

Chapter 2

Diatoms in the pelagic and benthic environment

2.1 INTRODUCTION

Coastal regions are among the most productive ecosystems in the world, where the environment is characterized by dramatic temporal fluctuations. Accordingly, the life history of phytoplankton will reflect adaptations for survival by forming specialized resting stages in fluctuating environments. Resting stages are a common survival strategy in diatoms and dinoflagellates, which form important components of coastal regions. In this chapter, the term 'resting stages' includes diatom spores, diatom resting cells and dinoflagellate hypnozygotes or cysts. The formation of resting stages is now a well-accepted phenomenon. These resting stages are able to repopulate waters if resuspended and exposed to suitable light, temperature and nutrients (McQuoid et al. 2002). Such a process is important in the life history of some diatoms and dinoflagellates (Smetacek 1985) and agrees with the concept of 'benthic-pelagic coupling.' This concept refers to the linkages between benthic and pelagic environments, which play a major role (along with terrigenous input and upwelling) in determining the production and biological structure of aquatic systems (Sommer 1989, Valiela 1995). However, most studies on benthic-pelagic coupling have only focused on the biogeochemical cycling (the turnover of nutrients in the form of either living matter or its decomposed constituents) (reviewed by Graf 1992). Marcus and Boero (1998) suggested that the classical models of production and plankton community dynamics in coastal waters will be more complete if they incorporate life-cycle patterns of planktonic and benthic organisms. The inclusion of such biological information into an ecological context will enhance the understanding of ecological patterns of global importance.

Until now, several experiments have been performed under laboratory conditions on cultured species and, also, in controlled experimental ecosystems to understand sporulation and germination processes in diatoms and dinoflagellates. The results from

these studies showed that nutrient depletion is the most important variable inducing sexuality and resting stage formation (Durbin 1978, Davis et al. 1980, Hollibaugh et al. 1981, Anderson et al. 1985, Imai 1989, Kuwata and Takahashi 1990, Ellegaard et al. 1998,) whereas light and temperature are the important triggers for germination (McQuoid and Hobson 1995). However, to some extent, temperature and light intensity also influence the rate of sporulation (Graf et al. 1983, Hoban et al. 1980, Bodungen et al. 1986, Pitcher 1986, Oku and Kamatani 1995) and can alter species composition and succession (McQuoid and Hobson 1995, Ishikawa and Taniguchi 1997).

At present, there are few long-term *in situ* observations of diatom resting stage production and deposition in the marine environment. These observations are from bays, coastal waters, fjords, upwelling regions, Baltic and Mediterranean seas (Garrison 1981, Pitcher 1990, Imai et al. 1990, Heiskanen 1993, Ishikawa and Taniguchi 1996, Mc Quoid and Hobson 1996, Itakura et al. 1997, Montresor et al. 1998, Kremp and Heiskanen 1999, Godhe et al. 2001). The number of resting stages deposited in the sediments have been compared to the number of planktonic diatoms found in the overlying waters and has contributed valuable information on the seasonal pattern of sporulation and germination of several diatom species. However, information to support such studies in tropical environments is limited.

This study addressed the phytoplankton community structure, patterns of bloom variability, qualitative, quantitative and temporal variation of diatom benthic propagules and also focused on the influence of environmental factors on the dormancy and rejuvenation of the dominant phytoplankton group, i.e., diatoms in tropical waters influenced by a clearly demarcated monsoon season.

2.2 MATERIALS AND METHODS

2.2.1. Description of the study area

Monthly sampling of sediment and water for a period of 17 months was carried out from September 1999 to January 2001 in the Zuari estuary at a fixed location (Fig. 2.1). This estuary is located along the central west coast of India, Goa. The Zuari River originates in the Western Ghats and extends up to 70 km before meeting the Arabian Sea. The width and depth of the mouth is approximately 5.5 km and 5 - 6 m respectively. This area is strongly influenced by the southwest monsoon and the changes associated with its onset have marked effects on the phytoplankton community and food web (Devassy 1983). During this period, a surplus amount of freshwater and land run-off from the Zuari River as well as precipitation (~275 cm) is added to the estuary resulting in marked changes in the physico-chemical nature of the water. Based on this, one year has been classified into three seasons, viz. monsoon season (June-September), followed by a recovery period during post-monsoon (October-January) and, thereafter, a stable pre-monsoon period (February-May) when the estuary resembles a marine environment.

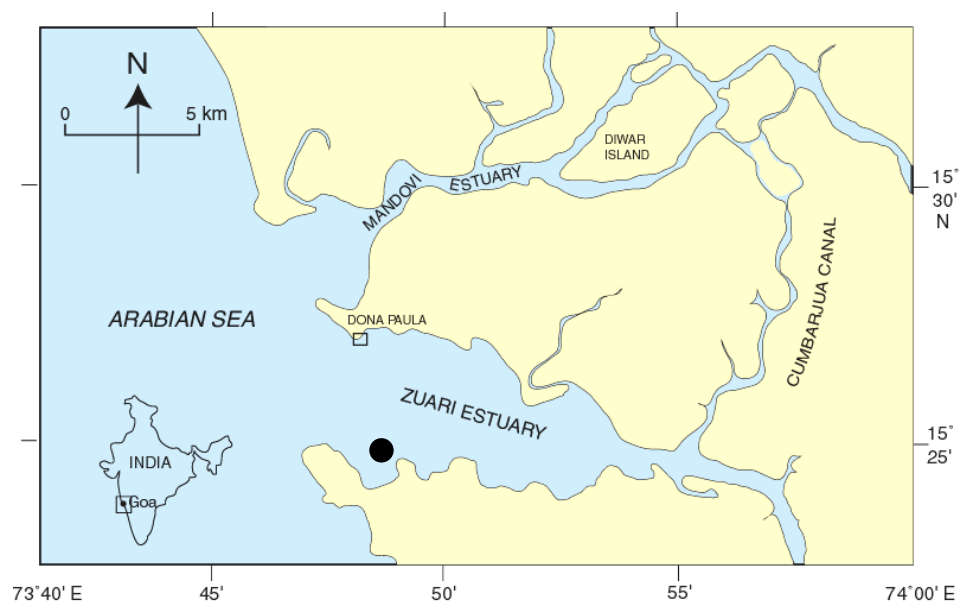


Fig. 2.1. Geographic location of the study site Zuari estuary (Goa), located on the west coast of India.

2.2.2. Sampling strategy

2.2.2a. Water sampling

Water samples were collected from the surface (bucket) and 1 m above the bottom (Niskin sampler). Water temperature and Secchi disc depth were recorded at the sampling site. Salinity was analyzed following Mohr – Knudsen titration method (Strickland and Parsons, 1965). Dissolved oxygen (DO) and nutrients ($\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, $\text{PO}_4\text{-P}$, and SiO_2) were analyzed by following standard procedures (Parsons et al. 1984) and are expressed as mL^{-1} for DO and μM for nutrients. The oxygen saturation was calculated as per the formulations given by Benson and Crause (1988) using temperature, salinity and dissolved oxygen values. Chlorophyll *a* was determined by filtering 500 ml of the sub-sample through pre-ignited GF/C filter paper. Extraction of pigments was carried out for 24 hr in 90% acetone at 4°C in the dark (UNESCO 1994). A known volume (1 L) of the water samples was fixed with 0.4% Lugol's iodine (Thronsen 1978) for the qualitative and quantitative enumeration of phytoplankton by sedimentation technique (Hasle 1978). The phytoplankton populations were enumerated in triplicates and are expressed in terms of cells L^{-1} . Phytoplankton populations were enumerated and identified to the lowest possible taxonomic level (normally species) based on the keys provided by Tomas (1997), Round et al. 1990, Desikachary (1987), Subrahmanyam (1946, 1959) and Heurck (1896). For further statistical analyses, phytoplankton species greater than 4% in abundance throughout the study period were used.

2.2.2b Sediment sampling

Sediment samples were collected using a gravity corer with an inner diameter of 4.8 cm. The top 1-2 cm depth of collected cores were sealed tightly and stored in the dark at 4°C until further analyses.

2.2.2b.1. Enumeration of diatom propagules from the sediments

From a technological viewpoint, finding diatom resting stages in sediments by normal microscopic observation is not easy because of the problem of cell aggregation and concealment by extraneous material. Enumeration of diatom cells from sediments was carried out by an extinction dilution method, (Most Probable Number method, MPN) (Imai et al. 1984, Yamochi 1989, Imai et al. 1990, Ishikawa and Tamaguchi 1994, Itakura et al. 1997), which allows estimation of resting stages through examination of germinated vegetative cells in culture. Currently, this is the only feasible method for the enumeration of relative abundance of diatom resting stages from sediments (Harris et al. 1998). This method is best treated as a semi-quantitative method and is most useful for distinguishing relative rather than absolute abundance. But it is unclear as to what proportions of cells are resting stages and vegetative cells, thus giving a minimum estimate. The approach of the present study is similar to other studies conducted previously in marine coastal waters (Itakura et al. 1997, Hansen and Josefson 2001).

A known weight (1 g) of wet sediment, in triplicates was suspended in 10 ml of the f/2 culture media (Guillard and Ryther 1962) at a concentration of 0.1 g wet wt ml⁻¹. Serial tenfold dilutions (10⁻² - 10⁻⁵) were made with the culture medium and then 1 ml aliquots of diluted samples were inoculated into five replicate petri-dishes (35 mm) and were incubated at a temperature of 20 ± 1 °C with a 12 h light:12 h dark photo cycle. The appearance of vegetative cells of diatoms was examined microscopically (Light Microscope; Olympus BH2) after an incubation period of 6-8 days. Petridishes in which vegetative cells were identified were scored as positive for each species. The MPN for a series of five ten-fold dilutions of resting stage cells in the sediment sample (MPN g⁻¹ wet sediment) was then calculated according to the statistical table (Thronsen 1978, Itoh and Imai 1987). This table covers a range of five dilution steps, and a set of three

dilutions have to be chosen out of the five cultured petridishes to get the MPN. The relative diatom cell density cm^{-3} wet sediment was obtained by multiplying the MPN value with the apparent specific gravity of wet sediment (Imai and Itakura 1999). The diatoms were identified based on the keys provided, as mentioned earlier. For further statistical analyses, diatom species greater than 4% in abundance throughout the study period were used.

2.2.2b.2. Enumeration of dinoflagellate cysts from sediments

The samples collected for the enumeration of diatom propagules from sediments were also analyzed for dinoflagellate cysts. The enumeration of dinoflagellate cysts was carried out using the techniques described by Matsuoka et al. (1989) and Matsuoka and Fukuyo (2000) with some modifications (excluding the steps of alkali and acetolysis (Matsuoka et al. 1999)). A known weight (2-3 g) of wet sediment was repeatedly washed with distilled water to remove salts followed by acid treatment i.e. 10% hydrochloric acid (HCl) and 25-35% hydrofluoric acid (HF) to dissolve calcareous (calcareous nanoplankton, molluscs, foraminifera and others) and silicate (sand/mud particles, diatom frustules, silicoflagellates and others), materials. Each chemically treated sample was washed with distilled water to remove acid and then placed in a 100 ml beaker with distilled water to make slurry. The slurry was sonicated for 30 s in an ultrasonicator (B. Braun Labsonic). Later, the slurry was sieved through a tier of two different meshes (i.e. 125 and 20 μm). The residue, which accumulated on the 20 μm mesh was then suspended in a known volume of distilled water and kept in a vial. Observations were carried out for 0.5-1.0 ml aliquot of the refined sample under a Light Microscope (Olympus BH2) equipped with a digital camera (Kodak DC 290) at 100 and 400 times magnification. The cyst populations were enumerated in triplicates and is expressed as number of cysts g^{-1} wet weight of sediment.

2.2.3 Meteorology

Data regarding meteorological parameters like solar radiation (mw cm^{-2}), wind speed (m sec^{-1}), wind direction (degrees), air temperature ($^{\circ}\text{C}$), relative humidity (%) and atmospheric pressure (m bar) have been collected from the Marine Instrumentation and Computer Division, NIO, Goa. The rainfall (mm), day length (h: from sunrise to sunset) and sunshine hours (the time of brightness [$\text{solar radiation} > 1 \text{ mw cm}^{-2}$] available in a day length) data were obtained from the Indian Meteorological Department, Panaji, Goa. For interpretation, average values of 7 consecutive days, prior to and inclusive of the sampling day, have been used.

2.2.4 Data analyses

Multivariate analyses is the best tool to reveal the complex interactions between the community structure changes and biotic/abiotic factors, when using data obtained during different periods, thus displaying temporal variability (Field et al. 1982, Ludwig and Reynolds 1988).

2.2.4a. Environmental data

In order to evaluate the climate variability, monthly data of various environmental parameters (as listed in Table 2.1) were subjected to Principal Component Analysis (PCA). This analysis was done using the software Statistica release 5.0 by Statsoft after normalisation of raw data.

2.2.4b. Phytoplankton data analyses

Univariate measures included calculation of Shannon – Wiener diversity index (H') using $\log(x+1)$ transformed data, species richness ($d = \log_2 S$, where S is the number of taxa) and evenness ($J' = H'/H' \text{ max}$) (Pielou 1969).

Table 2.1. List of environmental parameters monitored with abbreviations.

S. No.	Parameters	Abbreviation
<i>Surface layer</i>		
1	Temperature	ST
2	Salinity	SS
3	Dissolved oxygen	SDO
4	Nitrate	SNO ₃
5	Nitrite	SNO ₂
6	Phosphate	SPO ₄
7	Silicate	SSi
<i>Bottom layer</i>		
8	Temperature	BT
9	Salinity	BS
10	Dissolved oxygen	BDO
11	Nitrate	BNO ₃
12	Nitrite	BNO ₂
13	Phosphate	BPO ₄
14	Silicate	BSi
<i>Others</i>		
15	Secchi disc depth	SD
16	Wind speed	WS
17	Wind direction	WD
18	Day length	DL
19	Sunshine hours	SH
20	Solar radiation	SR
21	Rainfall	RF
22	Atmospheric pressure	PR
23	Relative humidity	RH
24	Air temperature	AT

A two-way analysis of variance (ANOVA), with equal replications, was performed on the fourth root ($\sqrt[4]{}$) transformed abundance data of total phytoplankton, diatoms and dinoflagellates to evaluate the significance of temporal variation (Sokal and Rohlf 1981). The diversity, evenness and richness values of the phytoplankton, diatoms and dinoflagellates were also subjected to two-way ANOVA with equal replications to evaluate the temporal variations.

2.2.4c. Diatom propagule data analyses

One-way analysis of variance (ANOVA), with equal replications, was performed on the fourth root ($\sqrt[4]{}$) transformed relative abundance data of total diatoms and dominant species (*Skeletonema costatum*, *Fragilariopsis oceanica*, *Thalassiosira subtilis*, *Thalassiosira* sp. 1, *Thalassiosira* sp. 2, and *Chaetoceros curvisetus*) to evaluate the significance of temporal variation (Sokal and Rohlf 1981).

2.2.4d. Dinoflagellate cyst data analyses

One-way analysis of variance (ANOVA), with equal replications, was also performed on the fourth root ($\sqrt[4]{}$) transformed abundance data of total dinoflagellate cysts to evaluate the significance of temporal variation (Sokal and Rohlf 1981).

2.2.4e. Clustering and ordination analyses

The fourth root ($\sqrt[4]{}$) transformed abundance data of water column phytoplankton and diatom propagules and dinoflagellate cysts from sediments were converted into a lower triangular similarity matrix using Bray-Curtis coefficients (Bray and Curtis 1957). These similarity matrices were then subjected to clustering and ordination techniques. Clustering was performed using the group average method (Pielou 1984). Ordination was done by Non-Metric Multidimensional Scaling (NMDS) (Kruskal and Wish 1978). There are advantages in applying more than one method, since each is based on different assumptions and may give different insights (Gray et al. 1988). In case of cluster analyses, a) the individual, once placed in a group, loses its identity, b) the sequence of individuals is arbitrary and c) only the inter-group relationships are shown. In view of these disadvantages, it is advisable to employ an additional method of presentation to show individual relationships such as NMDS ordination. Clustering and ordination

(NMDS) analyses were carried out using the software PRIMER version 5. These analyses were performed to evaluate temporal variation and species relationships.

2.2.4f. Spearman's Rank correlation test

Spearman's rank correlation test was performed to evaluate the relationship between the phytoplankton groups/dominant species and various observed environmental components, as mentioned in Table 2.1, which may be responsible for regulating their population. This test was also performed for sediment and planktonic forms. These tests were carried out using the software Statistica release 5.0 by Statsoft, after transformation of raw data.

