

Chapter 2

Phytoplankton community structure in a tropical,
monsoon-influenced environment

2.1. Introduction

The factors governing phytoplankton growth and dynamics can be broadly classified into growth (bottom-up) and mortality (top-down) factors. Growth factors deal with the availability of favourable physical conditions and resources (e.g., currents, light, nutrients, salinity, temperature) and have been the focus of numerous studies (Aebischer et al. 1990, Frederiksen et al. 2006, Irigoien et al. 2004, Roemmich and McGowan 1995). Mortality factors include pathogens, parasitoids and grazers (Smetacek et al. 2004) and also programmed cell death (Franklin et al. 2006).

Interactions with bacteria are one example of interactions across trophic levels that regulate phytoplankton community structure. The classification of such interactions as either bottom-up or top-down factors is ambiguous because they play various roles in the ecosystem. Firstly, bacteria are prey (resources) for several phagotrophic dinoflagellates (Jeong et al. 2008). Secondly, bacteria may either promote/retard phytoplankton growth through allelopathic interactions (Hulot and Huisman 2004). Yet, the potential of these interactions and their significance to marine ecology and trophic dynamics are still not fully understood. All these categories of regulating factors play important but different roles in structuring phytoplankton communities.

The relative significance of these regulating factors varies spatially and temporally. This is especially true in tropical environments influenced by monsoon. Monsoon events can be thought of as a disturbance, which impacts the niche opportunities available to a species in a system. This occurs either by altering the levels of available nutrients or by influencing mortality (Shea et al. 2004), through

effects on physiological processes such as cell division, and also by disorienting organisms (White 1976). The extent of nutrient inputs, dilution of the population, and the degree of turbulence in relation to the generation times of the diatoms involved are important factors to be considered. The intensity and frequency of the disturbance selects for particular 'resistant' species that will, through species succession and competitive exclusion, finally culminate in a characteristic community. The duration of the disturbance with respect to the generation times also shapes the species succession that occurs. All these factors determine the species that will survive and eventually dominate the community during and subsequent to a monsoon event.

The South West (SW) monsoon [Long term mean – 853 mm of rainfall (<http://www.tropmet.res.in>)], occurs from June to September whereas the other monsoon system affecting the Indian subcontinent, the North East (NE) monsoon, extends from October to December. The monsoons lead to a considerable input of nutrients in coastal water bodies through precipitation and run-off originating from terrigenous sources. Precipitation is accompanied by stormy weather, high wind speed and increased suspended load in the overlying waters. Cloudbursts (extreme rainfall events spanning a few minutes or hours) are sporadically reported. For example, on 26th July 2005, approximately 950 mm of rainfall was recorded over a span of eight to ten hours in Mumbai (the present study area).

Over the years, the Asian sub-continent has experienced fluctuations in the monsoon pattern. The frequency and magnitude of extreme rain events over central India from 1951 to 2000 has increased (Goswami et al. 2006). An increase in the Asian South West monsoon during the last four centuries in response to climate

change has also been reported (Anderson et al. 2002b). Such 'irregular' events, in terms of climate change, are known to affect the equilibrium between bottom-up and top-down control factors. Meserve et al. (2003) have reported that high rainfall events in semi-arid systems, caused by periodic El Niño Southern Oscillation (ENSO) events, have led to the region experiencing a trend of shifting bottom-up and top-down control. Trophic interactions are also affected, especially when the interacting components are affected differentially (Stenseth et al. 2002). In this context, it is imperative to understand the effect of fluctuating monsoon regimes on phytoplankton communities, through changes in not only bottom-up and top-down control factors, but also through interactions with bacteria.

Taking this into consideration, the changes in the phytoplankton community in a tropical, coastal environment, along the central west coast of India, was analyzed with regard to SW monsoon-driven changes in growth and mortality factors. The field observations used in the case study were carried out as part of the Global Ballast Water Management Program initiative in India.

The following questions were addressed. (1) What are the seasonal changes observed in the phytoplankton community in a tropical, monsoon-influenced environment? (2) What are the underlying ecological mechanisms involved? (3) How does anthropogenic enrichment affect the scenario? and (4) Where do interactions with bacteria fit into the suite of factors regulating phytoplankton community structure?

2.2. Materials and methods

2.2.1. Study area and sampling strategy

Samples for phytoplankton analysis were collected at Mumbai and Jawaharlal Nehru ports, along the west coast of India ($18^{\circ}54'N$, $72^{\circ}40'E$) (Fig. 2.1) as part of the Global Ballast Water Management Program initiative in India.

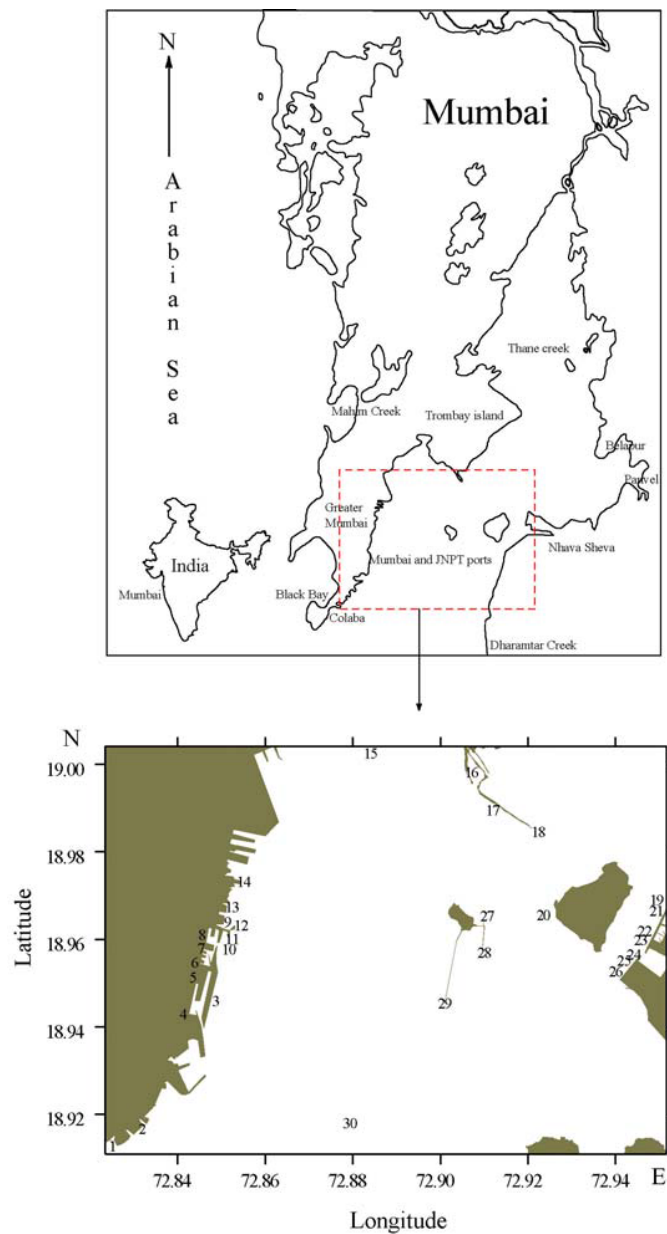


Fig. 2.1. Location of sampling stations at Mumbai and Jawaharlal Nehru Ports, India.

Sampling was conducted during two consecutive post-monsoon periods (November 2001 and October 2002) and the intervening pre-monsoon (April-May 2002). Sampling during the monsoon period was not possible due to inclement weather conditions. Thirty stations including anchorages, berths, dry docks, piers, spoil grounds and ship breaking areas were selected (Table 1). Three stations (28-30) were located offshore ($18^{\circ}47'N$, $72^{\circ}49'E$; $18^{\circ}52'N$, $72^{\circ}43'E$; $18^{\circ}57'N$, $72^{\circ}49'E$) and are not shown in Fig. 1.

Table 2.1. Details of stations in Mumbai and Jawaharlal Nehru Ports, India. JNPT, Jawaharlal Nehru Port Trust; *, depth varies with tide, values mentioned are Mean Sea Level (MSL) values

Station code	Station name	Depth (m)*
1	Sasoon Dock	6
2	Apollo Bandar	6
3	Harbour Wall Berth 20	9
4	Indira Dock 1*	10
5	Indira Dock 2*	10
6	Victoria Dock 1	8
7	Victoria Dock 2	9
8	Princess Dock 1	6
9	Princess Dock 2	6
10	Princess Dock 3	8
11	Ferry Wharf 1	6
12	Ferry Wharf 2	6
13	Kasara Basin	3
14	Break Yard	3
15	Mahul Creek	3
16	Old PirPau 1	10
17	New Pirpau 1	8
18	New Pirpau 2	11
19	JNPT Marker Buoy	12
20	Elephanta 1	11

Continued...

Table 2.1. ...Continued

Station code	Station name	Depth (m)*
21	JNPT Container Berth 1	14
22	JNPT Container Berth 2	16
23	JNPT Container Berth 3	11
24	JNPT Bulk Berth 1	10
25	JNPT Bulk Berth 2	12
26	JNPT Bulk Berth 3	11
27	Jawahar Dweep Berth 1	11
28	Jawahar Dweep Berth 3	10
29	Jawahar Dweep Berth 4	13
30	Mumbai Channel Marker Buoy	11
31	Spoil Ground Ebb	12
32	Spoil Ground Flood	18
33	Control	14

The currents in this area are semi diurnal; an average of one-third of the bay water is renewed per tidal cycle with the ingress of flood water (Patel et al. 1985). The details of tidal levels up to the period of the study are mentioned in Table 2.2.

Table 2.2. Tidal details during the period of the study.

Tide	Above (+) or Below (-) Chart Datum (m)
Highest High water recorded	+ 5.39
Mean High water spring tides	+ 4.42
Mean High water neap tides	+ 3.30
Mean sea level	+ 2.51
Mean Low water neap tides	+ 1.86
Mean Low water spring tides	+ 0.76
Lowest low water recorded	- 0.46
Highest low water	+ 2.74

The direction of the current is northeast during the flood tide and southwest during the ebb tide. Wind direction is mainly from North to West quarter; Northeasterly winds blow for a short duration during October-November, with a significant height < 1m, and with a period ranging from 3 to 5 seconds. The predominant waves are the

swell waves generated by deep sea storms, and arise just before and during the SW monsoon, which is the main source of climatic variation. The SW monsoon pattern from 2000-2005 at the Mumbai and Jawaharlal Nehru ports, is illustrated in Fig. 2.2.

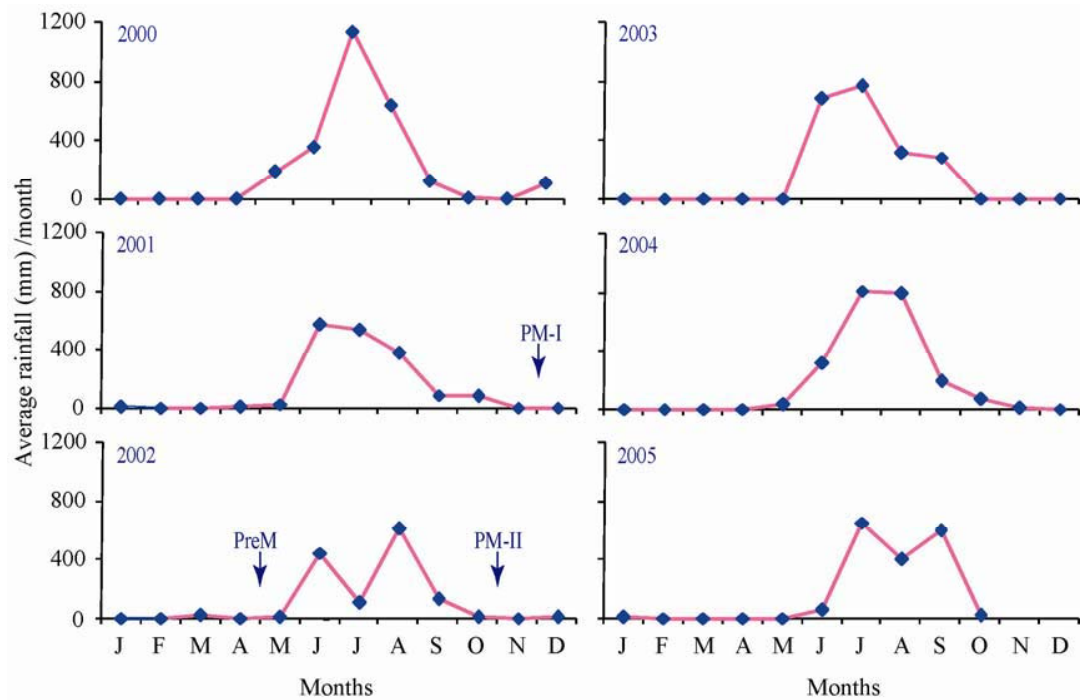


Fig. 2.2. Variation in SW monsoon from 2000 to 2005 at Mumbai and Jawaharlal Nehru ports, India. PM-I: post-monsoon I; PreM: pre-monsoon; PM-II: post-monsoon II.

These ports form a semi-enclosed basin, opening into the Arabian Sea, at the southwesterly side. They receive industrial waste from the heavily industrialized Thane-Belapur belt via the Thana Creek upstream, and also from the Dharamtar, Nhava-Sheva and Panvel Creeks on their eastern shores. The port areas are also influenced by industrial and domestic wastewater discharged in the Arabian Sea through several point sources (e.g., Mahim Creek, Back Bay in Colaba) along the west coast of Mumbai. These port areas are characterized as mesotrophic with regard to nitrate concentration. Based on the Assessment of Estuarine Trophic Status

(ASSETS) model, the present status is poor and the environment is degrading (Sawant et al. 2007).

2.2.2. Water sampling

Surface and near bottom water samples (1 L) were collected using a bucket and Niskin sampler respectively. The samples were immediately fixed with Lugol's iodine, allowed to stand undisturbed for 48 hours and concentrated to 250 mL. Aliquots of 2.5 mL, in triplicate, were analyzed using an inverted microscope, at 100 and 200 times magnification. Phytoplankton were identified based on the available literature (Desikachary and Prema 1987, Desikachary et al. 1987b, Horner 2002, Subrahmanyam 1946, Tomas 1997) and expressed as cells L⁻¹. Dinoflagellates, <25 µm, which could not be identified upto generic level, were grouped together as Unidentified Tiny Dinoflagellates (UTDs).

Water temperature, pH, suspended particulate matter (SPM), salinity, nutrient concentrations, dissolved oxygen (DO) and bacteria were analyzed following standard procedures and are published elsewhere (Sawant et al. 2007). The relevant data are considered here.

2.2.3. Sediment sampling, processing and microscopy

Sediment samples were collected, in triplicate, using 20 cm long PVC cores with an inner diameter of 2.5 cm. During the first sampling, core samples were collected by divers. But due to low light levels in the port waters and visibility problems faced by divers, a van Veen grab with a grabbing area of 0.04m² was used during the second and third sampling. The grab had windows on the top side, which allowed

collection of undisturbed sediment cores. Cores were sealed with airtight caps and stored in the dark at 4°C until analysis.

