

Chapter 2

*Spatio-temporal variation in surface water
dinoflagellates in the Bay of Bengal*

2.1. Introduction

In the contemporary ocean, large scale estimates of phytoplankton biomass and its production is possible with remote sensing of ocean color monitoring. These studies indicate climatic-driven changes in phytoplankton biomass and production (Behrenfeld et al. 2006, Doney 2006). It is also important to understand the taxonomic and physiological components of these changes (Doney 2006). This points to the need for studies on spatial and temporal variation in phytoplankton community structure. The taxonomic database of phytoplankton will not only help to understand the above query, but also to understand Harmful Algal Bloom (HAB) related problems (Hallegraeff 2010).

HABs are natural phenomena; historical records indicate their occurrence long before the advent of human activities in coastal ecosystems. Recent surveys have demonstrated a dramatic increase and geographic spread in HAB events in the last few decades (Anderson 1989, Smayda 1990, Hallegraeff 1993). Thus, knowledge of the present geographic distribution and seasonal fluctuations in HAB species is important to understand globally spreading HAB events (GEOHAB 2001). In fact, Hallegraeff (2010) has reported that unpreparedness for such significant range expansions or spreading of HAB problems in poorly monitored areas will be one of the greatest problems for human society in the future.

Among the total marine phytoplankton species, approximately 7% are capable of forming algal blooms (red tides) (Sournia 1995). Dinoflagellates are the most important group producing toxic and HABs (Steidinger 1983 and 1993, Anderson

1989, Hallegraeff 1993) accounting for 75% of the total HAB species (Smayda 1997).

The causative factors for such blooms, results from a coupling mechanism involving physical, chemical and biological factors, whereas the role or mechanism of chemical and biological factors are now reasonably understood (Fistarol et al. 2004, Solé et al. 2006, GEOHAB 2006, Adolf et al. 2007, Waggett et al. 2008). However comparable understanding about physical factors is lacking except for few examples (Maclean 1989, Karl et al. 1997, Belgrano 1999, Yin et al. 1999). Impacts of these factors in combination with local inter-annual meteorological conditions will vary from one geographical location to the other and will thus influence bloom dynamics differentially.

HAB studies in Indian waters indicate reasonable reports on HABs and their impacts along the west coast of India. Direct impacts of HABs on human health have also been reported from Mangalore (Karunasagar et al. 1984). Dinoflagellate toxins have also been recorded in shellfish from surrounding estuaries near Mangalore in 1985 and 1986 (Segar et al. 1989). Planktonic and cyst forms of *Gymnodinium catenatum*, a PSP-producing dinoflagellate from this region were detected later on (Godhe et al. 1996) and the importance of close monitoring of coastal waters, sediment and shellfish was highlighted.

Compared to the above regions, the Bay of Bengal (BOB), the eastern arm of the Indian Ocean, remains relatively unexplored in the context of HAB studies. The BOB is known for its unique characteristic features: large volume of freshwater input from

river discharge and rainfall, warmer sea surface temperatures, monsoonal clouds and reversal of currents. The riverine input into this area injects loads of nutrients and suspended sediment in the BOB (Gordon et al. 2002, Mukhopadhyay et al. 2006). These features point to the suitability of the BOB as a zone prone for algal blooms including HAB events. However, the strongly stratified surface layer of the BOB restricts the transport of nutrients from deeper layers to the surface (Prasanna Kumar et al. 2002). Thus, it is very interesting to understand the seasonal variations in dinoflagellate community structure in this inimitable geographic region.

Therefore, the present study, the first of its kind from the region, was undertaken to elucidate the spatial and temporal distribution of dinoflagellates in the BOB, with emphasis on HAB species. To do so, taking oceanic cruises on regular intervals is not cost-effective. Thus, the ‘ships-of-opportunity’ programme, supported by the Indian Expendable Bathythermograph (XBT) project, was used in the present study. The following objectives were addressed. (1) Dinoflagellate distribution in the surface waters of the BOB and (2) Detailing of the HAB species present and their seasonal occurrence.

2.2. Materials and Methods

2.2.1. Study area and sampling

This study was conducted with the support of the XBT programme. Surface water samples were collected using steel buckets from the moving ship. This method was selected in order to minimize the physical damage to cells compared to the method of

collecting samples using a pump. A similar approach was used by Smetacek et al. (2002). The samples were collected on 2 transects [Chennai to Port Blair (CP, 12

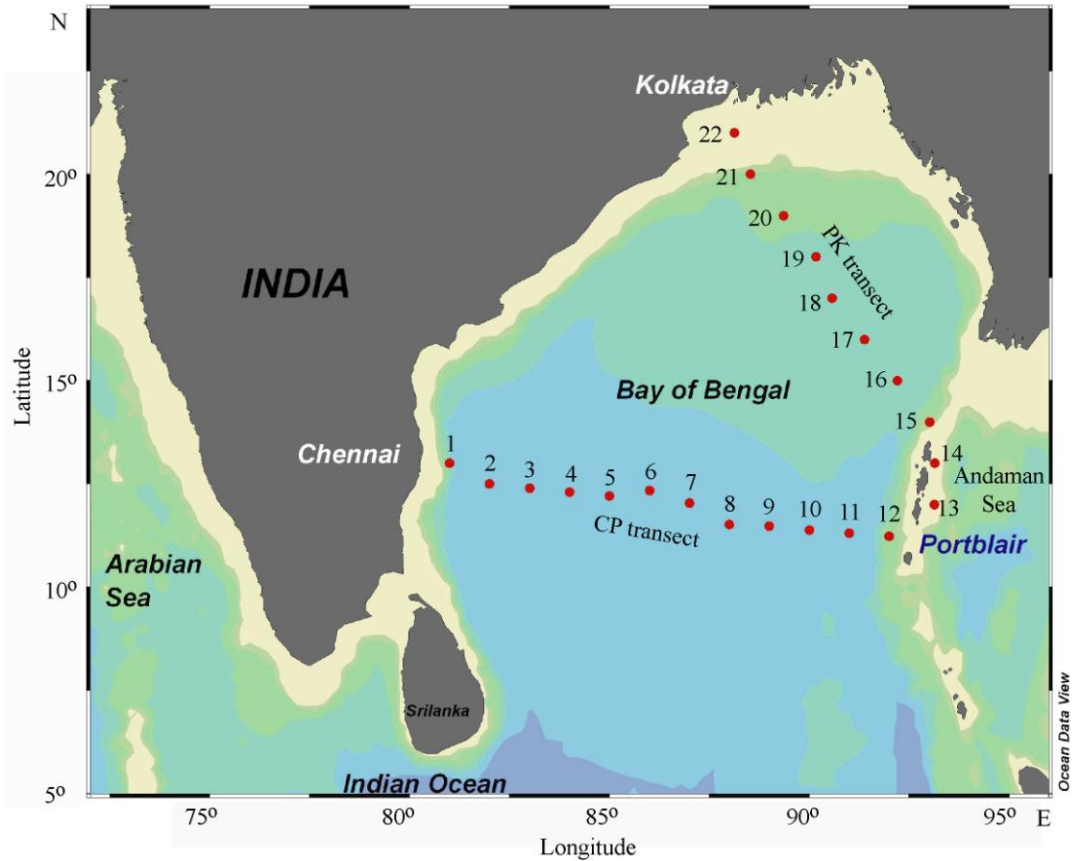


Fig. 2.1. Study area map showing station locations along the Chennai-Port Blair (CP) and Port Blair-Kolkata (PK) transects in the Bay of Bengal.

stations) and Port Blair to Kolkata (PK, 10 stations)] (Fig. 2.1), from passenger ships plying along these transects. Samples were collected at one degree intervals along both transects, from November 2003 to September 2006 covering different seasons. 1L of sample was fixed with Lugol's iodine solution for the microscopic enumeration and identification of dinoflagellates to the lowest possible taxonomic level.

2.2.2. Microscopic analysis

Samples (1L) were brought down to 10 mL final concentration by the settling and siphoning technique. Three mL of the concentrated sample was taken in a petri dish and examined under an Olympus inverted microscope at 100X to 400X magnification. Identification of the dinoflagellate taxa was carried out using the keys provided by Subrahmanyam (1968), Taylor (1976), Tomas (1997), Horner (2002) and Hallegraeff (2003).

2.2.3. Data analyses

To evaluate seasonal differences, the observational period was classified into three seasons: Pre-Monsoon (PrM – February-March 04), South West Monsoon (SWM – June 04, July 04, August 04, September 06) and Post-Monsoon (PoM – November 03, October 04).

Univariate measures [Shannon-Wiener diversity index (H'), Margalef's species richness (d) and Pielou's evenness (J')] were analyzed using PRIMER (version 5) and the variations in these were determined by two-way ANOVA. Two-way ANOVA was also performed on the $\log(x+1)$ -transformed dinoflagellate abundance data to evaluate spatial and temporal variation (Sokal and Rohlf 1981). Spatial variation in the dinoflagellate community and the abundance profiles of the five most dominant taxa during each sampling period in both transects are presented as SURFER plots using the SURFER 8 program. The percentage contribution of autotrophic,

mixotrophic and heterotrophic forms of dinoflagellates in each sampling period was also calculated and is presented as pie charts.

