

## **Preponderance of a few diatom species among the highly diverse microphytoplankton assemblages in the Bay of Bengal**

Jane T. Paul, Nagappa Ramaiah<sup>1</sup>, Mangesh Gauns and Veronica Fernandes

National Institute of Oceanography, Dona Paula, Goa- 403 004.INDIA

Short Title: Microphytoplankton assemblages in the Bay of Bengal

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**Abstract:** The microphytoplankton assemblages were studied from water samples collected at eight discrete depths in the top 120 m at five central [open ocean] and four western [shelf/slope region] locations in the Bay of Bengal. The Bay is a low-productive warm pool regime with poor inorganic nutrient inputs to its intensely stratified surface layer despite the very large riverine influx. In addition, the prolonged cloud cover has an adverse effect in the top 25-40 m, on primary production, chlorophyll concentration and phytoplankton assemblages. Microphytoplankton were the most abundant in the northern area of the Bay. A total of 153 phytoplankton species were identified during this study. The most abundant species (at least 1800 individual cells belonging to a given species or  $\geq 2\%$  of the total counts of identified specimens) during this study were: *Thalassiothrix longissima*, *Thalassiothrix fauelfeldii*, *Rhizosolenia styliformis*, *Nitzschia angularis*, *Thalassionema nitzschoides*, *Coscinodiscus radiatus*, *Chaetoceros eibonii*, *Skeletonema costatum*, *Coscinodiscus concinnus* and *Chaetoceros coarctatus*. Similarly, there were 20 moderately abundant ( $\geq 0.5$  but  $< 2\%$ ) species. Thirty three of the least abundant species ( $< 0.5\%$ ) occurred at one station. Diatom species, *T. fauelfeldii* and *T. longissima* were ubiquitous in the study area. The exclusive occurrence of *Skeletonema costatum* in the northern most stations suggests that it proliferates only in the low-salinity regions with adequate silica from the land inputs. Abundance of pennate diatoms was higher in the open Bay compared to that of centric diatoms in the more productive northern locations and the western Bay. There appears to be a basic difference between near shore flora and offshore flora. This first analysis of phytoplankton assemblages from the offshore Bay suggests that while there is predominance of only a few species, the Bay harbors very diverse diatom communities that seem to be syntrophic, non-competitive and co-habiting in the generally low nutrient, stratified surface waters.

**KEYWORDS:** Bay of Bengal, Bacillariophyceae, Centric and Pennate Diatoms, Dinoflagellates, Species Diversity, Tropical Micro-phytoplankton, Warm-pool oceanic region

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<sup>1</sup>Corresponding Author: Email: [ramaiah@nio.org](mailto:ramaiah@nio.org),

Tel: +91-832-2450 515; Fax: +91-832-2450606

## INTRODUCTION

The Bay of Bengal forming the eastern arm of the northern Indian Ocean is a relatively small basin, of  $2.2 \times 10^6 \text{ km}^2$  area (Shetye et al. 1991; Fig 1). It has several distinguishing features that make it different from the Arabian Sea. The surface salinity is quite low (22-33 psu) compared to that in the Arabian Sea (31-35 psu). Unlike the Arabian Sea, the southwest monsoon during June - September and northeast monsoon during November-February bring about large-scale precipitation far surpassing evaporation (Shetye 2000). Surface winds are generally weak ( $0$  to  $10 \text{ m s}^{-1}$ ) and highly variable, with warmer ( $30 \text{ }^\circ\text{C}$ ) and low saline ( $<34.0$  psu) surface waters leading to strong stratification in the upper 50 m (Prasanna Kumar et al. 2002). Thus, the Bay experiences contrasting physical conditions with changing seasons and is a particularly interesting oceanic area to study.

Although a large area of the Western Indian Ocean was studied during International Indian Ocean Expedition (IIOE) in 1964, when 237 phytoplankton taxa were recorded (Thorrington-Smith 1971), the attention on the phytoplankton composition in the Bay of Bengal was the least. Earlier studies from the West Coast and off Madras in the East Coast have recorded 134 species of phytoplankton with some new records of diatom species (Venkataraman 1939, Menon 1945, Subramanyan 1946, Subba Rao 1976, Devassy and Goes 1988, Tarran et al. 1999). Subba Rao (1973) reported the composition of phytoplankton for the years 1957, 1958, 1960 and 1962 from Lawson's Bay off Vizag in the East Coast. The phytoplankton composition analyses in Andaman waters (Devassy and Bhattathiri 1981, Sarojini and Sarma 2001) and coastal waters off Orissa (Gouda and Panigrahy 1996) and off Krishna and Godavari rivers (Umamaheshwararao and Sarojini 1992) revealed a variety of phytoplankton species. It is discernible from the foregoing that most studies in the Bay have been carried out in the coastal areas. There thus exists a gap in information on open ocean phytoplankton composition.

Analyses of phytoplankton composition are helpful in determining the fertility of the seas (Qasim and Kureishy 1986). Because phytoplankton are at the base of the food chain, compositional analyses are important to relate with types and biomass of micro and mesozooplankton. Along with the recent information on physico-chemical processes and biological productivity characteristics from the Bay of Bengal (Ittekkot et al. 2003, Prasanna Kumar et al. 2002, 2004, Madhupratap et al. 2003), analyses of phytoplankton composition and

their regional differences will help in realizing the influences that the above processes bear on autotrophic community structure. The objectives of this study were: (1) to characterize the microphytoplankton distribution and composition and to contrast differences between Central Bay (CB) and Western Bay (WB), and (2), to delineate influences, if any, of the physical and chemical parameters on distribution of microphytoplankton.

## MATERIALS AND METHODS

Samples were collected for this study onboard ORV Sagar Kanya during Southwest monsoon (SM, from July 6 to August 2), 2001. The sampling was along two transects, one in the Central Bay (CB, along 88 °E), and another along the Western Bay (WB, 81 °-85 °E, Fig. 1). In general, the stations south of 17 °N in the CB represent a low productive region. The WB stations on the shelf represent, in general, moderately productive waters throughout the year. At all nine stations (Fig.1), data on salinity, temperature and nutrients were collected. Further, water samples were collected from eight discrete depths (near surface, 10 m, 20 m and thereafter at 20 m intervals till 120 m) using a rosette sampler (Sea Bird Electronics) with CTD attached. These samples were used for estimating chlorophyll a (chl a), primary production (PP) from dawn to dusk *in situ* incubation, and phytoplankton cell counts (PPCC). Data on distribution of chl a and PP from this sampling are reported earlier by Madhupratap et al. (2003) during the same study.

For quantitative and qualitative analyses of phytoplankton cell counts and composition, water samples from each of the above depths were fixed with both Lugol's solution (1 % w/v) and 3 % formaldehyde and stored in the dark until analyzed. A settling and siphoning procedure was followed to concentrate samples from 250 ml to 10 ml. For counting nanophytoplankton (>5 to ~ 20µm) and microphytoplankton cells (> 20µm) and identification of genera and species, two one-ml replicates of concentrated samples were transferred to a Sedgwick-rafter plankton counting chamber and examined microscopically at 200 – 400X magnification. All 1000 squares on the chamber were screened. Empty frustules were not included in the total counts. Oil immersion 100X objective on a Zeiss (Axioskop, 2plus, Germany) microscope was used to identify the genera or species. Since both abundance and types (see Results) of nanophytoplankton were sparse, the main focus in this paper is on microphytoplankton whose generic and species identification were done according to various keys (Subramanyan 1946;

1961, 1968, Lebour 1978, Constance et al. 1985 a, b, Desikachary and Ranjithadevi 1986, Desikachary and Prema 1987, Desikachary et al. 1987, Tomas 1997).

For comparing the diversity of the phytoplankton in the Bay, the species diversity was calculated by the Shannon Weaver formula:  $H' = - \sum_{i=1}^S P_i \log_2 P_i$ .