2.3 RESULTS

2.3.1 Hydrographic conditions

Seasonal variation in the surface and near bottom seawater temperature is shown in Fig. 2.2a. Surface and bottom seawater temperature ranged from a maximum of 33°C (March 2000) and 31 °C (March 2000) to a minimum of 28 °C (August 2000) and 22 °C (August 2000) respectively. Thermal stratification, as judged by the difference in surface and bottom temperatures, developed from June 2000 to September 2000; the water was vertically mixed during the rest of the months. Salinity ranged between a high of 36 psu in March 2000 and a low of 18 psu in June 2000. Low salinity in the surface layer was due to freshwater influx from the Zuari River during the monsoon period. During this period, salinity stratification was also observed and existed till early post-monsoon season (Fig. 2.2b). The DO concentration ranged from 5.6 ml L⁻¹ (July 2000) - 3 ml L⁻¹ (September 1999) in surface and 4.35 ml L⁻¹ (March 2000) - 2.2 ml L⁻¹ (August 2000) in bottom waters (Fig. 2.2c). The DO concentration, in bottom waters, was lower than in surface waters but the maximum difference was observed during the monsoon

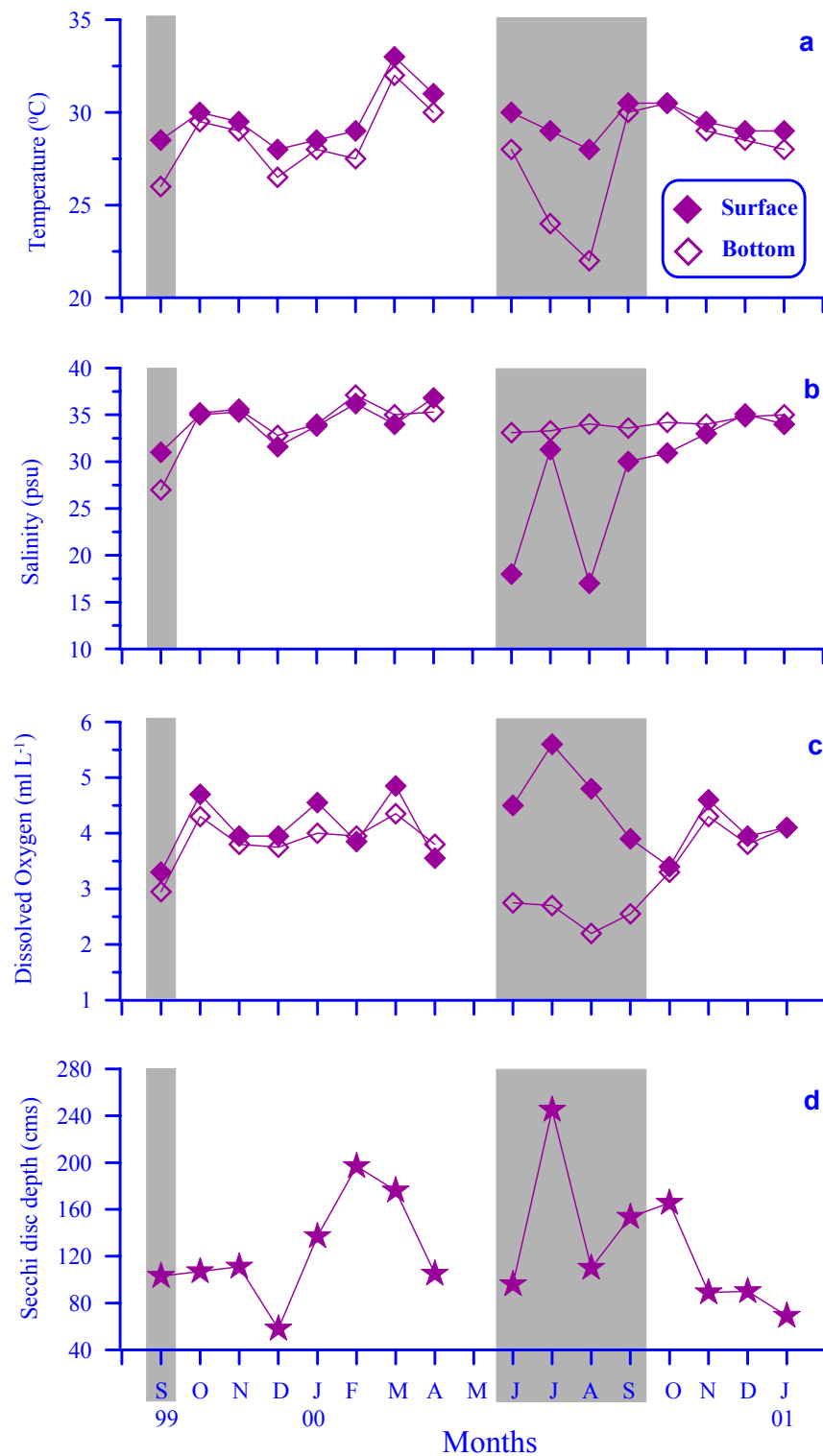


Fig. 2.2. Temporal variations in water parameters **a.** Temperature, **b.** Salinity, **c.** Dissolved oxygen and **d.** Secchi disc depth. (Note: Shaded region represents monsoon season).

season. Nutrient concentrations showed a definite seasonal trend over the sampling period. The maximum concentration of these nutrients was found during the early phase of the monsoon, which is due to land run-off and precipitation (Naqvi et al. 2000). A second peak of nitrate and nitrite was observed during both years (2000 and 2001) during November-December and, thus, was not a mere coincidence. In addition, surface and bottom waters exhibited high levels of nitrate ($\sim 7\mu\text{m}$) during April 2000. Nair (1980) reported two peaks of zooplankton production, one in November and the other in March/April. Higher zooplankton population results in ammonia-rich fecal matter and this might undergo nitrification in the presence of excess oxygen, leading to high nitrates. Similar observations from the study area have reported that these high concentrations were of local origin (Qasim and SenGupta 1981). The temporal variation in the nutrient concentration of the surface and bottom waters almost followed a similar pattern (Figs 2.3a, b, c and d). Maximum turbidity of water was observed during the monsoon season except during July 2000 and during the end of the post-monsoon (Fig. 2.2d) period. Secchi disc depth showed an increasing trend up to February 2000 (196 cms) except in December 1999 (45 cms), which was then followed by a decline till June 2000 (87 cms).

2.3.2 Meteorological conditions

Temporal variation in wind speed is shown in Fig. 2.4a. Maximum wind speed was observed during the onset of monsoon in April and June 2000 and during the late monsoon period (September 2000). Wind speed showed a small increase during November in both the years. Monthly profiles of wind direction are shown in Fig. 2.4b. The temporal variation in the duration of day length, sunshine hours and solar radiation showed a definite seasonal trend (Fig. 2.4c and d). Low sunshine hours and solar radiation were observed during June 2000 and increased thereafter to a maximum of 10.5

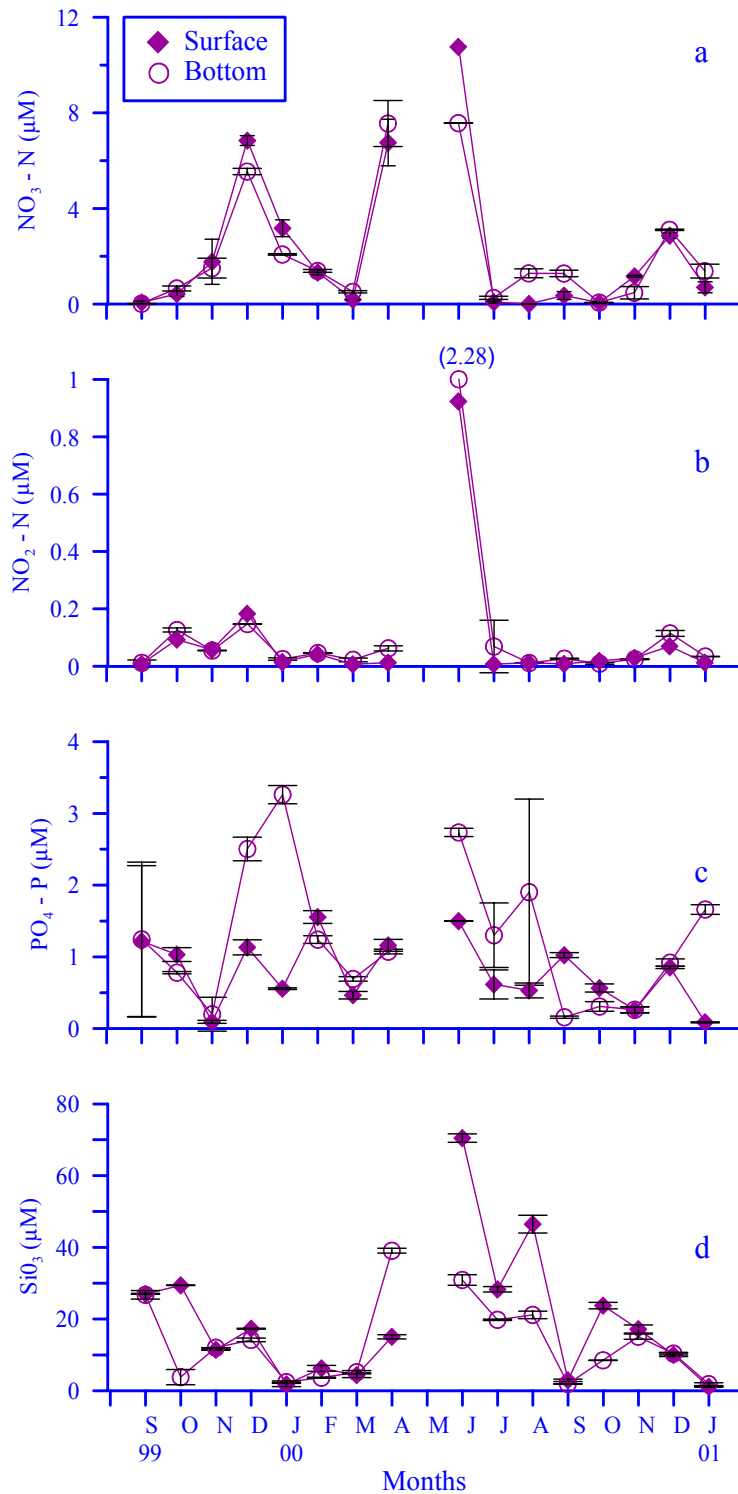


Fig. 2.3. Temporal variations in nutrient concentrations. **a.** Nitrate ($\text{NO}_3\text{-N}$), **b.** Nitrite ($\text{NO}_2\text{-N}$), **c.** Phosphate ($\text{PO}_4\text{-P}$) and **d.** Silicate (Si).

h in April 2000 (Figs. 2.4c and d). Maximum rainfall was observed during June (38 mm) and decreased thereafter. However, there was a slight increase during October 2000

period but traces/no rainfall during non-monsoon periods (Fig. 2.4e). The temporal variation in air temperature, relative humidity and atmospheric pressure are shown in Figs. 2.4 f-h.

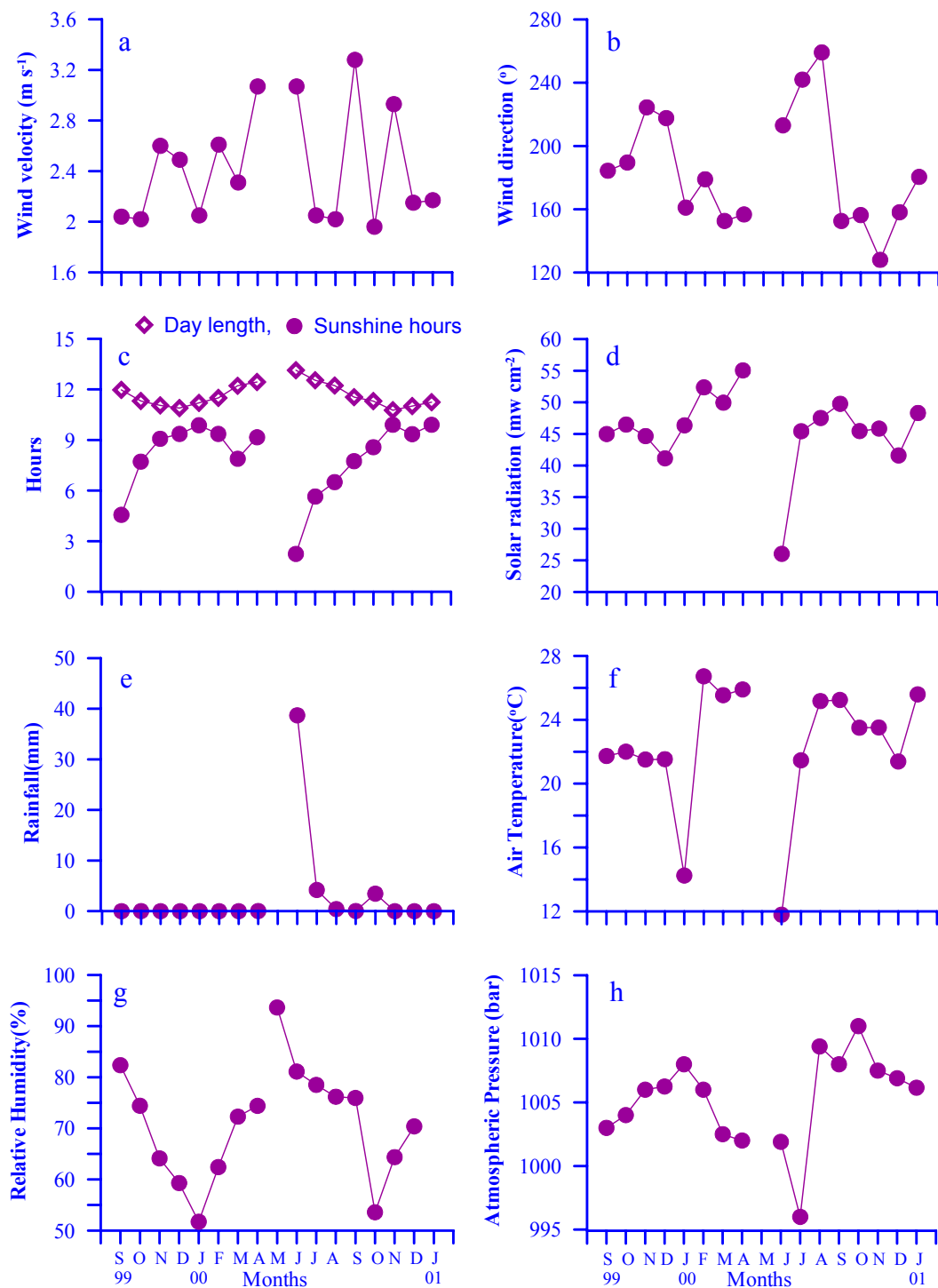


Fig. 2.4. Temporal variations in meteorological parameters. **a.** wind speed, **b.** wind direction, **c.** day length and sunshine hours, **d.** Solar radiation, **e.** Rainfall, **f.** Air temperature, **g.** Relative humidity and **h.** Atmospheric pressure.

Analysis of the present data set was further simplified by application of principal component analyses (PCA) in order to reduce dimensionality (Blanco et al. 1998). A correlation matrix was calculated using the environmental variables listed in Table 2.1. Six components were extracted with eigenvalues greater than 1, explaining 83.21% of total variance (Table 2.2a).

Table 2.2. Eigenvalues (a) and factor loadings (b) of environmental variables on six principal components extracted.

a. Eigenvalues				
	Eigenvalues	% Total Variance	Cumulative Eigenvalue	Cumulative (%)
1	8.86	36.93	8.86	36.93
2	3.68	15.34	12.55	52.27
3	2.78	11.58	15.33	63.85
4	1.89	7.88	17.22	71.74
5	1.54	6.42	18.76	78.16
6	1.21	5.05	19.97	83.21

b. Factor loadings							
S. No.	Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
1	ST	-0.04	0.02	0.85	0.31	0.07	0.18
2	SS	-0.40	-0.79	0.29	0.14	-0.02	-0.11
3	SDO	0.24	0.08	-0.27	0.58	-0.35	0.46
4	SD	-0.25	0.17	0.16	0.64	-0.31	0.14
5	SNO3	0.59	-0.06	-0.02	0.01	0.75	0.09
6	SNO2	0.83	0.31	0.05	0.01	0.37	0.06
7	SPO4	0.15	0.18	0.03	0.12	0.59	-0.31
8	SSI	0.52	0.69	-0.20	0.08	0.17	-0.05
9	BT	0.07	-0.40	0.87	-0.08	0.06	0.06
10	BS	-0.11	-0.28	0.18	0.01	0.04	0.86
11	BDO	0.01	-0.85	0.27	0.00	-0.04	0.14
12	BNO3	0.37	-0.02	-0.08	-0.05	0.87	0.12
13	BNO2	0.82	0.32	0.07	0.07	0.38	0.07
14	BPO4	0.51	-0.12	-0.64	0.08	0.24	-0.03
15	BSI	0.06	0.41	-0.16	0.18	0.65	-0.26
16	WS	0.06	0.11	0.41	-0.15	0.63	0.25
17	WD	0.10	0.47	-0.68	0.2	-0.01	0.15
18	DL	0.18	0.62	0.03	0.59	0.35	-0.02
19	SH	-0.44	-0.72	0.04	-0.34	-0.08	0.33
20	SR	-0.89	-0.26	0.11	0.10	-0.05	0.12
21	RF	0.80	0.43	0.10	0.12	0.29	0.05
22	AT	-0.87	0.04	0.20	-0.07	-0.03	0.17
23	RH	0.18	0.79	0.16	0.31	0.14	-0.22
24	PR	-0.11	-0.06	0.04	-0.87	-0.25	0.16
	Expl. Variance	5.18	4.52	2.98	2.36	3.38	1.55

The first principal component (PC1) explaining about 36.93% of variance is related to inputs of inorganic nutrients by river run-off and precipitation during the monsoon period. This is indicated by loadings, which were negative for solar radiation and air temperature and positive for inorganic nutrients and rainfall with slight decrease in surface salinity values (Table 2.2b and Fig. 2.5). The second principal component (PC2, explaining 15.34% of variance) is mainly associated with a single species diatom bloom (*S. costatum*) in low saline surface waters as indicated by negative values for surface salinity, bottom dissolved oxygen (BDO), sunshine hours (SH) and positive for silicate (Si) and day length. The third and fifth principal component (PC3 and PC5 explaining 11.58 % and 6.42 % variance respectively) reveals the seasonality and recycling of phosphate and nitrate respectively. The fourth principal component (PC4) explaining about 7.88 % is related to surface mixing during monsoon. This is indicated by positive loadings for surface dissolved oxygen.

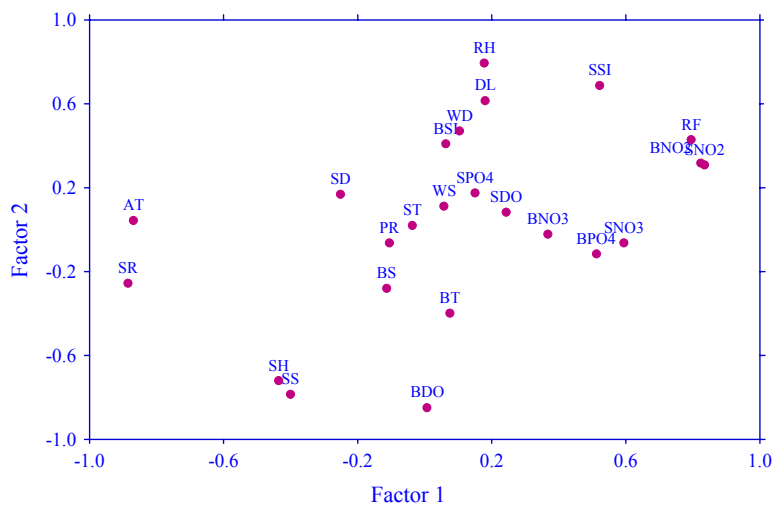


Fig. 2.5. Loadings of environmental variables on first two principal components extracted.