After transportation to the laboratory, sediment cores were sectioned at 2 cm intervals, mixed well and stored in airtight plastic bags at 4°C in the dark. The 0-2 cm core sections were palynologically processed (Matsuoka and Fukuyo 2000). 0.25-1.0 mL aliquots of the refined sample was diluted to a total volume of 2.5 mL in a transparent petridish (3.8 cm diameter), mixed well and placed on the microscope stage. After a settling period of 10 minutes, the entire petridish was scanned using an inverted Olympus IX71 microscope, with phase contrast attachment, at 100 and 200 times magnification. Depending on the volume of the aliquot, the refined sample was counted in duplicate or higher number of replicates such that a total of 1 mL of refined sample was analyzed. Dinoflagellate cysts were identified based on the available literature (Wall and Dale 1968, Bolch and Hallegraeff 1990, Bolch et al. 1991, Hallegraeff et al. 1991, Lewis 1991, Kokinos and Anderson 1995, Yu-zao et al. 1996, Nehring 1997, Sonneman and Hill 1997, Godhe et al. 2000, Matsuoka and Fukuyo 2000). Dinoflagellate cyst abundance was expressed as number of cysts g^{-1} dry sediment. The water content was calculated according to the formula given by Matsuoka and Fukuyo (2000). Due to the low abundance of cysts encountered, germination experiments were not carried out.

2.2.4. Data analyses

Phytoplankton display a marked heterogeneity in morphology, mode of nutrition and physiological traits. This is evident in diatoms and dinoflagellates, two different

groups of phytoplankton. Diatoms are largely autotrophic, with an ability to assimilate organic matter heterotrophically (Tuchman 1996). They are sessile organisms and are the dominant phytoplankton group in coastal waters. Dinoflagellates may be auto-, mixo- or heterotrophic; they are motile and contribute substantially to harmful algal blooms (HABs) (Anderson et al. 2002a). In view of these differences, diatoms and dinoflagellates were analyzed separately.

The various datasets (total phytoplankton, diatoms, vegetative and cysts forms of dinoflagellates) were analyzed for Shannon-Wiener diversity index (H'), Margalef's species richness (d) and Pielou's evenness (J') using PRIMER (version 5) and the variations in these determined by one-way ANOVA. One-way ANOVA was also performed on log-transformed abundance values to evaluate temporal variation (Sokal and Rohlf 1981). The contribution of individual diatom taxa/dinoflagellate groups to the respective communities are presented as SURFER plots using SURFER 7 program. The spatial variation in the diatom and dinoflagellate communities and the distribution of *Skeletonema costatum* were depicted using the SURFER 6 program. Canonical Correspondence Analysis (CCA) was performed to evaluate the relationships between diatoms, vegetative cells and cysts of dinoflagellates and environmental variables (ter Braak 1995) using the Multi-Variate Statistical Package (MVSP) program version 3.1 (Kovach 1998). Only those stations were considered for which physico-chemical variable data was available. Station and species plots were plotted separately for surface and near bottom waters. The changes in the phytoplankton community are discussed with regard to physico-chemical variables, zooplankton and bacterial abundance, data generated as part of the Global Ballast Water Management Program.

2.3. Results

2.3.1. Environmental variables

During pre-monsoon, the water column was warmer by 2°C (30°C) (Fig. 2.3a). Salinity, SPM and bacterial abundance were high compared to post-monsoon periods (Fig. 2.3b,c,e). Surface and near bottom waters were production-dominated, with average dissolved oxygen saturation values in the range of 104-106% (Fig. 2.3d). Nitrite (NO₂-N), phosphate (PO₄-P) and silicate (Si) levels dropped down considerably whereas nitrate (NO₃-N) levels were comparable to post-monsoon values (Fig. 2.3f-i). pH ranged between 7.5 and 8.1 in surface and near bottom waters.

2.3.2. Phytoplankton community

Overall, 117 species belonging to 48 genera were recorded in the water column. Phytoplankton abundance ranged from 2.7 x 10² to 1.2 x 10⁶ cells L⁻¹ in surface waters and from 2.3 x 10² to 1.3 x 10⁵ cells L⁻¹ in near bottom waters (average and standard deviation values in Fig. 2.4a). Species richness (d), Pielou's evenness (J') and Shannon-Wiener diversity (H') of the phytoplankton community in surface and near bottom waters were highest in pre-monsoon (Fig. 2.4b-d) whereas abundance was lowest (Fig. 2.4a).

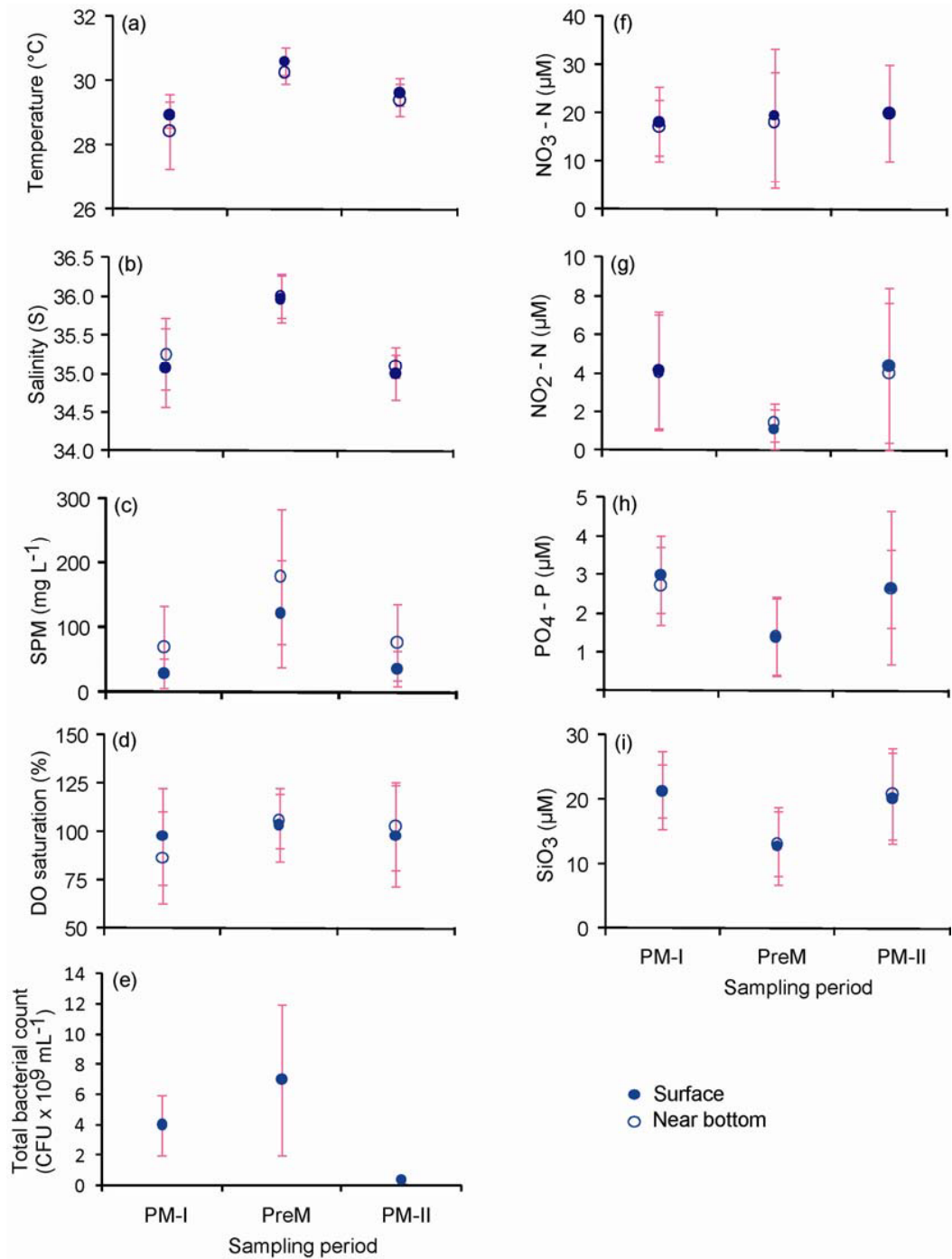


Fig. 2.3. Temporal variation in environmental variables in surface and near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. (a) temperature ($^{\circ}\text{C}$), (b) salinity (S), (c) suspended particulate matter (SPM) (mg L^{-1}), (d) DO saturation levels (%), (e) total bacterial count (CFU mL^{-1}), (f) nitrate concentration ($\mu\text{mol L}^{-1}$), (g) nitrite concentration ($\mu\text{mol L}^{-1}$), (h) phosphate concentration ($\mu\text{mol L}^{-1}$), and (i) silicate concentration ($\mu\text{mol L}^{-1}$). PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II.

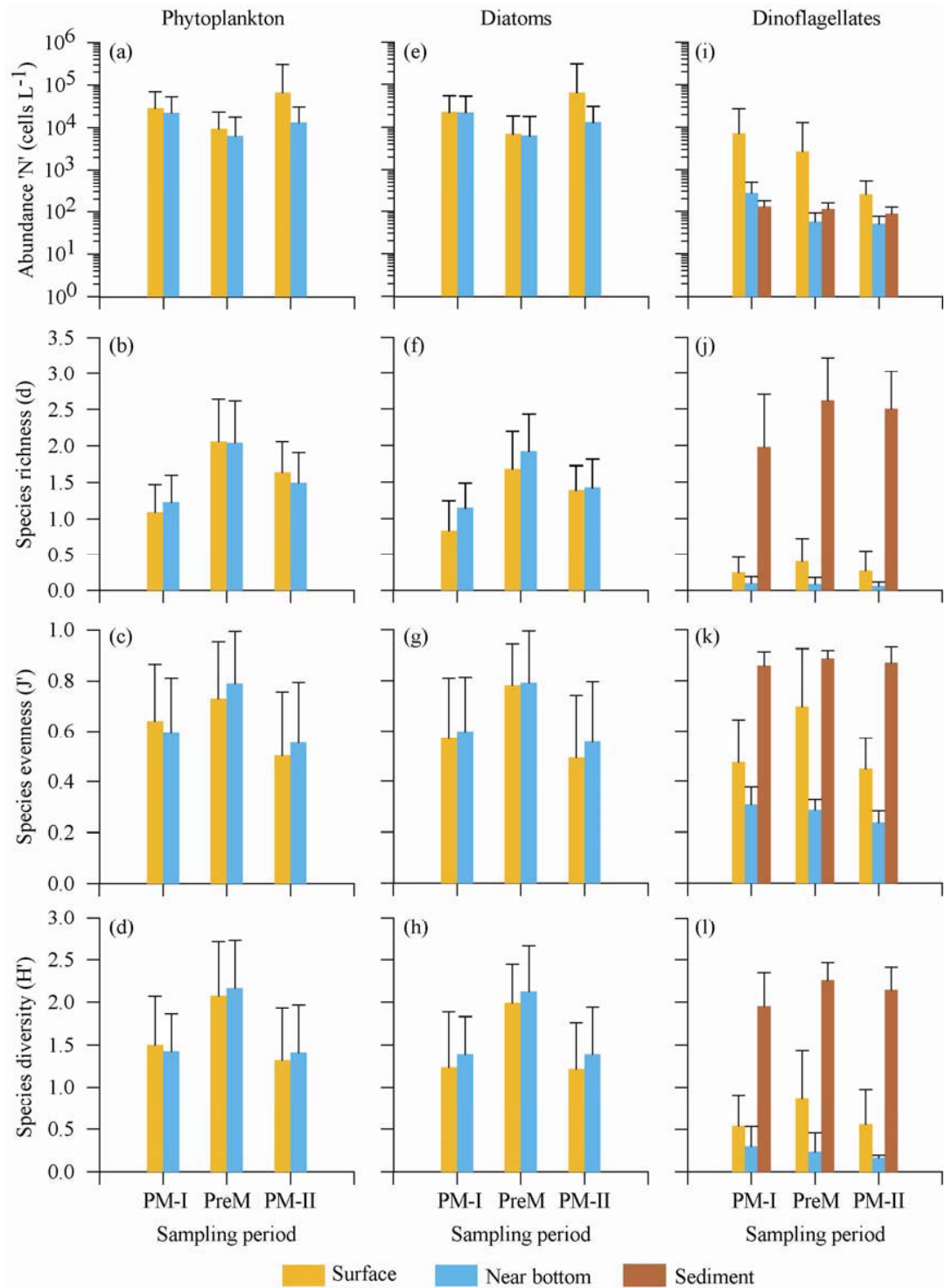


Fig. 2.4. Temporal variation in abundance (N), Margalef's species richness (d), Pielou's evenness (J') and Shannon-Wiener diversity (H') in surface and near bottom waters and sediment in Mumbai and Jawaharlal Nehru Ports, India. (a-d) phytoplankton, (e-h) diatom and (i-l) dinoflagellate communities. PM-I: Post-monsoon I, PreM: Pre-monsoon, PM-II: Post-monsoon II.

Table 2.3. One-way ANOVA to evaluate the variation in phytoplankton abundance, species richness, evenness and diversity in surface and near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. Values in bold indicate significant variation.

Factor	Surface				Near bottom			
	df	SS	MS	p-value	df	SS	MS	p-value
Phytoplankton abundance	2	2.77	1.39	0.0976	2	1.54	0.77	0.1400
Within sub-group err.	45	25.47	0.57		36	13.37	0.37	
Total	47	28.25			38	14.92		
Species richness	2	6.34	3.17	0.0000	2	4.89	2.45	0.0000
Within sub-group err.	45	8.47	0.19		36	6.32	0.18	
Total	47	14.81			38	11.22		
Species evenness	2	0.72	0.36	0.0072	2	0.55	0.28	0.0112
Within sub-group err.	45	2.95	0.07		36	1.95	0.05	
Total	47	3.67			38	2.51		
Species diversity	2	7.08	3.54	0.0007	2	5.65	2.83	0.0010
Within sub-group err.	45	18.44	0.41		36	12.00	0.33	
Total	47	25.51			38	17.65		

One-way ANOVA indicated significant temporal variation in Margalef's species richness Pielou's evenness and Shannon-Wiener diversity of the phytoplankton community in surface and near bottom waters (Table 2.3).

2.3.3. Diatom community

The changes in abundance and univariate measures of the phytoplankton community (Fig. 2.4a-d) were reflected in diatoms (Fig. 2.4e-h), which constituted 76-99% of the phytoplankton community in the water column (Fig. 2.5).