2.3. Results

2.3.1. Dinoflagellate assemblages

A total of 134 species of dinoflagellates were recorded in surface waters of the BOB during the observation period (Table 2.1). Dinoflagellate abundance ranged from 0 – 94 cells L⁻¹ throughout the observation period at both CP and PK transects (Fig. 2.2). Further grouping of these identified species based on their nutritional mode, revealed 40 autotrophic, 50 mixotrophic and 44 heterotrophic species, indicated the dominance of mixotrophic forms (Table 2.1). Autotrophic dinoflagellates ranged from 0 – 58 cells L⁻¹ (Fig. 2.3), mixotrophic dinoflagellates from 0 – 48 cells L⁻¹ (Fig. 2.4) and heterotrophic dinoflagellates from 0 – 60 cells L⁻¹ (Fig. 2.5), in both transects.

2.3.2. Spatial and temporal variation in dinoflagellate assemblages

Overall, the dinoflagellate assemblages did not show any significant spatial variation in abundance, species evenness, richness and diversity measures. The only exceptions were species richness and diversity in the PK transect (Table 2.2). Significant seasonal variation in dinoflagellate abundance was observed in the CP transect. Species richness and diversity varied significantly in the PK transect;

Table 2.1. Dinoflagellates observed during the study period along the Chennai-Port Blair (CP) and Port Blair-Kolkata (PK) transects (* potential HAB species, † new reporting). The values outside the bracket indicate the abundance range and values inside the bracket indicate the frequency of occurrence at CP (12 stations) and PK (10 stations) transects.

Dinoflagellates	CP transect						PK transect					
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06	Nov 03	Mar 04	Aug 04	Oct 04	Sep 06		
Autotrophic												
<i>Alexandrium concavum</i>		0-2 (1)	0-2 (2)		0-9 (1)			0-2 (1)	0-20 (1)	0-6 (1)		
<i>Alexandrium</i> spp.					0-12 (10)			0-8 (2)	0-5 (1)	0-9 (8)		
<i>Amphidinium</i> sp.*	0-7 (5)	0-2 (1)	0-2 (1)	0-5 (3)				0-2 (1)		0-9 (3)		
<i>Amphisolenia bidentata</i>		0-2 (2)	0-8 (7)	0-3 (1)	0-3 (3)					0-3 (2)		
<i>Amphisolenia globifera</i>										0-3 (1)		
<i>Blepharocysta</i> sp.		0-4 (2)	0-4 (3)	0-8 (2)				0-4 (5)	0-8 (6)			
<i>Ceratocorys armata</i>	0-2 (1)						0-2 (1)					
<i>Ceratocorys horrida</i>		0-4 (2)		0-3 (1)		0-2 (2)						
<i>Corythodinium constrictum</i>		0-2 (1)					0-4 (2)			0-3 (1)		
<i>Corythodinium elegans</i>			0-4 (1)	0-3 (1)	0-3 (1)							
<i>Corythodinium</i> <i>michaelsarsi</i>				0-8 (2)								
<i>Corythodinium reticulatum</i>	0-2 (2)						0-2 (2)					
<i>Corythodinium tessellatum</i>		0-2 (2)	0-2 (1)	0-3 (2)	0-3 (3)	0-2 (2)				0-3 (2)		
<i>Corythodinium</i> sp.			0-2 (1)		0-3 (1)							
<i>Ensiculifera</i> sp.									0-5 (1)			
<i>Gambierdiscus</i> sp.*†								0-4 (1)				
<i>Goniodoma polyedricum</i>		0-2 (2)				0-6 (2)	0-2 (1)		0-5 (1)			
<i>Goniodoma sphaericum</i>	0-6 (3)				0-3 (1)		0-6 (1)	0-2 (2)	0-5 (1)	0-3 (2)		

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Table 2.1.Contd.

Dinoflagellates	CP transect						PK transect					
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06		Nov 03	Mar 04	Aug 04	Oct 04	Sep 06	
Autotrophic												
<i>Gonyaulax brevisulcata</i>				0-5 (1)							0-3 (1)	
<i>Gonyaulax digitalis</i>	0-2 (1)			0-3 (1)	0-3 (1)						0-3 (1)	
<i>Gonyaulax grindleyi</i>												
<i>Gonyaulax monospina</i> †					0-3 (1)							
<i>Gonyaulax polyedra</i> *	0-4 (4)			0-3 (1)			0-2 (1)					
<i>Gonyaulax polygramma</i> *	0-8 (1)	0-2 (1)	0-2 (1)	0-8 (4)	0-6 (1)		0-4 (2)	0-4 (1)	0-4 (2)	0-8 (3)	0-6 (2)	
<i>Gonyaulax scrippsae</i>	0-4 (1)	0-2 (1)	0-2 (2)	0-3 (1)	0-3 (1)		0-6 (3)					
<i>Gonyaulax spinifera</i> *	0-4 (4)			0-3 (1)			0-4 (1)	0-2 (2)				
<i>Gonyaulax</i> sp.	0-2 (1)	0-2 (2)	0-2 (2)	0-3 (1)	0-6 (6)		0-2 (1)	0-4 (2)	0-6 (1)	0-3 (2)	0-3 (5)	
<i>Gymnodinium</i> spp.*			0-2 (1)	0-5 (1)	0-6 (3)				0-6 (1)		0-6 (3)	
<i>Oxytoxum globosum</i>	0-26 (1)											
<i>Oxytoxum laticeps</i>				0-3 (1)	0-6 (3)		0-2 (1)				0-6 (4)	
<i>Oxytoxum scolopax</i>	0-3 (5)	0-2 (2)	0-4 (6)	0-8 (4)	0-3 (5)			0-6 (2)	0-2 (2)	0-5 (1)	0-3 (4)	
<i>Oxytoxum sceptrum</i>		0-2 (1)	0-4 (5)	0-3 (4)					0-2 (3)		0-3 (1)	
<i>Oxytoxum</i> sp.	0-6 (3)	0-2 (1)						0-2 (2)			0-3 (1)	
<i>Podolampas bipes</i>		0-2 (3)		0-3 (1)	0-3 (2)		0-2 (1)		0-5 (1)		0-6 (2)	
<i>Podolampas elegans</i>	0-4 (3)							0-2 (1)				
<i>Podolampas palmipes</i>	0-4 (4)	0-2 (2)	0-2 (3)	0-3 (3)	0-6 (1)		0-2 (1)	0-2 (1)	0-2 (1)	0-5 (1)	0-3 (1)	
<i>Podolampas spinifera</i>		0-2 (1)	0-2 (2)	0-3 (1)						0-5 (1)		
<i>Pyrophacus steinii</i>	0-2 (1)			0-3 (1)			0-2 (3)	0-2 (1)			0-18 (1)	
<i>Pyrophacus</i> spp.				0-5 (2)								
<i>Torodinium teredo</i> †					0-3 (2)							

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Table 2.1.Contd.

Dinoflagellates	CP transect						PK transect					
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06	Nov 03	Mar 04	Aug 04	Oct 04	Sep 06		
Mixotrophic												
<i>Alexandrium minutum</i> *	0-10 (1)											
<i>Ceratium arietinum</i>					0-3 (1)	0-2 (1)			0-3 (2)			
<i>Ceratium azoricum</i>			0-2 (1)	0-3 (1)						0-3 (1)		
<i>Ceratium candelabrum</i> f. <i>depressum</i>			0-2 (1)	0-5 (4)	0-9 (4)		0-4 (1)		0-5 (1)	0-9 (3)		
<i>Ceratium contortum</i>	0-5 (3)	0-2 (1)	0-2 (1)	0-3 (1)					0-8 (1)			
<i>Ceratium declinatum</i>												
<i>Ceratium deflexum</i>					0-3 (1)							
<i>Ceratium dens</i>												
<i>Ceratium extensum</i>					0-3 (1)		0-4 (4)	0-6 (1)				
<i>Ceratium furca</i> *	0-2 (1)		0-2 (2)	0-5 (4)	0-9 (5)	0-20 (5)		0-6 (4)	0-13 (4)	0-18 (4)		
<i>Ceratium fusus</i> *	0-6 (4)	0-2 (4)	0-2 (3)	0-13 (9)	0-6 (4)	0-20 (1)	0-4 (1)	0-6 (5)	0-8 (7)	0-12 (3)		
<i>Ceratium gibberum</i>	0-2 (1)											
<i>Ceratium horridum</i>			0-2 (2)		0-6 (2)			0-2 (1)		0-3 (1)		
<i>Ceratium karstenii</i>	0-2 (4)						0-2 (1)					
<i>Ceratium kofoidii</i>		0-2 (1)	0-2 (1)			0-2 (1)						
<i>Ceratium lineatum</i>			0-2 (2)	0-3 (2)	0-3 (1)				0-5 (1)	0-3 (1)		
<i>Ceratium lumula</i>							0-2 (1)					
<i>Ceratium macroceros</i>		0-2 (3)	0-2 (1)			0-2 (3)		0-2 (1)				
<i>Ceratium pentagonum</i>					0-9 (7)			0-2 (1)		0-3 (1)		
<i>Ceratium schmidtii</i>			0-2 (2)	0-5 (3)	0-3 (1)				0-8 (2)			
<i>Ceratium symmetricum</i>	0-10 (4)			0-3 (1)			0-2 (2)					

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Table 2.1.Contd.