Where, S is total number of species and  $P_i$  is the proportion of the numbers of individuals of species i to the total number of individuals  $P_i = n_i/N$  (Omori and Ikeda 1984).

Species Richness (SR), the number of species recorded from a region, was calculated by Margalef's formula (Margalef 1951):  $SR = (S-1)/\log_n N$

Where, S= total number of species and, N= total individuals present in the sample.

For the convenience of grouping the assemblages, the species were categorized as the most (when  $\geq 2$  % of total), moderate ( $>0.5 - 1.99$  %) and least ( $\leq 0.49$  %) abundant. For this, individual species with  $\geq 1800$  cells in the total phytoplankton counted, were categorized as the most abundant; any species in the range of  $\geq 450$  to  $\leq 1800$  cells as moderately abundant and those  $< 450$  cells as least abundant.

## RESULTS

### *Hydrography*

Hydrographic parameters such as salinity, temperature and density; chemical: nutrients, DO, etc. were also analyzed during this study. These results are published elsewhere (Prasanna Kumar et al. 2002, Madhupratap et al. 2003). In brief, surface salinity along the CB [88 °E transect] showed a steady decrease from  $\sim 34.0$  psu at 7 °N to 32.0 psu at 16 °N. From 16 °N to 17 °N, it decreased by 3 psu and further north, at 20 °N it was around 28. Along the WB, the average salinity was 33.7 psu up to 16 °N in the surface layer but decreased northwards reaching as low as 29.6 at 19 °N. The salinity gradient in the upper 50 m was ca. 1 at 7 °N and 7 psu at 20 °N.

The temperature along the WB ranged from 28 °C- 29 °C in the south and from 27 °C- 28 °C in the north. A similar range was also found in the CB except at 9 °N where an upward shoaling of a cold core eddy was observed (Prasanna Kumar et al. 2004). The euphotic depths ranged from 20m in the north to about 45m at the southern most location.

During the southwest monsoon, the eastward flowing strong summer monsoon current (Cutler and Swallow, 1984) brings high saline Arabian Sea waters (ASHSW) into the southern Bay of Bengal (Prasanna Kumar et al, 2004). Along the western margin, up to north of 10°N, the East India Coastal Current is mostly northward (Shetye et al, 1991). In the northern Bay however, the low salinity plume moves towards the equator hugging the coast against local winds (Shetye et al, 1991). Thus, most part of the study area experiences 29 to 33 psu that increased equator-ward. The surface currents are northwesterly from the Pacific through the Malacca Strait in to the Bay during this time of the year.

During the 2001 southwest monsoon, the Bay of Bengal was devoid of nitrate in the upper 30 m, while shoaling of 1  $\mu\text{M}$   $\text{NO}_3\text{-N}$  isopleth to 20 m was observed at 19 °N. A nitracline was observed between 50 and 100 m. Along the WB, shoaling of nitracline (1 $\mu\text{M}$  isopleths) occurred between 16 °N and 18 °N. Silicate distribution was similar to nitrate except for higher surface concentrations ( $> 2 \mu\text{M}$ ) in the north. A nitracline occurred between 40 and 60 m. A 2  $\mu\text{M}$  isopleth of silicate was observed in the surface waters at the southern stations, but decreased to ca 1  $\mu\text{M}$  towards the north in the CB. There were pockets of 2  $\mu\text{M}$  isopleths at 17 °N and 15 °N along the WB. Phosphate was undetectable in the upper 30 m at all stations. Shoaling of isotherms and nitracline north of 12 °N in the CB and at 19 °N along the WB was due to the presence of cold core eddies at these locations.

### *Assemblages*

A total of 153 phytoplankton taxa were identified from the samples collected during this study (Table 1). Diatoms were the major group contributing to over 97.5 %, while dinoflagellates contributed 1.69 % followed by silicoflagellates 0.33 %. The rest of the phytoplankton i.e. 0.48% were unidentifiable. The number of species of centric diatoms was greater than that of pennate diatoms. However, the abundance of pennate diatoms was more than that of centric diatoms

Among diatoms in the CB, *Thalassiothrix longissima* (20 %), *Thalassiothrix fauelfeldii* (16 %), *Nitzschia angularis* (8 %), *Chaetoceros coarctatus*, *Skeletonema costatum* and *Thalassionema nitzschooides* ( $>4$  % each) were the most dominant. *Nitzschia delicatissima*, *Coscinodiscus concinnus*, *Rhizosolenia styliformis* were  $\geq 2$  but  $\leq 3$  %. The most abundant species in the WB were, *T. fauelfeldii* and *T. longissima* forming 23 % each. *S. costatum*, *C. coarctatus* and *T. nitzschooides*, *Coscinodiscus radiatus*, were  $> 4$  % in numbers. *Nitzschia delicatissima* and *N.*

*angularis* contributed 3% and 2% respectively. Some organisms could be identified as diatoms but could not be identified to species level and are listed as unidentified diatoms (Table 1).

Only a few taxa of dinoflagellates were observed. Among them, *Ceratium furca* (0.6 %) and *Peridinium* sp (0.5 %) were the main ones. *Dictyocha crux* and *Dictyocha speculum* were the only two silicoflagellate species observed.

The nanophytoplankton were a minor fraction in the Bay. They were represented by the least abundant *Leptocylindrus minimus* (0.08% in CB and 0.01% in WB), *Chaetoceros danicus* (0.32%; found only in CB) and *Thalassiosira anguste-lineata* (0.02%; only in CB). Further, the contribution of picoplankton (that passes through 10 µm mesh [Hydro-Bios]) to total chlorophyll measured fluorometrically was negligible or at best <0.5% of total chl *a*. The 10 µm passing autofluorescing cells ranged from 2.40 to 16.70 X 10<sup>4</sup> l<sup>-1</sup> during this study.

A cluster analysis (Ward 1963) was performed to see whether a holistic picture was obtainable on phytoplankton variability between the stations. When all the species from all nine stations were subjected to this analysis, the clustering resolution was very poor (for example, most abundant species clustered together or, the least abundant skewed together) and difficult to interpret. Therefore, based on their abundance the species were categorized as most, moderate and least abundant as defined in methods and then subjected independently to cluster analysis. This analysis was useful for discerning relatedness among these three categories somewhat more clearly than when all species were taken together for cluster analyses. Results of cluster analysis are not shown here.

Only 10 species categorized as most abundant were found in the CB (see Fig 2). The moderately abundant species, numbering 20, were found throughout the transect except at the southernmost station 9 °N 88 °E. Among these, five species viz., *Thalassiosira condensate*, *Biddulphia sinensis*, *B. mobiliensis*, *Nitzschia delicatissima*, and *Chaetoceros lorenzianus* were found only north of 17 °N. *Coscinodiscus rothii*, *C. gigas*, *C. curvatulus* and *Plagiotropis lepidoptera* were present only at the southern most station. The least abundant species, 85 in all, were distributed throughout the CB from 9 °N to 20 °N mostly in the top 60 m. Interestingly, *Skeletonema costatum* in particular was found exclusively at the northernmost station (20 °N 88 °E). Further, *Coscinodiscus concinnus*, *Thalassiothrix fauencfeldii* and *Chaetoceros coarctatus*

were found north of 17 °N 88 °E only and were totally absent in the southern stations along the CB. Thus, it is likely that they also prefer the low saline waters.

As for the WB, four of the eight most abundant species viz., *Coscinodiscus radiatus*, *Thalassiothrix fauенfeldii*, *T. longissima*, and *Thalassionema nitzschioides* were present at all the stations (Fig 3). The other four species, *Chaetoceros coarctatus*, *Nitzschia delicatissima*, *N. angularis* and *Skeletonema costatum* were mostly in the two northern locations indicating their preferences to regions with <32 psu. Interestingly, *Skeletonema costatum* was the only species that was exclusively found in the northernmost stations of both CB and WB apparently preferring low saline waters. From the cluster analysis it was discernible that all 15 of the moderately abundant species (see serial numbers 21, 23, 26, 36, 51, 52, 70, 71, 88, 99, 110, 125, 127, 135 and 150 in Table 1) showed a restricted pattern of distribution.