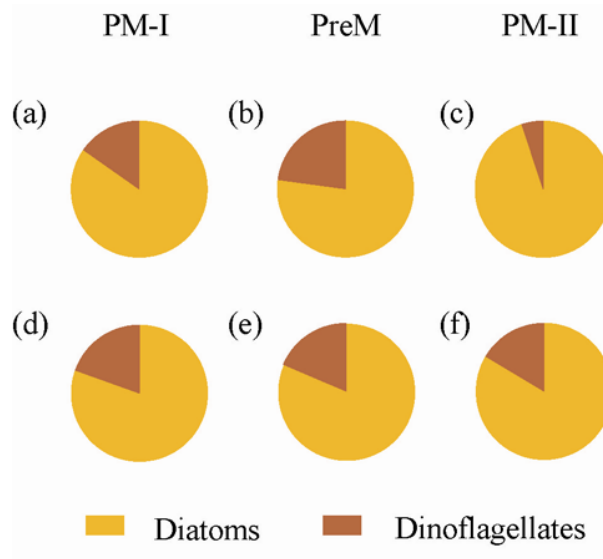


Fig. 2.5. Phytoplankton community composition in (a-c) surface and (d-f) near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II.

The maximum diatom abundance sampled was 1.2×10^6 cells L^{-1} in surface waters (Fig. 2.6a-c) and 1.3×10^5 cells L^{-1} in near bottom waters (Fig. 2.6d-f) and varied significantly in surface waters (Table 2.4). A total of 86 diatom species belonging to 35 genera (18 centric, 17 pennate) were recorded (Table 2.5). Margalef's species richness, Pielou's evenness and Shannon-Wiener diversity of the diatom community varied significantly in surface and near bottom waters (Table 2.4).

Among the genera contributing $>2\%$ to the diatom community, *Coscinodiscus*, *Cyclotella*, *Skeletonema*, *Thalassiosira*, *Triceratium*, *Pleurosigma* and *Surirella* spp. dominated in pre-monsoon (Fig. 2.7). *S. costatum* constituted 11-13% of the diatom community in pre-monsoon but dominated the diatom community in post-monsoon (approx. 42-60%) (Fig. 2.7), with very high abundance recorded at station 13 in post-monsoon I and at stations 15 and 16 in post-monsoon II (Fig. 2.8). Differences in species composition of the diatom community during the 2 post-monsoon periods

were also observed. *Thalassiosira* and *Thalassionema* spp. were most dominant during post-monsoon I whereas *Triceratium* and *Pleurosigma* spp. showed high dominance during post-monsoon II (Fig. 2.7).

Table 2.4. One-way ANOVA to evaluate the variation in diatom abundance, species richness, evenness and diversity in surface and near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. Values in bold indicate significant variation.

Factor	df	Surface			Near bottom			
		SS	MS	p-value	df	SS	MS	p-value
Diatom abundance	2	5.28	2.64	0.0289	2	1.59	0.79	0.1348
Within sub-group								
err.	45	30.92	0.69		36	13.49	0.37	
Total	47	36.20			38	15.08		
Species richness	2	4.53	2.27	0.0000	2	4.78	2.39	0.0000
Within sub-group								
err.	42	5.69	0.14		36	4.75	0.13	
Total	44	10.22			38	9.52		
Species evenness	2	1.21	0.61	0.0001	2	0.55	0.27	0.0119
Within sub-group								
err.	42	2.12	0.05		36	1.96	0.05	
Total	44	3.33			38	2.50		
Species diversity	2	8.92	4.46	0.0000	2	5.46	2.73	0.0009
Within sub-group								
err.	42	10.92	0.26		36	11.54	0.32	
Total	44	19.84			38	17.00		

2.3.4. Effect of environmental variables on diatoms

In the CCA biplots for surface waters (Fig. 2.9a,b), 3 axes explaining 70% of the relationship between diatoms and environmental variables were extracted. Temperature, salinity and SPM were the most important environmental variables influencing diatom community structure in surface waters.

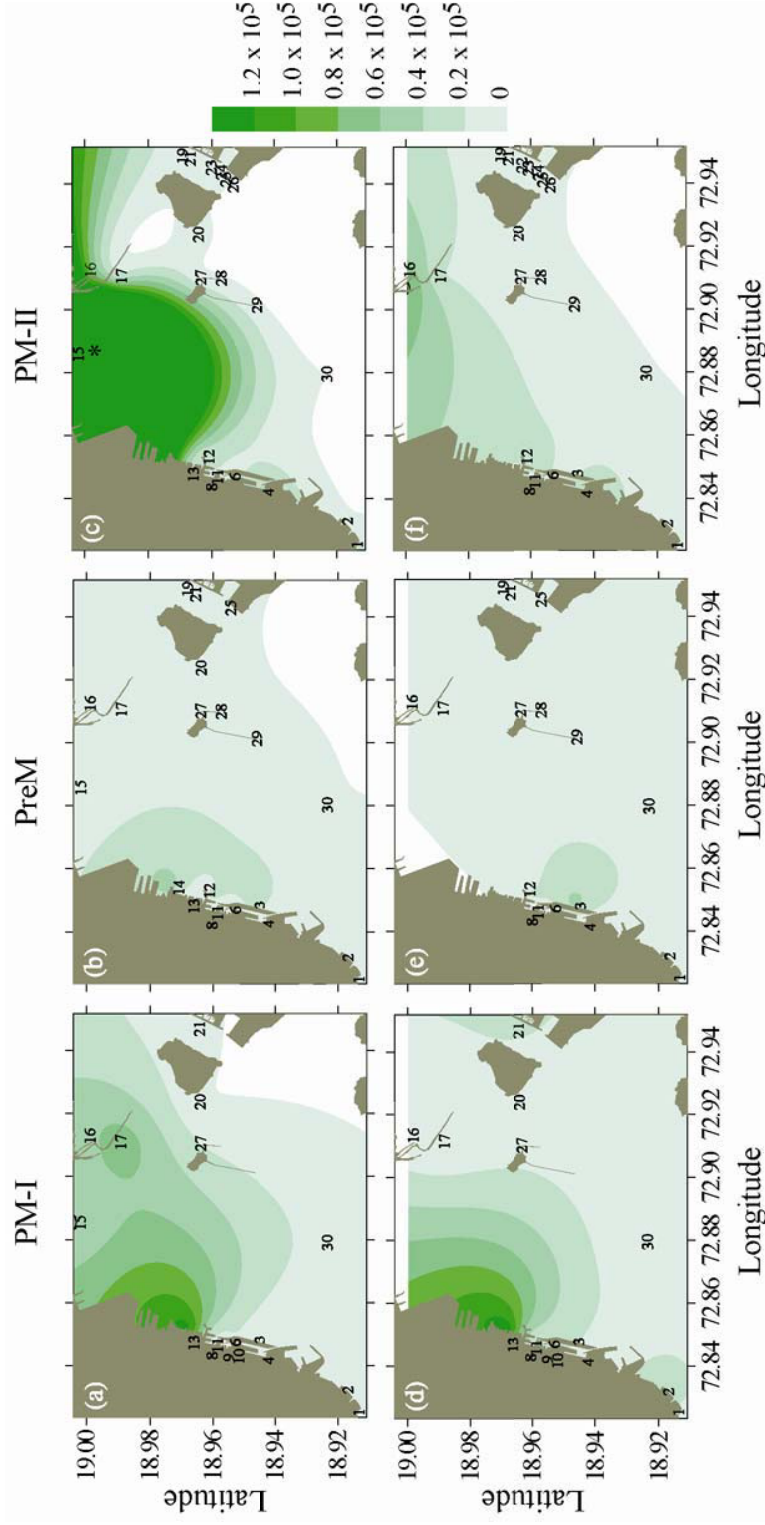


Fig. 2.6. Spatial variation in abundance of diatoms (cells L⁻¹) in (a-c) surface and (d-f) near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. Nos. 1-30 indicate the stations where sampling was carried out. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II. The asterisk at station 15 in PM-II represents 1.20 x 10⁶ cells L⁻¹.

Table 2.5. Diatoms recorded in surface and near bottom waters in Mumbai and Jawaharlal Nehru ports, India. PM-I, PreM and PM-II represent post-monsoon I, pre-monsoon and post-monsoon II sampling periods respectively. CCA codes for species are also indicated. su, surface; nb, near bottom. A, B and C represent CCA groups; NI indicates that the species were not included in the CCA analysis.

Taxon	CCA codes	CCA group (su/nb)	PM-I (su)	PM-I (nb)	PreM (su)	PreM (nb)	PM-II (su)	PM-II (nb)
Centrics								
<i>Asteromphalus</i> sp.	1	-/B		+				
<i>Biddulphia rhombus</i> (Ehrenberg) Wm. Smith	2	B/B	+	+			+	+
<i>Cerataulina bicornis</i> (Ehrenberg) Hasle	3	A/B	+	+	+	+	+	+
<i>Corethron criophilum</i> Castracane	4	B/A			+	+		
<i>Corethron</i> sp.	5	-/A				+		
<i>Coscinodiscus lineatus</i> Ehrenberg	6	A/A			+	+	+	+
<i>Coscinodiscus marginatus</i> Ehrenberg	7	B/B	+	+	+	+	+	+
<i>Coscinodiscus nodulifer</i> A. Schmidt	8	-/B						+
<i>Coscinodiscus oculus-iridis</i> Ehrenberg	9	-/A				+		
<i>Coscinodiscus radiatus</i> Ehrenberg	10	C/B	+	+	+	+	+	+
<i>Coscinodiscus</i> spp.	11	B/B	+		+	+	+	+
<i>Cyclotella caspia</i> Grunow	12	B/B			+	+	+	+
<i>Cyclotella litoralis</i> Lange & Syvertsen	13	B/A			+	+		
<i>Cyclotella striata</i> (Kutzing) Grunow	14	B/A			+	+	+	+
<i>Cyclotella stylorum</i> Brightwell	15	-/A				+		
<i>Cyclotella</i> spp.	16	B/A	+	+		+		
<i>Detonula</i> sp.	NI							+
<i>Ditylum brightwellii</i> (West) Grunow in Van Heurck	17	A/A		+	+	+		+
<i>Ditylum sol</i> Grunow in Van Heurck	18	-/A				+		
<i>Helicotheca tamesis</i> (Shrubssole) Ricard	19	A/A			+	+	+	
<i>Hyalodiscus</i> sp?	20	A/A			+	+	+	
<i>Lauderia annulata</i> Cleve	21	-/A				+		
<i>Lauderia</i> sp.	22	-/B						+
<i>Melosira nummuloides</i> C.A. Agardh	23	B/-			+		+	
<i>Odontella aurita</i> (Lyngbye) C.A. Agardh	24	C/B	+	+	+	+	+	+
<i>Odontella mobiliensis</i> (Bailey) Grunow	25	B/A	+	+	+	+	+	+
<i>Odontella regia</i> (Schultze) Simonsen	26	B/B			+	+		
<i>Odontella sinensis</i> (Greville) Grunow	27	B/A	+	+	+	+	+	
<i>Paralia sulcata</i> (Ehrenberg) Cleve	28	-/B				+		
<i>Planktoniella blanda</i> (A. Schmidt) Syvertsen & Hasle	29	-/A				+		
<i>Podosira stelliger</i> (Bailey) Mann	30	B/B					+	+
<i>Podosira</i> sp.	NI						+	
<i>Rhizosolenia alata</i> f. <i>indica</i> (Peragallo) Gran	31	B/-					+	
<i>Rhizosolenia hebetata</i> f. <i>semispina</i> (Hensen) Gran	32	B/B			+	+		
<i>Rhizosolenia imbricata</i> Brightwell	33	B/A			+	+		
<i>Rhizosolenia robusta</i> Norman in Pritchard	34	-/B						+
<i>Rhizosolenia setigera</i> Brightwell	35	B/A			+	+	+	+
<i>Rhizosolenia</i> sp.	36	-/A		+		+		

Continued...

Table 2.5. ...Continued

Taxon	CCA codes	CCA group (su/nb)	PM-I (su)	PM-I (nb)	PreM (su)	PreM (nb)	PM-II (su)	PM-II (nb)
<i>Skeletonema costatum</i> (Greville) Cleve	37	B/B	+	+	+	+	+	+
<i>Thalassiosira eccentrica</i> (Ehrenberg) Cleve	38	B/B	+	+			+	+
<i>Thalassiosira gravida</i> Cleve	39	B/-	+					
<i>Thalassiosira punctigera</i> (Castracane) Hasle	NI						+	
<i>Thalassiosira</i> spp.	40	B/B	+	+	+	+	+	+
<i>Triceratium caudatum</i> Witt	41	B/B			+	+	+	+
<i>Triceratium</i> sp.	42	C/C	+	+				
Unidentified centric spp.	43	B/B	+	+	+		+	+
Pennates								
<i>Achnanthes longipes</i> Agardh	NI		+					
<i>Achnanthes subsessilis</i> Kutzing	NI			+				
<i>Amphiprora angustata</i> spec. nov.	44	B/B	+				+	+
<i>Amphiprora</i> sp.	NI				+			
<i>Amphora coffeaeformis</i> (Agardh) Kutzing	NI			+				
<i>Amphora</i> sp.	45	-/A				+		
<i>Caloneis permagna</i>	NI					+		
<i>Caloneis westii</i> (Wm. Smith) comb. nov.	46	B/B			+		+	+
<i>Caloneis</i> spp.	NI					+		
<i>Cylindrotheca closterium</i> (Ehrenberg) Lewin & Reimann	47	B/B	+	+	+		+	+
<i>Diploneis crabro</i> Ehrenberg	48	B/A			+	+		
<i>Diploneis crabro</i> var. <i>gloriosa</i> (Grun.)	49	B/B			+			+
<i>Diploneis</i> sp.	NI			+				
<i>Grammatophora marina</i> var. <i>tropica</i> (Kutz.) Grun.	NI						+	+
<i>Grammatophora marina</i> var. <i>undulata</i> (Ehrenberg) Perag. & Perag.	NI				+			
<i>Gyrosigma balticum</i> (Ehrenberg) Cleve	50	B/-			+		+	
<i>Gyrosigma wansbeckii</i> (Donkin) Cleve	51	B/B			+		+	+
<i>Gyrosigma</i> sp.	52	C/B	+	+			+	
<i>Navicula abrupta</i>	NI			+				
<i>Navicula alpitia</i>	NI				+			
<i>Navicula directa</i> (W. Smith) Ralfs in Pritchard	53	B/A	+	+	+	+	+	+
<i>Navicula distans</i> (W. Smith) Ralfs in Pritchard	54	B/-			+		+	
<i>Navicula elegans</i> Wm. Smith	55	-/A				+		
<i>Navicula granii</i> (Jorgensen) Gran	NI				+			
<i>Navicula lyra</i> Ehrenberg	56	-/A				+		
<i>Navicula subinflata</i> Grunow	NI			+				
<i>Navicula transitans</i> var. <i>derasa</i> (Grunow, in Cleve and Grunow) Cleve	57	C/C	+	+	+	+		
<i>Navicula transitans</i> var. <i>derasa</i> f. <i>delicatula</i> Heimdal	58	B/B	+	+	+	+	+	+

Continued...