Dinoflagellates	CP transect					PK transect				
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06	Nov 03	Mar 04	Aug 04	Oct 04	Sep 06
Mixotrophic										
<i>Ceratium teres</i>		0-8 (6)	0-8 (7)	0-8 (7)	0-9 (7)	0-4 (1)		0-2 (1)	0-3 (2)	0-12 (3)
<i>Ceratium trichoceros</i>	0-2 (2)						0-8 (1)			
<i>Ceratium tripos</i>		0-2 (1)	0-2 (1)			0-2 (1)				
<i>Ceratium vultur</i>	0-4 (1)									0-3 (1)
<i>Ceratium</i> spp.			0-2 (1)	0-3 (2)	0-3 (3)				0-5 (1)	
<i>Dinophysis caudata</i> *								0-2 (1)	0-5 (1)	
<i>Dinophysis miles</i> *								0-12 (1)		
<i>Dinophysis schuetii</i>				0-3 (1)						
<i>Dinophysis</i> spp.	0-4 (5)		0-2 (2)	0-5 (2)		0-2 (1)	0-6 (6)		0-5 (1)	0-3 (1)
<i>Dissodinium asymmetricum</i>							0-4 (1)			
<i>Prorocentrum arcuatum</i> †	0-2 (1)									
<i>Prorocentrum belizeanum</i> *†		0-24 (1)								
<i>Prorocentrum compressum</i>		0-2 (1)		0-5 (1)				0-2 (1)		
<i>Prorocentrum gracile</i>				0-8 (4)						
<i>Prorocentrum lenticulatum</i>	0-4 (1)									
<i>Prorocentrum lima</i> *							0-2 (1)			
<i>Prorocentrum micans</i> *	0-20 (1)		0-2 (2)	0-3 (1)	0-3 (2)			0-10 (1)	0-10 (2)	0-9 (1)
<i>Prorocentrum minimus</i> *	0-2 (1)		0-2 (1)	0-3 (1)				0-2 (1)		
<i>Prorocentrum mexicanum</i> *	0-5 (6)									
<i>Prorocentrum obtusum</i>				0-8 (3)					0-3 (2)	0-3 (2)
<i>Prorocentrum scutellum</i> †								0-2 (1)		
<i>Prorocentrum sigmoides</i> *			0-2 (1)		0-3 (1)					0-9 (4)
<i>Prorocentrum</i> sp.	0-2 (2)	0-14 (2)	0-4 (3)	0-8 (5)	0-9 (7)	0-4 (4)	0-4 (1)	0-6 (2)	0-8 (3)	0-6 (5)

Continued...

Table 2.1.Contd.

Dinoflagellates	CP transect						PK transect					
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06	Nov 03	Mar 04	Aug 04	Oct 04	Sep 06		
Mixotrophic												
<i>Pyrocystis fusiformis</i>			0-2 (1)	0-3 (1)								
<i>Pyrocystis hamulus</i>	0-2 (1)		0-4 (2)			0-2 (1)						
<i>Pyrocystis lumula</i>	0-4 (1)											
<i>Pyrocystis</i> spp.		0-2 (1)	0-2 (1)	0-3 (1)	0-3 (2)	0-14 (5)	0-6 (1)		0-5 (2)	0-3 (1)		
<i>Scrippsiella trochoidea</i> *	0-14 (9)		0-2 (1)	0-3 (1)	0-9 (7)		0-26 (6)	0-4 (1)	0-5 (2)	0-15 (7)		
<i>Scrippsiella</i> spp.		0-2 (1)	0-6 (5)	0-10 (3)			0-2 (1)	0-6 (3)	0-8 (1)			
Heterotrophic												
<i>Gotoius abei</i> †		0-6 (4)		0-3 (1)		0-10 (5)			0-8 (4)	0-3 (1)		
<i>Histioneis carinata</i> †	0-2 (1)				0-3 (1)		0-4 (2)					
<i>Histioneis costata</i> †	0-2 (1)	0-2 (1)						0-2 (1)				
<i>Histioneis depressa</i>		0-2 (2)	0-2 (2)									
<i>Histioneis</i> spp.					0-3 (1)							
<i>Katodinium</i> sp.		0-2 (3)	0-4 (5)	0-10 (2)	0-3 (2)			0-2 (2)	0-5 (1)			
<i>Noctiluca scintillans</i>		0-2 (1)				0-40 (1)						
<i>Noctiluca</i> spp.	0-2 (1)											
<i>Ornithocercus heteroporus</i>	0-6 (2)						0-2 (1)					
<i>Ornithocercus magnificus</i>		0-2 (2)	0-4 (2)	0-18 (2)	0-3 (1)				0-5 (1)	0-6 (2)		
<i>Ornithocercus quadratus</i>		0-2 (1)	0-2 (1)	0-3 (1)					0-5 (1)			
<i>Ornithocercus steinii</i>			0-2 (1)			0-4 (2)	0-2 (1)	0-2 (1)	0-5 (1)			
<i>Ornithocercus thumii</i>		0-2 (1)				0-4 (2)		0-2 (1)	0-5 (1)	0-3 (1)		
<i>Ornithocercus</i> spp.					0-3 (1)			0-2 (1)				
<i>Oxyphysis</i> spp.												
<i>Pentaparsodinium</i> sp.†		0-2 (1)				0-4 (1)						

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Table 2.1.Contd.

Dinoflagellates	CP transect					PK transect				
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06	Nov 03	Mar 04	Aug 04	Oct 04	Sep 06
Heterotrophic										
<i>Phalacroma argus</i>	0-2 (1)									
<i>Phalacroma cuneus</i>	0-2 (2)	0-2 (1)		0-3 (1)				0-2 (1)	0-5 (1)	
<i>Phalacroma rapa</i>					0-3 (1)					0-3 (2)
<i>Phalacroma rotundatum</i>								0-2 (1)		
<i>Phalacroma</i> spp.		0-2 (2)	0-2 (2)							
<i>Pronoctiluca pelagica</i>						0-2 (1)				
<i>Pronoctiluca spinifera</i>		0-2 (2)	0-2 (1)	0-3 (1)	0-3 (1)					
<i>Protoperidinium</i>										
<i>asymmetricum</i>	0-4 (3)						0-2 (1)			
<i>Protoperidinium brevipes</i>		0-2 (1)								
<i>Protoperidinium crassipes</i> *	0-2 (1)						0-2 (1)			
<i>Protoperidinium depressum</i>	0-2 (4)	0-2 (1)					0-4 (2)	0-2 (1)	0-5 (1)	
<i>Protoperidinium divergens</i>		0-2 (1)	0-4 (3)	0-5 (6)	0-3 (1)	0-2 (1)		0-2 (2)	0-3 (5)	
<i>Protoperidinium elegans</i>				0-3 (2)						
<i>Protoperidinium grande</i>	0-4 (1)									
<i>Protoperidinium leonis</i>		0-2 (1)								0-3 (1)
<i>Protoperidinium minutum</i>										
<i>Protoperidinium oblongum</i>						0-2 (1)				
<i>Protoperidinium ovatum</i>	0-4 (8)						0-26 (2)			
<i>Protoperidinium pacificum</i>		0-2 (1)		0-10 (2)		0-6 (2)	0-4 (2)		0-8 (3)	

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Table 2.1.Contd.