2.3.3 Phytoplankton community

From the present study, 136 (83, 44 and 9 species corresponds to diatoms, dinoflagellates and others respectively) phytoplankton species have been recorded (Table 2.3). Altogether 120 species in surface (77 diatoms, 34 dinoflagellates and 9 others) and 117

Table 2.3. List of phytoplankton species recorded from Zuari estuary

a. Diatoms				
S. No.	Taxon	Abbrev.	Presence	
			S	B
CENTRICS				
1	<i>Asteromphalus sp.</i>	Ast.sp	P	P
2	<i>Bacteriastrum delicatulum</i> Cleve	Bac.del		P
3	<i>Bacteriastrum fusus</i>	Bac.fus	P	
4	<i>Bacteriastrum hyalinum</i> Lauder	Bac.hya	P	P
5	<i>Bacteriastrum varians</i>	Bac.var	P	P
6	<i>Biddulphia rhombus</i> (Ehrenberg) W. SM.	Odt.rho	P	P
7	<i>Cerataulina bicornis</i>	Cer.bic	P	P
8	<i>Chaetoceros curvisetus</i> Cleve	Cha.cur	P	P
9	<i>Chaetoceros diversus</i> Cleve	Cha.div	P	P
10	<i>Chaetoceros lacinosus</i> Schütt	Cha.lac	P	
11	<i>Chaetoceros lorenzianus</i> Grunow	Cha.lor	P	P
12	<i>Chaetoceros socialis</i> Lauder	Cha.soc	P	P
13	<i>Chaetoceros tenuissimus</i> Meunier	Cha.tes	P	P
14	<i>Climacodium frauenfeldianum</i> Grunow	Cli.fra	P	P
15	<i>Corethron criophilum</i> Castracane	Cor.cri	P	P
16	<i>Coscinodiscus marginatus</i> Ehrenberg	Cos.mar	P	P
17	<i>Coscinodiscus radiatus</i>	Cos.rad	P	P
18	<i>Coscinodiscus sp.</i>	Cos.sp	P	P
19	<i>Ditylum brightwellii</i> (West)Grunow	Dit.bri	P	P
20	<i>Eucampia zodiacus</i> Ehrenberg	Euc.zoo	P	P
21	<i>Guinardia flaccida</i> (Castracane) H. Peragallo	Gui fla	P	P
22	<i>Guinardia striata</i> Hasle com. nov	Gui.str	P	P
23	<i>Helicotheca tamesis</i> (Shrubsole) Ricard	Ste.tha	P	P
24	<i>Hemiaulus sinensis</i> Greville	Hem.sin	P	P
25	<i>Hemidiscus sp.</i>	Hem.sp	P	P
26	<i>Lauderia annulata</i> Cleve	Lau.bor	P	P
27	<i>Leptocylindrus danicus</i> Cleve	Lep.dan	P	P
28	<i>Melosira nummuloides</i> C.A. Agardh	Mel.num	P	P
29	<i>Odontella regia</i>	Odt.reg	P	P
30	<i>Odontella sinensis</i> (Greville)Grunow	Odt.sin	P	P
31	<i>Paralia sulcata</i> (Ehrenberg) Cleve	Mel.sul	P	P
32	<i>Planktoniella sol</i> (Wallich) Schutt	Pln.sol	P	P
33	<i>Proboscia alata</i> (Brightwell)Sundstrom	Rhi.ala	P	P
34	<i>Rhizosolenia imbricata</i> Brightwell	Rhi.imb		P
35	<i>Rhizosolenia styliformis</i> Brightwell	Rhi.sty	P	
36	<i>Schroederella shcroderi</i> (Bergon) Pavillard	Sch.sch	P	P
37	<i>Skeletonema costatum</i> Greville (Cleve)	Ske.cos	P	P
38	<i>Thalassiosira subtilis</i> (Ostenfeld) Gran	Tha.sub	P	P
39	<i>Thalassiosira eccentrica</i> (Ehrenberg) Cleve	Tha.exc	P	P
40	<i>Thalassiosira sp. 1</i>	Tha.sp1	P	P
41	<i>Thalassiosira sp. 2</i>	Tha.sp2	P	P
42	<i>Thalassiosira sp. 3</i>	Tha.sp3	P	P

Continued....

S. No.	Taxon	Abbrev.	Presence	
			S	B
PENNATES				
43	<i>Achnanthes longipes</i> Agardh	Ach.lon	P	P
44	<i>Achnanthes subsessilis</i> Kutzing	Ach.sub	P	P
45	<i>Amphiprora gigantea</i>	Amp.gig	P	P
46	<i>Amphora coffeaeformis</i> (Ag.) Kützing	Amp.cof	P	
47	<i>Amphora rostrata</i>	Amp.ros	P	
48	<i>Amphora</i> sp.	Amp.Sp	P	P
49	<i>Asterionellopsis glacialis</i> (Castracane) Round	Ast.jap	P	P
50	<i>Cocconeis scutellum</i> Ehrenberg	Coc.scu	P	P
51	<i>Cylindrotheca closterium</i> (Ehrenberg) Smith	Nit.clos	P	P
52	<i>Cymbella gastroides</i> Kütz	Cym.gas	P	P
53	<i>Diploneis</i> sp.	Dip.sp	P	P
54	<i>Fragilariopsis oceanica</i> (Cleve) Hasle	Fra.oce	P	P
55	<i>Grammatophora marina</i> (Lyngbye) Kützing	Gra.mar		P
56	<i>Haslea</i> sp.	Has. sp	P	P
57	<i>Licmophora juergensii</i> Agardh	Lic.jeu	P	P
58	<i>Licmophora paradoxa</i>	Lic.par		P
59	<i>Lioloma</i> sp.	Lio.sp	P	
60	<i>Navicula transitans</i> var. <i>derasa</i> f. <i>delicatula</i> Heimdal	Nav.del	P	P
61	<i>Navicula subinflata</i> Grun	Nav.sub	P	P
62	<i>Navicula</i> sp. 1	Nav.sp1		P
63	<i>Navicula</i> sp. 2	Nav.sp2	P	P
64	<i>Navicula</i> sp. 3	Nav.sp3		P
65	<i>Navicula</i> sp. 4	Nav.sp4	P	P
66	<i>Nitzschia angularis</i>	Nit.ang	P	P
67	<i>Nitzschia bilobata</i>	Nit.bil	P	P
68	<i>Nitzschia longissima</i> Ralfs in Pritchard.	Nit.lon	P	P
69	<i>Nitzschia panduriformis</i> Gregory	Nit.pan	P	P
70	<i>Nitzschia sigma</i> (Kützing)Wm.smith	Nit.sig	P	P
71	<i>Pleurosigma angulatum</i> Senu W. Smith	Ple.ang	P	P
72	<i>Pleurosigma elongatum</i> WM Smith	Ple.elo	P	P
73	<i>Pseudo-nitzschia seriata</i> (Cleve) H. Pergallo	Nit.ser	P	P
74	<i>Pseudo-nitzschia</i> sp. 1	Pnit.sp1	P	P
75	<i>Pseudo-nitzschia</i> sp. 2	Pnit.sp2	P	P
76	<i>Surirella ovata</i>	Sur.ova	P	P
77	<i>Surirella</i> sp.	Sur.sp	P	P
78	<i>Synedra gallioni</i> (Bory) Ehrenberg	Syn.gal	P	P
79	<i>Synedra affinis</i> Kützing	Syn.aff	P	P
80	<i>Synedra</i> sp.	Syn.sp	P	P
81	<i>Thalassionema frauenfeldii</i> (Grunow) Hallegraeff	Thx.fre	P	P
82	<i>Thalassionema nitzschoides</i> (Grunow)	Thn.nit	P	P
83	<i>Thalassiothrix longissima</i> Cleve and Grunow	Thx.lon	P	P

Continued....

b. Dinoflagellates

S. No	Taxon	Abbrev.	Presence	
			S	B
84	<i>Alexandrium minutum</i> Halim 1960	Ale.min		P
85	<i>Alexandrium</i> sp.	Ale.sp		P
86	<i>Amphisolenia</i> sp.	Apl.sp	P	P
87	<i>Ceratium declinatum</i> (Karsten) Jørgensen	Cer.del	P	P
88	<i>Ceratium furca</i> (Ehrenberg) Claparède & Lachmann	Cer.fur	P	P
89	<i>Ceratium fusus</i> (Ehrenberg) Dujardin	Cer.fus	P	P
90	<i>Ceratium kofoidii</i> Jørgensen	Cer.kof		P
91	<i>Ceratium lineatum</i> (Ehrenberg) Cleve	Cer.lin	P	P
92	<i>Ceratium macroceros</i> (Ehrenberg) Vanhöffen	Cer.mac	P	P
93	<i>Cochlodinium polykrikoides</i> Margelef	Coc.pol	P	P
94	<i>Dinophysis caudata</i> Saville-Kent	Din.cau	P	P
95	<i>Dinophysis</i> sp.	Din.sp	P	P
96	<i>Gonyaulax</i> sp.	Gon.sp	P	
97	<i>Gymnodinium breve</i> Davis	Gym.bre		P
98	<i>Gymnodinium catenatum</i> Graham	Gym.cat	P	P
99	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy	Noc.mil	P	P
100	<i>Nonthecate dinoflagellate</i>	Non.din	P	P
101	<i>Oxytoxum scolopax</i> Stein	Oxy.sco	P	P
102	<i>Peridiniopsis assymetrica</i> Mangin	Per.ass	P	
103	<i>Peridiniopsis globulum</i> Stein	Per.glo	P	
104	<i>Peridiniopsis steinii</i> Jørgensen	Per.ste	P	P
105	<i>Peridiniopsis</i> sp. 1	Per.sp1	P	P
106	<i>Peridiniopsis</i> sp. 2	Per.sp2	P	P
107	<i>Peridiniopsis</i> sp. 3	Per.sp3	P	P
108	<i>Peridiniopsis</i> sp. 4	Per.sp4		P
109	<i>Peridiniopsis</i> sp. 5	Per.sp5	P	
110	<i>Peridiniopsis</i> sp. 6	Per.sp6	P	
111	<i>Peridiniopsis</i> sp. 7	Per.sp7		P
112	<i>Peridiniopsis</i> sp. 8	Per.sp8		P
113	<i>Phalacroma</i> sp.	Pha.sp		P
114	<i>Prorocentrum gracile</i> Schütt	Pro.gra	P	P
115	<i>Prorocentrum micans</i> Ehrenberg	Pro.mic	P	
116	<i>Prorocentrum</i> sp. 1	Pro.sp1	P	P
117	<i>Prorocentrum</i> sp. 2	Pro.sp2	P	P
118	<i>Protooperidinium bicornis</i>	Ppe.bre	P	
119	<i>Protooperidinium conicum</i> (Gran) Balech	Ppe.con	P	P
120	<i>Protooperidinium elegans</i> (Cleve) Balech	Ppe.ele	P	
121	<i>Protooperidinium pentagonum</i> (Gran) Balech	Ppe.pen	P	P
122	<i>Protooperidinium</i> sp. 1	Ppe.sp1	P	P
123	<i>Protooperidinium</i> sp. 2	Ppe.sp2	P	
124	<i>Protooperidinium</i> sp. 3	Ppe.sp3		P
125	<i>Protooperidinium</i> sp. 4	Ppe.sp4		P
126	<i>Scrippsiella trochoidea</i> (Stein) Loeblich	Ppe.tro	P	
127	<i>Scrippsiella</i> sp.	Scr.sp	P	P

Continued....

c. Others

S. No.	Taxon	Abbrev.	Presence	
			S	B
128	Trichodesmium	Tric	P	P
129	Oscillatoria	Osci	P	
130	Chlorogloea	Chloro	P	P
131	<i>Dictyocha fibula</i> Ehrenberg	Dic.fib	P	P
132	Chromophyta	Chrom	P	P
133	Chlorophyta	Chloro	P	
134	Chaoflagellate	Chaof	P	P
135	<i>Phaeocystis globosa</i> Scherffel	Pha.glo	P	P
136	Unidentified sp.	UI	P	

species in bottom (77 diatoms, 34 dinoflagellates and 6 others) waters have been recorded (Table 2.3). Phytoplankton densities ranged from $9 \times 10^2 - 9.9 \times 10^5$ cells L^{-1} and $2.4 \times 10^3 - 1.8 \times 10^5$ cells L^{-1} in surface and bottom waters respectively (Fig. 2.6b).

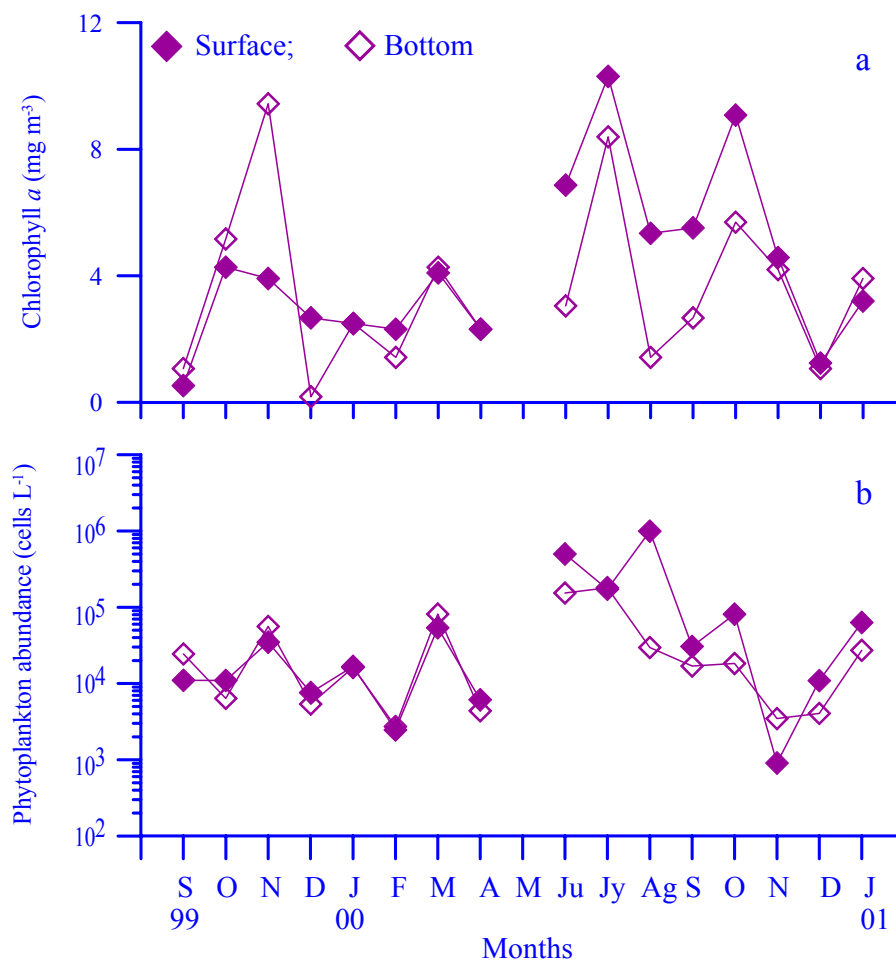


Fig. 2.6. Temporal variations in **a.** Chlorophyll *a* concentrations and **b.** Phytoplankton abundance

Two-way ANOVA, with equal replications, revealed that phytoplankton abundance showed significant variation between the water depths and sampling months ($p \leq 0.001$) (Table 2.4a). Temporal variation in chlorophyll *a* concentration, for surface and bottom waters, is shown in Fig. 2.6a. Except during southwest monsoon, chlorophyll *a* showed little variability. During the monsoon, the chlorophyll levels were very high and the maximum values were found in July 2000.

Table 2.4. Two-way analysis of variance (ANOVA) to evaluate the temporal variation of the abundance and univariate measures of phytoplankton, diatoms and dinoflagellates. (Note: **** = $p \leq 0.001$, *** = $p \leq 0.005$, ** = $p \leq 0.025$, * = $p \leq 0.05$, ns = Not significant)

a. Phytoplankton

Source of variation	Abundance				Diversity (H')			Evenness (J')			Species Richness (D)		
	<i>df</i>	SS	MS	F_s	SS	MS	F_s	SS	MS	F_s	SS	MS	F_s
Water column	1	82	81.6	56.1****	1.5	1.5	13.6****	0.02	0.02	6.3**	1.5	1.5	22.7****
Months	15	2462	164	112.9****	80.0	5.4	49.9****	4.20	0.30	72.7****	52.0	3.5	53.7****
Water column X Months	15	582	38.8	26.7****	9.0	0.6	5.4****	0.60	0.04	10.1****	5.0	0.3	5.1****
Within subgroup error	64	93	1.5		7.0	0.1		0.20	0.00		4.0	0.1	
Total	95	3219			97.0			5.00			63.0		

b. Diatoms

Source of variation	Abundance				Diversity (H')			Evenness (J')			Species Richness (D)		
	<i>df</i>	SS	MS	F_s	SS	MS	F_s	SS	MS	F_s	SS	MS	F_s
Water column	1	88	87.4	20.0****	1.2	1.2	11.8****	0.0	0.00	0.74ns	1.7	1.7	31.0****
Months	15	2437	162.5	37.1****	66.0	4.4	45.3****	4.0	0.30	65.8****	31.0	2.1	39.0****
Water column X Months	15	574	38.3	8.7****	9.0	0.6	5.8****	0.7	0.05	12.0****	2.0	0.2	2.9***
Within subgroup error	64	280	4.4		6.0	0.1		0.3	0.00		3.0	0.1	
Total	95	3379			82.0			5.0			39.0		

c. Dinoflagellates

Source of variation	Abundance				Diversity (H')			Evenness (J')			Species Richness (D)		
	<i>df</i>	SS	MS	F_s	SS	MS	F_s	SS	MS	F_s	SS	MS	F_s
Water column	1	10	9.5	4.7*	0.1	0.1	0.4 ns	0.02	0.02	0.2 ns	0.0	0.00	0.2 ns
Months	15	1063	70.8	34.9****	52.1	3.5	12.4****	8.90	0.60	7.0***	7.7	0.50	18.6****
Water column X Months	15	102	6.8	3.4****	5.8	0.4	1.4 ns	1.00	0.06	0.8 ns	1.8	0.10	4.4****
Within subgroup error	64	130	2.0		17.9	0.3		5.40	0.08		1.8	0.03	
Total	95	1304			75.9			15.30			11.3		

Among the phytoplankton, diatoms dominated by constituting an annual percentage of 85% and 92% in surface and bottom waters respectively (Fig. 2.7). Maximum percentage of diatoms was observed during monsoon (96%), followed by post-monsoon (84%) and pre-monsoon (69%) for surface waters and, for bottom waters, post-monsoon (94%) – monsoon (92%) – pre-monsoon (86%) (Fig. 2.7). Altogether, 77 species in both, surface (40 centrics and 37 pennates) and bottom (39 centrics and 38 pennates) waters, have been recorded (Table 2.3). The diatom densities ranged from 8.8×10^2 –