The least abundant species constituted the bulk of the phytoplankton composition along both the CB and WB suggesting that they are responsible for high diversity in the Bay.

The lowest numbers of species were observed at 15° N 81° E, nearly half of the 153 species observed during this season in the Bay occurred at 17 °N 88 °E (Table 2). As expected, the maximum and minimum H' and SR corroborated with high and low numbers of species along both the transects. Overall, the diversity was higher in the CB (H': 4.93; SR: 10.43) compared to the WB (H': 4.18; SR: 7.29). It was also inferable that the northernmost stations, receiving large influx of river water, had greater H' and SR than the southern stations along both transects (Table 2).

#### *Phytoplankton abundance*

In the CB, the highest cell counts ( $13.8 \times 10^3$  cells L<sup>-1</sup> or  $13.8 \times 10^6$  cells m<sup>-3</sup>) were observed at 20°N 88°E. *Thalassiothrix fauенfeldii* (with  $10.5 \times 10^3$  cells L<sup>-1</sup> or 35.7% of the total counts) was the dominant species at this station. This was followed by *Thalassiothrix longissima* and *Skeletonema costatum* with  $5.5 \times 10^3$  and  $4.1 \times 10^3$  cells L<sup>-1</sup> (with their maxima between 20 and 40 m). In general, phytoplankton counts decreased with depth (Fig. 4). The subsurface chlorophyll maximum at 9 °N, the southern most station, was around 40 m and shoaled northerly

to 10 m at 20 °N. The subsurface chlorophyll maximum did not generally coincide (Fig. 4) with the phytoplankton abundance except at 20°N, the northernmost station.

In the WB (Fig.4), a subsurface maximum ( $23.2 \times 10^3$  cells L<sup>-1</sup>) was observed at 20 m at 19 °N 85 °E. *Thalassiothrix fauelfeldii* ( $17.8 \times 10^3$  cells L<sup>-1</sup> or 42% of total counts) and *Skeletonema costatum* ( $4.1 \times 10^3$  cells L<sup>-1</sup> or 12% of total) were the major species at this depth. Their maximal abundance were between 20 and 40 m, usually coinciding with subsurface chlorophyll maxima.

*Thalassiothrix longissima* and *Nitzschia angularis* were dominant at the southernmost station (9 °N 88 °E) with  $4.4 \times 10^3$  and  $3.5 \times 10^3$  cells L<sup>-1</sup> respectively, with a maximum density observed at the surface for both the species in the CB. *T. longissima* ( $13.4 \times 10^3$  L<sup>-1</sup>), *Coscinodiscus radiatus* ( $3.0 \times 10^3$  L<sup>-1</sup>) and *Thalassiothrix fauelfeldii* ( $1.6 \times 10^3$  cells L<sup>-1</sup>) were the dominant species in the southern WB. Their maximum numbers were between 40 and 60 m coinciding with the subsurface chlorophyll maxima.

Integrated abundance of phytoplankton cell counts for the upper 120 m for different stations decreased from 20 °N ( $37 \times 10^7$  cells m<sup>-2</sup>) to 15 °N ( $8.1 \times 10^7$  cells m<sup>-2</sup>) and thereafter, increased towards 9 °N ( $12.6 \times 10^7$  cells m<sup>-2</sup>) in the CB (Fig 5). Along the WB, abundance decreased southwards till 15 °N 81 °E and, thereafter, increased at 12 °N 81 °E. The integrated counts ranged from  $5.3 \times 10^7$  to  $82.1 \times 10^7$  cells m<sup>-2</sup> in the WB.

## DISCUSSION

The highest phytoplankton abundance was observed at the northernmost stations viz. 20 °N 88 °E in the CB and 19 °N 85 °E along the WB. This could be attributed to the high concentrations of silica (ca. 2µM and 4µM respectively) input from the rivers (Madhupratap et al. 2003). Apart from higher silica concentrations, the 1µM isopleth of NO<sub>3</sub> was also observed to shoal to less than 30 m along the WB between 16 °N to 18 °N (Madhupratap et al. 2003), resulting in higher phytoplankton abundance in the WB compared to the CB. Since the early days of phytoplankton ecology, nutrients have been known for controlling the phytoplankton community structure and biomass (Raymont 1980, Tilman 1982, and, see Gouda and Panigrahy 1996), which is also evident in the Bay during this study. That the nutrients have the greatest influence on phytoplankton abundance is clear from the strong negative correlation between phytoplankton abundance and nitrate ( $r = -0.73$ ;  $p < 0.005$ ), silicate ( $r = -0.62$ ;  $p < 0.005$ ) and phosphate ( $r = -$



0.57;  $p < 0.005$ ). When the phytoplankton become abundant, nutrients in the water column are low or undetectable. In the present study, as also observed from the coastal Bay by Gouda and Panigrahy (1996) and Panigrahi (2004), the diatoms (Bacillariophyceae) predominated owing mostly to the availability of adequate concentrations of silicate (Madhupratap et al. 2003).

Kricher (1972), De Jong (1975) and Ilangovan (1987) reported that an increase in diversity is a function of increasing species numbers, environmental heterogeneity and, incomplete mixing of waters. Also, low levels of nutrients (Tilman 1994, Huisman et al. 1999) are known to promote species diversity (Raymont 1980). The higher  $H'$  in the northern stations,  $20^{\circ}\text{N}$  and  $19^{\circ}\text{N}$ , might be explained by the intense stratification in the top layers. As Madhupratap et al. (2003) and Prasanna Kumar et al. (2004) report, this stratification leads to incomplete mixing and formation of low saline surface-lenses over the high saline waters. The greatest diversity noticed at  $17^{\circ}\text{N}$   $88^{\circ}\text{E}$  might be due to higher concentrations of nutrients, in particular below 60 m ( $\text{NO}_3$ : 0-27  $\mu\text{M}$ ;  $\text{PO}_4$ : 0-1.88  $\mu\text{M}$ ;  $\text{SiO}_4$ : 0-21  $\mu\text{M}$ ).

The phytoplankton composition showed a number of temperate - tropical and tropical species (Table 1). *Thalassiothrix fauenfeldii*, *Biddulphia longicuris*, *Chaetoceros diversus*, *C. messanensis*, *C. eibonii*, *Bacteriastrum comosum*, are the known temperate-tropical species observed in the Bay. While some of them, such as *Corethron criophilum*, *Coscinodiscus asteromphalus*, *Rhizosolenia stolterfothii*, *R. styliformis*, *R. hebetata*, *Bacteriastrum delicatulum*, *B. furcatum*, *B. hyalinum*, *Eucampia zodiacus*, *Ditylum brightwellii*, *Biddulphia mobiliensis*, *Thalassiothrix longissima*, *Chaetoceros socialis*, *C. curvisetus*, were some of the known temperate and/or polar/cosmopolitan species found during this study in the Bay of Bengal.

All the species observed during this study have been previously reported in Indian waters by Subramanyan et al. (1946, 1961, 1968), Desikachary (1986, 1987), Menon (1945) and Ilangovan (1987). In this respect, the phytoplankton in the Bay of Bengal is composed of a wide mix of species belonging to various biogeographical realms. This could be due to its being open to the Equatorial Indian Ocean, the Arabian Sea, also to the Pacific Ocean via the Malacca Strait. Approximately 50,000 ships traverse this Strait annually. The Bay of Bengal with many ports receiving ships from the world over can add to microphytoplankton communities (through transport on their hulls and in ballast water) in the generally oligohaline regimes of the Bay north of  $10^{\circ}\text{N}$ . It is well recognized that each species is a variable and, on the basis of its relationship

with other species, the patterns of structure emerge (Sokal and Rolf 1981) that implicitly describes the assembling or grouping at related species.

