except at R-1 where in place of green algae the cyanobacteria was in 3rd position (Fig. 4). Species number for total phytoplankton ranged from 28 (at station R-4) to 63 (at station R-1) (Table 3).

Table 2—Phytoplankton number in different months during 2010-11

Group	Mar	Apr	May	June	PRM	Jul	Aug	Sep	Oct	MON	Nov	Dec	Jan	Feb	POM
Diatom	25	27	32	27	54	29	30	36	38	71	30	50	27	26	79
Dinoflagellates	10	9	8	4	17	7	8	9	6	16	3	14	7	6	18
Green algae	6	6	5	4	6	5	4	4	4	5	5	3	4	4	5
Cyanobacteria	2	2	2	2	4	1	1	2	2	2	1	1	1	0	1
Cocolithophores	0	0	2	0	2	1	2	0	0	1	2	0	1	0	2
Total	43	44	49	37	83	43	45	51	50	95	41	68	40	36	105

Table 3—Station-wise phytoplankton number in different seasons during 2010-11

Group	R-1			R-2			R-3			R-4			R-5		
	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM	PRM	MON	POM
Diatom	27	52	28	19	41	34	23	29	33	17	19	34	20	25	31
Dinoflagellates	5	7	7	7	8	7	5	5	10	6	5	7	5	7	6
Green algae	3	2	3	4	3	4	2	3	3	5	3	4	3	3	3
Cyanobacteria	2	2	1	0	0	0	2	1	0	0	0	1	3	1	0
Cocolithophores	0	0	1	1	0	0	0	0	1	1	1	0	0	0	0
Total	37	63	40	31	52	45	32	38	47	29	28	46	31	36	40

The species *viz. Thalassiothrix longissima* (9.31 %), *Skeletonema costatum* (6.12%), *Coscinodiscus eccentricus (5.11%) Thalassiosira subtilis* (2.99%), *Coscinodiscus gigas* (2.8%) were the dominant species among the diatoms. *Prorocentrum micans* (2.06%), *Chlorella salina* (1.89%), *Trichodesmium erythraeum* (1.50%), *Phaeocystis* sp. (0.36%) were dominated the dinoflagellates, green algae, cyanobacteria and cocolithophore population. During POM, the phytoplankton population varied from 1.5 x 10^4 cells L^{-1} to 3.3 x 10^4 cells L^{-1} (avg 2.4 x 10^4 cells L^{-1}). Of total 105 species of phytoplankton, 79 species of diatoms, 18 species of dinoflagellates, 5 species of green algae, 1 species of cyanobacteria (blue green algae) and 2 species of cocolithophore were observed during this season (Table 2). Like PRM and MON diatoms dominated the phytoplankton community in POM (Fig. 3). Diatoms populations were higher in R-1 in comparison to other stations (Fig. 4). In POM diatoms dominated the phytoplankton community followed by dinoflagellate and green algae in all the stations (Fig. 4). As compared to other seasons, this season had shown low population density (Table 1). Number of species of total phytoplankton ranged from 40 (at station R-1 & R-5) to 47 (at station R-3) (Table 3). The species *viz. Thalassiothrix longissima* (7.56%), *Skeletonema costatum* (5.62%), *Coscinodiscus eccentricus* (4.92%), *Rhizosolenia setigera* (4.59%), *Cylindrotheca closterium* (4.12%) were found abundant.

Table 4—Pearson correlation coefficient matrix between different environmental variables