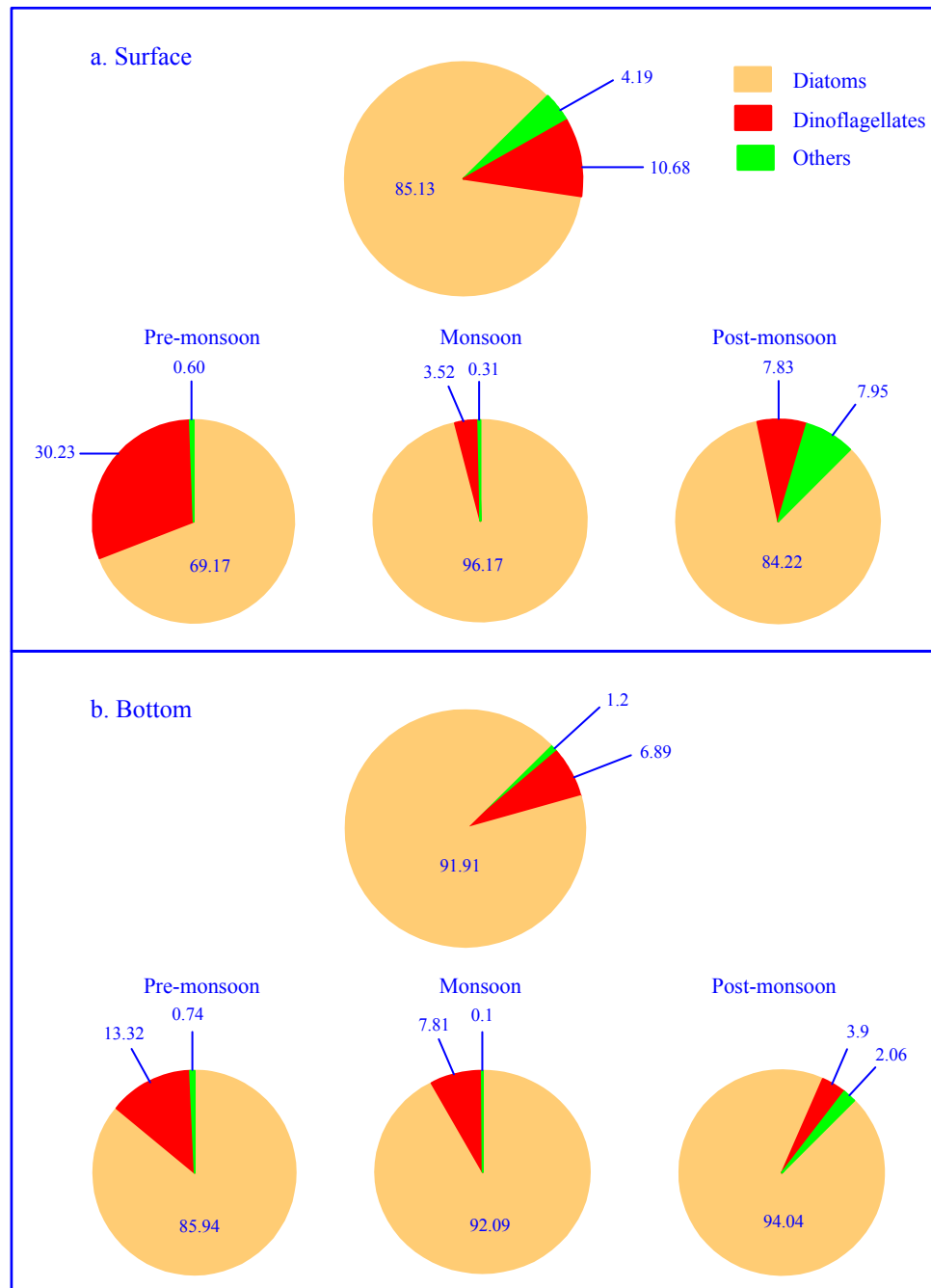


Fig. 2.7. Phytoplankton composition in **a.** surface and **b.** bottom waters

9.9×10^5 cells L^{-1} in surface and $2.2 \times 10^3 - 1.8 \times 10^5$ cells L^{-1} in bottom waters (Fig. 2.8a). Two-way ANOVA, with equal replications, revealed that diatom abundance, diversity and species richness showed significant variation between the water depths and sampling months ($p \leq 0.001$) (Table 2.4b). In the present investigation, two peaks of

diatoms were observed as a recurrent feature of the annual diatom cycle. The first peak (spring bloom) was observed when there was a break in rainfall (July 2000) or after the end of southwest monsoon (November 1999 and October 2000) and the second peak (autumn bloom) was observed during pre-monsoon (March 2000) (Fig. 2.8a). The spring bloom was dominated by *C. curvisetus*, *Leptocylindrus danicus*, *Licmophora juergensii*, *Navicula transitans* var. *derasa* f. *delicatula*, *S. costatum*, *F. oceanica*, *Thalassionema nitzschioides*. In June and August 2000, a single species-bloom of *S. costatum* was observed with densities ranging up to 7×10^5 and 1×10^6 cells L^{-1} respectively (Fig. 2.8a). The autumn bloom was dominated by *Chaetoceros* spp. (*C. curvisetus*, *C. lorenzianus*, *C. diversus*), *T. nitzschioides*, *Guinardia flaccida*, *Cylindrotheca closterium*, *Pleurosigma angulatum*, *N. transitans* var. *derasa* f. *delicatula*, *S. costatum* and *Asterionellopsis glacialis*. In November 2000, the diatom densities scaled down to 900 cells L^{-1} (Fig. 2.8a). This may be due to a sudden increase in turbidity. In January 2001, a single species-bloom of *Thalassiosira* sp. was observed in surface (4×10^4) and bottom (2×10^4) waters (Fig. 2.8a). Maximum diatom abundance was observed in surface rather than bottom waters during July and August 2000 (Fig. 2.8a). The development of such differences was mainly influenced by the existence of two different water bodies, which is evident from salinity profiles.

Dinoflagellates formed the next dominant group by constituting an annual percentage of 10.7 and 7% in surface and bottom waters respectively (Fig. 2.7). Maximum percentage of dinoflagellates was observed during pre-monsoon (30.2%) followed by post-monsoon (8%) and monsoon (3.5%) in surface waters and pre-monsoon (13.3%), monsoon (8%) and post-monsoon (4%) in bottom waters (Fig. 2.7). Altogether, 34 species, in both, surface and bottom waters, have been recorded (Table 2.3). The dinoflagellate densities ranged up to 8.5×10^4 cells L^{-1} in surface and up to 2.8×10^4 cells L^{-1} in bottom waters

(Fig. 2.8b). Blooms of *Gymnodinium catenatum* and *Cochlodinium polykrikoides* were observed when there was a monsoon break i.e. July 2000.

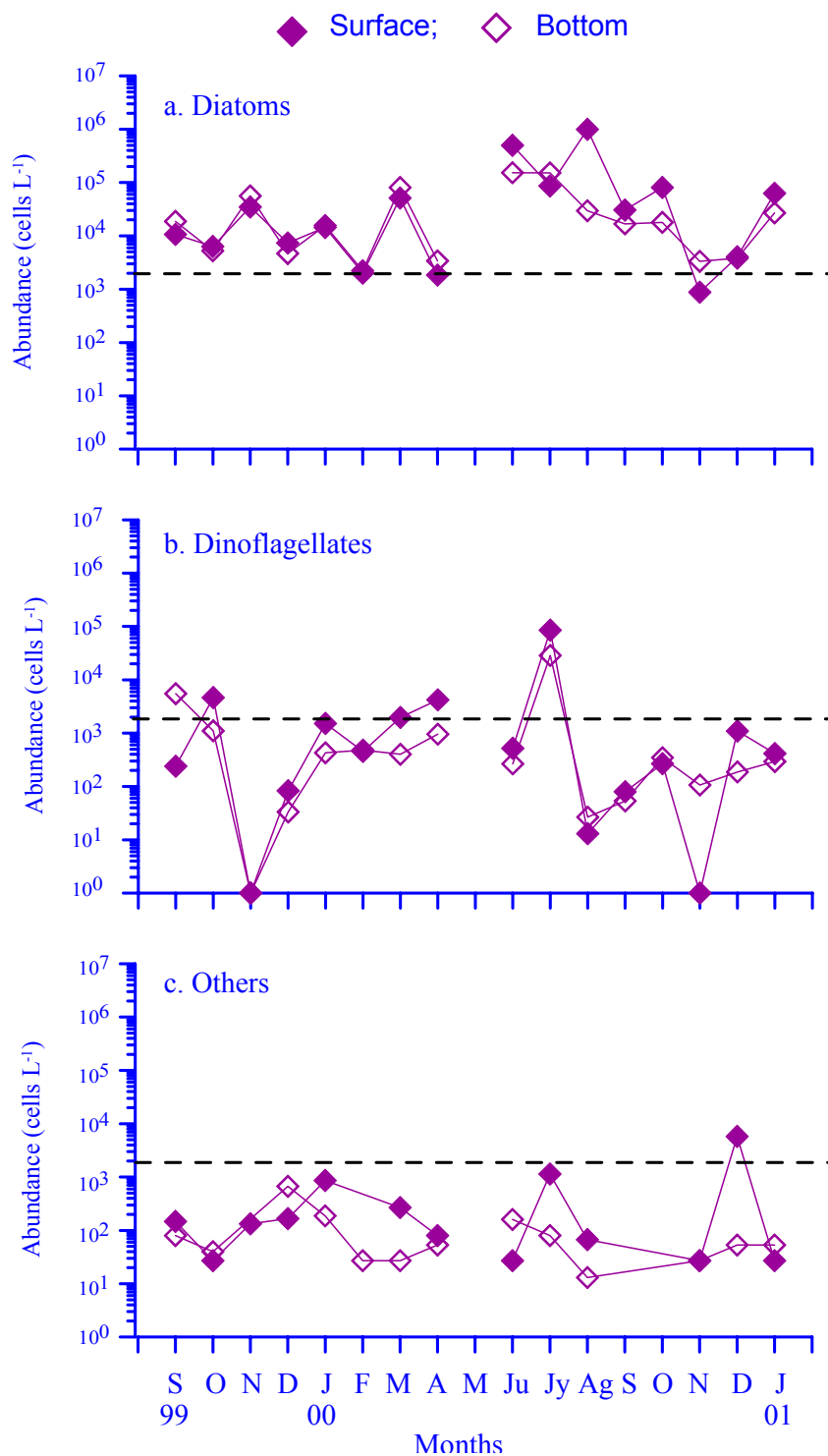


Fig. 2.8. Temporal variations in the abundance of **a.** Diatoms, **b.** Dinoflagellates and **c.** Other phytoplankton groups. (Note: Dotted line is shown only to compare between

Other forms such as silicoflagellates, blue green algae, prymnesiophytes, etc. constituted an annual percentage of only 4.2 % in surface and 1.2 % in bottom waters (Fig. 2.7), thus forming a minor component. They followed the order post-monsoon (8%), pre-monsoon (0.60%) and monsoon (0.3%) for surface waters and monsoon (2.1%), pre-monsoon (0.7%) and post-monsoon (0.1%) for bottom waters (Fig. 2.8c).

2.3.3.1. Temporal variation

Results of the univariate measures are shown in figure 2.9. The univariate measures showed a definite seasonal trend over the sampling period. The maximum

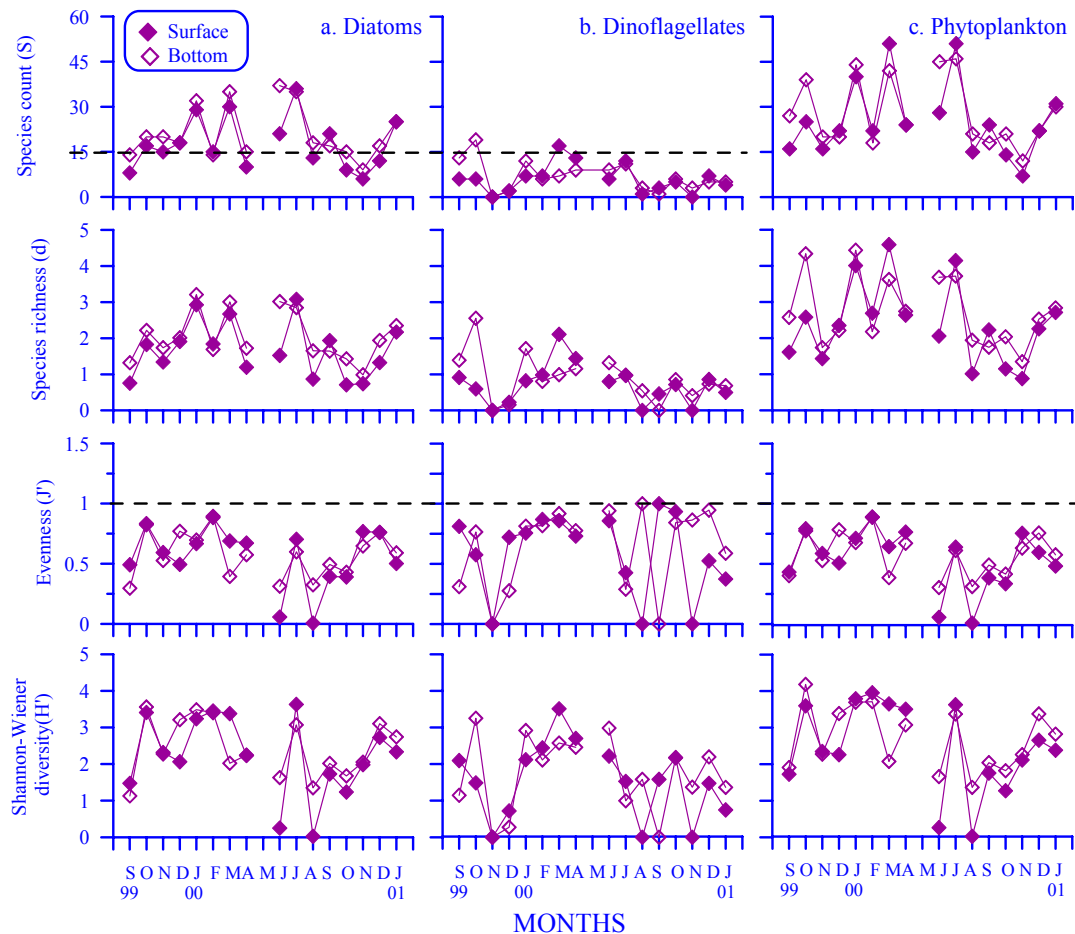


Fig. 2.9. Temporal variations in the univariate measures of **a.** Diatoms, **b.** Dinoflagellates and **c.** Total phytoplankton. (Note: Dotted line shown in Fig a. is only to differentiate between diatoms and dinoflagellates).

phytoplankton diversity, species count, evenness and species richness were observed during the monsoon break (July 2000), early post-monsoon and pre-monsoon (March 2000) seasons in both, surface and bottom waters (Fig. 2.9). These univariate measures decreased drastically in the surface waters during monsoon (June and August 2000) due to the bloom of single species, *S. costatum*. Diatoms, constituting 85-90% of the total phytoplankton community, showed a similar trend (Fig. 2.9a) whereas dinoflagellates, constituting about 7-10% of the total phytoplankton community, exhibited a lower profile (Fig. 2.9b). Temporal variation in the univariate measures of total phytoplankton, diatom and dinoflagellates for surface and bottom water almost followed a similar pattern (Fig. 2.9). Two-way ANOVA, with equal replications, revealed that phytoplankton, diatom and dinoflagellate species count, diversity, evenness and species richness significantly varied with the sampling months ($p \leq 0.001$) (Table 2.4); whereas, with respect to water depths, only phytoplankton and diatoms (except diatom evenness) showed significant variation (Table 2.4c).

Cluster analyses of the sampling months based on phytoplankton abundance (>4%) at 40% similarity level revealed five and two groups at the surface and bottom waters respectively (Figs. 2.10a and b). At the surface, February 2000 and November 1999, were separate units, which are characterized by low abundance. Cluster I comprised of two sampling months (September 1999 and November 2000). Clusters II and III each comprised of two subgroups. Subgroups IIA (June and August 2000) and IIB (September and October 2000) each comprised of two sampling months. Subgroup IIA was characterized by high abundance of *S. costatum*. Subgroups IIIA and IIIB each comprised of 4 sampling months. Subgroup IIIB was characterized by high abundance of mixed phytoplankton population (diatoms and dinoflagellates). At the bottom, cluster I comprised of two subgroups. Subgroups IA and IB each comprised of two sampling

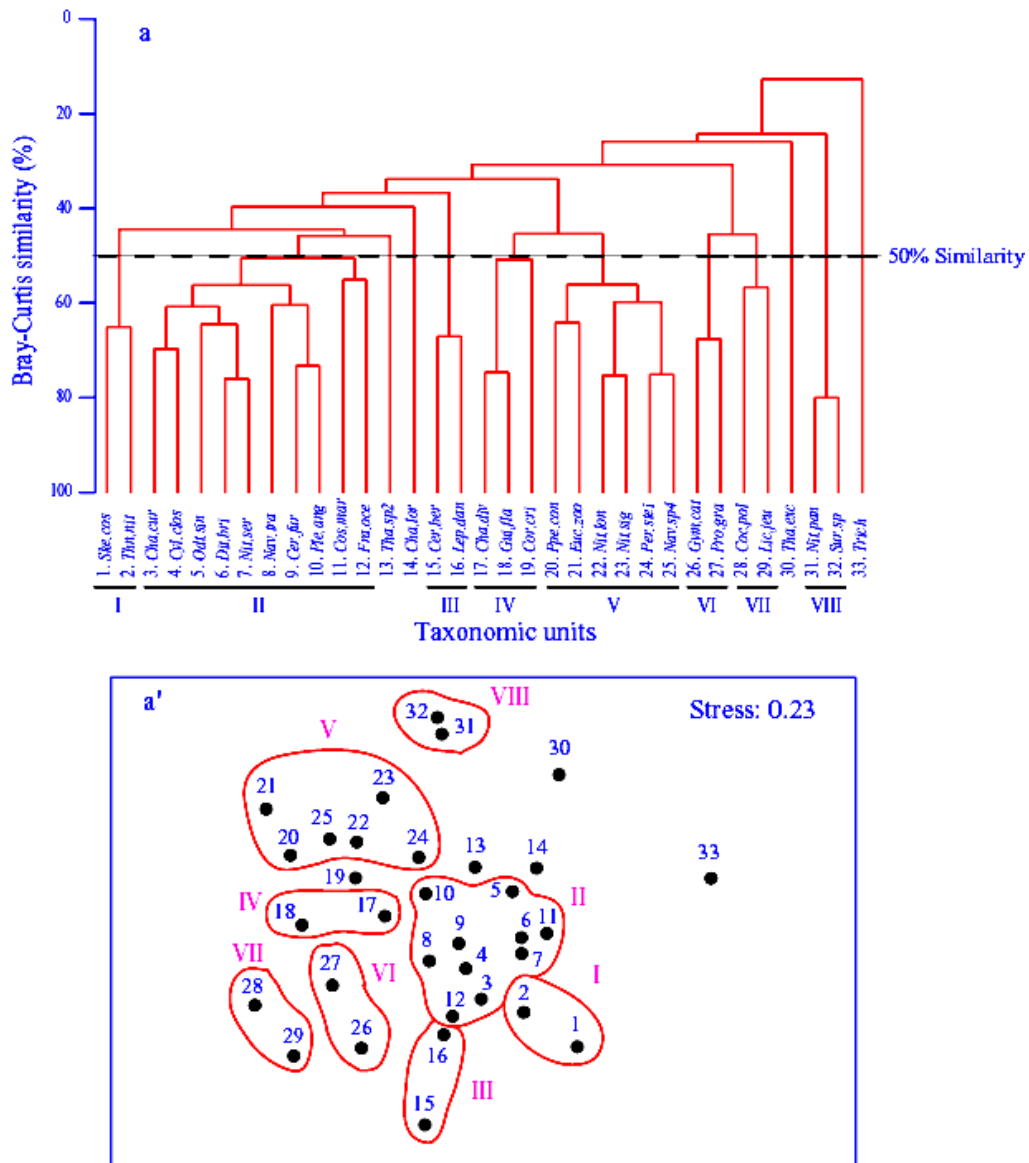


Fig. 2.11a. Cluster dendrogram of the phytoplankton species (>4%) from the surface water using Bray-Curtis similarity (%) and group average method. **a'**. Non-metric Multidimensional scaling (NMDS) ordination based on Bray-Curtis similarity (%) of the phytoplankton community.

respectively. At the bottom, cluster analyses at 50 % similarity level divided 28 species (> 4%) into five groups (I to V) and 9 ungrouped individuals (Fig. 2.11b). Clusters I to V consisted of 9, 3, 2, 3 and 2 species respectively. The phytoplankton distribution pattern as seen through 2D NMDS ordination is presented in Figs. 2.11 a' and b'. The stress values in these cases exceed 0.05; hence the positioning of the points in the NMDS and the cluster is likely to be different. To bring in a similarity the lines encircling the points

is adopted. Amongst these species, *S. costatum*, *F. oceanica*, *T. nitzschioides*, *C. curvisetus* and *Thalassiosira* sp. are bloom-forming species while the others contributed significantly to the phytoplankton community on a few occasions. Based on these criteria, the species formed groups in the cluster and ordination analyses.