Higher silicate concentrations in the north of 18 °N appear to be important in sustaining higher abundance of phytoplankton in the Bay. Further, the ubiquity and sheer abundance of *T. fauensis* and *T. longissima* in the Bay seem to be important in contributing to dimethyl sulphide (DMS) concentrations in the Bay. Although diatoms are considered to be insignificant in DMS production (Liss et al. 1993), there was a strong relationship between *T. fauensis* and the DMS concentrations in the Bay during the sampling period (Shenoy et al. 2006). Contribution of diatoms to DMS production and fluxes may be lower compared to coccolithophores, prymnesiophyceans (*Phaeocystis* spp) and dinoflagellates.

Presence of high numbers of *Thalassiothrix longissima* and *Nitzschia angularis* appear to contribute in a large way to the biomass along both transects as well as to the material fluxes. Ramaswamy and Nair (1994) reported the highest particle flux and organic carbon to carbonate carbon ratios in the deep traps being during the summer monsoon. Although there can be inter-annual differences in the dominant flora, it is possible to suggest that the large sizes, chain forming characteristics and predominance of microphytoplankton such as *T. longissima*, *Coscinodiscus radiatus* and *Thalassiothrix fauensis*, among others, are important for material fluxes to the deep. The percentage contribution of Dinophyta to the total microphytoplankton counts was not very high. We think that their abundance is low in the Bay of Bengal. The 25 fold concentration of the water samples and careful screening of the entire 1000 cells in the Sedgewick-rafter are adequate for measuring the abundance of microphytoplankton in general. However, further confirmation of low abundance of Dinophyta will be useful.

The abundant pennate diatoms viz., *T. longissima*, *T. fauensis* and *Navicula angularis* usually with high surface to volume ratio might be absorbing nutrients rapidly. But, the highly diverse centric diatoms viz., (*Skeletonema*, *Coscinodiscus*, *Chaetoceros*, etc., with low surface to volume ratio) might begin multiplying after the optimal nutrient concentrations are attained. Mixture of these communities, therefore, may be well suited to inhabit the low nutrient, generally stratified upper water column in the Bay. Although this is the first detailed phytoplankton compositional analysis from the offshore Bay, it is possible to suggest that the hydrographic conditions during the monsoon months of June-September permit non-competitive-coexistence of diverse

microphytoplankton in this nutrient-limited regime. It is probable that the abilities of different species of phytoplankton to utilize nutrients and other essential inorganic compounds effectively at low concentrations account for the high diversity in the Bay. It is also well known that oligotrophic waters are more diverse compared to mesotrophic and/or eutrophic waters (Raymont, 1980). From the abundance of many species at certain depths, they appeared to be stratified by depth. However, it is difficult to recognize any one depth as their stratum in different locations or regions.

Contrastingly, all four of the most dominant species (i.e., *Skeletonema costatum*, *Coscinodiscus radiatus*, *T. longissima*, *T. fauelfeldii*) during the monsoon 2001 were very low in abundance during the post-monsoon months of September-October 2002 (unpublished data). For example, the total number of species along the cruise tracks of this study area during the post monsoon months of September-October 2002 were 129 and those during the pre monsoon months of April-May 2003 were 69. During the post monsoon, species such as *Thalassionema nitzschioides*, *Navicula* sp, *Rhizosolenia styliformis*, *Synedra hennedyna*, *Rhizosolenia shrubsolei*, *Rhizosolenia* sp, *Chaetoceros didymus*, *Pseudonitzschia* sp, *Thalassiothrix fauelfeldii*, *Thalassiosira* sp were the most abundant ( $\geq 2\%$ ) in the CB. *Chaetoceros lorenzianus*, *C. curvisetus*, *Navicula* sp, *Thalassiosira* sp, *T. gravida*, *Chaetoceros eibenii*, *Ditylum brightwelli*, *Chaetoceros didymus*, *Pseudonitzschia* sp, *Nitzschia longissima*, *Chaetoceros coarctatus*, *C. paradoxus* were the most abundant in the WB. During the pre monsoon, *Navicula* sp, *Coscinodiscus* sp, *Pseudonitzschia* sp, *Leptocylindrus mediterraneans*, *Thalassionema nitzschioides*, *Navicula distans*, *Rhizosolenia cylindrus*, *Fragilariopsis doliolus* and *Trichodesmium* sp, were the most abundant ones in the CB. *Chaetoceros didymus*, *Navicula* sp, *Bacteriastrum comosum*, *B. furcatum*, *B. hyalinum*, *Chaetoceros curvisetus*, *Rhizosolenia striata*, *R. cylindrus*, *Navicula messanensis*, *Rhizosolenia flaccida*, *Stephanopyxis palmeriana*, *Chaetoceros* sp, *Nitzschia* sp were the most abundant in the WB.

Few detailed analyses of microphytoplankton communities from the offshore regions in the tropics are available. For this reason it is not possible to compare the results of this study with existing literature. From the Arabian Sea, Sawant and Madhupratap (1996) reported that the most abundant diatoms during the summer monsoon were, *Thalassiothrix longissima* (22%), *Chaetoceros* sp (5%), *Rhizosolenia* sp (5%), *Rhizosolenia stolterfothii* (4%), *Nitzschia serriata*

(4%) and *Thalassiosira* sp (2%). Interestingly, the same species, *T. longissima* contributed up to 20 and 23% in the CB and WB respectively in the Bay of Bengal. Apparently, oligohaline waters (<30 psu) and warm temperatures around 28-30 °C at this location are ideal for *Skeletonema costatum*. Low salinity near-coastal tropical regions are reported to aid the proliferation of this species (Mitbavkar and Anil 2000, Babu et al. 2001). Apart from a few commonalities, the phytoplankton composition in these hydrographically differing areas is quite different. From these observations it is suggested that the hydrological regimes of the Bay strongly influence the microphytoplankton communities. In general, the abundance of pennate diatoms was more abundant in the CB compared to the abundance of centric diatoms in the more productive northern locations and the WB. Thus, there appears to be a basic difference between near shore flora and offshore flora.

#### ACKNOWLEDGEMENTS:

We thank the Department of Ocean Development, New Delhi for financial support for this research under the Bay of Bengal Process Studies programme. We thank Dr. Aditi Pant, Dr. N. Anand, University of Madras and V.T. Shridharan, Reader, University of Tiruchirapally for confirming the identification of many phytoplankton species. JTP and VF acknowledge the Council of Scientific and Industrial Research, New Delhi for an award of Senior Research Fellowship. We are grateful to Late Dr. M. Madhuratap for his leadership and many advices. The crew and all participants of SK 166 are thanked for their help. Comments of three anonymous reviewers were very helpful in improving this ms. This is NIO contribution No: (will be provided after final acceptance of the ms).

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Table 1: Phytoplankton composition (% of total counts) along the central bay (CB) and western bay (WB) during summer monsoon 2001 in the Bay of Bengal.