Table 2.5. ...Continued

Taxon	CCA codes	CCA group (su/nb)	PM-I (su)	PM-I (nb)	PreM (su)	PreM (nb)	PM-II (su)	PM-II (nb)
<i>Navicula</i> spp.	59	B/B	+	+	+	+	+	+
<i>Nitzschia angulata</i> Wm. Smith	60	-/B		+				
<i>Nitzschia bilobata</i> Wm. Smith	61	-/B		+				
<i>Nitzschia levidensis</i> (Wm. Smith) van Heurck	62	B/-			+			
<i>Nitzschia longissima</i> (Brebisson, in Kützing) Ralfs in Pritchard	63	C/A	+	+		+		+
<i>Nitzschia panduriformis</i> Gregory	64	B/A			+	+		
<i>Nitzschia seriata</i> Cleve	65	B/A			+	+		+
<i>Nitzschia sigma</i> (Kützing) Wm. Smith	66	B/B			+	+	+	+
<i>Nitzschia</i> spp.	67	B/A	+	+	+	+	+	+
<i>Pinnularia rectangulata</i> (Gregory) Rabenhorst	68	B/B				+	+	
<i>Pinnularia</i> sp.	69	-/B		+				
<i>Pleurosigma angulatum</i> sensu W. Smith emend. Sterrenburg	70	B/B	+	+	+	+	+	+
<i>Pleurosigma directum</i> Grunow in Cleve & Grunow	71	B/A			+	+	+	+
<i>Pleurosigma elongatum</i> Wm. Smith	72	B/B	+	+	+	+	+	+
<i>Pleurosigma naviculaceum</i> Breb.	73	B/A		+	+	+	+	+
<i>Pleurosigma normanii</i> Ralfs in Pritchard	74	B/B			+	+	+	+
<i>Pleurosigma</i> sp.	75	B/-			+			
<i>Pseudo-nitzschia delicatissima</i> (Cleve) Heiden in Heiden & Kolbe	76	B/-			+			
<i>Pseudo-nitzschia fraudulenta</i> (Cleve) Hasle	77	B/B					+	+
<i>Pseudo-nitzschia lineola</i> (Cleve) Hasle	78	B/A			+	+		
<i>Pseudo-nitzschia</i> spp.	79	B/B	+	+	+	+	+	+
<i>Surirella fastuosa</i> (Ehrenberg) Kützing	80	B/B	+	+				
<i>Surirella ovalis</i> Kützing	81	B/A			+	+		
<i>Surirella ovata</i> Kützing	82	B/B	+	+	+	+	+	+
<i>Surirella spiralis</i>	83	-/A				+		
<i>Synedra</i> sp?	84	B/B					+	+
<i>Thalassionema bacillare</i> (Heiden in Heiden & Kolbe) Kolbe	85	B/B			+	+	+	+
<i>Thalassionema frauenfeldii</i> (Grunow) Hallegraeff	86	B/B	+	+	+	+	+	+
<i>Thalassionema nitzschioides</i> (Grunow) Mereschkowsky	87	B/C	+	+	+	+	+	+
<i>Thalassionema pseudonitzschioides</i> (Schuette & Schrader) Hasle comb. nov.	88	-/B		+				
<i>Thalassionema</i> sp.	89	B/B	+	+				
<i>Thalassiothrix</i> spp.	90	B/A	+	+	+	+	+	
Unidentified pennate spp.	91	A/A			+	+	+	+

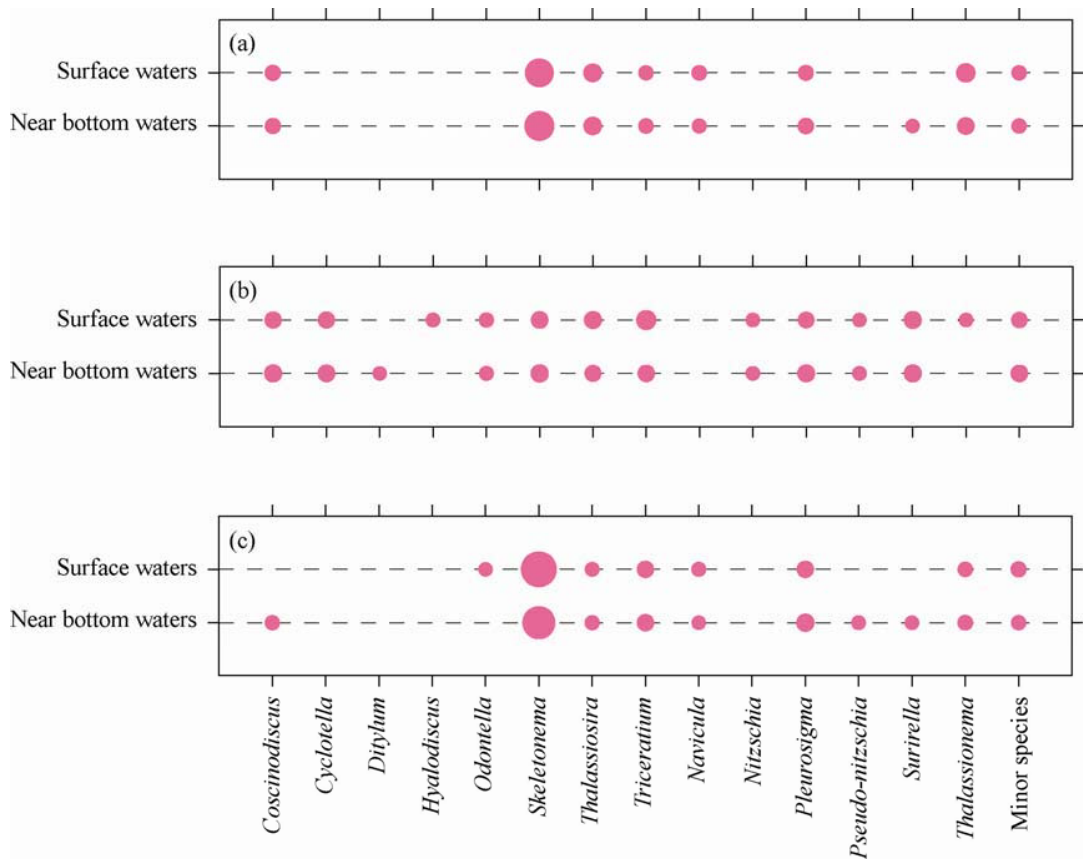


Fig. 2.7. Contribution of diatom genera (%) to the diatom community in surface and near bottom waters in Mumbai and Jawaharlal Nehru Ports, India, during (a) post-monsoon I, (b) pre-monsoon, (c) monsoon and (d) post-monsoon II. Minor species represent those that contribute < 2%. The maximum symbol diameter corresponds to 60.52%.

Three groups were recognized within the diatom community (Fig. 2.9a). Group A diatoms (*Cerataulina bicornis*, *Coscinodiscus lineatus*, *Ditylum brightwellii*, *Helicotheca tamesis*, *Hyalodiscus* sp? and unidentified pennate diatoms) showed preference for elevated salinity, SPM and dissolved oxygen saturation levels and lower concentrations of nutrients. These species were either restricted to or most abundant in the pre-monsoon period, characterized by the above environmental conditions.

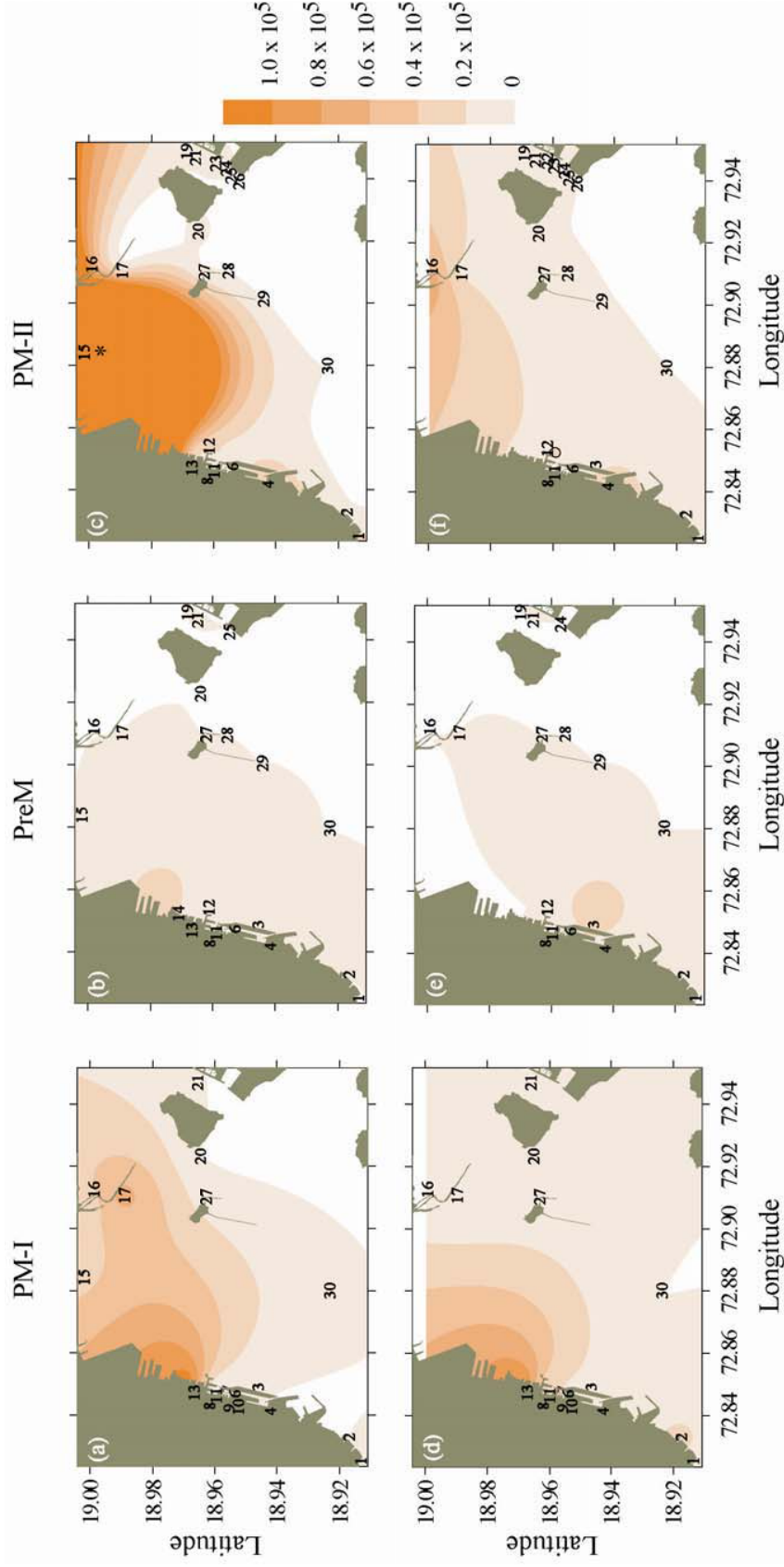


Fig. 2.8. Spatial variation in abundance of *Skeletonema costatum* (cells L⁻¹) in (a-c) surface and (d-f) near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. Nos. 1-30 indicate the stations where sampling was carried out. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II. The asterisk at station 15 in PM-II represents 1.18 x 10⁶ cells L⁻¹.

The majority of diatoms constituted Group B and preferred moderate to elevated levels of temperature. These species were most abundant in both post-monsoon periods. Group C consisted of *Coscinodiscus radiatus*, *Gyrosigma* sp., *Odontella aurita*, *Navicula transitans* var. *derasa*, *Nitzschia longissima* and *Triceratium* sp. and were either restricted to or were most abundant in post-monsoon I, indicating differences in diatom community structure during both post-monsoon periods. The difference between the two post-monsoon periods is also evident in the accompanying station biplot (Fig. 2.9b).

In the CCA biplots for near bottom waters (Fig. 2.10a,b), 3 axes explaining 73% of the relationship between diatoms and environmental variables were extracted. Temperature, salinity, dissolved oxygen saturation and nitrite concentration were the most important environmental variables influencing diatom community structure in near bottom waters. Three diatom groups could be discerned (Fig. 2.10a). Group A diatoms were associated with elevated conditions of temperature, salinity, SPM and lower concentration of nutrients, and were restricted to or most abundant in pre-monsoon period. Group B diatoms were abundant during post-monsoon II. Group C diatoms (*Navicula transitans* var. *derasa*, *Thalassionema nitzschioides* and *Triceratium* sp.) were associated with elevated nitrite concentration and lower dissolved oxygen saturation levels and preferentially occurred in post-monsoon I period. As in surface waters, the accompanying station biplot for near bottom waters (Fig. 2.10b) revealed the differences between the two post-monsoon periods.

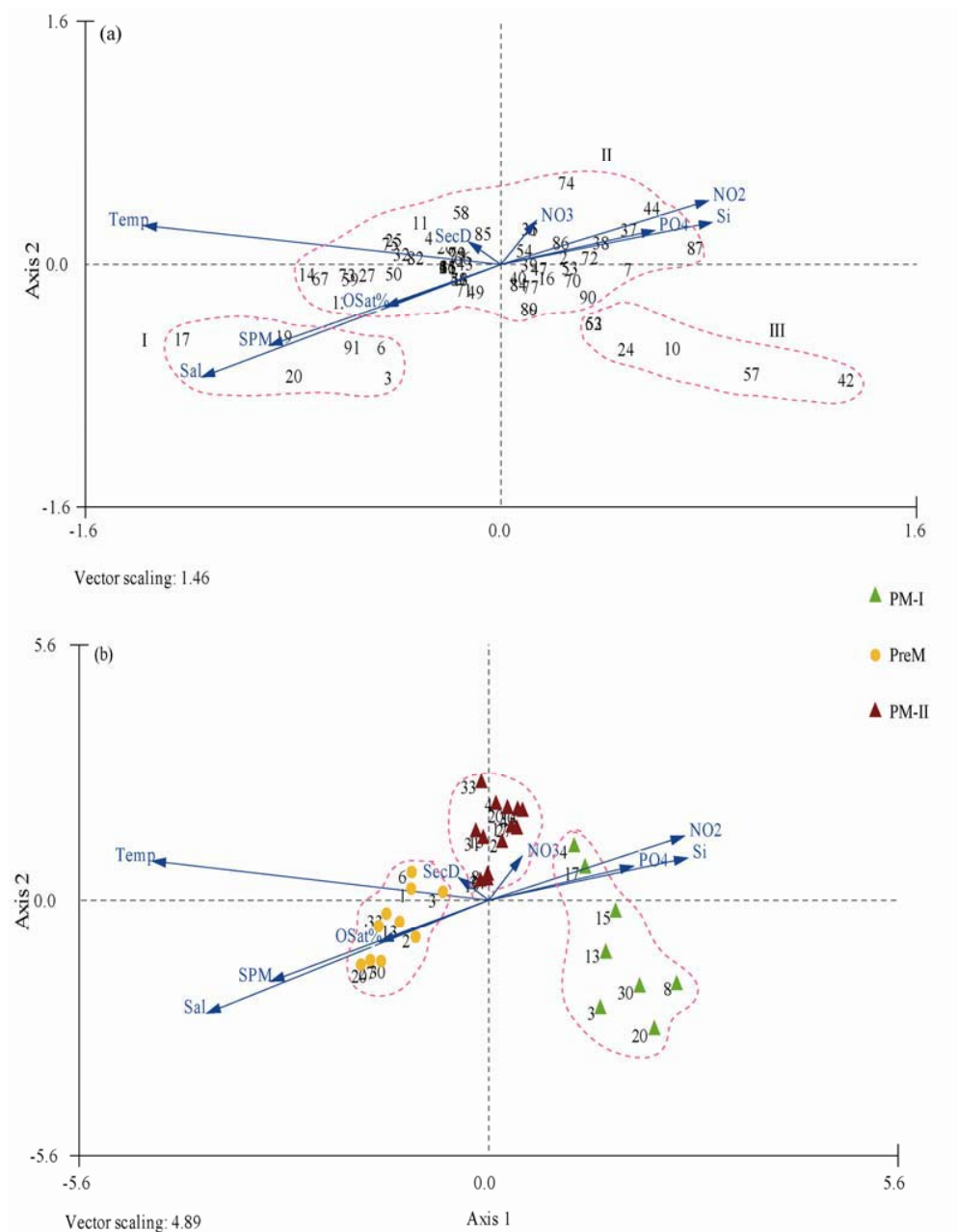


Fig. 2.9. Ordination diagrams for (a) species and (b) stations based on Canonical Correspondence Analysis (CCA) of the diatom community in surface waters. The physico-chemical variables (temperature, salinity, SPM, dissolved oxygen saturation percentage, nitrate, nitrite, phosphate and silicate) are indicated by arrows, labeled Temp, Sal, SPM, OSat%, NO₃, NO₂, PO₄ and Si respectively. General grouping of species and stations are indicated. Station codes are given in Table 2.1, species codes (nos) and grouping details are presented in Table 2.5. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II.