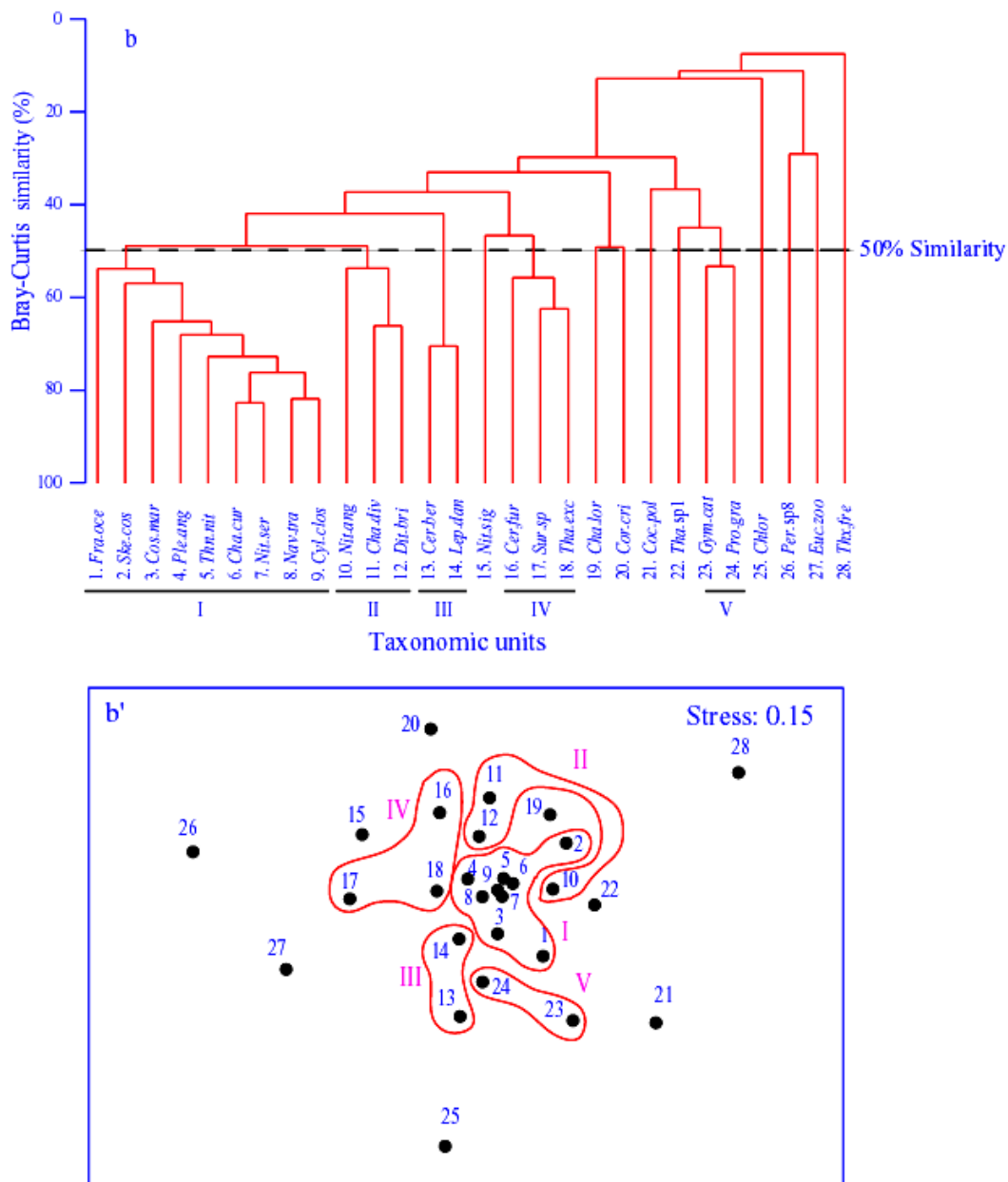


Fig. 2.11b. Cluster dendrogram of the phytoplankton species (>4%) from the bottom water using Bray-Curtis similarity (%) and group average method. **b'**. Non-metric Multidimensional scaling (NMDS) ordination based on Bray-Curtis similarity (%) of the phytoplankton community.

2.3.3.3. Spearman's rank correlation coefficient test

The results of these analyses are shown in table 2.5. The results revealed that phytoplankton and diatoms showed a significant relationship with surface salinity, day length, and rainfall (Table 2.5). In case of dinoflagellates, a significant relationship was observed with surface phosphate concentrations and atmospheric pressure. These results indicate that diatoms, which form the dominant group among the phytoplankton community, are governed by freshwater discharge during the monsoon.

Table 2.5. Results of Spearman's Rank Correlation Coefficient between environmental variables and phytoplankton. Significance level >95% has been considered.

Parameters	Phytoplankton				Diatoms				Dinoflagellates			
	Surface		Bottom		Surface		Bottom		Surface		Bottom	
	R	p	R	p	R	p	R	p	R	p	R	p
SS	-0.611	0.012			-0.646	0.007	-0.490	0.054				
SPO ₄											0.545	0.029
BDO					-0.511	0.043						
LD	-0.567	0.022	-0.626	0.009	-0.533	0.033	-0.629	0.009				
RF	0.590	0.016			0.553	0.026						
RH	0.626	0.009	0.609	0.012	0.582	0.018	0.606	0.013				
PR									-0.570	0.021	-0.602	0.014

2.3.4 Diatom propagules from the sediments

Altogether 41 species (22 centrales and 19 pennales) belonging to 20 genera of germinable diatoms have been recorded from sediments (Table 2.6). Of the 41 species, resting stages for only 16 species belonging to 12 genera have been reported (Table 2.6). Among these, benthic propagules of *S. costatum* and *F. oceanica* were observed throughout the investigation period, thus forming a major group, by constituting an average (16 months) of 43 and 30 % respectively throughout the investigation period. Benthic propagules of *T. subtilis*, *Thalassiosira* sp.1, *Thalassiosira* sp. 2, and *C. curvisetus* are the next dominant groups comprising an average of >2% annually but their distribution was discontinuous. The rest of the thirty-five forms were considered minor components.

Table 2.6. List of viable diatom species recorded and their abbreviations.
* indicate resting stages recorded for the respective species.

S. No.	Species	Abbreviations
CENTRICS		
1	<i>Biddulphia granulata</i>	BG
2	<i>B. rhombus</i> (Ehrenberg) Smith, W.	BRO
3	<i>Chaetoceros calcitrans</i> *	CCL
4	<i>Chaetoceros curvisetus</i> Cleve *	CCR
5	<i>Chaetoceros lorenzianus</i> Grunow *	CHL
6	<i>Coscinodiscus marginatus</i> Ehrenberg	CM
7	<i>Coscinodiscus</i> sp.	CSP
8	<i>Ditylum brightwellii</i> (West) Grunow *	DB
9	<i>Helicotheca tamesis</i> Shrubs	HT
10	<i>Leptocylindrus danicus</i> Cleve *	LD
11	<i>Odontella aurita</i> (Lyngbye) Agardh *	OA
12	<i>O. regia</i>	ORE
13	<i>O. sinensis</i> (Greville)Grunow	OS
14	<i>Melosira granulata</i> *	MG
15	<i>M. nummuloides</i> C.A. Agardh	MN
16	<i>Paralia sulcata</i> (Ehrenberg) Cleve *	MS
17	<i>Rhizosolenia stolterfothii</i> *	RS
18	<i>Skeletonema costatum</i> Greville (Cleve) *	SC
19	<i>Thalassiosira subtilis</i> (Ostenfeld) Gran *	TSUB
20	<i>Thalassiosira</i> sp. 1*	TSP1
21	<i>Thalassiosira</i> sp. 2*	TSP2
PENNATES		
22	<i>Amphora coffeaeformis</i> (Ag.) Kützing*	ACF
23	<i>A. rostrata</i> Wm. Smith	ART
24	<i>Amphora</i> sp	ASP
25	<i>Asterionellopsis glacialis</i> (Castracane)*	AG
26	<i>Cocconeis</i> sp.	CSP
27	<i>Cylindrotheca closterium</i> (Ehrenberg) Smith	CIC
28	<i>Fragilariopsis oceanica</i> (Cleve) Hasle*	FO
29	<i>Meuniera membranacea</i> (Cleve) P. C. Silva comb. nov	MM
30	<i>Navicula crucicula</i> (Wm. Smith) Donkin	NC
31	<i>N. transitrans</i> var. <i>derasa</i> f. <i>delicatula</i> Heimdal	ND
32	<i>N. inflexa</i>	NI
33	<i>N. subinflata</i> Grunow	NS
34	<i>Navicula</i> sp. 1	NS1
35	<i>Navicula</i> sp. 2	NS2
36	<i>Nitzschia bilobata</i> Wm. Smith	NIB
37	<i>N. panduriformis</i> Gregory	NIP
38	<i>Pleurosigma angulatum</i> Sensu W. Smith	PA
39	<i>Pseudo-nitzschia seriata</i> (Cleve) H. Pergallo	NIS
40	<i>Thalassionema nitzschioides</i> (Grunow) Mereschkowsky	TN
41	Unidentified sp.	UI

2.3.4.1. Temporal variation

Diatom benthic propagules persisted in sediments round the year and their relative abundance ranged up to 10^4 cells cm^{-3} wet wt of sediment (Fig. 2.12). Among the

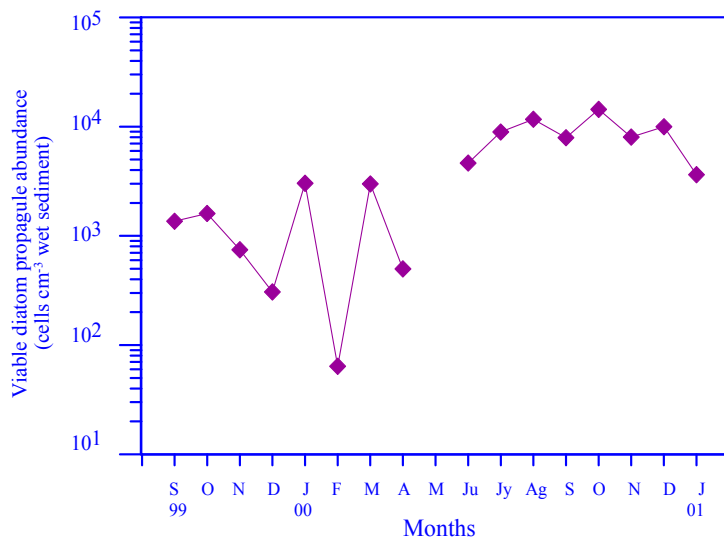


Fig. 2.12. Temporal variations in the relative abundance of diatom benthic propagules from the sediments.

centrics, *S. costatum* and, among the pennates, *F. oceanica* were dominant. One-way ANOVA revealed that benthic propagules of total diatoms, *S. costatum*, *F. oceanica*, *T. subtilis*, *T. sp. 1*, *T. sp. 2* and *C. curvisetus* showed a significant temporal variation ($p \leq 0.001$) (Tables 2.7 a-g). The two major forms bloomed during the monsoon in the water column but disappeared sporadically (Figs. 2.13 a and b) whereas the next major forms showed small peaks followed by decline on certain occasions (Figs. 2.13 c-f).

Table 2.7. One-way analysis of variance (ANOVA) to evaluate the temporal variations of the relative abundance of total and dominant diatoms (***= $p \leq 0.001$).

a. Total diatom viable cells					b. <i>Skeletonema costatum</i>		
Source of variation	df	SS	MS	fs	SS	MS	fs
Between Groups	15	19.7	1.31	31.8***	35.9	2.4	50.80***
Within Groups	32	1.3	0.04		1.5	0.05	
Total	47	20.9			37.4		

c. <i>Fragilariopsis oceanica</i>					d. <i>Thalassiosira subtilis</i>		
Source of variation	df	SS	MS	fs	SS	MS	fs
Between Groups	15	28.3	1.9	12.8***	59	3.93	15.57***
Within Groups	32	4.7	0.15		8.08	0.25	
Total	47	32.9			67.1		

e. <i>Thalassiosira sp. 1</i>					f. <i>Thalassiosira sp. 2</i>		
Source of variation	df	SS	MS	fs	SS	MS	fs
Between Groups	15	45.8	3.05	10.5***	53	3.53	23.09***
Within Groups	32	9.34	0.29		4.9	0.15	
Total	47	55.1			57.9		

g. <i>Chaetoceros curvisetus</i>				
Source of variation	df	SS	MS	fs
Between Groups	15	30.6	2.04	6.55***
Within Groups	32	9.96	0.31	
Total	47	40.6		

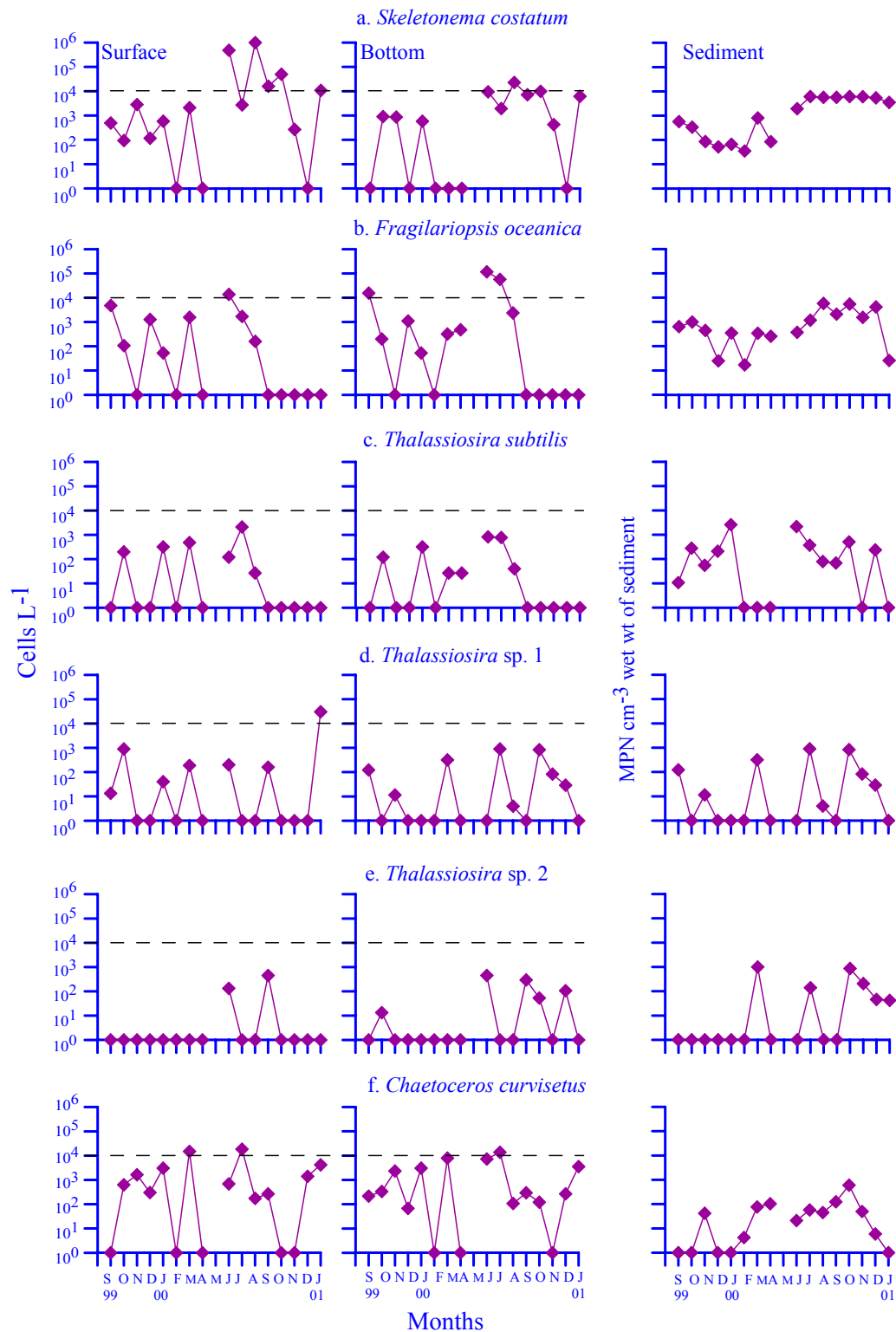


Fig. 2.13. Comparison between water column and viable diatoms. a) *Skeletonema costatum*, b) *Fragilariopsis oceanica*, c) *Thalassiosira subtilis*, d) *Thalassiosira* sp.1, e) *Thalassiosira* sp.2 and f) *Chaetoceros curvisetus*.