Serial No	Phytoplankton	CB	WB	Serial No	Phytoplankton	CB	WB
	<b>Centric Diatoms</b>				<b>Centric Diatoms</b>		
1	<i>Actinocyclus octonarius</i>	-	0.31	80	<i>Thalassiosira antarctica</i> <sup>§</sup>	0.05	-
2	<i>Asteromphalus flabellatus</i> *	0.08	-	81	<i>Thalassiosira baltica</i> *	-	0.31
3	<i>Bacteriastrium comosum</i> <sup>+,*</sup>	0.14	0.37	82	<i>Thalassiosira condensate</i> *	0.63	-
4	<i>Bacteriastrium delicatulum</i> *	0.20	-	83	<i>Thalassiosira convexa</i> *	0.24	-
5	<i>Bacteriastrium furcatum</i> <sup>§</sup>	0.39	0.42	84	<i>Thalassiosira eccentrica</i> *	0.13	-
6	<i>Bacteriastrium hyalinum</i> <sup>*,§</sup>	0.13	0.29	85	<i>Thalassiosira gracilis</i>	-	0.14
7	<i>Bacteriastrium mediterranean</i>	-	0.07	86	<i>Thalassiosira gravida</i> <sup>§,*</sup>	0.20	0.11
8	<i>Biddulphia mobiliensis</i> <sup>*,§</sup>	1.07	0.46	87	<i>Thalassiosira lineate</i> *	-	0.07
9	<i>Biddulphia granulate</i>	0.03	-	88	<i>Thalassiosira sp</i>	-	1.19
10	<i>Biddulphia longicuris</i> <sup>+,*</sup>	-	0.19	89	<i>Thalassiosira trifulta</i>	0.08	-
11	<i>Biddulphia rhombus</i> *	0.02	-	90	<i>Triceratium weissei</i>	-	0.05
12	<i>Biddulphia sinensis</i> *	0.67	0.44		<b>Pennate</b>		
13	<i>Chaetoceros affinis</i> *	0.02	-	91	<i>Achnanthes brevipes</i> *	0.04	-
14	<i>Chaetoceros bacteriostriodes</i>	0.02	-	92	<i>Amphora ventricosa</i>	0.03	-
15	<i>Chaetoceros coarctatus</i> *	3.92	4.77	93	<i>Fragilariopsis cylindrus</i>	0.38	-
16	<i>Chaetoceros curvisetus</i> <sup>*,§</sup>	0.03	-	94	<i>Fragilaria striatula</i>	0.23	-
17	<i>Chaetoceros crinitus</i>	0.10	-	95	<i>Grammatophora kerguelensis</i>	0.05	-
18	<i>Chaetoceros danicus</i> *	0.32	-	96	<i>Grammatophora marina</i> *	0.13	-
19	<i>Chaetoceros didymus</i> *	-	0.19	97	<i>Licomophora</i> *	0.11	-
20	<i>Chaetoceros difficilis</i> *	0.05	-	98	<i>Mastogloia rostrata</i>	0.01	-
21	<i>Chaetoceros diversus</i> <sup>+,*</sup>	1.66	0.52	99	<i>Navicula directa</i> *	0.32	0.85
22	<i>Chaetoceros distans</i> *	0.08	-	100	<i>Navicula distans</i> *	0.11	-
23	<i>Chaetoceros eibeni</i> <sup>+,*</sup>	2.37	0.95	101	<i>Navicula fusiformis</i> <sup>*,+</sup>	0.07	-
24	<i>Chaetoceros gracilis</i>	0.01	-	102	<i>Navicula granii</i> <sup>§</sup>	0.11	-
25	<i>Chaetoceros lauderi</i> *	0.05	-	103	<i>Navicula gracilis</i> *	-	0.07
26	<i>Chaetoceros lorenzianus</i> *	1.99	1.73	104	<i>Navicula gutata</i>	0.23	-
27	<i>Chaetoceros messanensis</i> <sup>+,*</sup>	-	0.10	105	<i>Navicula monilifera</i> <sup>+</sup>	0.05	-
28	<i>Chaetoceros socialis</i> <sup>*,§</sup>	-	0.11	106	<i>Navicula naviculaus</i>	-	0.11
29	<i>Chaetoceros subtilis</i> *	-	0.10	107	<i>Navicula pelagica</i> <sup>§</sup>	0.54	-
30	<i>Chaetoceros tortissimus</i> <sup>**</sup>	0.04	-	108	<i>Navicula peregina</i> *	-	0.21
31	<i>Chaetoceros peruvianus</i> *	0.31	-	109	<i>Navicula radiosa</i> *	-	0.04
32	<i>Climacodium biconcavum</i> *	0.21	-	110	<i>Navicula rectangulata</i>	-	1.07
33	<i>Corethron criophilum</i> <sup>*,§</sup>	0.03	0.06	111	<i>Navicula rhyncocephala</i> *	-	0.14
34	<i>Coscinodiscus asteromphalus</i> <sup>*,§</sup>	0.24	-	112	<i>Navicula sp</i>	0.25	0.34
35	<i>Coscinodiscus curvatulus</i> *	0.65	-	113	<i>Navicula tuscula</i> <sup>+</sup>	0.13	-
36	<i>Coscinodiscus concinnus</i> *	2.95	1.01	114	<i>Navicula lyra</i> *	0.04	-
37	<i>Coscinodiscus gemmatulus</i> *	-	0.11	115	<i>Navicula schumanniana</i>	-	0.10
38	<i>Coscinodiscus gigas</i> *	0.87	-	116	<i>Navicula vanhoeffenii</i>	-	0.19
39	<i>Coscinodiscus jonesianus</i> *	0.01	0.06	117	<i>Navicula viridula</i> <sup>+</sup>	0.04	-
40	<i>Coscinodiscus lewisianus</i> <sup>**</sup>	0.83	-	118	<i>Nitzschia angularis</i> *	8.55	2.28
41	<i>Coscinodiscus lineatus</i> *	-	0.11	119	<i>Nitzschia angusta</i> *	0.23	0.07
42	<i>Coscinodiscus minor</i>	0.41	0.15	120	<i>Nitzschia delicatissima</i> *	1.85	3.61
43	<i>Coscinodiscus radiatus</i> *	3.62	4.37	121	<i>Nitzschia fasciculata</i>	-	0.74
				122	<i>Nitzschia fossilis</i>	0.08	-