Dinoflagellates	CP transect						PK transect					
	Feb 04	Jun 04	Jul 04	Oct 04	Sep 06		Nov 03	Mar 04	Aug 04	Oct 04	Sep 06	
Heterotrophic												
<i>Protoperidinium pallidum</i>		0-2 (1)										
<i>Protoperidinium pedunculatum</i>	0-4 (3)	0-2 (2)	0-8 (4)			0-4 (1)	0-2 (3)	0-4 (1)	0-5 (1)			
<i>Protoperidinium pellucidum</i>	0-4 (2)				0-3 (1)	0-4 (1)	0-2 (3)	0-4 (1)				
<i>Protoperidinium pentagonum</i>		0-2 (1)				0-10 (1)		0-2 (1)				
<i>Protoperidinium pyriforme</i>							0-2 (1)					
<i>Protoperidinium steinii</i>		0-2 (1)	0-3 (2)	0-3 (1)	0-6 (1)	0-4 (1)		0-8 (2)	0-3 (4)			
<i>Protoperidinium subinerme</i>								0-2 (2)				
<i>Protoperidinium</i> sp.	0-4 (4)	0-4 (6)	0-3 (4)	0-3 (4)	0-9 (8)	0-2 (1)	0-4 (2)	0-8 (3)	0-5 (1)	0-9 (9)		
<i>Zygabikodinium</i> sp.	0-2 (1)											

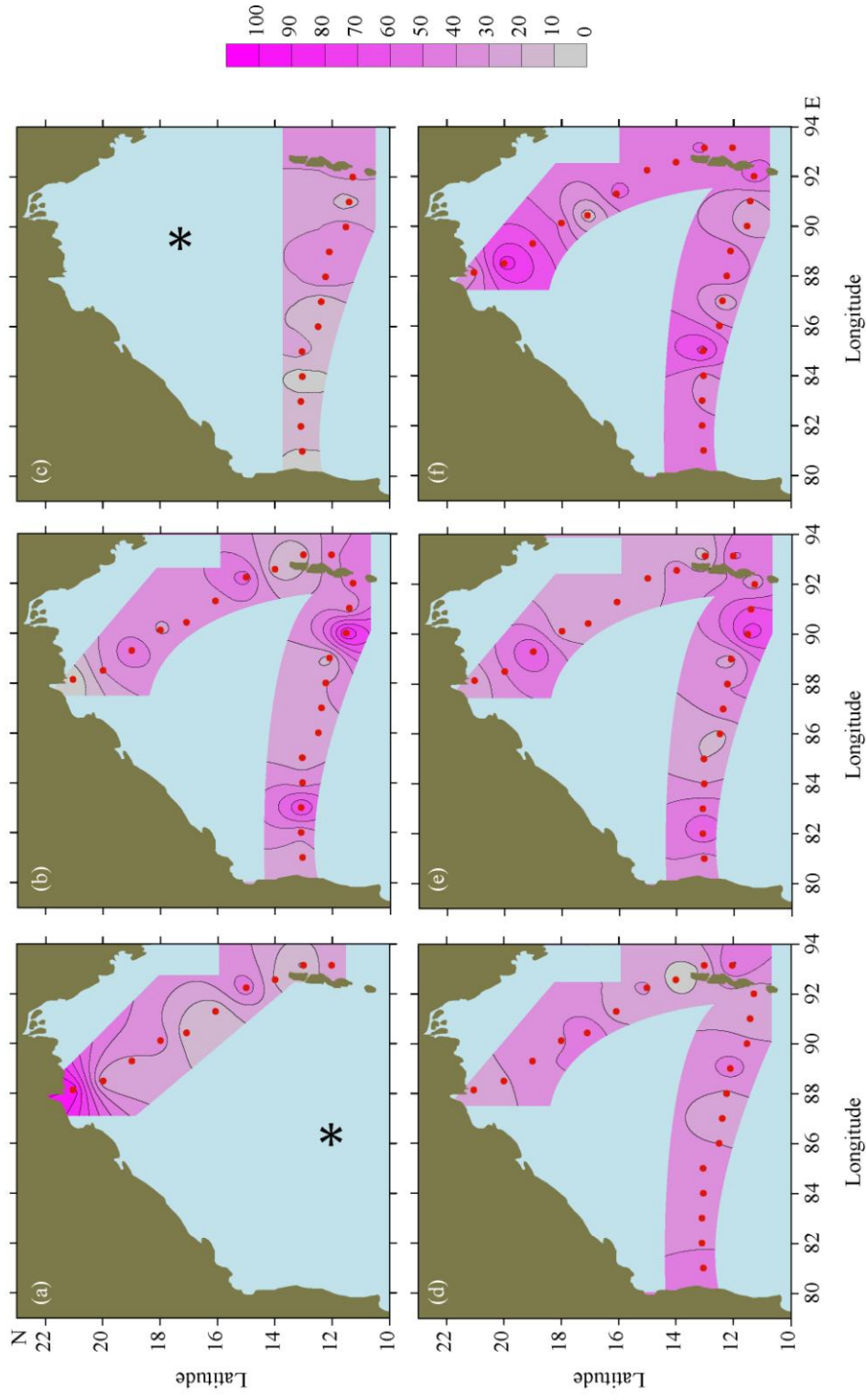


Fig. 2.2. Spatio-temporal variation in total dinoflagellate abundance (cells L^{-1}) along the Chennai-Port Blair (CP) and Port Blair-Kolkata (PK) transects in (a) Nov 03, (b) Feb-Mar 04, (c) Jun 04, (d) Jul-Aug 04, (e) Oct 04 and (f) Sep 06. * transect not sampled.

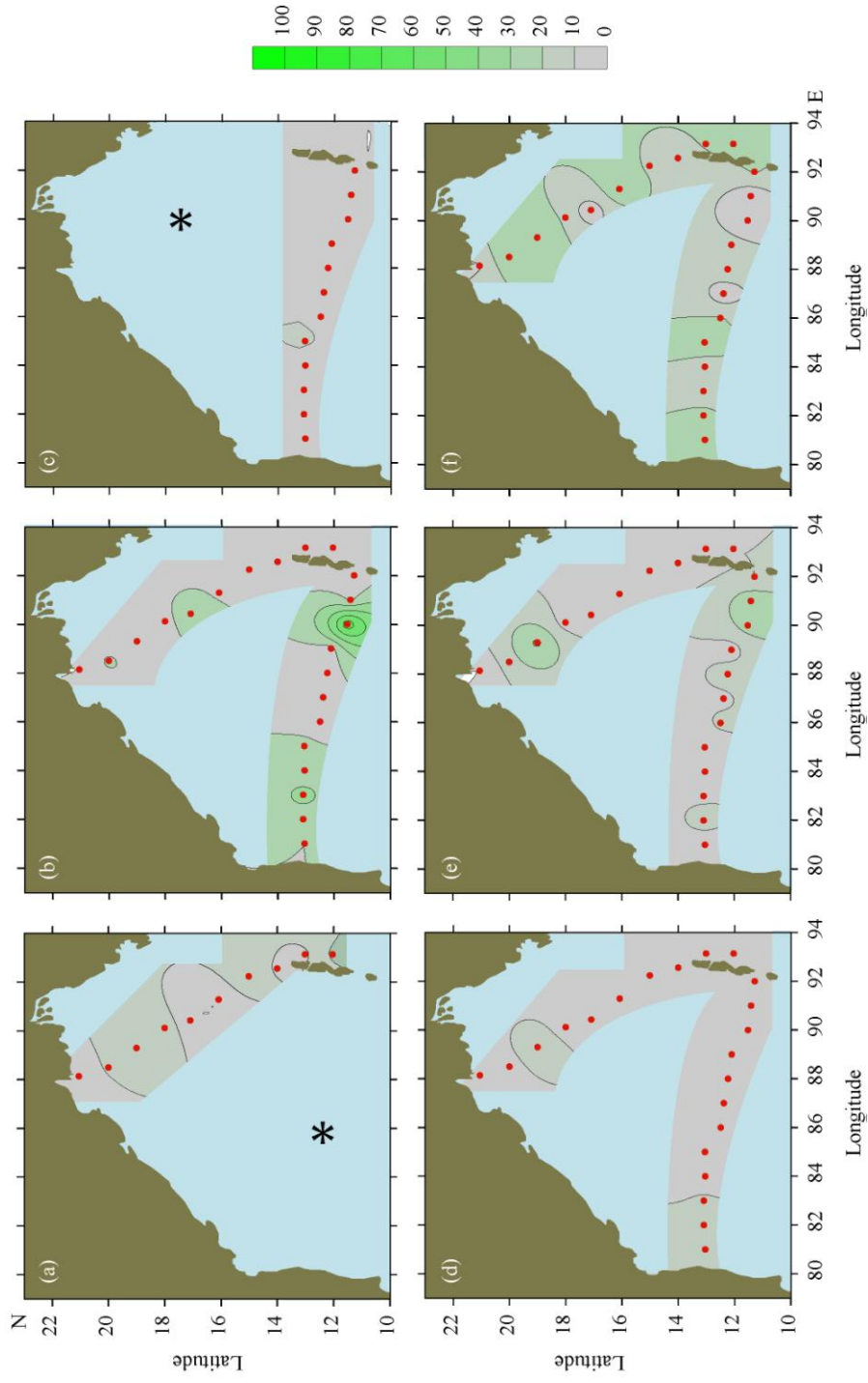


Fig. 2.3. Spatio-temporal variation in autotrophic dinoflagellate abundance (cells L^{-1}) along the Chennai–Port Blair (CP) and Port Blair–Kolkata (PK) transects in (a) Nov 03, (b) Feb–Mar 04, (c) Jun 04, (d) Jul–Aug 04, (e) Oct 04 and (f) Sep 06. * transect not sampled.