Cluster analyses of the sampling months based on relative abundance of diatom benthic propagules at 50% similarity level revealed two groups with five ungrouped individual

sampling months (Fig. 2.14a). Clusters I and II comprised of 3 and 8 sampling months (March, June, July, August, September, October, November, December 2000) respectively, whereas, the other sampling months formed a separate unit. Cluster II represented the sampling periods that are characterized by high abundance of diatom benthic propagules. The diatom propagule distribution portrayed a pattern similar to that of cluster analyses when subjected to 2D NMDS ordinations (Fig. 2.14b).

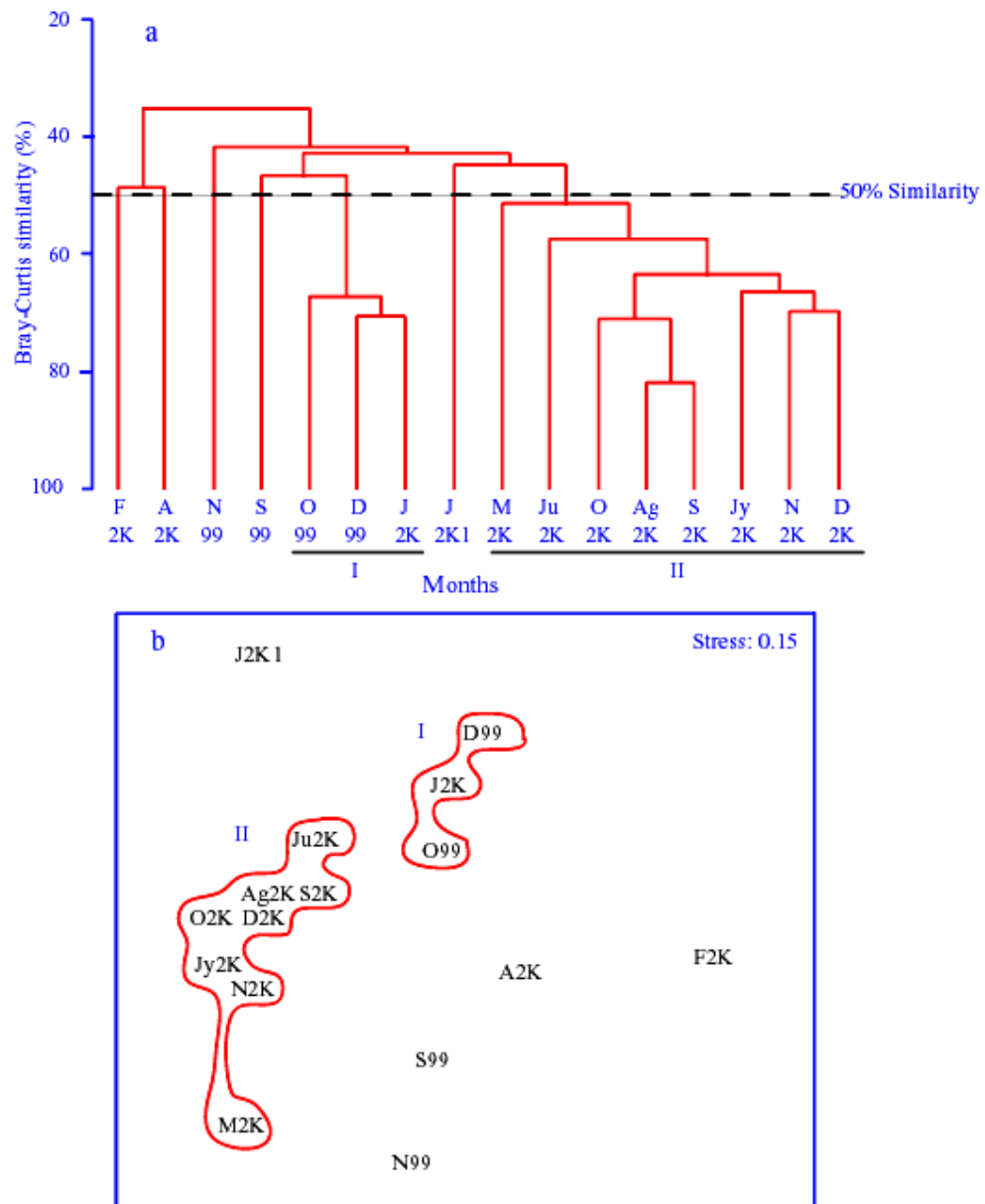


Fig. 2.14. a. Cluster dendrogram of the sampling periods based on the relative abundance of diatom benthic propagules from the sediments using the Bray-Curtis similarity coefficient and group average method. **b.** Non-metric Multidimensional scaling (NMDS) ordination based on the Bray-Curtis similarity coefficient.

2.3.4.2. Species relationships

Cluster analyses of the diatom benthic propagules (>4% relative abundance data) at 50% dissimilarity level divided 11 species into 2 clusters with 3 ungrouped individuals (Fig. 2.15a). Clusters I and II consisted of 3 (*S. costatum*, *F. oceanica* and *T. subtilis*) and 5 (*Thalassiosira* sp. 1, *Thalassiosira* sp. 2, *C. curvisetus*, *N. transitans* var. *derasa* f. *delicatula* and *N. panduriformis*) species respectively. Among these, *S. costatum* and *F. oceanica*, which were most similar, (Fig. 2.15) constituted the dominant group, while the others formed the next major group. The two dominant forms, *S. costatum* and *F. oceanica* occurred throughout the investigation period and their relative abundance

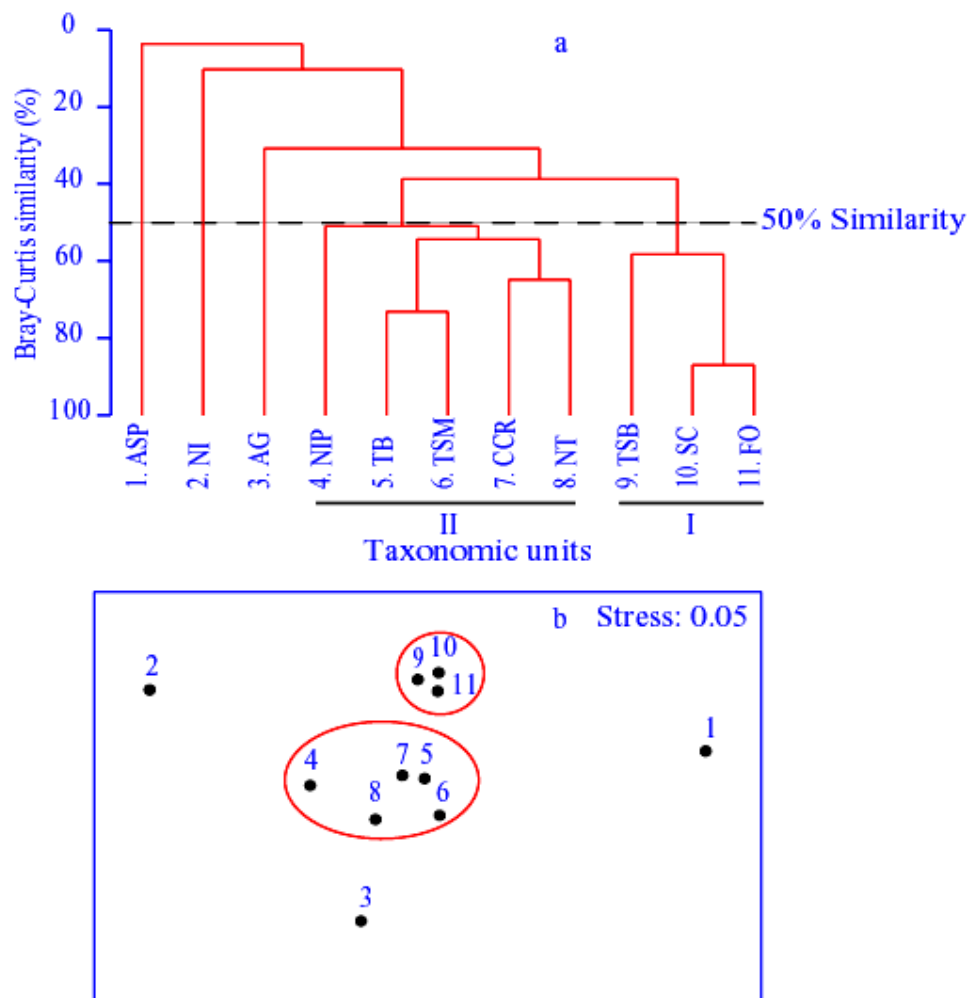


Fig. 2.15. a. Cluster dendrogram of diatom benthic propagules from the sediments using Euclidean distance and group average method. **b.** Non-metric Multidimensional scaling (NMDS) ordination based on Euclidean distance of the diatom community.

ranged upto 10^4 cells cm^{-3} wet wt of sediment. Clusters III-VI, each comprised of a single species and formed the minor group (as they occurred once or twice in high or low numbers). The diatom distribution portrayed a pattern similar to that of cluster analyses when subjected to 2D NMDS ordinations (Fig. 2.15b).

2.3.4.3. Relationship between dominant benthic and planktonic diatoms

In order to evaluate whether there was any density-dependent relationship between planktonic cells and the number of benthic propagules from the sediment of the same species, Spearman's rank correlation test was performed for the dominant species groups SC, FO, TSUB, TSP1, TSP2 and CCR (Table 2.6). The results revealed that the benthic propagules and vegetative cells of *S. costatum* showed a linear relationship while the others did not show any type of relationship (Table 2.8).

Table 2.8. Results of Spearman's rank–correlation test between planktonic cells and benthic propagules of diatoms. Significance level >95% as been considered.

	<i>S. costatum</i>		<i>F. oceanica</i>		<i>T. subtilis</i>		T. sp. 1		T. sp. 2		<i>C. curvisetus</i>	
	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>
Surface	0.64	0.007	-0.07	0.81	0.45	0.083	-0.37	0.164	-0.28	0.289	-0.22	0.404
Bottom	0.6	0.014	-0.08	0.78	0.51	0.04	0.01	0.966	0.01	0.982	-0.05	0.869

2.3.4.4. Spearman's rank correlation coefficient test

The results of this test are presented in Table 2.9. The abundance of planktonic cells and benthic propagules of *S. costatum* showed a significant negative correlation with surface salinity and nitrate and a positive relationship with rainfall. The relative abundance of *F. oceanica* showed a significant negative correlation with surface salinity and surface nitrate whereas planktonic cells showed a negative relationship between sunshine hours and atmospheric pressure and positive relationship with bottom phosphate, silicate, wind direction and relative humidity. The relative abundance of *T. subtilis* showed a significant negative correlation with solar radiation and air temperature (AT) whereas planktonic cells showed a positive relationship with wind velocity for surface population

and positive for bottom phosphate (BPO₄). The relative abundance of *Thalassiosira* sp. 1 showed a significant negative correlation with surface nutrients (SNO₃, SNO₂ and SPO₄) and bottom nitrate (BNO₃). The relative abundance of *Thalassiosira* sp. 2 showed a negative correlation with surface phosphate (SPO₄) and bottom nitrate (BNO₃). The relative abundance of *C. curvisetus* showed a significant positive correlation with temperature (surface and bottom), rainfall and a negative correlation with surface nitrite and bottom phosphate.

Table 2.9. Results of Spearman's rank–correlation test between environmental variables and diatoms from sediment and water column. Significance level >95% as been considered.

a. Sediment

Parameters	DBP		<i>S. costatum</i>		<i>F. oceanica</i>		<i>T. subtilis</i>		T. sp. 1		T. sp. 2		<i>C. curvisetus</i>	
	R	p	R	p	R	p	R	p	R	p	R	p	R	p
ST													0.65	0.006
SS	-0.58	0.018	-0.57	0.023	-0.52	0.041								
SNO ₃			-0.57	0.022	-0.62	0.011			-0.66	0.005				
SNO ₂									-0.54	0.033			-0.51	0.042
SPO ₄									-0.50	0.048	-0.50	0.048		
BT													0.50	0.049
BNO ₃			-0.54	0.029					-0.70	0.003	-0.49	0.052		
BPO ₄													-0.51	0.046
SR							-0.57	0.02						
RF			0.51	0.045									0.52	0.041
AT							-0.79	0.000						

B. Surface water

Parameters	<i>S. costatum</i>		<i>F. oceanica</i>		<i>T. subtilis</i>		T. sp. 2		<i>C. curvisetus</i>	
	R	p	R	p	R	p	R	p	R	p
SS	-0.69	0.003								
SDO					0.8	0.000			0.53	0.035
SNO ₃	-0.52	0.039								
SSi			0.53	0.034						
WV							0.58	0.02		
WD			0.50	0.046						
SH			-0.67	0.004						
RF	0.51	0.046								
RH			0.52	0.040						
PR			-0.61	0.013						

C. Bottom water

Parameters	<i>S. costatum</i>		<i>F. oceanica</i>		<i>T. subtilis</i>	
	R	p	R	p	R	p
BDO			-0.54	0.030		
BPO ₄			0.61	0.012	0.50	0.050
BSi			0.68	0.004		
WD			0.56	0.025		
SH			-0.67	0.004		
RF	0.69	0.003			0.56	0.024
RH			0.58	0.018		
PR			-0.54	0.029		

2.3.5 Dinoflagellate cysts from the sediments

Altogether 66 types of dinoflagellate cysts were recorded from the sediment (Table 2.10). Of these, 34 species belonging to 15 genera were identified. Dinoflagellate cyst densities ranged from $1.5 \times 10^2 - 5.7 \times 10^2$ cysts g^{-1} wet wt sediment (Fig. 2.16). One-way ANOVA, with equal replications, revealed that cyst densities showed significant temporal variation ($p \leq 0.001$) (Table 2.11).

Table 2.10. Checklist of dinoflagellate cysts from the sediments.

S. No.	Taxon	Abbrev.	S. No.	Taxon	Abbrev.
1	<i>Alexandrium affine</i> (Inoue & Fukuyo) Balech 1992	<i>Ale.aff</i>	34	Dinocyst 1	Deyst 1
2	<i>Alexandrium minutum</i> Halim 1960	<i>Ale.min</i>	35	Dinocyst 2	Deyst 2
3	<i>Alexandrium</i> sp.	<i>Ale. sp</i>	36	Dinocyst 3	Deyst 3
4	<i>Cochlodinium</i> sp.	<i>Coc. sp</i>	37	Dinocyst 4	Deyst 4
5	<i>Diplopsalis lenticula</i> Berg 1881	<i>Dip.len</i>	38	Dinocyst 5	Deyst 5
6	<i>Gonyaulax grindleyi</i> (Reinecke 1967)	<i>Gon.gri</i>	39	Dinocyst 6	Deyst 6
7	<i>Gonyaulax scrippsae</i> Kofoid 1911	<i>Gon.scr</i>	40	Dinocyst 7	Deyst 7
8	<i>Gonyaulax scrippsae</i> Kofoid 1912	<i>Gon.scr</i>	41	Dinocyst 8	Deyst 8
9	<i>Gonyaulax spiniferites</i> (Claparede & Lachmann)	<i>Gon.spi</i>	42	Dinocyst 9	Deyst 9
10	<i>Gonyaulax spiniferites</i> (Claparede & Lachmann)	<i>Gon.spi</i>	43	Dinocyst 10	Deyst 10
11	<i>Gonyaulax</i> sp. 1	<i>Gon sp1</i>	44	Dinocyst 11	Deyst 11
12	<i>Gonyaulax</i> sp. 2	<i>Gon sp2</i>	45	Dinocyst 12	Deyst 12
13	<i>Gymnodinium catenatum</i> Graham 1943	<i>Gym. cat</i>	46	Dinocyst 13	Deyst 13
14	<i>Gyrodinium impudicum</i>	<i>Gyr. imp</i>	47	Dinocyst 14	Deyst 14
15	<i>Lebouraia minuta</i>	<i>Leb. min</i>	48	Dinocyst 15	Deyst 15
16	<i>Lingulodinium polyedrum</i> (Stein) Dodge	<i>Lin. pol</i>	49	Dinocyst 16	Deyst 16
17	<i>Pheopolykrikos hartmannii</i> (Zimmerman)	<i>Phe. har</i>	50	Dinocyst 17	Deyst 17
18	<i>Protoceratium reticulatum</i> (Claparede & Lachmann)	<i>Prot. ret</i>	51	Dinocyst 18	Deyst 18
19	<i>Protoperidinium claudicans</i> (Paulsen) Balech 1974	<i>Prot. cla</i>	52	Dinocyst 19	Deyst 19
20	<i>Protoperidinium compressum</i> (Nie) Balech	<i>Prot. com</i>	53	Dinocyst 20	Deyst 20
21	<i>Protoperidinium conicum</i> (Gran) Balech 1974	<i>Prot. con</i>	54	Dinocyst 21	Deyst 21
22	<i>Protoperidinium divaricatum</i>	<i>Prot. div</i>	55	Dinocyst 22	Deyst 22
23	<i>Protoperidinium latissimum</i> (Kofoid) Balech	<i>Prot. lat</i>	56	Dinocyst 23	Deyst 23
24	<i>Protoperidinium leonis</i> (Pavillard) Balech 1974	<i>Prot. leo</i>	57	Dinocyst 24	Deyst 24
25	<i>Protoperidinium oblongum</i> (Aurivillius) Parke & Dodge	<i>Prot. obl</i>	58	Dinocyst 25	Deyst 25
26	<i>Protoperidinium pentagonum</i> (Gran) Balech 1974	<i>Prot. pen</i>	59	Dinocyst 26	Deyst 26
27	<i>Protoperidinium</i> sp.	<i>Prot. sp</i>	60	Dinocyst 27	Deyst 27
28	<i>Pyrophacus steinii</i> (Schiller)	<i>Pyr. ste</i>	61	Dinocyst 28	Deyst 28
29	<i>Scrippsiella trochoidea</i> (Stein) Loeblich III 1976	<i>Scr. tro</i>	62	Dinocyst 29	Deyst 29
30	<i>Scrippsiella</i> sp. 1	<i>Scr. sp1</i>	63	Dinocyst 30	Deyst 30
31	<i>Scrippsiella</i> sp. 2	<i>Scr. sp2</i>	64	Dinocyst 31	Deyst 31
32	<i>Scrippsiella</i> sp. 3	<i>Scr. sp3</i>	65	Dinocyst 32	Deyst 32
33	<i>Spiniferites mirabilis</i>	<i>Spi. mir</i>	66	Dinocyst 33	Deyst 33

Table 2.11. One-way analysis of variance (ANOVA) to evaluate the temporal variations of the dinoflagellate cysts abundance from the sediments (***) = $p \leq 0.001$.