44	<i>Coscinodiscus rothii</i> *	1.37	-	123	<i>Nitzschia insignis</i>	-	0.14
45	<i>Coscinodiscus insignis</i>	0.13	-	124	<i>Nitzschia interruptestriata</i>	0.30	-
46	<i>Coscinodiscus subtilis</i> *	0.06	-	125	<i>Nitzschia longissima</i> *	0.35	1.50
47	<i>Coscinodiscus sp</i> *	0.69	0.40	126	<i>Nitzschia macilenta</i>	0.05	-
48	<i>Coscinodiscus superbus</i>	0.23	0.13	127	<i>Nitzschia marina</i>	-	0.93
49	<i>Cylindrotheca closterium</i> *	0.08	-	128	<i>Nitzschia paradoxa</i>	-	0.21
50	<i>Denticulopsis lauta</i> **	0.22	0.19	129	<i>Nitzschia pelagica</i> *	-	0.15
51	<i>Denticulopsis seminae</i> *	1.42	1.20	130	<i>Nitzschia sigma</i> *	0.01	-
52	<i>Ditylum brightwelli</i> *.s	0.91	1.84	131	<i>Nitzschia socialis</i> *	0.75	0.15
53	<i>Ditylum sol</i> *	0.49	0.41	132	<i>Nitzschia reinholdii</i> *	0.32	-
54	<i>Ethmodiscus sp</i> **	0.08	-	133	<i>Nitzschia ventricosa</i>	0.01	-
55	<i>Eucampia balaustium</i>	0.05	-	134	<i>Nitzschia sp</i>	0.06	0.31
56	<i>Eucampia zodiacus</i> **.*s	0.01	0.33	135	<i>Synedra affinis</i> *	-	0.97
57	<i>Hemiaulus sinensis</i> *	0.61	0.26	136	<i>Synedra tabulata</i> *	0.05	-
58	<i>Hyalodiscus nobilis</i> **	0.11	-	137	<i>Thalassionema oestrupii</i> *	0.09	0.14
59	<i>Hyalodiscus stelliger</i> **	0.12	0.04	138	<i>Thalassionema nitzschioides</i> *	4.65	4.92
60	<i>Leptocylindrus minimus</i> *	0.08	0.01	139	<i>Thalassiothrix fauencfeldii</i> *.*	16.21	23.55
61	<i>Plagiotropis lepidoptera</i>	0.65	-	140	<i>Thalassiothrix longissima</i> *.*s	20.29	23.58
62	<i>Planktoniella sol</i> *	0.28	0.10		<b>Unidentified</b>		
63	<i>Pleurosigma fomosum</i>	0.21	-	141	diatom 1	0.05	0.07
64	<i>Rhizosolenia alata</i> *	0.26	0.23	142	diatom 2	0.03	-
65	<i>Rhizosolenia hebetata</i> *.*s	0.04	-	143	diatom 3	0.40	0.37
66	<i>Rhizosolenia imbricata</i> *	0.06	-		<b>Dinoflagellate</b>		
67	<i>Rhizosolenia robusta</i> **	0.01	-	144	<i>Amphisolenia bidentata</i> *	0.07	-
68	<i>Rhizosolenia setigera</i> *	-	0.15	145	<i>Ceratium furca</i> *	0.60	0.41
69	<i>Rhizosolenia shrubsolei</i> *	0.01	0.11	146	<i>Ceratium trichoceros</i> *	0.20	-
70	<i>Rhizosolenia stolterforthii</i> *.*s	0.46	1.16	147	<i>Oxytosum sp</i> *	-	0.06
71	<i>Rhizosolenia styliformis</i> *.*s	2.22	1.93	148	<i>Peridinium sp</i> *	0.53	-
72	<i>Rhizosolenia sp</i>	-	0.13	149	<i>Prorocentrum micans</i> *	0.14	0.14
73	<i>Skeletonema costatum</i> *	4.42	4.35	150	<i>Pseudoceratium punctatum</i>	-	0.63
74	<i>Streptothecha thamensis</i>	0.47	-	151	<i>Pyrocystus lunula</i> *	0.15	
75	<i>Striatella delicatula</i>	-	0.04		<b>Silicoflagellates</b>		
76	<i>Surirella anceps</i> *	-	0.06	152	<i>Dictyocha cruz</i>	0.33	
77	<i>Surirella cruciata</i> *	-	0.06	153	<i>Dictyocha speculum</i>	-	0.03
78	<i>Surirella fastuosa</i> *	0.12	0.03		<b>Total abundance</b>	<b>91928</b>	<b>92993</b>
79	<i>Thalassiosira anguste-lineata</i> *	0.02	-		<b>Total percentage</b>	<b>100</b>	<b>100</b>

\*reported mostly from tropical regions; \*\* from subtropical regions; + from tropical and/or temperate regions; \$ from temperate and/or polar regions. Any combination of symbols denotes the reports from both/all of those regions

Table 2: Diversity indices ( $H'$ ), species richness, ranges of phytoplankton cell counts (no.  $\times 10^3 L^{-1}$ ), chlorophyll  $a$  (Chl  $a$ ,  $mg m^{-3}$ ) and the most dominant species at different sampling locations in the Bay of Bengal during the 2001 summer monsoon

Station	$H'$	Species richness	PPCC (range; no. $\times 10^3 L^{-1}$ )	Chl $a$ ; $mg m^{-3}$ (range)	Most dominant species (%)
9° N 88°E	2.83	1.62	0.05- 4.80	0.02-0.19	<i>Thalassiothrix longissima</i> (36.47)
12° N 88°E	3.45	2.50	0.08- 3.90	0.02-0.14	<i>Thalassiothrix longissima</i> (42.17)
15° N 88°E	3.74	2.82	0.05- 2.35	0.01-0.16	<i>Thalassiothrix longissima</i> (17.39)
17° N 88°E	4.58	6.85	0.06- 8.59	0.01-0.15	<i>Thalassiothrix fauencfeldii</i> (17.41)
20° N 88°E	4.01	5.19	0.11-13.83	0.01-0.28	<i>Thalassiothrix fauencfeldii</i> (29.04)
19°N 85°E	4.00	4.88	0.11-10.75	0.02-0.36	<i>Thalassiothrix fauencfeldii</i> (31.58)
17°N 83°E	3.60	3.32	0.10- 3.20	0.01-0.36	<i>Thalassionema nitzschioides</i> (20.16)
15°N 81°E	2.93	1.63	0.78- 1.14	0.04-0.19	<i>Thalassiothrix longissima</i> (28.1)
12°N 81°E	2.71	2.02	0.10- 3.70	0.01-0.17	<i>Thalassiothrix longissima</i> (60.48)