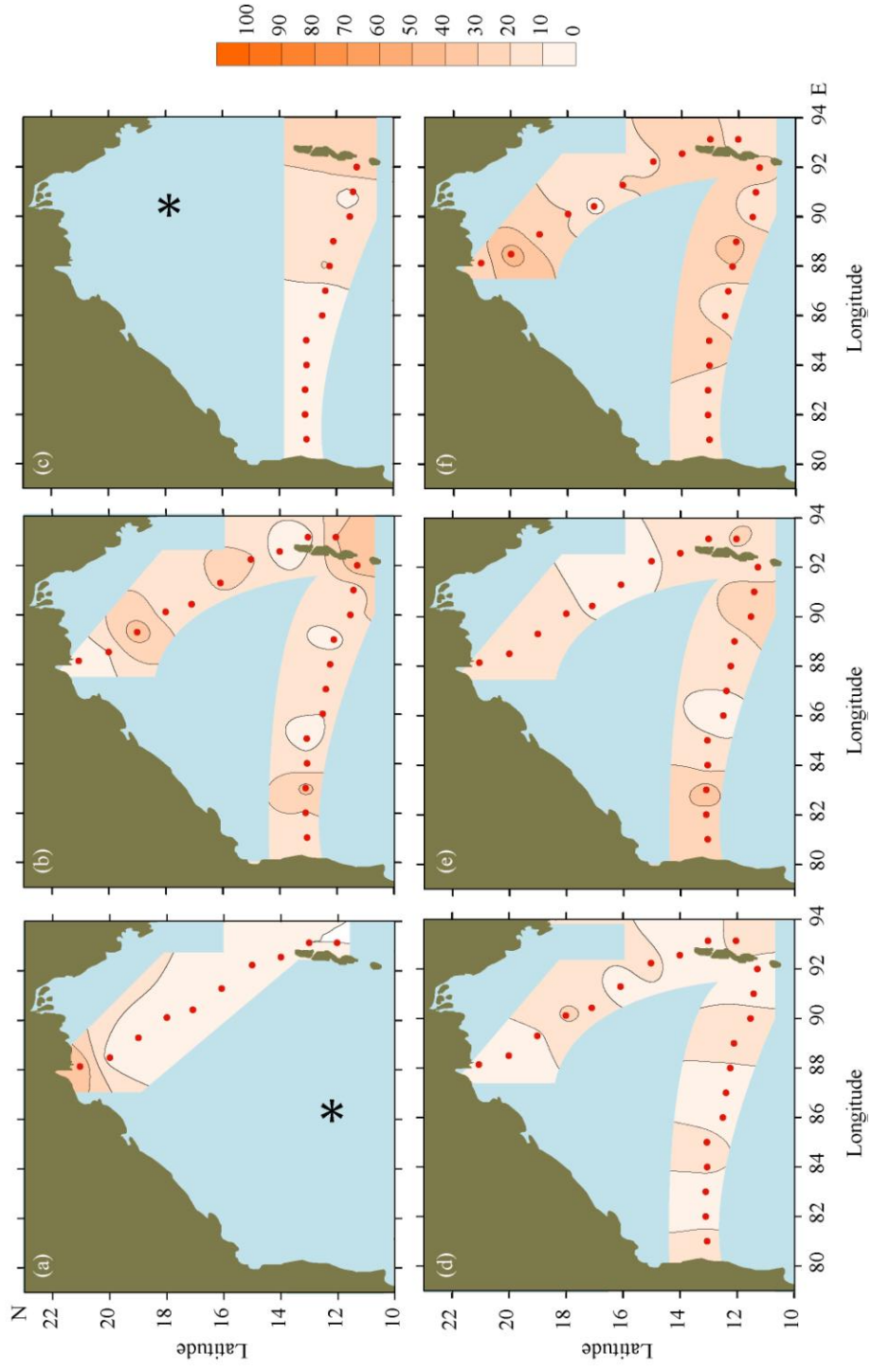


Fig. 2.4. Spatio-temporal variation in mixotrophic dinoflagellate abundance (cells L⁻¹) along the Chennai–Port Blair (CP) and Port Blair–Kolkata (PK) transects in (a) Nov 03, (b) Feb–Mar 04, (c) Jun 04, (d) Jul–Aug 04, (e) Oct 04 and (f) Sep 06. * transect not sampled.

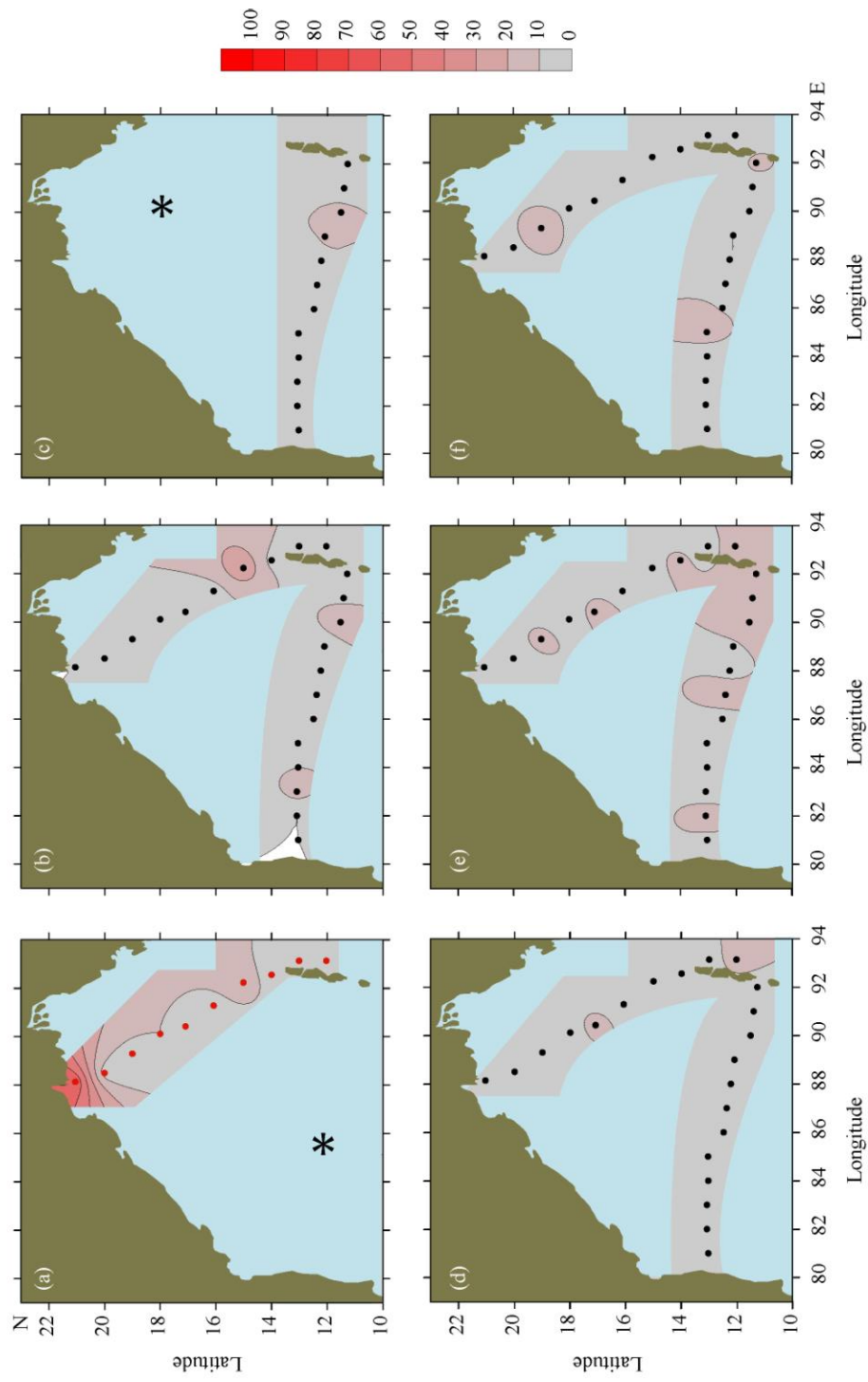


Fig. 2.5. Spatio-temporal variation in heterotrophic dinoflagellate abundance (cells L⁻¹) along the Chennai-Port Blair (CP) and Port Blair-Kolkata (PK) transects in (a) Nov 03, (b) Feb-Mar 04, (c) Jun 04, (d) Jul-Aug 04, (e) Oct 04 and (f) Sep 06. * transect not sampled.

Table 2.2. Two-way ANOVA to evaluate the variation in dinoflagellate abundance, species richness, evenness and diversity along the Chennai-Port Blair (CP) and Port Blair-Kolkata (PK) transects. Values in bold indicate significant variation.