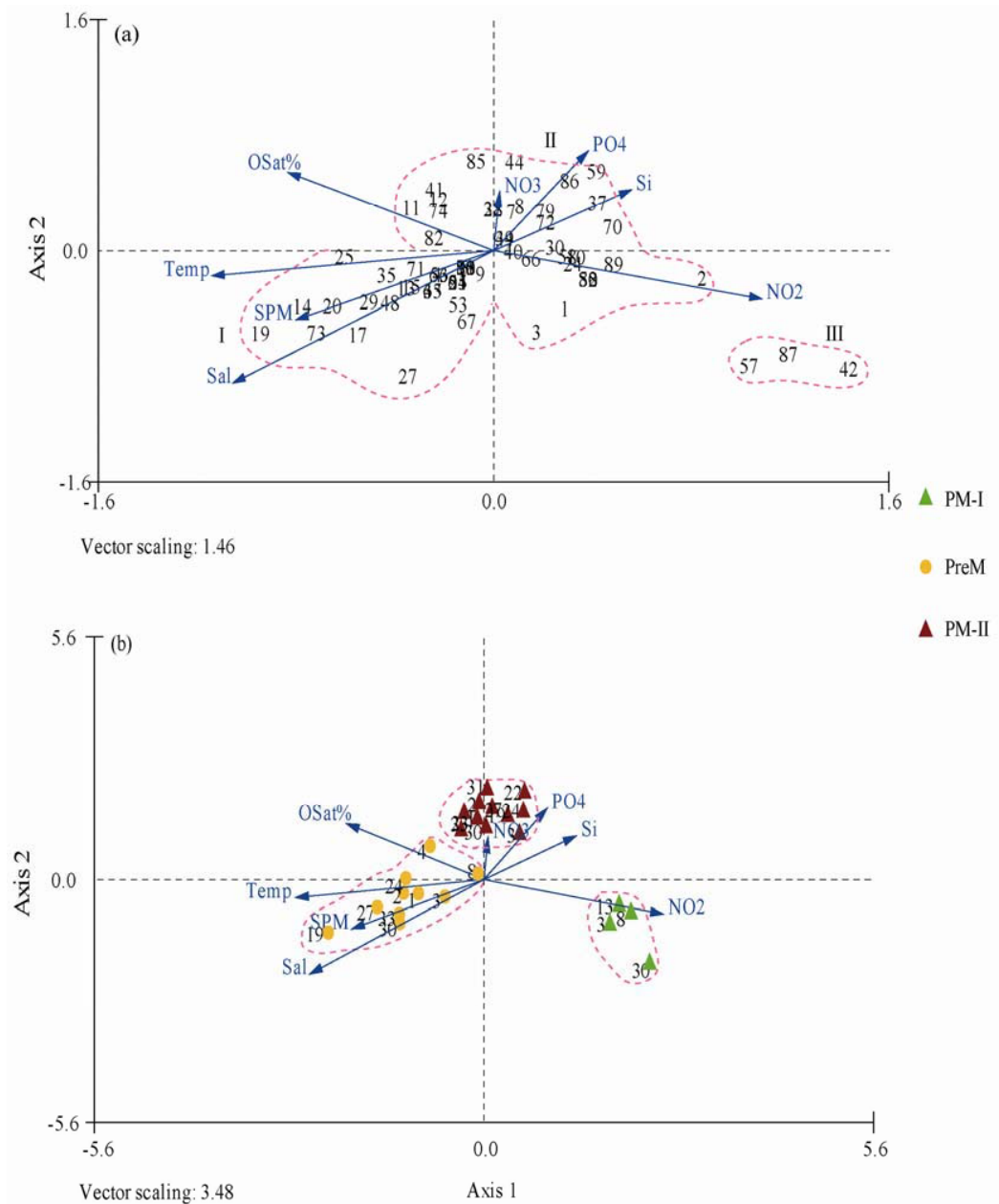


Fig. 2.10. Ordination diagrams for (a) species and (b) stations based on Canonical Correspondence Analysis (CCA) of the diatom community in near bottom waters. The physico-chemical variables (temperature, salinity, SPM, dissolved oxygen saturation percentage, nitrate, nitrite, phosphate and silicate) are indicated by arrows, labeled Temp, Sal, SPM, OSat%, NO₃, NO₂, PO₄ and Si respectively. General grouping of species and stations are indicated. Station codes are given in Table 1, species codes (nos) and grouping details are presented in Table 4. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II.

2.3.5. *The dinoflagellate community*

2.3.5a. *Planktonic dinoflagellates*

28 dinoflagellate species were observed (Table 2.6) with abundance between 0 – 8.7×10^4 cells L⁻¹ in surface waters (Fig. 2.11a-c) and 0 – 8×10^2 cells L⁻¹ in near bottom waters (Fig. 2.11d-f). Dinoflagellates were more abundant in surface waters (5-24% of the phytoplankton community) compared to near bottom waters (1-2%) (Fig. 2.5). Abundance, species richness, diversity and Pielou's evenness of the vegetative dinoflagellate community in surface and near bottom waters (Fig. 2.4i-l) did not show significant temporal variation (Table 2.7). Autotrophic dinoflagellates dominated in both post-monsoon periods whereas heterotrophs (mainly peridinioids) dominated in the pre-monsoon period (Fig. 2.12). Ceratians were restricted to the post-monsoon periods with the exception of *C. furca* that was recorded in surface waters during pre-monsoon (Table 2.6). Post-monsoon I and post-monsoon II were dominated by different dinoflagellates. Prorocentroids and gonyaulacoids predominated during post-monsoon I whereas dinophysoids and UTDs predominated during post-monsoon II. UTDs were higher in near bottom waters (39% of the vegetative dinoflagellate community) compared to surface waters (19%) during post-monsoon II (Fig. 2.12).

Table 2.6. Dinoflagellates recorded in surface and near bottom waters in Mumbai and Jawaharlal Nehru ports, India. PM-I, PreM and PM-II represent post-monsoon I, pre-monsoon and post-monsoon II sampling periods respectively. Species codes are also indicated. Su, surface; nb, near bottom. A, B and C represent CCA groups; NI indicates that the species were not included in the CCA analysis.

Taxon	Species code	CCA group (su/nb)	PM-I (su)	PM-I (nb)	PreM (su)	PreM (nb)	PM-II (su)	PM-II (nb)
Autotrophic								
<i>Alexandrium insuetum</i> Balech	AxI	B/-					+	
<i>Alexandrium</i> sp.	Axs	-/NI						+
<i>Ceratium furca</i> (Ehrenberg) Claparède & Lachmann	CerFr CerFs	B/C B/-	+	+	+		+	+
<i>Ceratium fusus</i> (Ehrenberg) Dujardin	CerK	NI/-	+				+	
<i>Ceratium kofoidii</i> Jørgensen	CerL	B/-	+					
<i>Ceratium lineatum</i> (Ehrenberg) Cleve	Cers	B/A	+	+				
<i>Dinophysis acuta</i> Ehrenberg	DyAct	B/C					+	+
<i>Dinophysis caudata</i> Saville-Kent	DyC	B/C				+	+	+
<i>Dinophysis norvegica</i> Claparède & Lachmann	DyN Dys	B/C NI/-			+		+	+
<i>Dinophysis</i> sp.					+			
<i>Dissodinium asymmetricum</i> (Mangin) Loeblich	DisA Gnxs	A/NI B/-			+	+		
<i>Gonyaulax</i> sp.			+		+			
<i>Prorocentrum compressum</i> (Bailey) Abé ex Dodge	ProC ProE	B/- A/-					+	
<i>Prorocentrum emarginatum</i> Fukuyo	ProG	A/A			+			
<i>Prorocentrum gracile</i> Schütt	ProM	B/A	+	+	+	+	+	
<i>Prorocentrum micans</i> Ehrenberg	Pros	A/NI			+	+		
<i>Prorocentrum</i> sp.	PysR	-/NI						+
<i>Pyrocystis robusta</i> Kofoid								
<i>Pyrophacus steinii</i> (Schiller) Wall & Dale	PyhS	B/-					+	
<i>Scrippsiella trochoidea</i> (Stein) Loeblich III	ScT Scs	B/NI A/-	+	+			+	
<i>Scrippsiella</i> spp.			+		+		+	
Minute thecate dinoflagellate (<i>Alexandrium</i>)	MTD(Ax)	A/-			+		+	
Minute thecate dinoflagellate (<i>Gonyaulax</i>)	MTD(Gnx)	A/B			+	+	+	
Minute thecate dinoflagellate (<i>Scrippsiella</i>)	MTD(Sc)	A/B			+	+		

Continued...

Table 2.6. ...Continued

Taxon	Species code	CCA group (su/nb)	PM-I (su)	PM-I (nb)	PreM (su)	PreM (nb)	PM-II (su)	PM-II (nb)
Heterotrophic								
<i>Gotoius abei</i> Matsuoka	GotA	A/-			+		+	
<i>Protoperidinium conicum</i> (Gran) Balech	PpC	NI/-			+		+	
<i>Protoperidinium divergens</i> (Ehrenberg) Balech	PpDi	A/B			+	+		
<i>Protoperidinium leonis</i> (Pavillard) Balech	PpL	-/B				+		
<i>Protoperidinium oblongum</i> (Aurivillius) Parke & Dodge	PpOb	A/-			+			
<i>Protoperidinium pedunculatum</i> (Schütt) Balech	PpPd	A/NI			+	+		
<i>Protoperidinium pellucidum</i> Bergh	PpPl	A/A			+	+	+	
<i>Protoperidinium pentagonum</i> (Gran) Balech	pPn	A/B			+	+		
<i>Protoperidinium cf. pentagonum</i> Gran	PpcfP	NI/-					+	
<i>Protoperidinium steinii</i> (Jørgensen) Balech	PpSt	A/A	+		+	+	+	
<i>Protoperidinium subinermis</i> (Paulsen) Loeblich III	PpSu	A/-			+			
<i>Protoperidinium</i> spp.	Pps	A/A	+	+	+		+	+
Unidentified globular dinoflagellate	UDi(g)	NI/-			+			
Unidentified tiny dinoflagellate	UTD	B/C			+	+	+	+

Table 2.7. One-way ANOVA to evaluate the variation in dinoflagellate abundance, species richness, evenness and diversity, in surface and near bottom waters in Mumbai and Jawaharlal Nehru Ports, India. Values in bold indicate significant variation.

Factor	df	Surface			Near bottom			
		SS	MS	p-value	df	SS	MS	p-value
Dinoflagellate abundance	2	1.63	0.82	0.5473	2	0.05	0.03	0.9766
Within sub-group err.	45	60.06	1.33		36	38.93	1.08	
Total	47	61.69			38	38.98		
Species richness	2	0.34	0.17	0.1390	2	0.01	0.00	0.7942
Within sub-group err.	45	3.66	0.08		36	0.49	0.01	
Total	47	4.00			38	0.49		
Species evenness	2	0.65	0.32	0.1498	2	0.04	0.02	0.8643
Within sub-group err.	45	7.34	0.16		36	5.03	0.14	
Total	47	7.99			38	5.07		
Species diversity	2	1.43	0.71	0.1088	2	0.08	0.04	0.7104
Within sub-group err.	45	13.79	0.31		36	3.98	0.11	
Total	47	15.22			38	4.06		