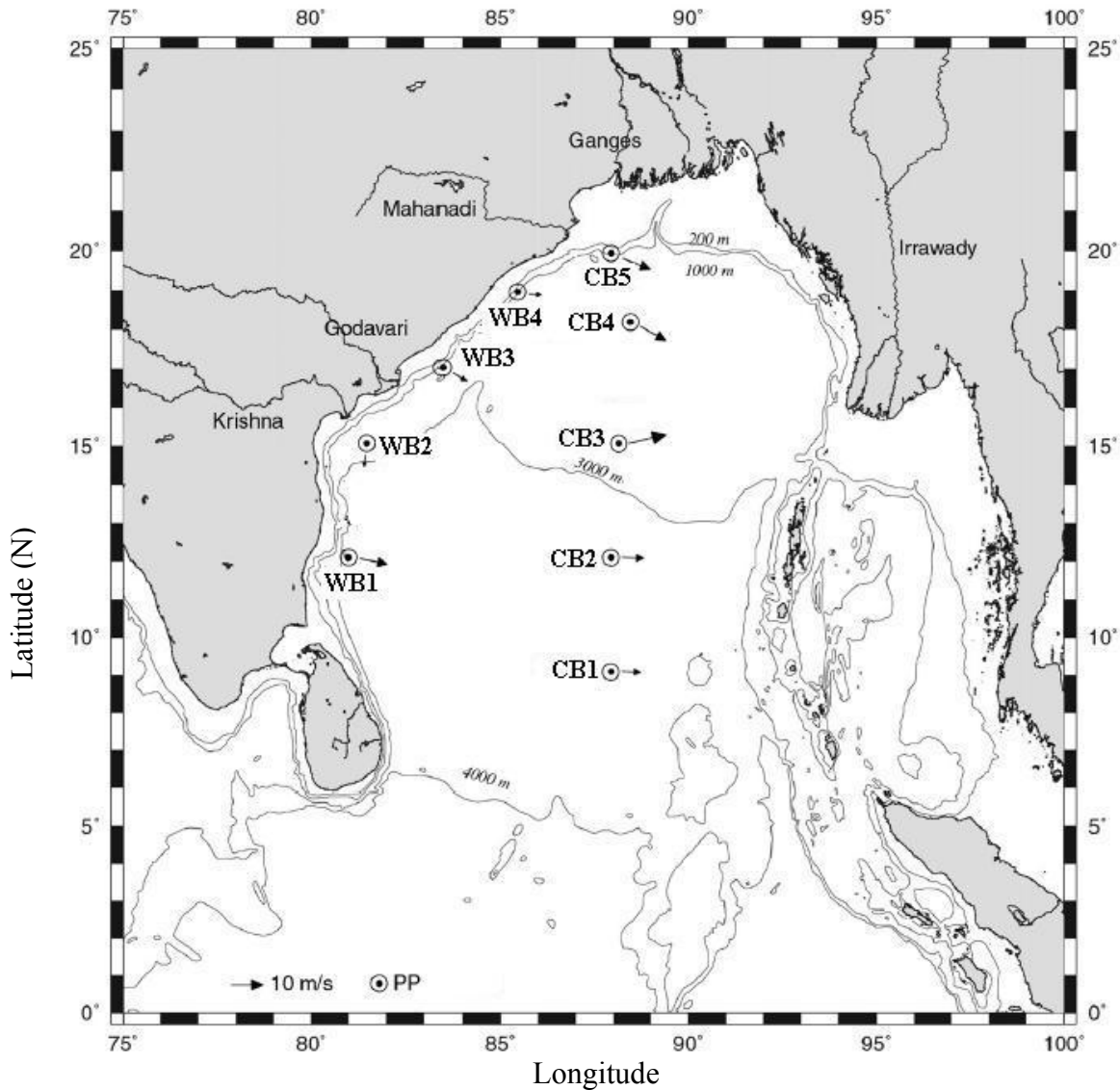
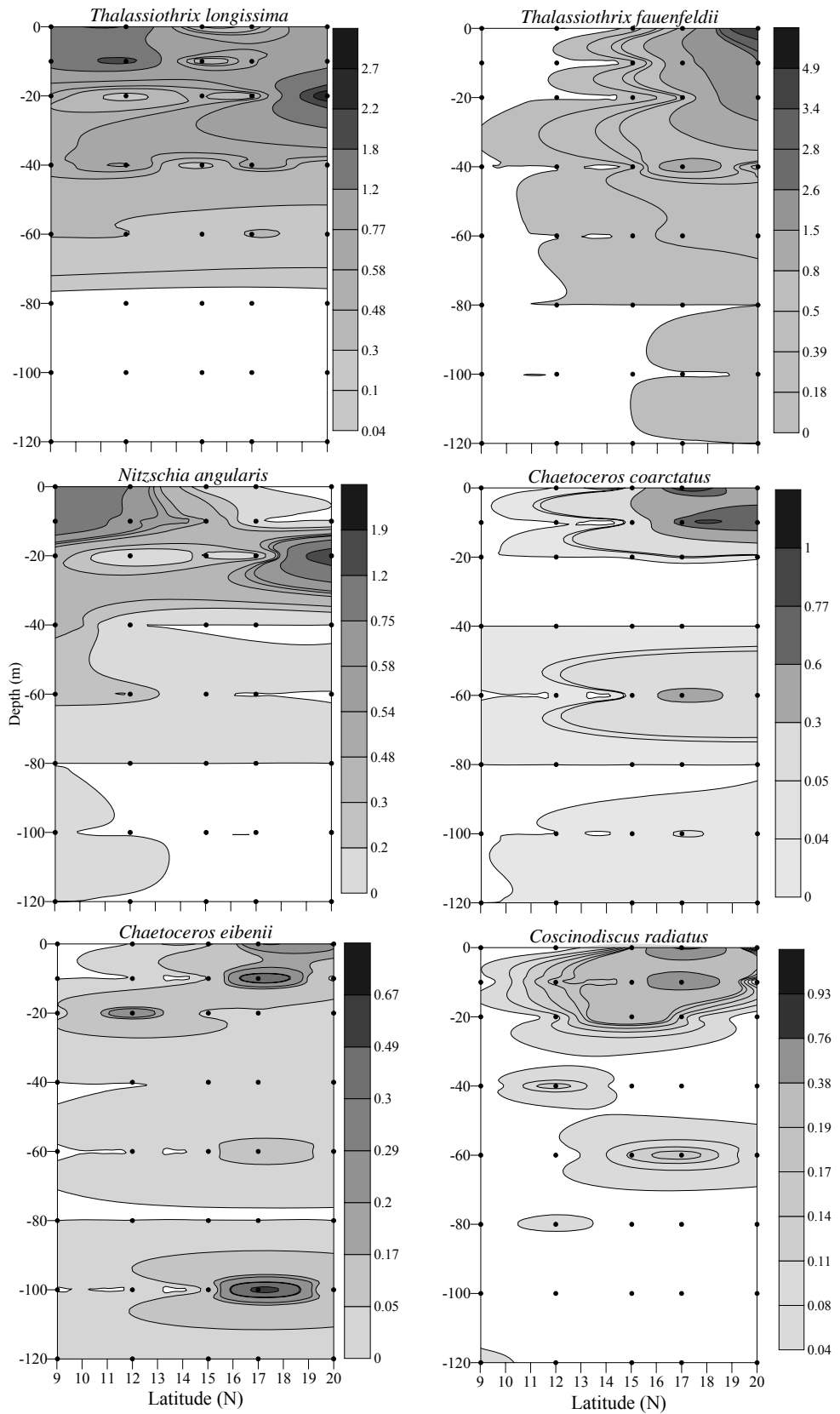


Fig 1: Map showing the locations sampled during the 2001 summer monsoon for analyzing phytoplankton cell counts, chl *a* and primary productivity in the Central (along 88°E) and Western Bay of Bengal. The arrows indicate the observed wind vectors at the sampling locations. Figure modified from Madhupratap et al (2003).

Jane et al Fig 1



Jane et al Fig 2.....continued..

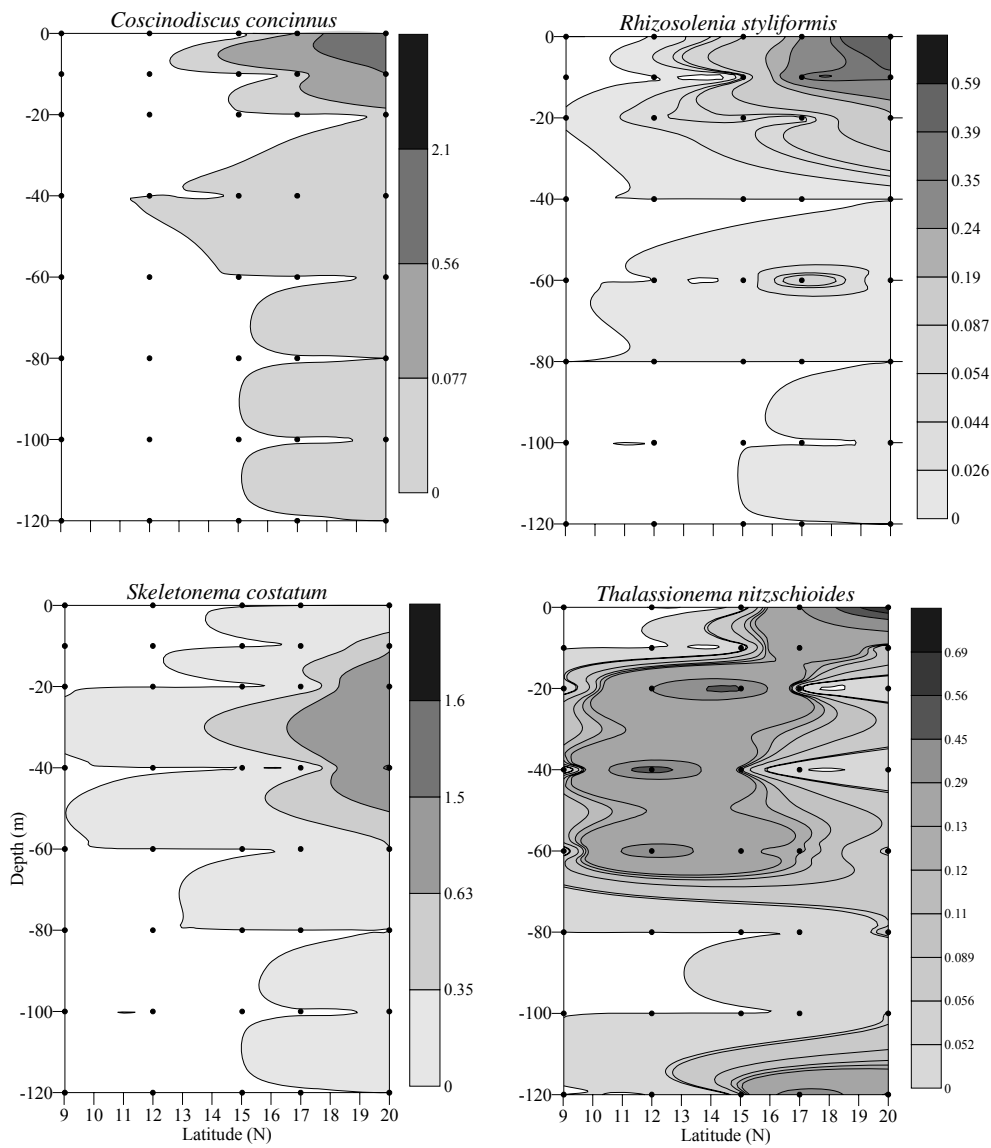


Fig 2: Spatio-vertical distribution of the most abundant microphytoplankton species in Central Bay during the 2001 summer monsoon in the Bay of Bengal