Factor	CP transect				PK transect			
	<i>df</i>	SS	MS	<i>p-value</i>	<i>df</i>	SS	MS	<i>p-value</i>
Abundance								
Stations	11	0.5781	0.0526	0.3281	9	1.1035	0.1226	0.3102
Seasons	4	1.2082	0.3021	0.0002	4	0.7474	0.1869	0.1373
Within sub-group error	44	1.9596	0.0445		36	3.6006	0.1000	
Total	59	3.7459			49	5.4516		
Species richness								
Stations	10	10.1732	1.0173	0.1661	9	9.5642	1.0627	0.0180
Seasons	4	0.4200	0.1050	0.9585	4	2.7963	0.6991	0.1614
Within sub-group error	40	26.6678	0.6667		36	14.4171	0.4005	
Total	54	37.2610			49	26.7776		
Species evenness								
Stations	10	0.0504	0.0050	0.1922	9	0.2111	0.0235	0.2578
Seasons	4	0.0170	0.0043	0.3145	4	0.1674	0.0419	0.0710
Within sub-group error	40	0.1385	0.0035		36	0.6365	0.0177	
Total	54	0.2059			49	1.0151		
Species diversity								
Stations	10	2.6394	0.2639	0.1033	9	3.7540	0.4171	0.0338
Seasons	4	0.6172	0.1543	0.4078	4	1.8929	0.4732	0.0483
Within sub-group error	40	6.0408	0.1510		36	6.4055	0.1779	
Total	54	9.2974			49	12		

species richness only across stations and diversity across both stations and seasons (Table 2.2). The highest abundance of dinoflagellates was observed during September 06 followed by October 04 whereas low abundance was recorded during June, July and August 04 (Fig. 2.2). Mixotrophic dinoflagellates dominated across both transects, with the exception of October 04 at CP and September 06 at PK transects,

that were dominated by heterotrophic forms (Fig. 2.6). Autotrophic dinoflagellates contributed 18-41% whereas heterotrophic forms contributed in the range of 13-49% (Fig. 2.6).

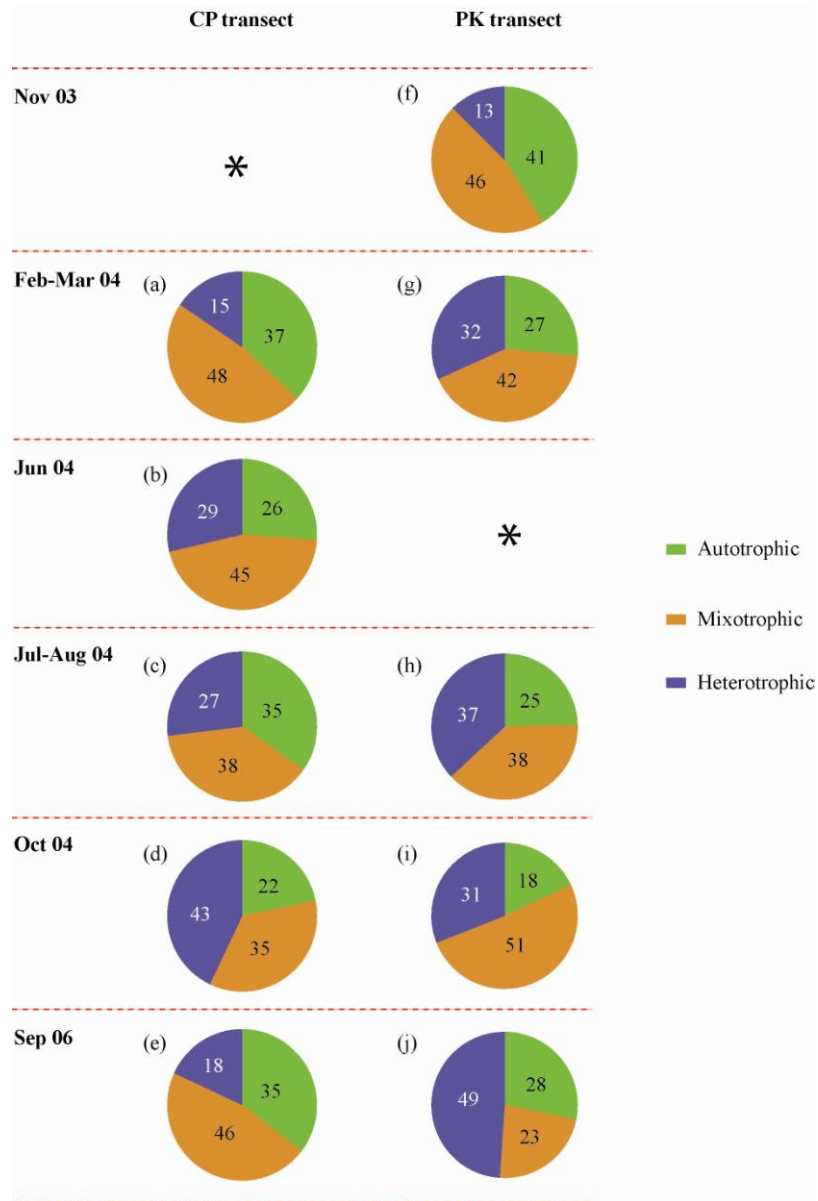


Fig. 2.6. The percentage contribution of autotrophic, mixotrophic and heterotrophic dinoflagellates along the (a-e) Chennai–Port Blair (CP) and (f-j) Port Blair–Kolkata (PK) transects. (a) Feb 04, (b) Jun 04, (c) Jul 04, (d) Oct 04, (e) Sep 06, (f) Nov 03, (g) Mar 04, (h) Aug 04, (i) Oct 04 and (j) Sep 06. * transect not sampled.

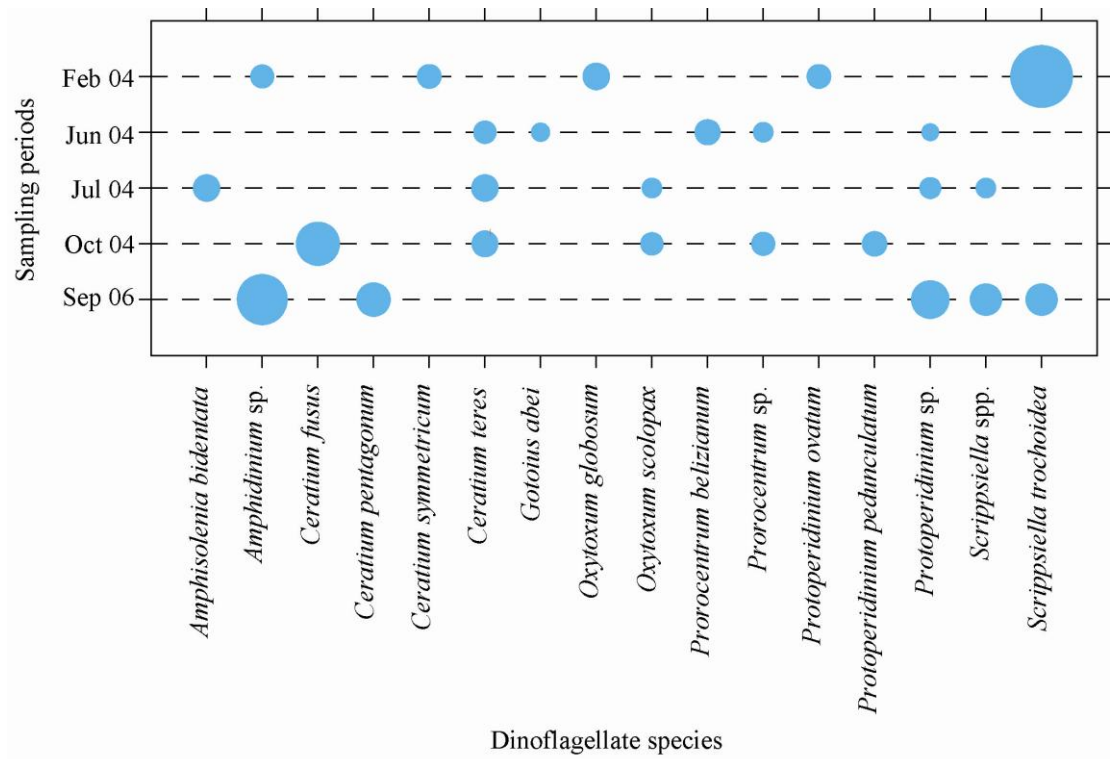


Fig. 2.7. The five most abundant dinoflagellate species during each sampling period along the Chennai–Port Blair (CP) transect. The maximum diameter of the circles corresponds to an average abundance of 8 cells L⁻¹.

Ceratium was the dominant genus among the mixotrophic forms whereas *Protoperidinium* was the dominant heterotrophic form. *Ceratium fusus*, *C. teres*, *Gotoius abei*, *Oxytoxum scolopax*, *Protoperidinium ovatum* and *Scrippsiella trochoidea* were among the abundant forms in both transects. *Amphisolenia bidentata*, *C. pentagonum*, *C. symmetricum*, *O. globosum* and *Prorocentrum belizianum* were abundant only in CP transect (Fig. 2.7).