Source of variation	df	SS	MS	Fs
Between groups	15	7.19	0.48	6.11***
Within groups	32	2.51	0.08	
Total	47	9.69		

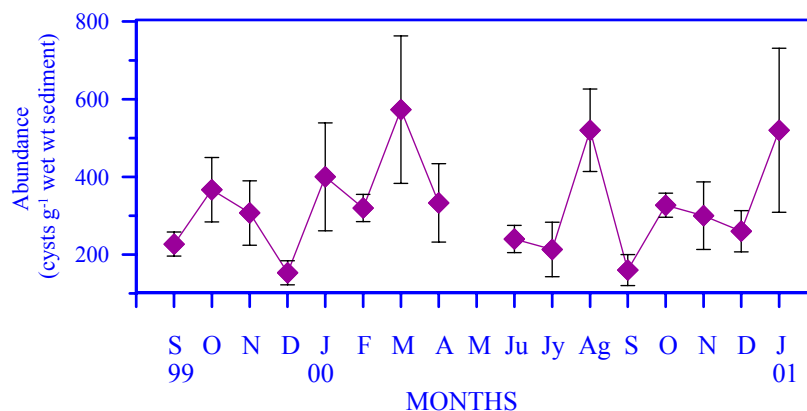


Fig. 2.16. Temporal variations in the abundance of dinoflagellate cysts from the sediments.

2.3.5.1 Temporal variation

Cluster analyses of the sampling months based on the dinoflagellate cysts abundance (>4%) at 50% similarity level revealed 2 groups and 3 ungrouped individual sampling months (Fig. 2.17a). June 2000, September 2000 and December 1999 which formed separate units, were represented by low density. Clusters I and II comprised of 4 (November 1999, January, April and November 2000) and 9 (September – October 1999, February, March, July, August, October, December 2000 and January 2001) sampling months respectively. Cluster I represented the sampling periods that are characterized by moderate abundance of cysts whereas cluster II was characterized by high abundance.

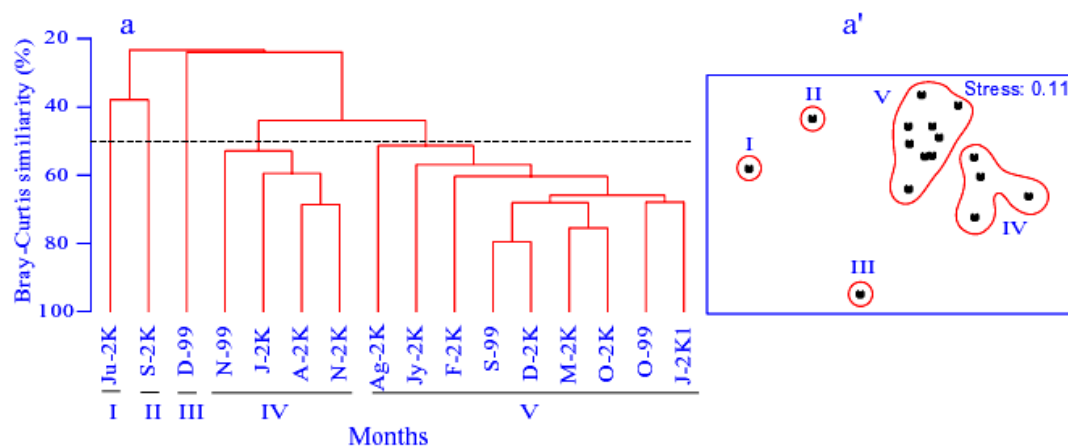


Fig. 2.17a. Cluster dendrogram of the sampling periods based on the abundance of dinoflagellate cysts from the sediments using the Bray-Curtis similarity coefficient and group average method. **a'** Non-metric Multidimensional scaling (NMS) ordination based on the Bray-Curtis similarity coefficient of the dinoflagellate cyst community.

The cyst distribution portrayed a pattern similar to that of cluster analyses when subjected to 2D NMDS ordinations (Fig. 2.17a’).

2.3.5.2 Species relationship

Cluster analyses of the dinoflagellate cysts (>4% abundance data) at 50% similarity level divided 35 species into ten clusters with seven ungrouped individuals (Fig. 2.17b).

Cluster I consisted of 8 species: *Gonyaulax scrippsae*, *G. spiniferites*, *Scrippsiella*

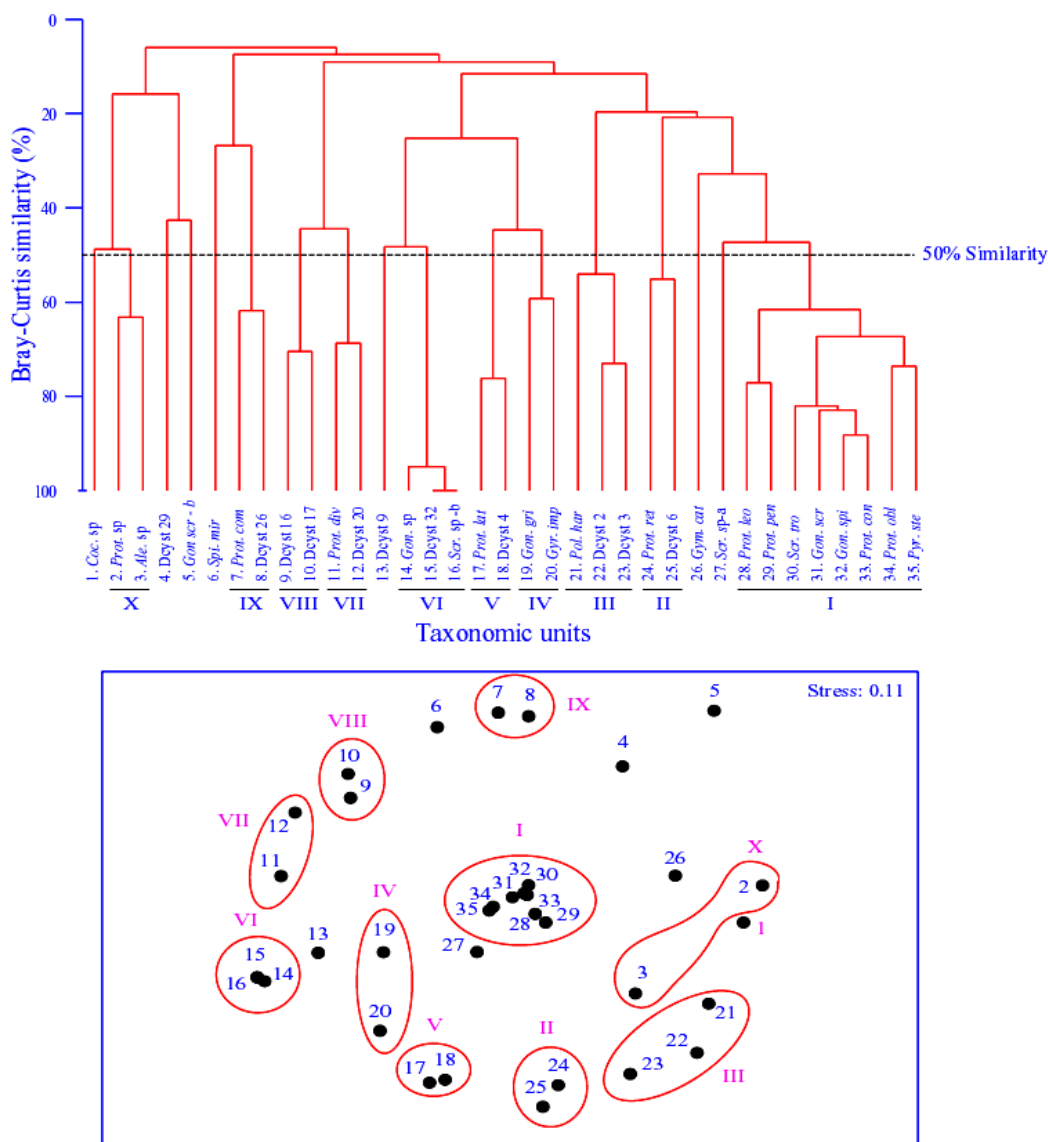


Fig. 2.17b. Cluster dendrogram of the dinoflagellate cysts from the sediments using the Bray-Curtis similarity coefficient and group average method. **b’.** Non-metric Multidimensional scaling (NMDS) ordination based on the Bray-Curtis similarity coefficient of the dinoflagellate cyst community.

trochoidea, *Protoperidinium conicum*, *P. oblongum*, *P. leonis*, *P. pentagonum* and *Pyrophacus steinii*, the dominant groups. These forms occurred frequently and their densities ranged up to 10^2 cysts per g wet wt of sediment while the rest of the species belonging to other clusters and ungrouped individuals formed the next minor group (as they occurred once or twice in high or low numbers). The dinoflagellate cyst distribution portrayed a pattern similar to that of cluster analyses when subjected to 2D NMDS ordinations (Fig. 2.17b').

2.4 DISCUSSION

Zuari estuary is a dynamic aquatic ecosystem exhibiting a strong seasonal gradient, both in environmental variables and plankton assemblages, because of the tight physico-chemical and biological coupling. Of these, physical variability, driven primarily by external forcing events like meteorology and climatology, is fundamental. Wind- and weather-driven events cause physical changes and disruptions. These events lead to variability in temperature, irradiance, precipitation, run-off, nutrient-loading etc. in coastal environments. Such changes are instrumental in the complete transformation of the phytoplankton community structure and production (Devassy and Goes 1988, Bhattathiri et al. 1976). Therefore, in this attempt, the focus was on the patterns of variability, which characterize the occurrence of phytoplankton species, community organization and the processes that influence diatom dormancy and rejuvenation in tropical waters, with a clearly demarcated monsoon season.

Zuari estuary sustains diverse assemblage of phytoplankton species in the water column that differ seasonally. The phytoplankton community comprises of the following groups: diatoms, dinoflagellates, blue green algae, silicoflagellates and prymnesiophytes. The present investigation supported by earlier studies (Devassy 1983, Devassy and Goes

1988), reveals that diatoms followed by dinoflagellates dominate the phytoplankton community (Fig. 2.7) in both surface and bottom waters of this estuary. Diatoms comprised 85 and 92 % and dinoflagellates 11 and 7% of the total phytoplankton community in surface and bottom waters (Fig. 2.7) respectively. The phytoplankton abundance, diversity, evenness, and species richness showed significant variation between water depths and sampling months (Table 2.4).

Of the 137 phytoplankton species recorded (Table 2.3), only 33 species in the surface and 28 species in the bottom contributed more than 4% to the total population (Fig. 2.11a). Cluster analyses divided these species into various groups and subgroups at 50% similarity level depending upon their occurrence. Most of these forms are known to form blooms. However, there are considerable variations like timing, frequencies, intensity, trend, etc. in the bloom and occurrence pattern of individual blooms. At least 8 distinct recognizable patterns of variability were observed during this investigation (Table 2.12). *S. costatum* and *F. oceanica* were the most dissimilar forms from surface and bottom waters. The blooming of *S. costatum* (~1000 cells ml⁻¹) and *F. oceanica* (~120 cells ml⁻¹) is an annual phenomenon during monsoon along the west coast of India (Devassy 1983, Gopinathan 1974, Mitbavkar and Anil 2002, Personal observation). Even though the numbers of these species were high, the chlorophyll concentrations were low (Fig. 2.6a). Trends of disappearance are also known for *S. costatum* bloom elsewhere (Boalch 1987) and this was also observed in the Zuari estuary (Personal observation). Trends of decreasing abundance were also observed. An *F. oceanica* bloom, observed during early phase of the monsoon, decreased gradually from June to September 2000 in the bottom waters indicating a decreasing trend. Episodic bloom occurrences of indigenous species that normally do not bloom, or show only modest seasonal increases, are common. Many of the species responsible for the apparent global

increase in harmful algal blooms (HABs) are of this type (Smayda 1989, 1990). In the present study, blooms of harmful species such as *C. polykrikoides* (~ 60 cells ml^{-1}) and *G. catenatum* (~ 22 cells ml^{-1}) were observed in the water column (Fig. 2.7a) during monsoon, when there was a break in rainfall (July 2000). During this period, fish deaths were observed (Personal observation) and this went unnoticed, as the bloom existed for a very short period. A red tide caused by this species was also observed in the subsequent year during the early phase of post-monsoon (October 2001) with a cell density of ~ 2000 cells ml^{-1} , and caused mass fish mortality. *G. catenatum* is known to cause paralytic shell fish poisoning (PSP) and its toxic effects have been reported from the Mangalore coast (Karunasagar et al. 1984, 1990).

A single species-bloom of *Thalassiosira* sp. 1 (~ 30 cells ml^{-1} at surface and ~ 10 cells ml^{-1} at bottom) was observed during December 2000 and January 2001 but not in December 1999 and January 2000 responding to increased loading of nitrate concentration of local origin (Fig. 2.3a). Some species were present throughout the year, e.g. a diatom species, *T. nitzschoides*. On certain occasions, species like *E. zodiacus*, *Coscinodiscus marginatus*, *G. flaccida*, *L. juergensii*, and *N. angularis* were predominant in the community. Stochastic blooms caused by many taxa are a common phenomenon. Such blooms occurred twice in a year in this estuary, i.e., once during the monsoon break (~ 152 cells ml^{-1}) or at the end of the monsoon period (~ 80 cells ml^{-1}) and the next during the pre-monsoon period (~ 52 cells ml^{-1} at surface and ~ 80 cells ml^{-1} at bottom). The blooms occurring during the monsoon can be the resultant effect of increased discharge of nutrients by land run-off and precipitation, i.e., ‘bottom up’ effect, whereas, the pre-monsoon blooms can be related to decreased grazing pressure, i.e., ‘top down’ effect. During these periods, the chlorophyll *a* concentration also peaked (Fig. 2.6a). Most of the pennate diatoms like *Navicula* and *Pleurosigma*, which are primarily encountered in

sediments and tidal flats, were also found in the water column (~ 10 cells ml^{-1}) through resuspension (de Jonge and van Beusekom 1992, Tomas 1997), and it seems reasonable to assume that their primary production in the water column is as effective as on tidal flats (de Jonge and van Beusekom 1995).

Whatever factors influence these different patterns, including recruitment from hidden flora or ballast water introductions of immigrant species, the ultimate fate of phytoplankton is death or the formation of resting stages as a survival alternative. The typical fate of these blooms is to settle (local or distant places) onto sediments in the form of live cells or resting stages (Smetacek 1980, 1985, Alldredge and Gotschalk 1989, Kiorboe et al. 1994). Other than this, the phytoplankton cells reaching the sea floor have a variety of fates. They may be recycled by the benthic fauna, bacteria or chemical dissolution (Sancetta 1989, Smetacek 1999) or they may become buried in the stratigraphic record. For most cells, the end result is death. However, some cells survive up to many years as resting stages within the sediment (Lewis et al. 1999, McQuoid et al. 2002). These resting stages act as a repository of genetic material, which are able to seed the surface waters for further primary production (Carrick et al. 1993) under suitable growth conditions.

The ecological role of phytoplankton resting stages in sediments has been actively investigated, mainly in several harmful species (Fukuyo 1982, Imai and Itoh 1987, Ishikawa and Taniguchi 1994). In order to consider the role of dominant phytoplankton resting stages, it would be helpful to compare the ecological characteristics of phytoplankton resting stages between dominant groups. In the present study, the diatom benthic propagules dominated over the dinoflagellates by the order of 10 - 10^3 times, despite the fact that the maximum abundance of the planktonic cells in the water column

was of similar order. This may indicate different seeding strategies between diatoms and dinoflagellates. Itakura et al. (1997) also reported similar observations. Viewed from the evolutionary ecology of phytoplankton, diatoms are considered to be *r*-selected organisms (Kilham and Kilham 1980), which are characterized by their faster growth response and /or opportunistic appearance in highly turbulent environments (Margalef 1978, Kilham and Kilham 1980). On the other hand, dinoflagellates are considered to be *k*-selected organisms, specialists in resource-limited environments where there is intense interference from neighbors (Harper 1977). In the study of terrestrial plants, *r*-species are known to form larger numbers of small seeds, which have shorter periods of innate dormancy (Harper 1977). The population of benthic propagules, which seems to be controlled by the *r*-strategy, may serve as a continual source of vegetative cells in fluctuating coastal environments throughout the year. Although, these concepts are based on the relative evaluation of ecological characteristics, *r*- vs *k* selection, is a rather simplistic comparison between two groups or species; differences in the ecological characteristics (*r*- and *k*-selection) could be observed in the diatom groups (eg. planktonic and benthic) or even in one species (eg. winter and summer clone) (Fryxell 1991 and 1994). Nevertheless, in general, improved knowledge of the different strategies of phytoplankton will help to understand the mechanisms of species succession in coastal environments.

Smayda (2002) considered that diatoms and dinoflagellates have contrasting bloom behavior. Blooms (independent of species composition) of the most dominant group, diatoms, are annually recurrent, predictable, prolonged, of high species diversity and a species succession occurs (Guillard and Kilham 1977, Smayda 1980) as compared to dinoflagellate blooms. In the Zuari estuary, diatoms are not only dominant by numbers but also by high species count, richness and diversity as compared to dinoflagellates

(Fig. 2.9). Considering such a scenario, the present discussion is further focused on the pattern of diatom dormancy and rejuvenation in a monsoon influenced tropical environment. Among the population of diatom benthic propagules, *Skeletonema*, *Fragilariopsis*, *Chaetoceros* and *Thalassiosira* were dominant. Amongst these, benthic propagules of *S. costatum* and *F. oceanica* persisted round the year in the sediments (Figs. 2.13 a and b) and were dominant, constituting 73% of the total benthic propagules. This reveals that *S. costatum* and *F. oceanica* are permanent residents of this region and their benthic propagules may function as short term resting stages between intermittent blooms. Of the 41 species (Table 2.6), benthic propagules for 6 species belonging to 4 genera were dominant (Fig. 2.15, Cluster I and II) suggesting that only the pelagic forms contributed significantly to the pool of benthic propagules. The dominant species followed the order of *S. costatum* > *F. oceanica* > *Thalassiosira* spp. > *C. curvisetus*. Among the dominant species, only *S. costatum* showed a linear relationship (Table 2.8) between the benthic propagules and planktonic cells indicating that this species is particularly important for the coupling of pelagic and benthic ecosystems.

Diatom community structure in the present study site is linked to various physico-chemical (Table 2.5) and biological factors such as advection, mixing rates, light, salinity, turbulence, sedimentation, nutrient availability, grazing, etc. and the interaction between these factors. The influence of various factors on diatom dormancy, rejuvenation as well as the temporal distribution of diatom benthic propagules in a tropical estuary is discussed further based on a schematic pathway (Fig. 2.18). This schematic pathway describes the probable processes involved in diatom dormancy and rejuvenation, emphasizing on the events during monsoon. Only four species (*S. costatum*, *F. oceanica*, *C. curvisetus*, *Thalassiosira* sp. 1) are considered in the schematic pathway based on their abundance in the water column. In this schematic pathway,

regular letters and the continuous lines indicate data from this study, whereas italic letters and discontinuous lines indicate hypotheses supported with published data from this area.