	WT	pH	DO	Salinity	NO_2	NO_3	NH_4	PO_4	SiO_4	Chl-*a*	TSM	TP	Diatom
SST	1.00												
pH	0.19	1.00											Premonsoon
DO	-0.18	-0.19	1.00										
Salinity	.626**	.490*	-0.26	1.00									
NO_2	-0.03	-0.34	0.06	0.12	1.00								
NO_3	-.716**	-0.18	0.21	-.570**	0.15	1.00							
NH_4	-.570**	-0.16	.474*	-0.35	0.25	.639**	1.00						
PO_4	-0.25	-0.36	0.33	-0.18	.503*	0.33	0.32	1.00					
SiO_4	-0.05	0.16	0.05	-0.04	-.507*	0.30	0.22	-0.07	1.00				
Chl-*a*	-.485*	-0.43	0.24	-0.40	-.460*	.535*	.510*	.563**	-0.04	1.00			
TSM	-.538*	-0.11	-0.02	-0.17	0.18	.445*	0.29	0.17	0.10	.631**	1.00		
TP	-.509*	0.01	-0.31	-0.29	-0.15	0.34	-0.01	-0.09	-0.14	0.35	.764**	1.00	
Diatom	-.460*	0.11	-0.32	-0.26	-0.12	0.35	-0.02	-0.04	0.19	0.23	.699**	.955**	1.00
SST	1.00												
pH	.766**	1.00											Monsoon
DO	-0.18	-0.05	1.00										
Salinity	.644**	.826**	-0.33	1.00									
NO_2	0.22	0.22	.472*	-0.12	1.00								
NO_3	0.25	0.15	.619**	-0.21	.739**	1.00							
NH_4	0.15	0.13	0.21	-0.12	0.39	.606**	1.00						
PO_4	0.13	0.04	.682**	-0.25	.731**	.659**	0.21	1.00					
SiO_4	-0.37	-.644**	-0.02	-.673**	-0.01	-0.08	-0.06	-0.07	1.00				
Chl-*a*	.468*	0.44	.660**	0.07	.644**	.740**	0.30	.695**	-0.22	1.00			
TSM	-.639**	-.679**	0.40	-.680**	-0.02	-0.05	-0.09	0.08	.547*	0.00	1.00		
TP	-0.13	-0.09	.621**	-0.34	.794**	.670**	0.25	.650**	0.15	.499*	0.18	1.00	
Diatom	-0.09	-0.14	.597**	-0.43	.828**	.743**	0.31	.718**	0.17	.558*	0.23	.966**	1.00
SST	1.00												
pH	-.571**	1.00											Postmonsoon
DO	0.02	-0.34	1.00										
Salinity	0.25	0.20	-0.27	1.00									
NO_2	.578**	-.455*	0.20	-0.31	1.00								
NO_3	0.13	-0.10	0.10	-0.01	0.03	1.00							
NH_4	0.19	0.11	-0.17	-0.07	0.23	-0.10	1.00						
PO_4	0.24	-.600**	.473*	-0.27	0.31	0.18	-0.03	1.00					
SiO4	-0.02	0.12	.517*	0.17	-0.24	0.23	-0.02	0.27	1.00				
Chl-*a*	0.42	-.528*	-0.15	-0.03	.521*	-0.10	0.06	0.43	-0.31	1.00			
TSM	-0.42	0.11	0.09	-0.20	-0.19	0.24	0.11	0.05	-0.08	-0.37	1.00		
TP	-0.41	-0.13	.517*	-0.18	-0.32	0.25	-0.40	0.38	.450*	-0.40	0.31	1.00	
Diatom	-0.33	-0.13	.535*	-0.08	-0.34	0.06	-0.36	0.40	.513*	-0.38	0.15	.954**	1.00

Relationship between phytoplankton biomass (Chl-a), phytoplankton abundance and other physico-chemical parameters

Pearson correlation coefficient matrix was computed between different physico-chemical parameters, Chl-*a*, phytoplankton abundance and dominant phytoplankton groups (Table 4). This helped to understand the strength of relationships between the variables. In PRM Chl-*a* exhibited positive correlation with all the nutrients except NO_2 (Table 4). TSM exhibited significant positive relation with Chl-*a*, total phytoplankton density and all phytoplankton groups. Diatom exhibited strong positive relationship with total phytoplankton abundance. In MON Chl-*a* was found to be positively correlated with SST, DO, NO_2, NO_3 and PO_4. It was found negative with SiO_4. Total phytoplankton density had positive relationship with DO, NO_2, NO_3, PO_4 and Chl-*a* with diatom following same trend. Moreover it established a high significant correlation with total phytoplankton density. During POM Chl-*a* was positively related with nitrogenous nutrient NO_2. Total phytoplankton density was positively correlated with both DO and SiO_4. Diatom followed same trend as of total phytoplankton density and found at high positive significant correlation with total phytoplankton abundance.

Regression analysis between Chl-*a* and phytoplankton density showed a linear trend (R^2=0.58) (Fig. 5). Station-wise temporal relation between these two parameters also resulted the same with a little deviation marked at station R-2 in MON (Fig. 6). A stable state of distribution of both Chl-*a* and phytoplankton was observed at almost all the station during POM.