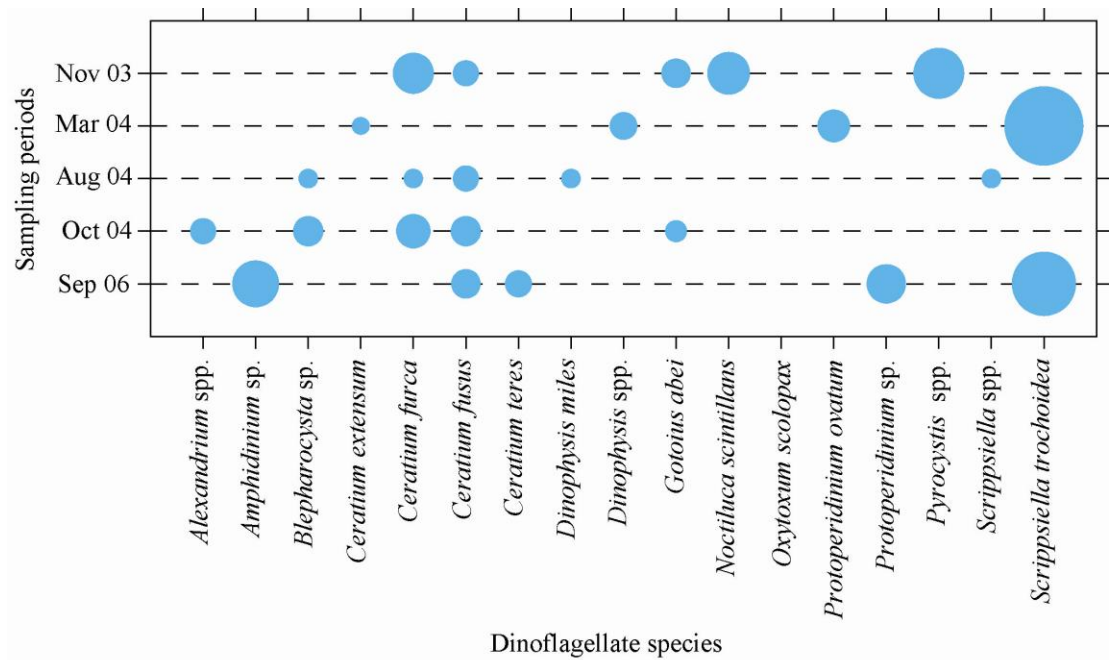


Fig. 2.8. The five most abundant dinoflagellate species during each sampling period along the Port Blair-Kolkata (PK) transect. The maximum diameter of the circles corresponds to an average abundance of 8 cells L⁻¹.

C. extensum, *C. furca*, *Dinophysis miles* and *Noctiluca scintillans* were abundant only in the PK transect (Fig. 2.8).

2.3.3. Seasonal variation in HAB species

Overall, 19 potentially HAB species were encountered in this area (Table 2.1; some species in Fig.2.9). Some HAB species were present during all the seasons throughout the study period. These frequently occurring HAB species were *C. furca*, *C. fusus*, *Dinophysis* sp., *Gonyaulax polygramma*, *Gonyaulax* sp., *N. scintillans*, *Prorocentrum* sp., *S. trochoidea*, *Scrippsiella* sp. (Table 2.1). Season-specific trends were also observed. *Alexandrium minutum*, *Prorocentrum lima* and *Protoperidinium*

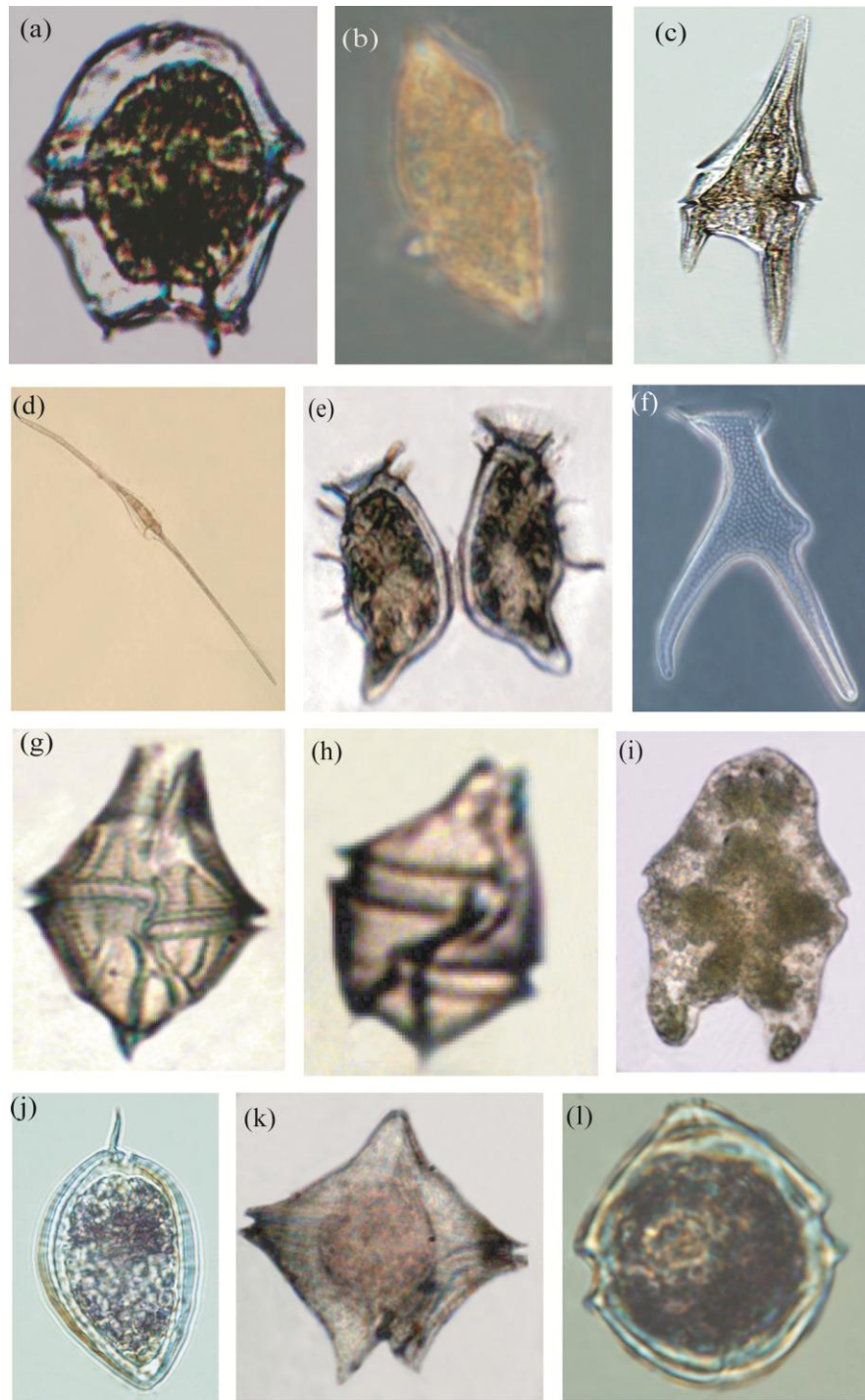


Fig. 2.9. Potential HAB species. (a) *Alexandrium* sp., (b) *Amphidinium* sp., (c) *Ceratium furca*, (d) *Ceratium fusus*, (e) *Dinophysis caudata*, (f) *Dinophysis miles*, (g) *Gonyaulax polygramma*, (h) *Gonyaulax spinifera*, (i) *Gymnodinium* sp., (j) *Prorocentrum micans*, (k) *Protoperidinium crassipes* and (l) *Scrippsiella trochoidea*.

crassipes occurred only during PrM whereas *Dinophysis caudata*, *D. miles*, *Prorocentrum micans*, *P. mexicanum*, *P. minimus*, *Gymnodinium* sp. and *Gambierdiscus* sp. were found during SWM and PoM periods. *Gonyaulax polyedra* and *G. spinifera* occurred in PrM and PoM but not during SWM. In contrast to this, *P. belizeanum* and *P. sigmoides* occurred only during the SWM (Table 2.1).

2.4. Discussion

The BOB is a unique geographic region; it is characterized by a stratified water column that restricts the vertical transport of nutrients from the bottom layers to the surface, and therefore phytoplankton productivity as well (Prasanna Kumar et al. 2002). The stratification is especially intense during the SWM period due to the enormous influx of freshwater through precipitation and riverine discharges that leads to the formation of a low salinity cap at the surface. This study revealed that dinoflagellate abundance in surface waters was generally in the range of 0-94 cells L⁻¹ and did not vary significantly across stations (Table 2.2). This could be related to the environmental conditions of the study area. Stratified water columns, with their characteristic oligotrophic conditions, tend to promote stasis of the resident population, rather than promoting growth or blooms (Smayda 2002). In fact, many studies (McGill 1973, Paul et al. 2008) have reported that the surface waters of the BOB are nitrate-deficient. Yet, even though the stratified BOB environment supports a rather homogeneous dinoflagellate community in surface waters, significant seasonal variations in abundance and species diversity of the dinoflagellate

community were observed (Table 2.2). Minimum values were observed during SWM, correlating to the intensification of the stratified layer, and maximum during the withdrawal of the SWM and PoM (Fig. 2.2).