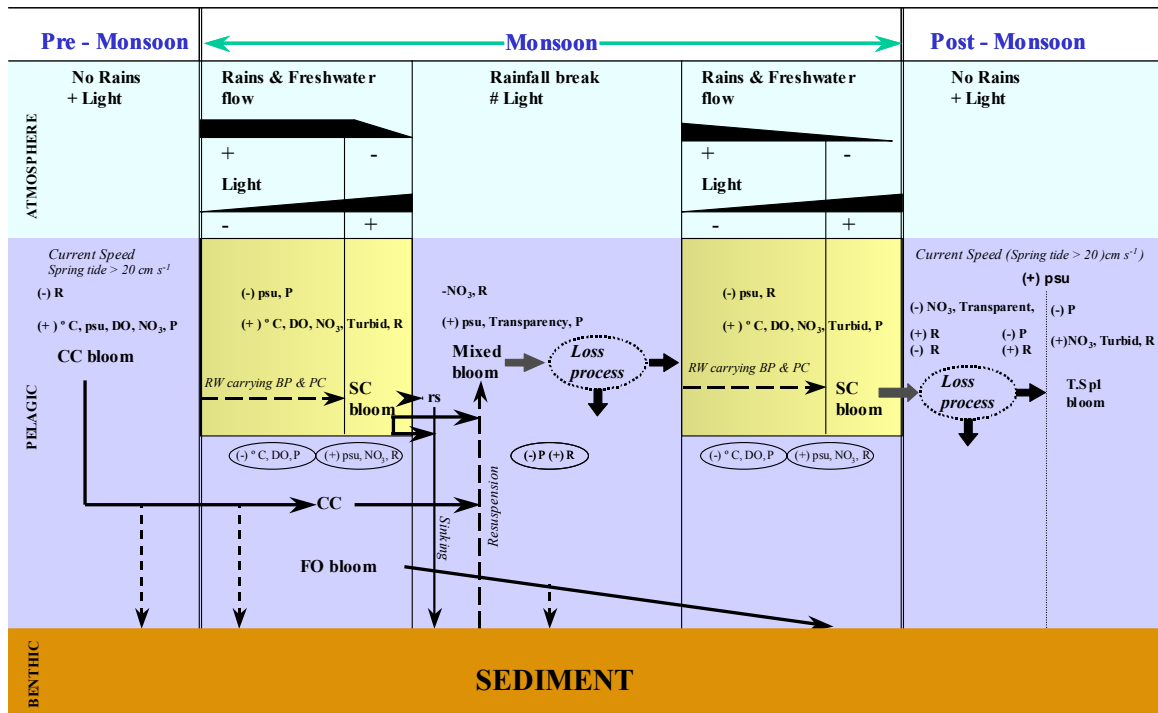


Fig. 2. 18. Schematic pathway explaining the process involved in diatom dormancy and rejuvenation in a tropical estuary. SC - *Skeletonema costatum*, FO - *Fragilariopsis oceanica*, Tsp1 - *Thalassiosira* sp.1, CC - *Chaetoceros curvisetus*, rs – Resting stages, # - Optimal conditions, - - Minimal conditions, + - Maximum conditions, psu - Salinity, °C – Water temperature, DO – Dissolved oxygen and NO₃ – Nitrate concentration, RW – River water, BP – Benthic propagules, PC - Pelagial cells, P - Production, R - Respiration

Note: 1) Stratification observed during monsoon is marked with dotted region for surface waters. 2) Regular letters and continuous lines are supported with observed/processed data from this study, whereas italic letters and discontinuous lines are hypothesis supported with published data for this area.

The classical scenario begins with the onset of the southwest monsoon, which causes a drastic change in the hydrodynamic characteristics. Such changes are instrumental in the complete transformation of the phytoplankton population size and structure (Devassy and Goes 1988). The coastal zone off western India experiences moderate upwelling during June-November (Banse 1959, 1968); the intrusion of this upwelled water is felt in the present study site. With the onset of the monsoon, the study site experiences a high freshwater influx (Shetye et al. 1995) at a flow rate of >10,000 ML day⁻¹ when most of

the annual precipitation occurs over the catchment area (Unnikrishnan et al. 1997). Hence, during this period, stratification develops (Fig. 2.2), with a warmer, lower salinity layer arising from large land run-off and local precipitation in the surface and the cold, saline, oxygen depleted upwelled water at the bottom (Naqvi et al. 2000). These processes have a pronounced influence on the native phytoplankton community in this estuary. The increased flow rate caused by riverine discharge can physically affect the phytoplankton community by either flushing the existing diatom cells (marine forms) from the surface waters (loss processes) or inoculating the accumulated seed stock from the bottom sediment along with nutrients (Fig. 2.3) into the water column (gain processes). In the present study, this phenomenon occurred twice during the monsoon i.e. once at the onset (June 2000) and the other at the restart of rainfall after a monsoon break (August 2000).

Wind velocity, currents and tides are the other important physical factors that resuspend the microphytobenthos along with sediment, thereby influencing the phytoplankton community (de Jonge 1995, de Jonge and van Beusekom 1995). The maximum current speed in this estuary occurs during the monsoon whereas an average of $\sim 20 \text{ cm s}^{-1}$ exists during the dry season (non-monsoon period) (Jayakumar et al. 1996). The microcosm experiment conducted by de Jonge and van den Bergs (1987) showed that, under natural conditions in shallow waters, clear resuspension of mud, sand and benthic diatoms starts at current velocities as low as ca. 10 cm s^{-1} . In the present study site, the current speed is greater during spring tide (Jayakumar et al. 1996) than the critical current speed ($>20 \text{ cm s}^{-1}$), which is required to resuspend the bottom sediment (Bloesch, 1994). Beaulieu (2003), who conducted a laboratory flume study using *S. costatum* and *Chaetoceros* spp. suggested that the coupling of settled phytodetritus and other sticky organic flocs to the water column is enhanced by waves. Thus, it may be possible that the distribution of

resting stages is influenced by their frequent resuspension along with the sediment followed by sinking at the same or distant places. Such frequent resuspension of resting stages for a short time and subsequent resinking at the same or distant place could provide them with 'recharging' periods of brief photosynthesis without inducing germination (French and Hargraves 1980). Hence, the flow pattern in Zuari estuary plays a dual role in influencing the diatom community structure both, in the water column (growing stage) by affecting the residence time available for different species to grow, and on the seabed (benthic propagules) by frequent resuspension followed by transportation to distant places.

The specific hydrodynamic conditions during the onset of monsoon and again at the restart of rainfall after an intermittent monsoon break affects the phytoplankton biomass not only through physical flushing but also by controlling the salinity and nutrient gradients to which the cells are exposed. It is evident from Fig. 2.2 that during the monsoon, salinity stratification occurs indicating the influence of freshwater discharge at the surface (lower salinity). The freshwater discharge resuspends and further carries the accumulated benthic diatom propagules that are present round the year (Fig 2.12) along with nutrients and other detrital particles from the bottom. At the same time, the nutrient-rich upwelled water at the bottom is also capable of resuspending the accumulated benthic propagules. This process occurred twice in the present investigation, once at the onset (June 2000) and the other after an intermittent monsoon break (August 2000). Once resuspended, the propagules will not be able to sink because of the stratification. Among the diatom propagules, opportunistic species like *S. costatum* at the surface and *F. oceanica* at the bottom, take advantage of the prevailing environmental conditions and bloom. In the present study, *S. costatum* bloomed in June 2000 and August 2000 in less saline (Figs. 2.13a and 2.2b), nutrient-rich, turbid, surface

waters, whereas *F. oceanica* bloomed once (June 2000) in high saline, low oxygen and temperature, nutrient-rich bottom waters and continued to be present till the end of monsoon (Figs. 2.13b and 2.2). In case of *S. costatum*, the propagules once suspended at the surface will not sink to the bottom because of the stratification. As a result, the *S. costatum* propagules get ample opportunity to remain at the surface. During minimum rains, the resuspended *S. costatum* propagules are able to rejuvenate and proliferate even under turbulent flow conditions because of their faster growth rate (Table 2.4b). Fogg (1966) reported that *S. costatum* grows at the rate of ~ 2 doublings day⁻¹. Thus, freshwater flow rate and upwelled water during monsoon play a crucial role in influencing the diatom population structure in surface and bottom waters respectively. During this period, sunshine hours ranged from 2 to 6 h (Fig. 2.4c), whereas salinity was 18 and 30 psu in surface and bottom waters (Fig. 2.2b) respectively. This stratification is an ideal condition for blooming of the two species in nutrient-rich waters. The rejuvenation/proliferation process proceeds rapidly once the benthic propagules find themselves in a suitable environment. It has been reported that diatom germination is influenced by a combination of temperature and light (photoperiod and irradiance) similar to those in the environment during sporulation (Hollibaugh et al. 1981, Hobson 1981, Eilertsen et al. 1995). Figs. 2.4 (c and d) and 2.18 (a and b) reveal that *S. costatum* and *F. oceanica* are capable of rejuvenating and proliferating even under minimum light conditions; these forms bloom in the water column due to their faster growth rate even when the photoperiod and irradiance are minimal. The opportunities for growth of other diatom species in the water column could be minimal because of the following reasons 1) the conditions are not favorable 2) slower growth rate or 3) the blooming of *S. costatum* suppresses the growth of other diatoms (either by oxygen depletion [GEOHAB, 2001] or by acting as a flocculating agent [Hansen et al. 1995]).

In case of *S. costatum*, the bloom observed in June declined by two-folds during the next month (July 2000) (Fig. 2.13a). This may be attributed to the following reasons 1) ‘bottom up’ effect, 2) competition, and 3) cell-cell contact. Usually, a *S. costatum* bloom lasts for a few days to weeks. Figs. 2.2b and 2.3a revealed that a sudden rise in salinity, coupled with nitrate depletion, might be one of the possible reasons for the decline, revealing a ‘bottom up’ (limitation by resources) rather than ‘top down’ (predation control) effect as grazing pressure during this period was minimal. In addition, during this period (July 2000), the percentage of oxygen saturation exceeded 100% indicating that production is dominant over respiration (Fig. 2.19).

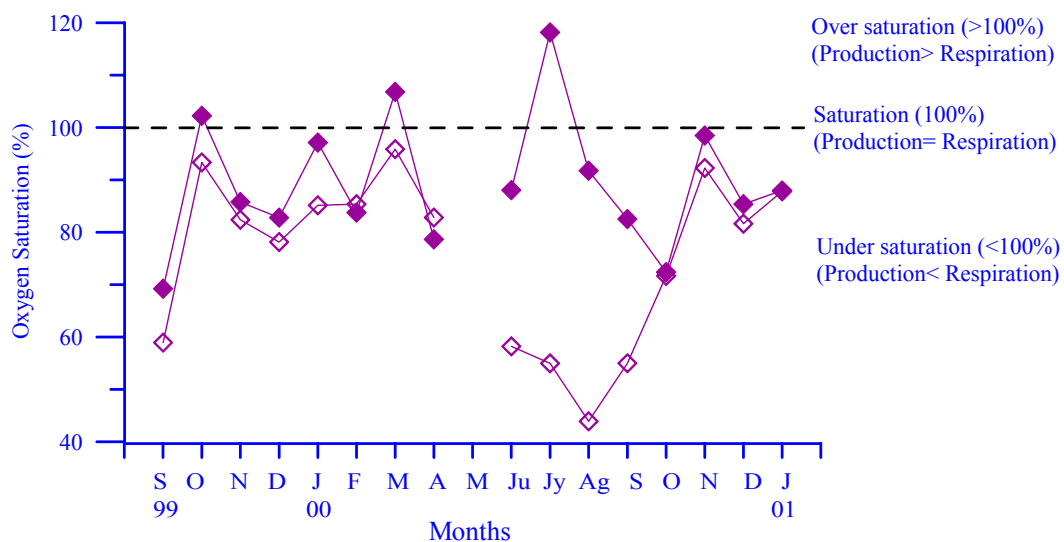


Fig. 2.19. Temporal variations in the oxygen saturation (%) from the water column

Gran (1912) hypothesized that resting stage formation is believed to be initiated by poor growth conditions in the water column. Once formed, they sink to the sediment, where they remain as benthic stages. This hypothesis is by far the most widely used interpretation for the role of resting stages in marine environments (French and Hargraves 1980, Garrison 1981, Hollibaugh et al. 1981). Most authors have reported nitrogen depletion to be the most important environmental variable causing dormancy in

marine diatoms. In the present study, it was nitrate depletion in the water column that induced dormancy in *S. costatum* (Table 2.9a). The maximum number of resting stages may be formed during or just after a period of maximum vegetative cell division (Heaney et al. 1983, McQuoid and Hobson 1996, Zohary et al. 1998). Once formed, they sink out of the euphotic zone into the sediment (Fig. 2.12b), when the sea is calm and well mixed. Since the sinking rate for *S. costatum* is high (Von Bodungen et al. 1981), during the bloom, large numbers of resting and senescent cells, in aggregates, sank to the bottom in a short span of time as the present study site is shallow (<10 m deep). This indicates that sedimentation of the bloom diatom (*S. costatum*) is one of the important loss processes from the surface waters. Smetacek (1985) reported that such a process (sedimentation) plays a crucial role in the survival strategy as it represents the transition from a surface growing stage to a benthic or deep-water resting stage in their life cycles. Once settled at the bottom, the diatom resting stages survive for a long time in the sediment (Lewis et al. 1999). Hansen and Josefson (2001) reported a new aspect of diatom longevity in sediments: that the diatom pool persists for several months even though benthic macrofauna, including deposit feeders, are abundant in the sediment. The settled benthic propagules would serve as the seeding units for the next bloom.

Subsequent to the decline of the *S. costatum* bloom, a mixed bloom of diatoms and dinoflagellates was observed during July 2002 when there was a break in rainfall; nutrient-poor water was well mixed (Figs. 2.2 a, b, 2.3a) and the sea was calm. The mixed bloom consisted of slow-growing, large-sized diatoms (*C. curvisetus*, *P. seriata*, *T. nitzschoides*, *L. danicus*) and dinoflagellates (*C. polykrikoides* and *G. catenatum*) with still slower growth rates. This type of succession follows the general succession pattern (Margalef 1958, Devassy and Goes 1988). These slow-growing, large-sized phytoplankton contribute much to the chlorophyll pool (Fig. 2.6a). Normally, such

blooms are observed during the end of the monsoon or at the beginning of the post-monsoon season. It may be possible that the mixed blooms might have out-competed the *S. costatum* bloom. Garrison (1981) reported that certain species might drop out of competition by sporulation, if faced with a competitor that can take up a nutrient, such as nitrate, more efficiently at low concentrations. It has also been reported that exocrine substances released by species that come later in the sequence might mediate the replacement of species typical of the first stage, such as *S. costatum* (Pratt 1966). Uchida (2001) also suggested that inter- and intra-specific cell contact plays an important role in the life cycle of some dinoflagellate species. Hence, it may be possible that the mixed blooms might have affected the ecological behavior of *S. costatum* or the decline of the bloom might have induced the other species to flourish; however, this aspect requires a detailed investigation. Hence, it may be possible that the benthic propagules of *S. costatum* bloom first (June 2000) and the pelagial cells serve as seeding units for the second bloom (August 2000). This bloom further undergoes various loss processes like herbivore grazing (Fig. 2.19), sedimentation and resting stage formation due to nitrate depletion (Table 2.9).

C. curvisetus, one of the dominant species in the mixed bloom, is favoured by high salinity and transparent conditions for growth (Fig. 2.13d). This species also bloomed in surface waters during the pre-monsoon period (March 2000, Fig. 2.13d), when the herbivore grazing pressure was minimum (Fig. 2.19). Thus, it may be possible that the induction of low saline waters by freshwater discharge either at the onset (June 2000) or restart of the monsoon after a break (August 2000) might have triggered them to undergo sporulation in the surface waters and be flushed out physically from the surface. The sinking pattern of the resting stages, if formed, is influenced by stratification. This

reveals that salinity plays an important role in controlling the surface diatom populations under estuarine conditions.

These observations revealed for the first time that a bimodal oscillation trend (BOT) in the rainfall during the monsoon shifted the blooms from those of species adapted to low salinities to blooms adapted to high salinities and vice versa. Thus, the timing and magnitude of physical events like rainfall and land run-off during the monsoon is critical in the occurrence of phytoplankton blooms of different species.

It is well known that phytoplankton blooms stimulate zooplankton production and indirectly the entire food chain (Devassy et al. 1979). Synchronization of larval release with phytoplankton blooms has been observed in some invertebrates like barnacles, bivalves and echinoderms (Starr et al. 1991). A separate investigation carried out on barnacle recruitment in the study site revealed that *S. costatum* blooms could provide positive cues to barnacles (*Balanus amphitrite*) to release their larvae. However, such impulsive release of larvae during the monsoon break could be a shortsighted luxury and lead to recruitment failure (Desai 2002). It was also observed that during the *S. costatum* bloom i.e. before and after the monsoon break i.e. June and August 2000, during which highest cell counts were recorded in the present investigation, production is lower than respiration (Fig. 2.19). It may be due to grazing pressure as these blooms stimulate secondary production or the microbial loop (bacterial respiration). Among the planktivorous fishes i.e. oil sardines (*Sardinella longiceps*) and Indian mackerels (*Rastrelliger kanagurta*) form the major groups in the pelagic fishery from this region. Their stocks are influenced by several environmental parameters. It has been reported that *F. oceanica* seems to be a good indicator of the abundance of oil sardine stocks in coastal waters (Devassy 1974). The growth and abundance of these pelagic fishes are

associated with phytoplankton blooms, dominated by diatoms. In this region, diatom abundance results in higher population density of zooplankton during early post-monsoon months. The report on zooplankton community from this region indicates that copepods constitute the dominant group (Padmavati and Goswami 1996); in addition, they are the major herbivores grazing on phytoplankton blooms (Smetacek 1985, Kiørboe and Nielsen 1994). Hence, it may be possible that oscillations in rainfall during the monsoon resulting in shift of phytoplankton blooms might give differing signals to higher trophic organisms. The long-standing view that zooplankton utilize most of the phytoplankton within the surface layer has led to the implicit assumption that copepod fecal matter comprises the bulk of sinking particles (Steele 1974). Since resting cells and spores of several species have thick outer coverings that are resistant to digestion by grazers (Hargraves and French 1983), this may greatly influence food web dynamics in the euphotic zone. Such fluxes and the oscillations in the factors that influence them are critical to ecosystem functioning.