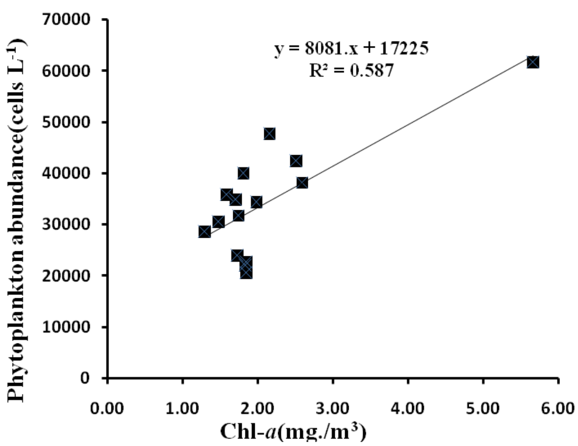

Fig. 5—regression between Chl-*a* and phytoplankton abundance

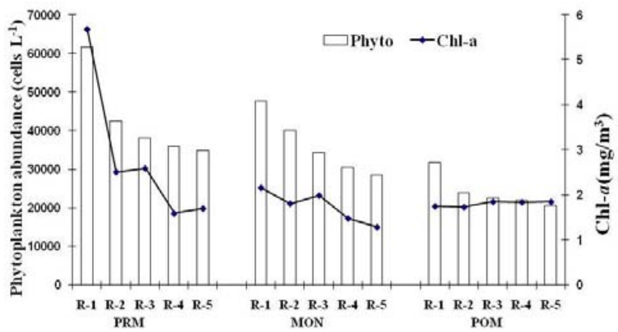

Fig. 6—variation of Chl-*a* and Phytoplankton abundance during the study period

Univariate biodiversity indices

To understand any difference in the phytoplankton diversity and seasonal dominance, univariate diversity indices are employed (Table 5). The diversity indices have shown variation in different seasons. Marglef's species richness (d) was found higher in MON (0.953-3.392) than other two seasons. It showed a significant variation (0.705-3.392) among all the seasons. Shannon Weiner Diversity index (H') computed highest for MON and lowest for PRM but the degree of variation is quite low (1.70-3.23). Other diversity indices *viz.* Pielou's evenness (J') and Simpson's dominance (D) have shown little variation among seasons indicating homogenous distribution of species in the ecosystem. Different diversity indices showed high values in POM and MON compared to PRM (Table 5).

Table 5—Univariate diversity indices during PRM, MON and POM

Univariate Diversity indices	PRM	MON	POM
Marglef's species richness (d)	0.787-1.446 (1.178)	0.953-3.392 (1.404)	0.705-2.914 (1.294)
Shannon Wiener Diversity index (H')	1.700-2.724 (2.380)	2.243-3.234 (2.547)	2.053-3.195 (2.407)
Pielou's evenness (J')	0.774-0.985 (0.921)	0.883-0.987 (0.945)	0.861-0.987 (0.939)
Simpson's dominance (D)	0.069-0.269 (0.117)	0.053-0.119 (0.091)	0.048-0.143 (0.107)

Temporal cluster analysis

Non-metric multidimensional scaling (MDS) ordinations based on Bray-Curtis[45] similarities of species abundance data were produced to provide a visual representation in a two-dimensional plot of the relative similarities in phytoplankton community composition and abundance at the different sampling sites and on the different sampling occasions. Hierarchical agglomerative cluster analysis (using group average linking) was also conducted on the Bray-Curtis similarity matrices to enable identification of phytoplankton communities based on percentage similarity. Cluster analysis reveals the degree to which samples resemble each other for certain species. The ordination clearly separated the phytoplankton assemblages of March and April (80% similarity), December and June (40% similarity) and, November (Fig. 7). The phytoplankton composition of other months: January, February, May, July, August, September and October clustered together with 40% similarity. The cluster analysis of the phytoplankton community also expressed the same. It showed groupings of sites by sampling months at different similarity levels (Fig. 8).