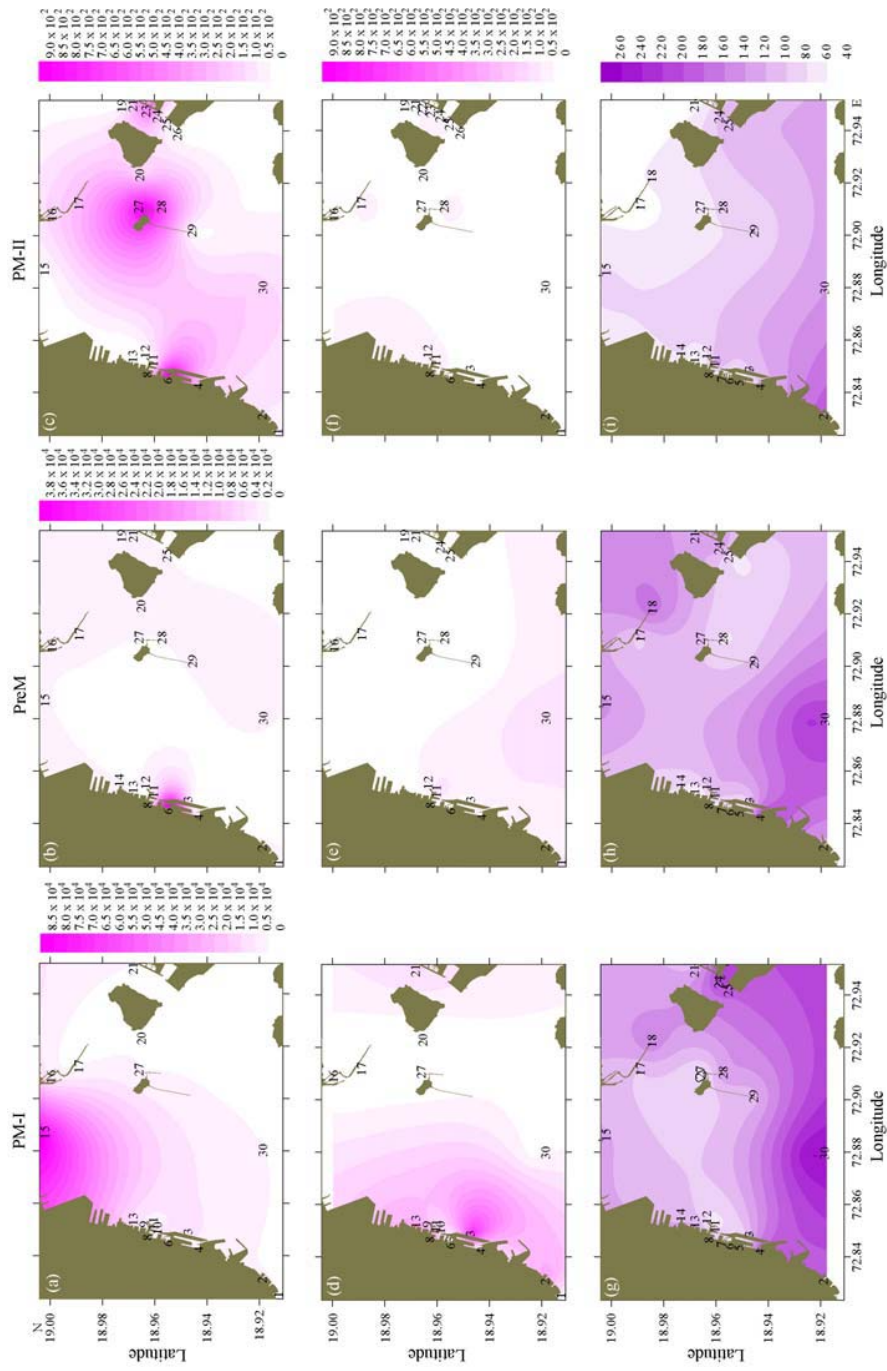


Fig. 2.11. Spatial variation in abundance of vegetative dinoflagellates (cells L⁻¹) in (a-c) surface and (d-f) near bottom waters and (g-i) dinoflagellate cyst abundance in Mumbai and Jawaharlal Nehru Ports, India. Nos. 1-30 indicate the stations where sampling was carried out. PM-I: Post-monsoon I; PreM: Pre-monsoon; PM-II: Post-monsoon II.

2.3.5b. Dinoflagellate cyst community

Dinoflagellate cyst abundance varied from 36 - 262 cysts g⁻¹ dry sediment during the entire study period (Fig. 2.4i-l). 32 species belonging to 15 genera were recorded (Table 2.8). Overall, dinoflagellate cyst abundance was low at station 5 (60±9 cysts g⁻¹ dry sediment) whereas moderate to high abundance was recorded at stations 4, 24 and 30 (162±54, 155±63 and 206±67 cysts g⁻¹ dry sediment respectively) (Fig. 2.11g-i). One-way ANOVA indicated significant temporal variation in the abundance, Margalef's species richness and Shannon-Wiener diversity of the dinoflagellate cyst community (Table 2.9).

Table 2.8. Dinoflagellate cysts recorded in sediment in Mumbai and Jawaharlal Nehru ports, India. PM-I, PreM and PM-II represent post-monsoon I, pre-monsoon and post-monsoon II sampling periods respectively. Species codes are also indicated.

Species	Species code	PM-I	PreM	PM-II
Autotrophic				
<i>Alexandrium</i> cf. <i>affine</i> (Inoue et Fukuyo) Balech	AxA		+	
<i>Alexandrium</i> cf. <i>minutum</i> Halim	AxM			+
<i>Alexandrium</i> cf. <i>tamarensis</i> (Lebour) Balech	AxT	+		
<i>Cochlodinium polykrikoides</i> Margalef	CocP	+		
<i>Gonyaulax digitalis</i> (Pouchet) Kofoid	GnxD	+	+	+
<i>Gonyaulax scrippsae</i> Kofoid	GnxS	+	+	+
<i>Gonyaulax spinifera</i> (Claparède et Lachmann) complex	GnxSp	+	+	+
<i>Gymnodinium</i> cf. <i>catenatum</i> Graham	GymC			+
<i>Lingulodinium polyedrum</i> (Stein) Dodge	LngP	+	+	+
<i>Pentapharsodinium dalei</i> Indelicato et Loeblich	PenD		+	+
<i>Pheopolykrikos hartmannii</i> (Zimmermann) Matsuoka et Fukuyo	PheH	+		
<i>Protoceratium reticulatum</i> (Claparède et Lachmann) Bütschli	PcerR	+	+	+
<i>Pyrodinium</i> cf. <i>bahamense</i> (Böhm) Steidinger	PyrBah	+	+	
<i>Pyrophacus steinii</i> (Schiller) Wall et Dale	PyhS	+	+	+
<i>Scripsiella trochoidea</i> (Stein) Loeblich III	ScT	+	+	+

Continued...

Table 2.8. ...Continued

Species	Species code	PM-I	PreM	PM-II
Heterotrophic				
<i>Diplopsalis lenticula</i> Bergh	DipL	+		
<i>Lebouraia</i> cf. <i>minuta</i> Abé	LebM	+	+	+
<i>Polykrikos</i> cf. <i>kofoidii</i> Chatton	PoK	+	+	+
<i>Polykrikos</i> cf. <i>schwartzii</i> Bütschli	PoS		+	+
<i>Protoperidinium claudicans</i> Paulsen	PpCla	+	+	+
<i>Protoperidinium compressum</i> (Abé) Balech	PpCom		+	+
<i>Protoperidinium conicooides</i> Paulsen	PpCds	+	+	+
<i>Protoperidinium conicum</i> (Gran) Balech	PpC	+	+	+
<i>Protoperidinium divaricatum</i> (Meunier) Balech	PpDiv	+	+	+
<i>Protoperidinium latissimum</i> (Kofoid) Balech	PpLa	+	+	+
<i>Protoperidinium leonis</i> (Pavillard) Balech	PpL	+	+	+
<i>Protoperidinium oblongum</i> (Aurivillius) Balech	PpOb	+	+	+
<i>Protoperidinium pentagonum</i> (Gran) Balech	PpPn	+	+	+
<i>Protoperidinium</i> cf. <i>pentagonum</i> Gran	PpcfP	+	+	+
<i>Protoperidinium subinermis</i> (Paulsen)	PpSu	+	+	+
<i>Protoperidinium</i> sp. (<i>Stelladinium robustum</i> Zonneveld)	PpcfS		+	+
<i>Protoperidinium</i> sp. (<i>Trinovantedinium palidifluvum</i> Matsuoka)	PpsT			+
<i>Zygabikodinium lenticulatum</i> (Paulsen) Loeblich et Loeblich	ZyLen		+	+

Table 2.9. One-way ANOVA to evaluate the variation in dinoflagellate cyst abundance, species richness, evenness and diversity in sediment in Mumbai and Jawaharlal Nehru Ports, India. Values in bold indicate significant variation.

Factor	df	SS	MS	p-value
Dinoflagellate cyst abundance	2	0.32	0.16	0.0090
Within sub-group err.	63	2.01	0.03	
Total	65	2.33		
Species richness	2	5.19	2.60	0.0007
Within sub-group err.	63	24.39	0.39	
Total	65	29.58		
Species evenness	2	0.01	0.00	0.2766
Within sub-group err.	63	0.16	0.00	
Total	65	0.17		
Species diversity	2	1.06	0.53	0.0031
Within sub-group err.	63	5.65	0.09	
Total	65	6.71		

Heterotrophic dinoflagellate cysts (mainly peridinioids) were observed at all stations and contributed 23-97% of the cyst population. They dominated during both post-monsoon periods whereas autotrophic (mainly gonyaulacoids) and heterotrophic dinoflagellate cysts were equally dominant during pre-monsoon (Fig. 2.12). *Protoperidinium* spp. was the most dominant heterotrophic dinoflagellate, followed by *Polykrikos* spp. (data not shown).

A characteristic seasonal cycling was observed for peridinioids. They were the dominant dinoflagellate cysts (64%) during post-monsoon I and contributed 13% and 21% of the vegetative dinoflagellate community in surface and near bottom waters respectively. During pre-monsoon, peridinioid cysts decreased to 49% whereas relative abundance of peridinioids in the water column increased to 54% (surface) and 56% (near bottom waters). During the next post-monsoon period, the peridinioids in the water column switched back to post-monsoon I levels (upto 15% and 39% respectively) with corresponding increase in their cyst abundance (67%) (Fig. 2.12).

2.3.6. Effect of environmental variables on planktonic and cyst communities of dinoflagellates

In the CCA plot for surface waters (Fig. 2.13a), 3 axes explained 67% of the relationship between vegetative dinoflagellates and physico-chemical variables. Temperature, salinity, SPM and oxygen saturation were the most important environmental variables influencing dinoflagellate community structure in surface waters. Increase in temperature, salinity and SPM were associated with decrease in concentration of nutrients (nitrate, nitrite and phosphate).

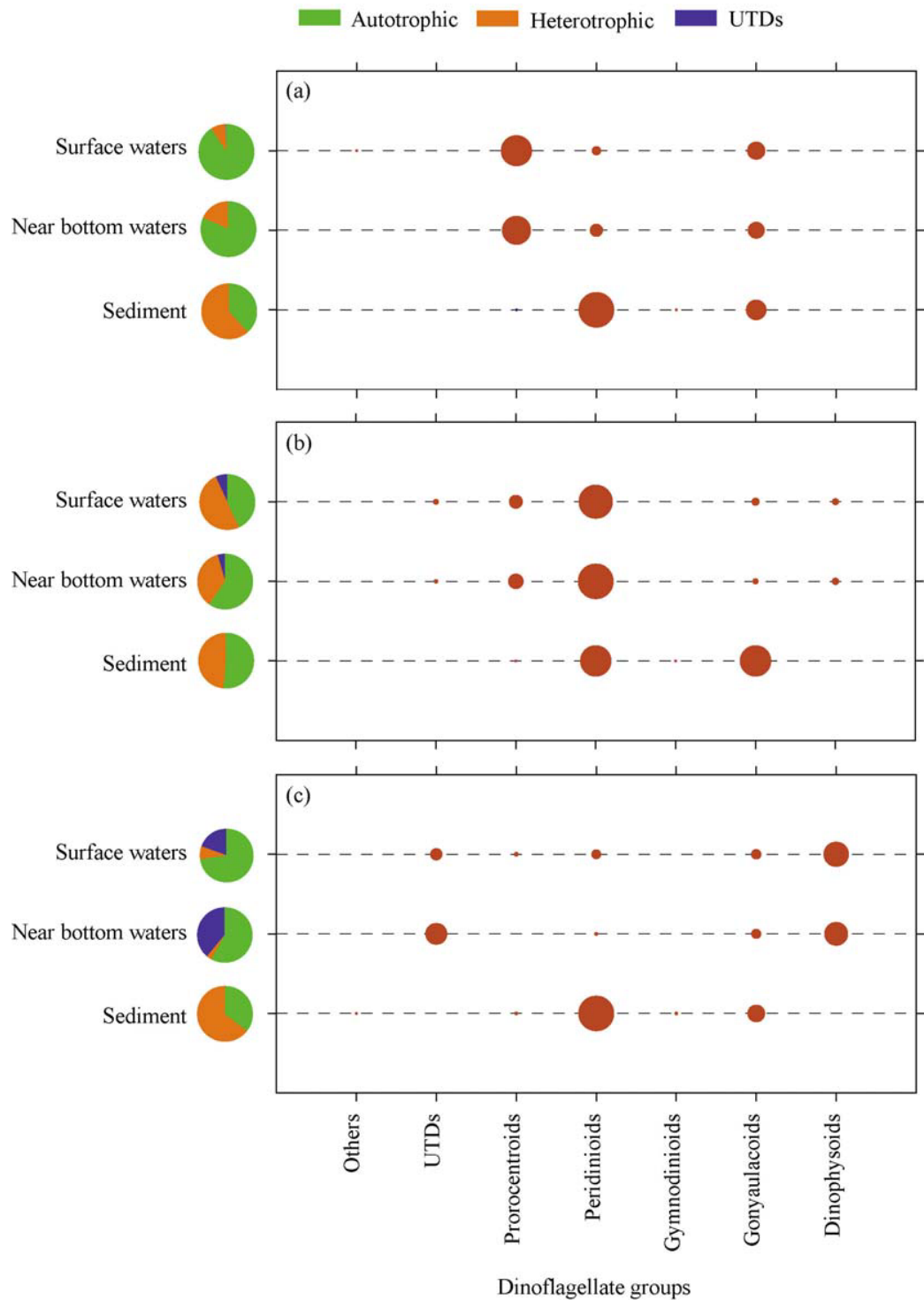


Fig. 2.12. Dinoflagellate community composition based on nutrition in the vegetative state and contribution of dinoflagellate groups (%) to the dinoflagellate community in surface and near bottom waters, and sediment in Mumbai and Jawaharlal Nehru Ports, India. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II. The maximum symbol diameter corresponds to 66.92%.

Two groups were discerned among the vegetative dinoflagellates. Group I encompassed a diverse assemblage of dinoflagellates (mainly heterotrophic forms) and showed preference for elevated temperature, salinity and SPM and lower concentration of nutrients. Most of these species dominated in the pre-monsoon period, characterized by the above environmental conditions. Group II consisted of species that preferred low temperature, salinity and SPM and elevated concentration of nutrients. These species dominated in both post-monsoon periods. Species located in the upper half of the plot in both Groups I and II preferred higher values of oxygen saturation whereas the reverse was true for the species located in the lower half of the plot. The seasonal variation in the dinoflagellate community in surface waters, evident in the species plot, was confirmed by the clustering pattern of stations in the accompanying station plot (Fig. 2.13b). However, some dissimilar stations were noticed. These included stations 2, 8, 11 and 30 during the post-monsoon II period and stations 11 and 13 during the pre-monsoon period (Fig. 2.13b). Minute thecate dinoflagellates (*Alexandrium* and *Gonyaulax*) were recorded at only the above mentioned stations during the post-monsoon II and pre-monsoon sampling (Table 2.6) resulting in these stations being dissimilar from the rest.

In the CCA plot for near bottom waters (Fig. 2.13c), 3 axes explained 70% of the relationship between vegetative dinoflagellates and physico-chemical variables. Temperature, salinity, nitrate and SPM were the most important environmental variables influencing dinoflagellate community structure in near bottom waters. Increase in salinity was associated with decrease in nitrite concentration. Nitrate, phosphate and SPM showed a positive correlation with temperature.