The dominance of mixotrophic dinoflagellates in the study area (Fig. 2.6) could be a consequence of the prevalent low light and/or nutrient scarcity, conditions that are known to promote mixotrophy (Legrand et al. 1998, Stoecker et al. 2006). *Ceratium* and *Protoperidinium* were the most abundant representatives of the mixotrophic and heterotrophic forms in the BOB respectively (Figs. 2.7&2.8); their unique characteristics of vertical migration, and heterotrophy are reasonably well understood (Baek et al. 2006 and 2007, Baek et al. 2008 a, b and c, Latz and Jeong 1996), and probably confer on them a competitive advantage in both coastal and oceanic environments.

Comparison of the present study with earlier reports from the same area (Taylor 1976, Jyothibabu et al. 2003, Paul et al. 2007) indicated 10 new dinoflagellate species (Table 2.1 species marked with †; some species in Fig. 2.10). Approximately 14% of the identified species were potential HAB species (Table 2.1 species marked with *). Among the frequently occurring HAB species (hereafter FOS) recorded in the region; *C. furca* and *C. fusus* showed a characteristic transect-specific distribution. *C. furca* was abundant only in the PK transect. *C. fusus* which was predominant in the PK transect (Fig. 2.8) was abundant only during October 04 in the CP transect (Fig. 2.7).

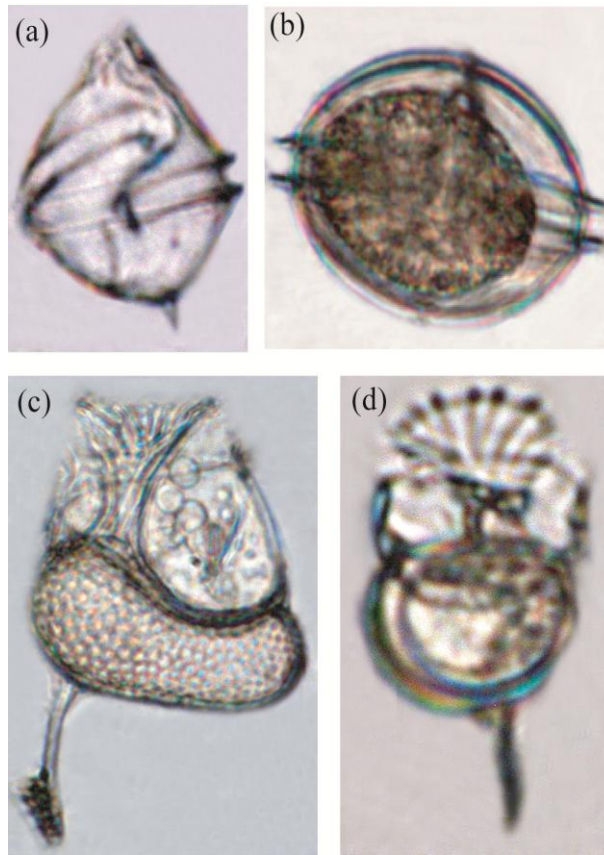


Fig. 2.10. Newly reported species from the region. (a) *Gonyaulax monospina*, (b) *Gotoius abei*, (c) *Histioneis carinata* and (d) *Histioneis costata*.

C. furca and *C. fusus* are characteristically found in stable stratified water columns (Baek et al. 2006 and 2007). However, both species differ in several characteristics. In recent observations in Sagami Bay, Japan, Baek et al. (2009) reported that *C. furca* had a competitive edge over *C. fusus*, because of its efficient diel vertical migration capability (a ‘biological’ factor). *C. fusus* was stimulated by low salinity and showed dependence on external environmental conditions such as enhanced nutrient concentrations following fresh water discharge by heavy rainfall (combination of ‘physical’ and ‘chemical’ factors). In light of this, the observations in this study point

out that the water mass of the PK transect is influenced by riverine discharge to a much greater extent compared to the CP transect. Additionally, the differential capabilities of *Ceratium* species to acclimatize to such niches can be an important factor in determining their diversity and spatio-temporal distribution.

S. trochoidea, another FOS in the region, was abundant during September 06/February-March 04 (Figs. 2.7, 2.8). September is known as the period of withdrawal of SWM, during which cloud cover reduces, whereas March is known for clear sky and with no rainfall. Studies on the factors triggering the growth/bloom formation of *S. trochoidea*, point to different regulating factors. For e.g., in Hong Kong waters, the initiation, maintenance and disappearance of a *S. trochoidea* red tide was not directly driven by changes in nutrients (Yin et al. 2008). Subsequently, Zhuo-Ping et al. (2009) observed that the cell density of *S. trochoidea* was positively influenced by high irradiance and further enhanced by iron concentration. These conditions of high irradiance could possibly be responsible for the predominance of *S. trochoidea* in March.

Blooms of *N. scintillans*, yet another FOS in the region, have been reported from Indian waters (Raghu Prasad 1953 and 1956, Santha Joseph 1975, Naqvi et al. 1998, Eashwar et al. 2001, Mohanty et al. 2007, Gomes et al. 2008). Most of these blooms occurred during the SWM. However, as discussed above for *S. trochoidea*, additional studies in other parts of the world reveal different triggering factors. For e.g., a *N. scintillans* bloom observed in the Gulf of Thailand was mainly influenced by the SWM (Sriwoon et al. 2008). Since the SWM is a major meteorological event

influencing the BOB, it is absolutely necessary to investigate in detail the factors sustaining the population of *N. scintillans* in the BOB and their bloom dynamics.

Dinophysis sp., another FOS in the region, was abundant during March at PK transect (Fig. 2.8). *Dinophysis* are known to increase in cell density immediately after a storm-induced mixing event (Nishitani et al. 2005). They can also migrate through strong gradients and survive under unfavorable conditions (Setala et al. 2005). In a recent observation in Portuguese waters, Escalera et al. (2010) found that the increased numbers of *Dinophysis* was a result of physically-driven accumulation due to long-shore transport. They also found the bloom to be associated with much warmer temperatures. In these observation, its predominance during March indicates its preference for high temperature since this period is considered a warmer season in the BOB (Narvekar and Prasanna Kumar 2006).

Given that the FOS observed in this study ranged from 0-40 cells L⁻¹, their presence may not be a population growth issue, as suggested by Smayda (2002). However, they may play a significant role in the development of pelagic seed banks, which can serve as inocula for bloom events elsewhere, on the onset of favorable conditions. An earlier study (Avaria 1979) suggested that the Chilean frontal zone located 100 km offshore supported a *P. micans* bloom. Transport of offshore-seeded *Prorocentrum* and *Ceratium* blooms to inshore waters (Pitcher and Boyd 1996) also supports the above assumption.

Another intriguing aspect to be considered is the enhancement of phytoplankton biomass to bloom levels by physical processes occurring in the BOB like eddies

(Gomes et al. 2000, Prasanna Kumar et al. 2004) and cyclones (Madhu et al. 2002, Vinayachandran and Mathew 2003, Rao et al. 2006). In both eddies and cyclones, bloom formation takes place due to transport of nutrients from bottom layers to the surface. During cyclones, due to strong wind speed, the stratified layer breaks and deepens the mixed layer, leading to introduction of nutrients into the surface layers whereas during eddies, Ekman pumping plays an important role in transporting nutrients to surface waters. Eddies are most likely to occur during the SWM (Prasanna Kumar et al. 2004) whereas cyclones are common during November (Madhu et al. 2002, Vinayachandran and Mathew 2003, Rao et al. 2006). The combination of such physical effects including turbulence and advection, with the diverse behavioral characteristics of dinoflagellates (e.g., migration, physiological adaptation) holds the key to understanding HAB dynamics in stratified oceanic areas. Even though some of these physical processes may play a crucial role in the formation of HABs, these processes are not well defined and thus knowledge in this context remains weak (GEOHAB 2003). For e.g., the above studies were based on remote sensing (chlorophyll *a*) and primary productivity values and none of the reported blooms/enhancement of phytoplankton biomass was taxonomically characterized. In this context, the present investigation pointing out the presence of *N. scintillans* and *C. furca* during November (Table 2.1) further strengthens their probable candidature for bloom formation in the region.

Summarizing the results, the present study is the first of its kind detailing the HAB species from the stratified surface waters of the BOB and their seasonal occurrence.

The frequently occurring HAB species indicate their ability to survive even under such conditions. Their low abundance in the region may not be a growth issue but they may serve as inocula for blooms if coupled with population-triggering physical processes like eddies and cyclones in the region. In this scenario, the characteristic ability of FOS like *C. furca* and *N. scintillans* and their predominance during cyclone-prone months, make their candidature stronger for future bloom occurrences in the region.