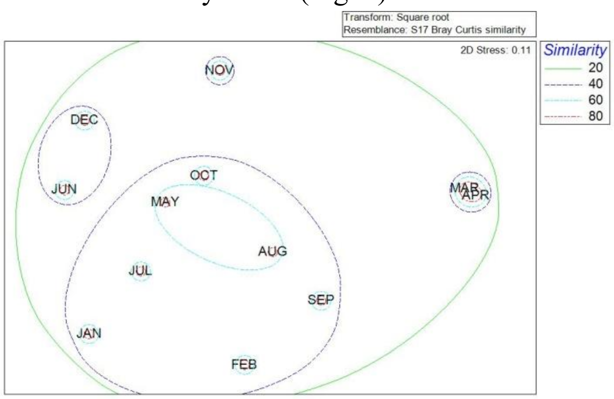

Fig. 7—Non-metric multi-dimensional scaling (MDS) ordination of the square-root transformed phytoplankton community of each month

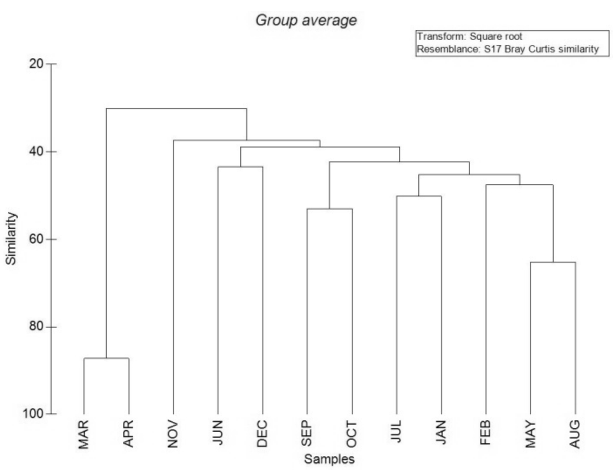

Fig. 8—hierarchical cluster analysis of percentage similarity among phytoplankton communities

Discussion

Hydrographic parameters such as SST, salinity and DO have shown significant seasonal variation during the study period. Lowest water temperature was recorded in POM season which might be due to influx of freshwater and cloudy condition and highest values in PRM was due to the extended sunny period. pH values were found to be more during POM as compared to other seasons which might be due to low freshwater influx and more availability of alkali metals in their ionic forms[46]. A seasonal salinity trend of PRM>POM >MON was noticed. Achary et al. (2010)[47] reported similar type of seasonal variation at Kalpakkam coastal waters.

In all the three seasons diatom was found to be in a significant positive relationship with total phytoplankton abundance and performed similar relationships with other environmental variables which justified it as the dominant phytoplankton group. Compared to other two seasons during POM total phytoplankton abundance found to be non-significantly related with Chl-*a*. Different phytoplankton groups also followed the same trend during POM. This deviation might be due to the contribution of small sized phytoplankton (nano or pico) to total Chl-*a* which were not enumerated in the present study[48]. Nitrogenous nutrients found to have an influencing character for phytoplankton growth during different seasons. In agreement with the present study, linear regression between Chl-*a* and phytoplankton density was also reported by many investigators[49,50](Fig. 5). Deviation in this trend observed during MON might be attributed to low contribution rate of quantified phytoplankton fraction to total Chl-*a* at particular station of particular season[48] (Fig. 6).

In PRM a significant variation in WT, pH and salinity was observed among stations (Table 6). Among nutrients only nitrate had shown significant variation as resulted from one way ANOVA test performed among the stations. During MON; pH, salinity and silicate exhibited wide variations. The significant variation of many hydrographic parameters in tropical countries like India is highly influenced by monsoonal rainfall, tidal characteristics, evaporation and water current[51]. TSM had also shown wide variation during MON period. Diatom too exhibited variation during this season. There is no such variation of any of the parameters resulted from ANOVA test performed for POM datasets. In case of ANOVA computed among three different seasons, seasonal variation was pronounced for WT, NO_3 and SiO_4. The significant variation among seasons was due to the prevalent hydrographic environments in different seasons[52]. There had been significant variation in total phytoplankton abundance and diatoms. Seasonality in phytoplankton is well pronounced from the ANOVA test.

As far as species number is concerned, diatom dominance in Indian coastal water was previously reported[46,53,54]. These types of diatom dominance over dinoflagellates coincides a lot of reports on diatom dominance in world oceans[55-57]. This might be due to the eurythermal and euryhaline nature of diatom which favours diatom dominance[58]. Diatoms can tolerate a wide range of fluctuation in salinity and temperature[18]. During PRM and MON periods phytoplankton groups observed a sequence of diatom > dinoflagellate > green algae > cyanobacteria > cocolithophore. This sequence in PRM and MON is different from the sequence (diatoms >dinoflagellates > cyanobacteria > green algae) reported by others in Indian coast[47,59]. During the POM, abundance values were decreased in the ecosystem as compared to the PRM and MON. In POM, diatom dominated the phytoplankton community followed by dinoflagellates, Green algae, Coccolithophores and Cyanobacteria. Though diatom group was represented by highest number of species (79), population density accounted for 2.4 x 10^{-4} cells L^{-1}which was lower as compared to PRM and MON (Table 2 &Table 1). Though nutrients registered in higher concentrations during this season, still phytoplankton abundance found the lowest. So in this case it is worth to mention here that the instantaneous concentration of nutrients as inorganic salts does not seem to provide a significant source for more production of phytoplankton[60].