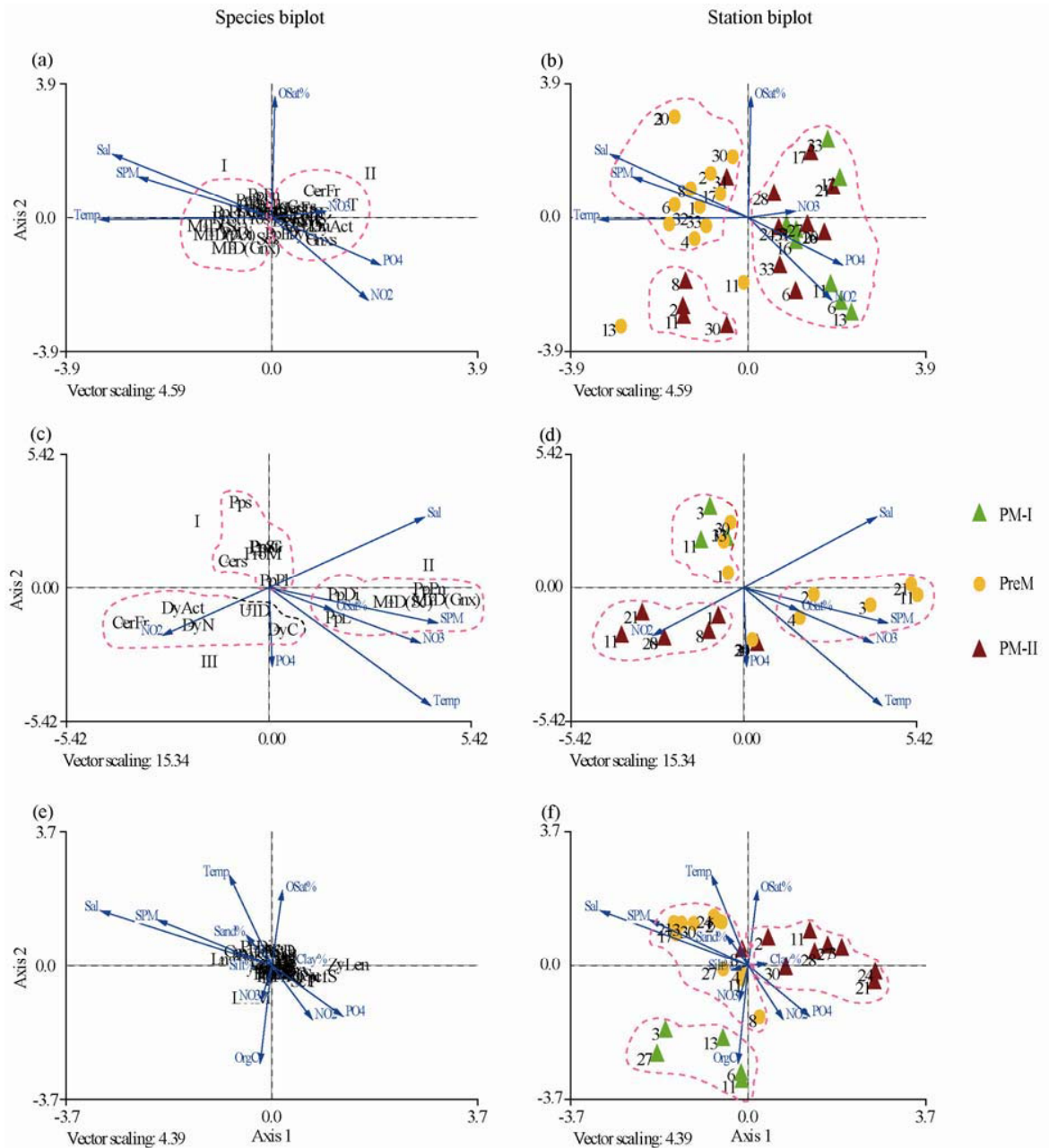


Fig. 2.13. Ordination diagrams for species and stations based on Canonical Correspondence Analysis (CCA) of the vegetative and cyst communities of dinoflagellates. The physico-chemical variables (temperature, salinity, SPM, nitrate, nitrite, phosphate, dissolved oxygen saturation percentage, sand%, silt%, clay% and organic carbon) are indicated by arrows, labeled Temp, Sal, SPM, NO₃, NO₂, PO₄, OSat%, Sand%, Silt%, Clay% and OrgC, respectively. General grouping of species and stations are indicated with a red dashed line. Station codes are given in Table 2.1, species codes and grouping details are presented in Tables 2.6 and 2.8. PM-I: Post-monsoon I; PreM: Pre-monsoon, PM-II: Post-monsoon II.

Three groups were recognized among the vegetative dinoflagellates. Group I dinoflagellate species dominated in post-monsoon I and pre-monsoon periods. These species were favoured by lower values of temperature, SPM, nitrate and phosphate. Group II, the largest group, consisted of the most dominant species in the pre-monsoon period. These species preferred elevated conditions of temperature, salinity, SPM, nitrate and phosphate. The third group (Group III) consisted of the dominant species in post-monsoon II sampling. This group preferred high concentration of nitrite and low values of salinity. The seasonal trend observed in the species plot was further confirmed by clustering together of stations sampled during each sampling period at distinct points in the station plot (Fig. 2.13d).

In the CCA plot for dinoflagellate cysts (Fig. 2.13e), 5 axes explained 83% of the relationship between dinoflagellate cysts and physico-chemical variables. Salinity, SPM, temperature and organic carbon were the most important environmental variables influencing dinoflagellate cyst community structure in sediment. Majority of the dinoflagellate cyst species were located near the centre of the ordination diagram indicating that these species were not associated with any particular environmental variable. However, some autotrophic species (*Gonyaulax digitalis*, *Lingulodinium polyedrum* and *Protoceratium reticulatum*) showed preference for high values of salinity and SPM, conditions prevalent during the pre-monsoon period, as indicated in the accompanying station plot (Fig. 2.13f). A distinct difference between the three sampling periods is clear in the station plot (Fig. 2.13f). The position of 2 heterotrophic species (*Lebouraia* cf. *minuta* and *Zygabikodinium*

lenticulatum) in the species plot correlated with the post-monsoon I and post-monsoon II periods respectively (Fig. 2.13e-f).

2.4. Discussion

During pre-monsoon, the water column was warm (30°C) and production-dominated (Fig. 2.3a,e). Salinity, Suspended Particulate Matter (SPM) and bacterial abundance were high compared to post-monsoon periods (Fig. 2.3b-c, f), whereas nutrients (except nitrate) were low. In fact, silica concentration ranged from 2.3 – 23.9 $\mu\text{mol L}^{-1}$ (Fig. 2.3d) and was above the limiting level required for diatom growth, i.e., 2 $\mu\text{mol L}^{-1}$ (Egge and Aksnes 1992). However, according to Redfield ratios, diatom growth in marine waters is limited by Si:N ratios less than 1 (Piehler et al. 2004). Si:N ratios of 1:1 and below were reported at majority of the stations in pre-monsoon whereas they peaked to much higher values during post-monsoon (approximately 2:1 and 4:1 in post-monsoons I and II respectively). These changes in nutrient concentrations and ratios were reflected in altered species composition of the diatom and dinoflagellate communities and are clearly evident in CCA species biplots (Figs. 2.9, 2.10, 2.13). Overall, temperature, salinity and SPM were the crucial environmental variables affecting diatom and dinoflagellate communities in the water column and dinoflagellate cysts in sediment. Changes in salinity, in addition to nutrient availability, affect the diatom community (Patil and Anil 2008). Temperature, salinity and light conditions (reversely correlated with SPM) affect germination of dinoflagellate cysts and thus the seasonal cycling between pelagic and benthic domains (Kremp and Anderson 2000).

Diatom abundance in surface and near bottom waters was lowest in pre-monsoon. However, univariate measures of the diatom community, namely species richness (d), Pielou's evenness (J') and Shannon-Wiener diversity (H') were highest during the same period (Fig. 2.4e-h). Similar changes in species richness and diversity parameters were also evident in the vegetative dinoflagellate community (Fig. 2.4j,l) that constituted a maximum of 24% and were largely restricted to surface waters (Fig. 2.5). These similarities in diatoms and planktonic dinoflagellates, even though both groups of organisms differ in their mode of nutrition and physiological characteristics, indicate the consistent nature of these trends across different physiological groups.

The high species richness, evenness and diversity of the diatom and planktonic dinoflagellate communities in pre-monsoon (Fig. 2.4f-h, j-l) have important consequences in terms of resistance to predation. Firstly, phytoplankton tend to be more resistant to grazing under nutrient-stressed conditions (especially P-stressed conditions, as in pre-monsoon) compared to nutrient-replete conditions (van Donk and Hessen 1993). Secondly, diverse prey assemblages have a higher chance of containing less edible species (Duffy 2002). Thirdly, high prey diversity maximizes the utilization of limiting resources in a way that facilitates recovery from the impacts of grazing. Fourthly, positive species interactions such as facilitation are often stronger and more likely to be expressed in diverse assemblages (Cardinale et al. 2002), especially when many species contribute significantly to the total community, i.e., high evenness (Hillebrand and Cardinale 2004). This holds true for the pre-monsoon period, with high evenness (0.76) compared to both post-monsoon periods (0.57). Such internal, community-led (autogenic) processes (competitive

interactions) tilt the system towards biotic interaction-driven succession (Reynolds 1980) and strengthen the organization of the system (Reynolds 1993).

Multiple diatoms (*Coscinodiscus*, *Cyclotella*, *Skeletonema*, *Thalassiosira*, *Triceratium*, *Pleurosigma* and *Surirella*) dominated in the diverse and species-rich pre-monsoon period (Fig. 2.7). These genera could possibly have favourable resource acquisition strategies (e.g., low half-saturation constants for uptake that optimize nutrient acquisition under low nutrient conditions). Using resource competition models, Huisman and Weissing (1999) have shown that oscillations and chaotic population fluctuations are generated when species compete for three or more resources. This allows many species to co-exist on just a handful of resources. In addition, these genera may also have the ability to produce allelopathic substances that allow them to survive the biotic interactions, predominant in the nutrient-poor pre-monsoon (Fistarol et al. 2005), including interactions with the same and other trophic levels.

An interesting trend was observed in the dinoflagellate component of the population. Among the planktonic dinoflagellates, mixotrophs decreased whereas heterotrophs (mainly peridinioids) increased during pre-monsoon. In the benthic environment, cysts of autotrophic and heterotrophic dinoflagellates dominated equally (Figs. 2.12, 2.14). Mixotrophic dinoflagellates (considered 'generalists' in this particular pre-monsoon scenario) are less efficient in converting food to energy. Heterotrophic dinoflagellates, considered 'specialists' due to their mode of nutrition, proliferate under the comparatively 'nutrient-poor' conditions. These changes were also reflected in the zooplankton population in the study area. Herbivorous copepods

(*Nanocalanus minor*, *Paracalanus* sp., *Temora discaudata*) decreased in abundance whereas carnivorous (*Tortanus barbatus*) and omnivorous (*Centropages furcatus*, *Oithona* sp., *Corycaeus* sp.) forms were comparatively more abundant (Gaonkar et al. 2010).

The observed increase in heterotrophic dinoflagellates (mainly peridinioids), and carnivorous and omnivorous copepods (Gaonkar et al. 2010) may be attributed to the microbial loop. This is supported by the observations of increased bacterial abundance (Fig. 2.3e) and SPM (Fig. 2.3c) in the water column, conditions typical of the warmer summer months. The microbial loop has been reported earlier in the northeastern Arabian Sea (west coast of India) where it supports the high-biomass mesozooplankton community in the oligotrophic, warm, summer months (Madhupratap et al. 1996) (corresponding to pre-monsoon in this study). The ability to ingest bacteria not only decreases competition for resources but also serves as an additional source of nutrients and energy for phagotrophs. This is particularly important under nutrient-poor conditions where the uptake of bacteria may contribute significantly to the phosphorus budget of the cell (Weithoff 2003).

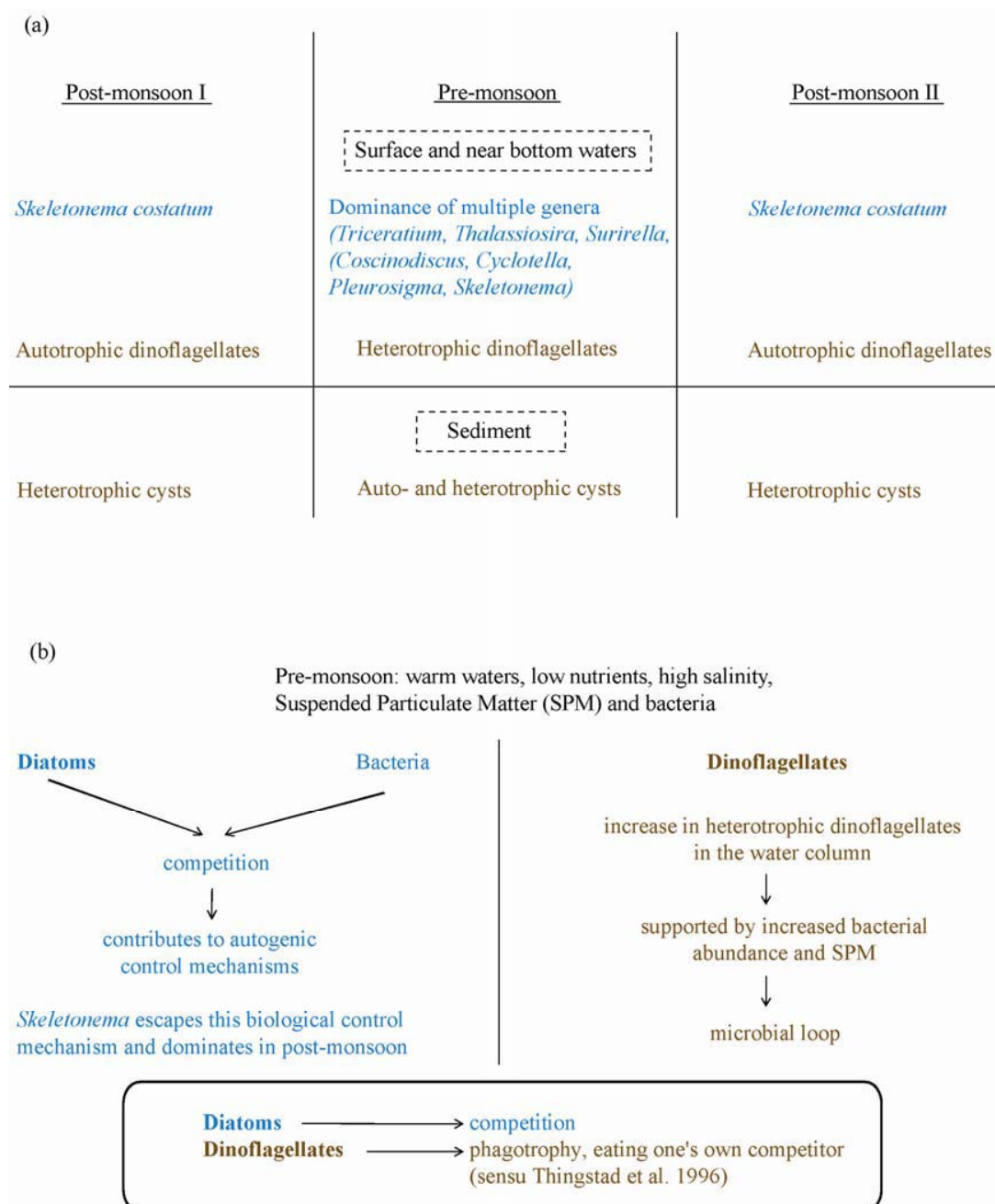


Fig. 2.14. Schematic representation of the seasonal modulations in the diatom and dinoflagellate communities in the water column and sediment in Mumbai and Jawaharlal Nehru Ports, India during post-monsoon I, pre-monsoon and post-monsoon II.