Table 6—One way ANOVA results of hydrographic and biological parameters 2010-11

	ANOVA among Stations- PRM		ANOVA among Stations- MON		ANOVA among Stations -POM		ANOVA among Seasons	
	F	Sig.	Sig.	Sig.	F	Sig.	F	Sig.
SST	4.022	.021	.244	.244	.585	.679	21.495	.000
pH	3.267	.041	.026	.026	.110	.977	1.330	.273
DO	.748	.575	.136	.136	2.747	.068	.783	.462
Salinity	20.839	.000	.000	.000	3.032	.051	1.217	.304
NO_2	.504	.733	.428	.428	.443	.776	.727	.488
NO_3	6.444	.003	.403	.403	1.285	.320	6.683	.002
NH_4	2.805	.064	.274	.274	.655	.632	1.693	.193
PO_4	.854	.513	.187	.187	.804	.541	.025	.975
SiO_4	.469	.758	.044	.044	.308	.868	4.105	.022
Chl-*a*	2.386	.097	.908	.908	.018	.999	2.615	.082
TSM	2.074	.135	.011	.011	1.470	.260	1.864	.164
Tot. Phyto	.652	.634	.125	.125	.523	.720	5.660	.006
Diatom	.465	.760	.042	.042	.396	.809	4.787	.012
Dinoflagellate	.947	.464	.678	.678	1.521	.246	2.880	.064

Higher phytoplankton density was observed during PRM *i.e.* 4.2 x 10^{-4} cells L^{-1} than other two seasons which might be attributed to increased SST, DO and more intensity of light prevailed during this season[59]. During MON the phytoplankton population density and species number were 3.6 x 10^{-4} cells $L^{-1}$and 95 nos. respectively (Table 1 & 2). The population density was higher as compared to POM. But several workers reported lower phytoplankton population density in MON attributed to high turbidity, reduced salinity, decreased temperature and pH[47]. In this season phytoplankton density showed complete dominance of diatom. Similar observation was also reported by Paul et al. (2007)[61]. So in this case it can be said that higher abundance in MON compared to POM might be due to the ecological adaptation by phytoplankton community to utilize the available nutrients[62,63]. Phytoplankton population density as well as Chl-*a* (proxy for phytoplankton biomass) exhibited positive correlation with all the measured nutrients specifically with NO_2, NO_3 and PO_4. Phytoplankton requires a wide array of nutrients for its growth among which nitrogen and phosphorous are proved to be important[64]. Strong positive correlation between these parameters justifies higher phytoplankton abundance in MON compared to POM.

From the different diversified distribution and composition of phytoplankton obtained from present study it can be assumed that phytoplankton population and their growth depend on several environmental factors which are variable in spatio-temporal scale[52]. Among the diatoms, the species like *Thalassiothix longissima, Skeletonema costatum, Coscinodiscus eccentricus were* predominated in terms of their abundance during MON and POM while in PRM, *Thalassiothix longissima, Coscinodiscus gigas* and *Odontella sinensis* were the dominants.

Dinnoflagellates which constituted the second largest group in terms of population density and species diversity after diatoms were represented by *Dinophysis caudata*, *Gonyaulax minima*, *Noctiluca miliaris*, *Noctiluca scintillans*, *Prorocentrum maximum*, *Protoperidinium* sp., *Pyrocystis* sp., *Pyrophacus horologicum*. These species were encountered in all the seasons. Among the green algae, the species like *Chlamydomonas marina*, *Chlorella marina*, *Chlorella salina*, Oocyctis sp, *Pediastrum duplex* were seen in all the three seasons. Oscillatoria is the only sp. among the cyanobacteria group and *Phaeocystis* sp. among coccolithophores that were recorded in all the season. Other species of both the groups were sporadic in their appearance. The genus like *Asterionella, Biddulphia, Coscinodiscus*, *Nitzschia, Rhizosolenia, Ceratium, Prorocentrum, Surirella, Thalassiothrix, Thalassionema, Noctiluca, Bacillaria, Cyclotella, Gyrosigma, Chlorella* etc were common in all seasons but with different compositions. These results conceded with the observations of Naik et al. (2009)[58] and Madhav et al. (2004)[65].

A striking feature of our study is the first report of 26 species of phytoplankton (14 diatom, 9 dinoflafellate, 1 green Algae,1 cyanobacteria and 1cocolithophore) from vicinity off Rushikulya estuary (coastal and estuarine waters extending from Rushikulya to Bahuda) and 15 species (5 diatom, 8 dinoflafellate,1 cyanobacteria and 1cocolithophore) from the entire coastal waters of Odisha. The first report was confirmed through detailed survey of previous literatures pertaining to the vicinity off Rushikulya estuary[13,16,18,19,66-71] and coastal waters of Odisha coast including Chilika Lagoon[58,72-85]. Detail information regarding newly reported species are given in Table 1. The occurrence of new species and non occurrence of previously reported species might be due to the change in ambient environment and marine invasion. Moreover the surveys carried out by previous workers were mostly limited to nearshore and estuarine zone. Hence our continuous monthly study on selected time series locations extending from coastal to offshore region helped to bring out a clear picture of floristic composition of phytoplankton.

Diversity index analyses determined the variations in community structure in the study area in order to find out degree of variation in population structure. Water quality of an area can be reflected by means of alterations in phytoplankton community structure, its type of distribution and the percentage of eco-sensitive species in plankton spectrum[86]. Marglef's species richness (d) showed a significant variation among all the seasons compared to other diversity indices. But this result depicts the stabilized species richness in the study area in comparison to the results reported by Achary et al. (2010)[47]. A low value of species richness in PRM was also previously reported by Choudhury and Pal (2010)[46] at coastal waters of West Bengal.

Though total phytoplankton abundance found highest in PRM, different diversity indices resulted with high values in other two seasons compared to PRM and this observation is in agree with Margalef (1978)[87] (Table 7). The low diversity indices in PRM might be due to the dominance of some species *viz. Thalassiothrix longissima* (12.8%), *Coscinodiscus gigas* (8.2%), *Paralia* sp. (7.4%), *Rhizosolenia alata* (6.7%), *Noctiluca scintillans* (5.7%), *Skeletonema costatum* (3.9%) over the phytoplankton community during this season. High diversity indices in POM and MON is attributed to the occurrence of more number of diatomic species in POM [79 no. (80.84%)] and MON [71 no. (79.71%)]. The species diversity index values recorded for all seasons were comparatively higher than that of the observations of Gharib et al. (2011)[86] & Choudhury & Pal (2010)[46] at coastal stations of southeastern Mediterranean Sea. So it can be assumed a healthier less polluted ecosystem due to high H′ values[86,88].

The nm-MDS plot (Fig. 7) and cluster analysis (Fig. 8) based on Bray-Curtis similarity matrices confirmed that the phytoplankton communities sampled in March and April 2010 were the least similar to those on other sampling occasions. As discussed earlier and resulted from univariate diversity indices, the high similarity between March and April 2010 (months under PRM) was due to high contribution rate of few species to total abundance with lower species richness. From the cluster and MDS plot a lower similarity level (20%)

for the entire study period was obtained which is lower than the observations of Gomi et al.(2010)[89] (27.6%) and Jalal et al. (2011)[90] (59.43%). Thus the resultant cluster and nm-MDS plot clearly depict a significant temporal variation in phytoplankton composition and distribution.

Conclusions

The present effort was made to explore the phytoplankton diversity considering its uniqueness in multiple fronts of oceanographic research and also to determine a picture of current state of pelagic autotrophic life in coastal waters off Rushikulya Estuary. This study discovered that the floral spectrum of phytoplankton off Rushikulya Estuary is significantly diverse except primary PRM months (March & April). Effect of monsoon which is the major climatic factor and riverine influence on the distribution of plankton community were observed from the study. Diatom is again proven to be the dominant phytoplankton group prevailing in the coastal waters of Odisha. Further it also revealed that phytoplankton flora of the research site is susceptible to salinity and different nutrient concentrations of the ambient medium. Seasonality in phytoplankton diversity of the study area is well established.

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