Among diatoms, *S. costatum*, an inferior competitor in the pre-monsoon period, contributed substantially to the diatom community (max. 60%) in both post-monsoon periods (Figs. 2.7, 2.8) and could be considered a keystone species. *S. costatum* is a chain-forming species, 4-12 μm in diameter, with a cosmopolitan distribution. Its blooms have been linked with monsoons and increased run-off (Lee and Kim 2008, Liu et al. 2005, Patil and Anil 2008). This species has been extensively reported in Indian waters (Madhu et al. 2006, Patil and Anil 2008). Its blooms have been observed at the onset and restart of monsoon after an intermittent break in the Zuari estuary along the west coast of India (Patil and Anil 2008); and also in the vicinity of the study area in October (post-monsoon) during consecutive years (1984 – 1985) (Tiwari and Nair 1998).

S. costatum shows large fluctuations in cell density in response to nutrient pulses (Yamamoto and Hatta 2004). It has a higher growth rate and nitrate uptake rate, and can adapt to warmer temperatures and lower salinity compared to many diatom species (Liu et al. 2005 and references therein; Mitbavkar and Anil 2000). Its ‘affinity’ for nutrients is corroborated by its occurrence in high numbers (approx. 10^5 - 10^6 cells L^{-1}) at station no. 13 (3 m depth) in post-monsoon I (Fig. 2.8a,d) and stations 15 (3 m depth) and 16 (10 m depth) in post-monsoon II (Fig. 2.8 c,f), that had comparatively higher concentrations of nitrate (upto 47.2 μM), phosphate (upto 9.5 μM) and silicate (upto 31.1 μM). It is interesting to note that *S. costatum* was conspicuously absent in pre-monsoon at all these stations, when nutrient concentrations were lower.

According to Irigoien et al. (2005), some phytoplankton species grow explosively to form dense blooms when perturbations (nutrients and light) open a ‘loophole’ in

the microbial loop. These potential ‘blooming’ species must escape predatory pressure at the critical point of entry into the loophole i.e., they have the potential to escape microzooplankton grazing. *S. costatum* produces aldehydes that affect copepod egg viability and sea urchin egg division (d’Ippolito et al. 2002). This strategy could be part of the triggering mechanism for *S. costatum* blooms in post-monsoon, i.e., nutrient pulses in the preceding monsoon period (bottom-up control) as well as escape from microzooplankton grazing (top-down control) and could be playing a far more important role in the system than previously thought.

Considering dinoflagellates, autotrophs dominated in the water column during the post-monsoon period (Figs. 2.12, 2.14). Most of them (*Prorocentrum*, *Ceratium* and *Dinophysis* spp.) were non-cyst forming and capable of mixotrophy. Mixotrophy is an important adaptation to life in planktonic habitats and increases access to growth-limiting nutrients, carbon and other growth factors. Mixotrophic organisms can sustain growth when mixed out of the euphotic zone by switching to phagotrophy. They survive better than heterotrophic dinoflagellates during periods of reduced particulate food, despite their low predation rates due to their ability to photosynthesize (Jost et al. 2004 and references therein).

There are several mechanisms by which *Skeletonema costatum* survives unfavourable conditions, in this case, the nutrient-poor, warm surface waters in pre-monsoon. Seeding by fugitive cells (Kilham and Kilham 1980) and deep-living refuge populations (Smetacek 1985) that have been transported by currents (Saravanane et al. 2000) are some of the mechanisms involved. Another survival strategy is the formation of resting stages, induced by nitrate depletion and changes in salinity (Patil and Anil 2008). Such a mechanism incorporating meroplanktic

behavior is an efficient life strategy in shallow waters (Carrick et al. 1993). Post-bloom sedimentation provides nutrient-depleted diatoms with the opportunity to take up minerals from the sediment surface and restart photosynthesis immediately after resuspension (Sicko-Goad et al. 1986). The study area with depths ranging from 3 m to 18 m, possibly supports a similar scenario, wherein monsoon-driven turbulence causes repopulation of the water column with *S. costatum* in post-monsoon.

Incidentally, resting stage formation may also be used by other diatoms that usually dominate in pre-monsoon (*Coscinodiscus*, *Cyclotella*, *Thalassiosira*, *Triceratium*, *Pleurosigma* and *Surirella*) to survive the unfavourable post-monsoon periods. *Coscinodiscus* and *Pleurosigma* are known to be tychopelagic, i.e., they inhabit both the sediments as well as the water column during their life-cycle and have been reported from both environments (Mitbavkar and Anil 2002, Patil and Anil 2008). All these genera have also been observed in sediments collected from the current study area (personal observation).

Considering dinoflagellates, cyst abundance recorded in the study area (36 - 262 cysts g⁻¹ dry sediment) was less than that reported from other areas [in the range of a few thousand cysts g⁻¹ dry sediment] (refer Cho and Matsuoka 2001 and references therein). Still, a seasonal cycling pattern between pelagic and benthic domains was very clear (Fig. 2.14). While the cyst population had consistent domination of heterotrophs (mainly *Protoperidinium* spp.) with autotrophic dinoflagellate cysts being equally dominant during pre-monsoon, the water column oscillated between autotrophic (post-monsoon) and heterotrophic dinoflagellate dominance (pre-monsoon) (Fig. 2.14). Such seasonal cycling patterns between pelagic and benthic

domains are clearly evident in peridinioids (Fig.2.12a-c) and indicate a possible annual cycling for this group of dinoflagellates. However, species-specific differences were observed in the peridinioids recorded in the water column and sediment (Tables 2.6, 2.8).

Surviving unfavourable conditions through benthic propagule formation, as speculated for diatoms and observed for dinoflagellates, is a common strategy in several phytoplankton groups. It is reminiscent of the storage effect in Intermediate Disturbance Hypothesis (IDH) terminology (Connell 1978) according to which species with low tolerance of competition, can endure unfavourable periods in a dormant life stage. This mechanism is also referred to as ‘temporal niche sharing’ wherein species coexist in the same space and use the same resources but avoid direct competition in some periods through unsynchronized life-history schedules (Shea et al. 2004).

The ecological mechanisms discussed above are useful in discerning the short-term variations in phytoplankton communities. But what about long term changes brought about by variations in the SW monsoon?

Fluctuations in the SW monsoon impact the phytoplankton community. High abundance of *S. costatum* was observed at different stations during both post-monsoon periods (Fig. 2.8). Additionally, *Thalassiosira* and *Thalassionema* spp. dominated in post-monsoon I whereas *Triceratium* and *Pleurosigma* spp. dominated in post-monsoon II (Fig. 2.7). Occurrence of characteristic diatom species in both post-monsoon periods was also evident in the CCA species biplots (Figs. 2.9, 2.10).

Among dinoflagellates, gonyaulacoids and prorocentroids dominated in post-monsoon I whereas dinophysoids and Unidentified Tiny Dinoflagellates (UTDs) dominated in post-monsoon II. Dinophysoids and UTDs were associated with low values of temperature, salinity and SPM and high nutrient concentrations in surface waters. In near bottom waters, they preferred low salinity and high concentration of nitrite, reduced form of nitrogen. *Dinophysis* spp. are associated with thermal (Delmas et al. 1992) and salinity-induced stratifications (Godhe et al. 2002). However, Nishitani et al. (2005) have recorded maximum cell densities of *Dinophysis* spp. in Mutsu Bay immediately after a storm-induced mixing event. These organisms are able to migrate through strong gradients as well and survive for long periods under unfavourable conditions (Setala et al. 2005). UTDs, the other dominant dinoflagellates in the post-monsoon II period were more abundant in near bottom waters (39% of the vegetative dinoflagellate community) compared to surface waters (19%). This feature is consistent with the higher DO saturation levels in near bottom waters (production-dominated) compared to surface waters (respiration-dominated) during the post-monsoon II period (Fig. 2.3d). This was contrary to the trend observed during post-monsoon I. In addition, bacterial abundance in post-monsoon II was also low compared to post-monsoon I (Fig. 2.3e).

The differences in dominant phytoplankton in the 2 post-monsoons reflect variations in the duration and intensity of the SW monsoon during the sampling period. In 2001, the monsoon was prolonged. It started in May, peaked during June-July and ended in October. The 2002 monsoon was erratic; it started in June, dipped sharply in July (monsoon break), and ended in September (Fig. 2.2). These changes

were reflected in physico-chemical variables, bacterial abundance and grazing pressure. Contrary to the trend in post-monsoon I, DO saturation levels in near bottom waters were higher (production-dominated) than in surface waters (respiration-dominated) in post-monsoon II (Fig. 2.3d). Bacterial abundance was low in post-monsoon II compared to post-monsoon I (Fig. 2.3e). Differences in the copepod population were also observed. *Microsetella* sp. and *Oncea* sp. were absent in post-monsoon I; *Acartia centrura* and *Nanocalanus* sp. were absent in post-monsoon II (Gaonkar et al. 2010).

This study spanning two monsoon events, revealed differences in the phytoplankton community subsequent to two differing monsoon events. However, fluctuations in the SW monsoon, both long-term and short-term, have been observed (Anderson et al. 2002b, Goswami et al. 2006). In the study area, maximum rainfall (up to 1200 mm) was recorded in the year 2000 (Fig. 2.2). In the subsequent years, maximum rainfall was much lower (in the range of 500-800 mm). The SW monsoon pattern also varied over the years (Fig. 2.2). As mentioned in the introduction, a cloudburst occurred on 26th July 2005 wherein approximately 950 mm of rainfall was recorded over a span of eight to ten hours. This is not reflected in Fig. 2.2 that takes into account the average rainfall for each month.

The nature of monsoon fluctuations, whether press (sustained) or pulsed (relatively instantaneous), is very important, as both have different effects on communities. Communities usually adapt to a gradual change in conditions, i.e., pressed perturbations, with corresponding gradual changes in structure and function. However, it is possible that at some critical point, they may collapse and form a completely new system (Shea et al. 2004). Thus, in fluctuating environments, the

rate of environmental change (fluctuations) is more important than its magnitude, known as the critical-rate hypothesis (Scheffer et al. 2008).

Several studies (documented in Heil et al. 1998) have reported diatom blooms after anomalous rainfall and run-off events. However, such effects depend on the resilience of the system. Two factors affecting the resilience of the system need to be considered here: (1) intra-annual variability in resilience of the system; and (2) the mesotrophic nutrient status of the study area. Concerning the former, post-monsoon periods are less diverse compared to pre-monsoon, and dominated by *S. costatum*, that shows “boom-and-bust” population cycles in response to resource availability. Such synchronization of population cycles heightens the susceptibility of the system to disturbance (Stachowicz et al. 1999). Concerning the mesotrophic nutrient status of the study area (Sawant et al. 2007), the increase in nitrate concentration and corresponding decrease in DO observed over the years, further compromises the resilience of the system. Already, signals of elevated nutrient conditions have been observed in the dinoflagellate cyst community in sediment. Cysts of heterotrophic dinoflagellates, mainly *Protoperidinium* followed by *Polykrikos*, were abundant in the study area, suggesting nutrient-rich conditions and abundance of prey organisms (Harland et al. 2006).

Presently, the study area is characterized by bloom-like conditions of *S. costatum* at some stations along the coast in post-monsoon and a diverse phytoplankton assemblage in pre-monsoon. The abundance of *S. costatum* decreases in the nutrient-poor pre-monsoon as it is sensitive to a dip in nutrient concentrations. It is tempting to speculate whether continuing nutrient enrichment in the study area will alter the dynamics of *S. costatum*, especially since it is a better competitor than many diatoms

under eutrophication conditions (Liu et al. 2005). Additionally, if nutrient concentrations increase above a certain threshold value, will *S. costatum* dominate throughout the year? This aspect can be addressed only through long-term studies in the study area. However, it is evident that anthropogenic enrichment has the potential to confound the effects of variations in the SW monsoon on the population dynamics of *S. costatum*, particularly the exact point of entry into the loophole, as suggested by Irigoien et al. (2005), and must be considered in future studies. This is especially important in view of the consequences for trophic dynamics, as many intermittently-breeding invertebrates like bivalves, interpret *Skeletonema* blooms as signals for release of their larvae. Thus, the effects of fluctuating monsoon regimes on diatom communities will ripple through higher trophic levels as well.

Summarizing the results, though several studies on phytoplankton communities from this monsoon-influenced region exist, very few have attempted to unravel the underlying ecological mechanisms in addition to species distribution patterns. This study emphasizes the relevance of incorporating ecological mechanisms into studies on phytoplankton dynamics. This approach provides valuable insights into the allogenic/external pathways (driven by environmental variables) and autogenic, internally-driven biotic interactions that regulate diatom and dinoflagellate communities. Biotic interactions appear to be most relevant in the nutrient-poor pre-monsoon period, characterized by high species richness, evenness and diversity but low abundance.

The role of bacteria (an example of an autogenic interaction) in modulating diatom and dinoflagellate communities differs. In case of diatoms, bacteria are probably

important as competitors for nutrients in the pre-monsoon period. Presumably, they also function as a biological 'control' mechanism (sensu Irigoien et al. 2005), which diatoms must escape to bloom to large numbers, as in the case of *Skeletonema costatum* in the post-monsoon period. In case of dinoflagellates, the increase in heterotrophic dinoflagellates in the water column in the pre-monsoon period may be supported by increased bacterial abundance and SPM (the microbial loop). In this manner, while the interactions of bacteria with diatoms are largely restricted to competitive/autogenic mechanisms, dinoflagellates have gone a step further. They have evolved phagotrophy, a means of eating one's own competitor (sensu Thingstad et al. 1996). In view of this, interactions of diatoms and dinoflagellates with bacteria must be given due attention in future studies on phytoplankton community structure, especially in response to monsoon-influenced changes and anthropogenic enrichment.