Jane et al Fig 2

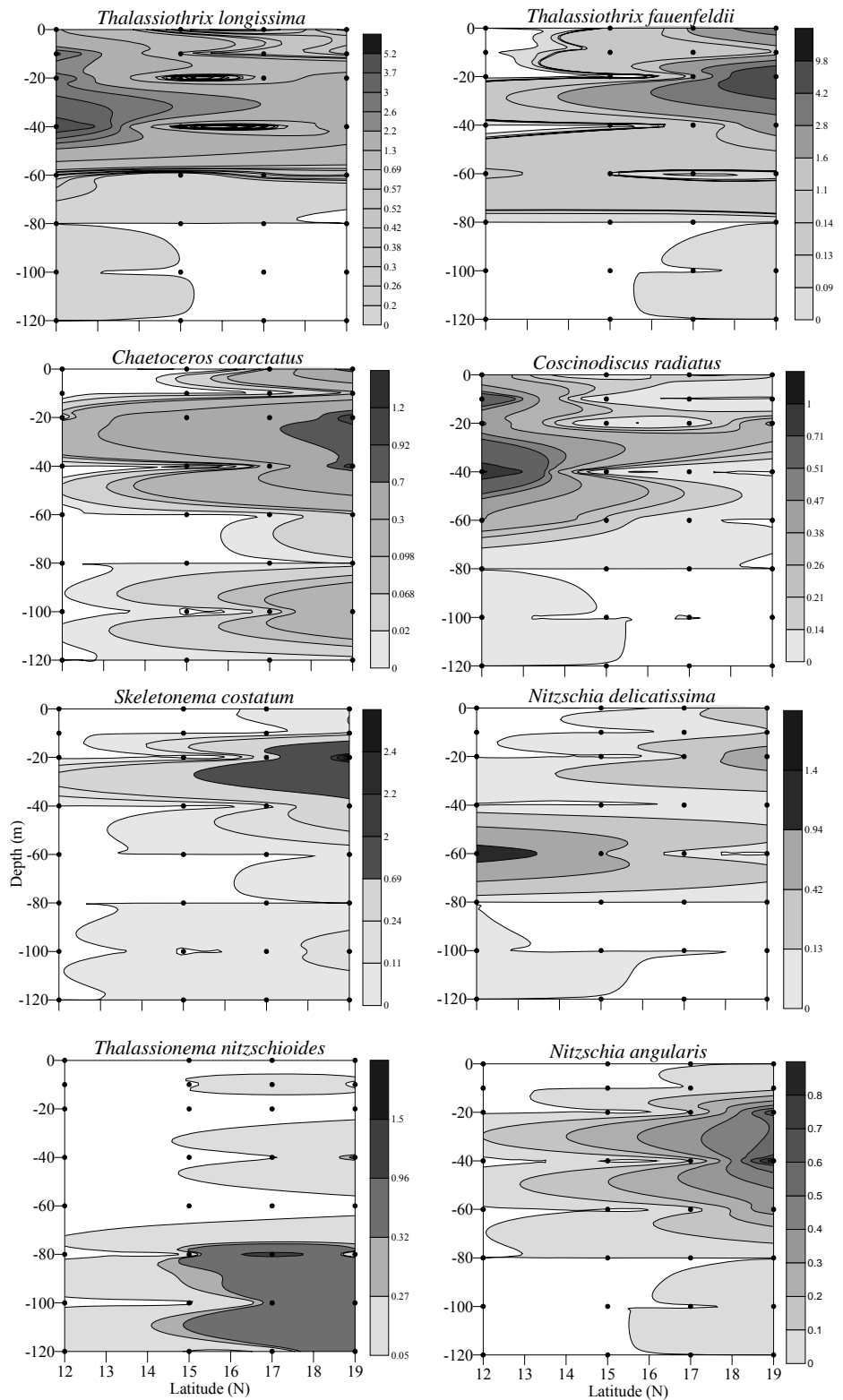
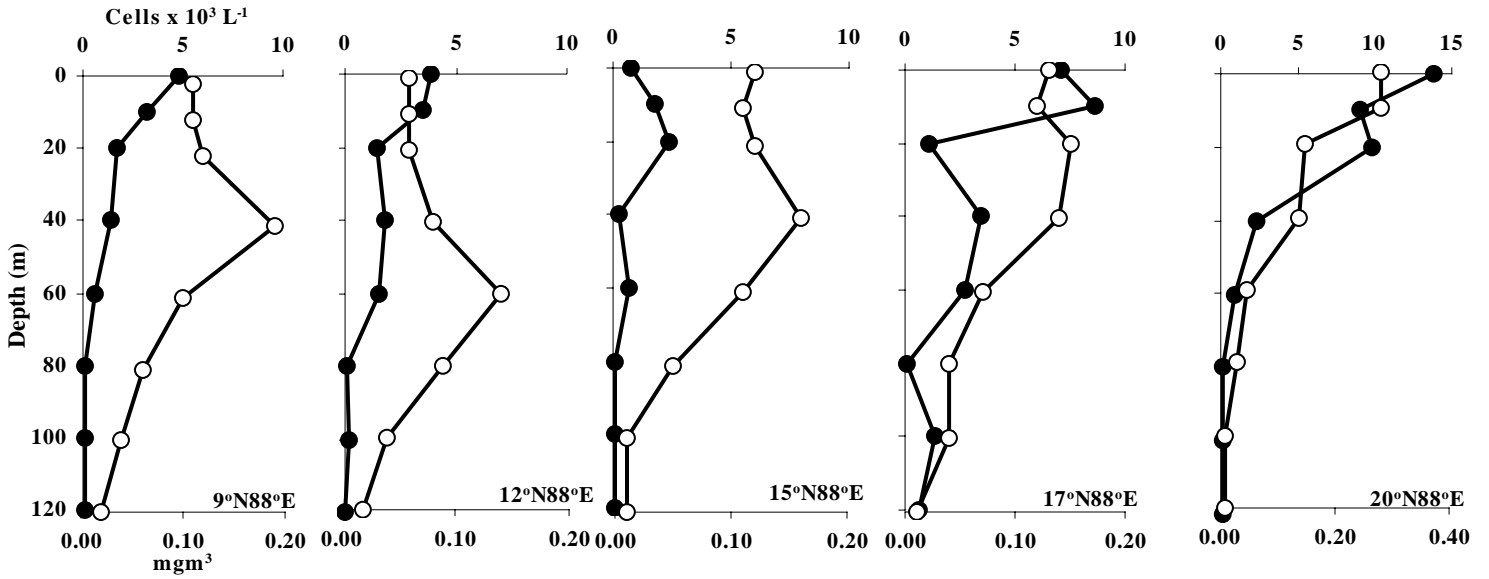


Fig 3: Spatio-vertical distribution of the most abundant microphytoplankton in the Western Bay of Bengal during the 2001 summer monsoon  
Jane et al Fig 3

a) Central Bay



b) Western Bay

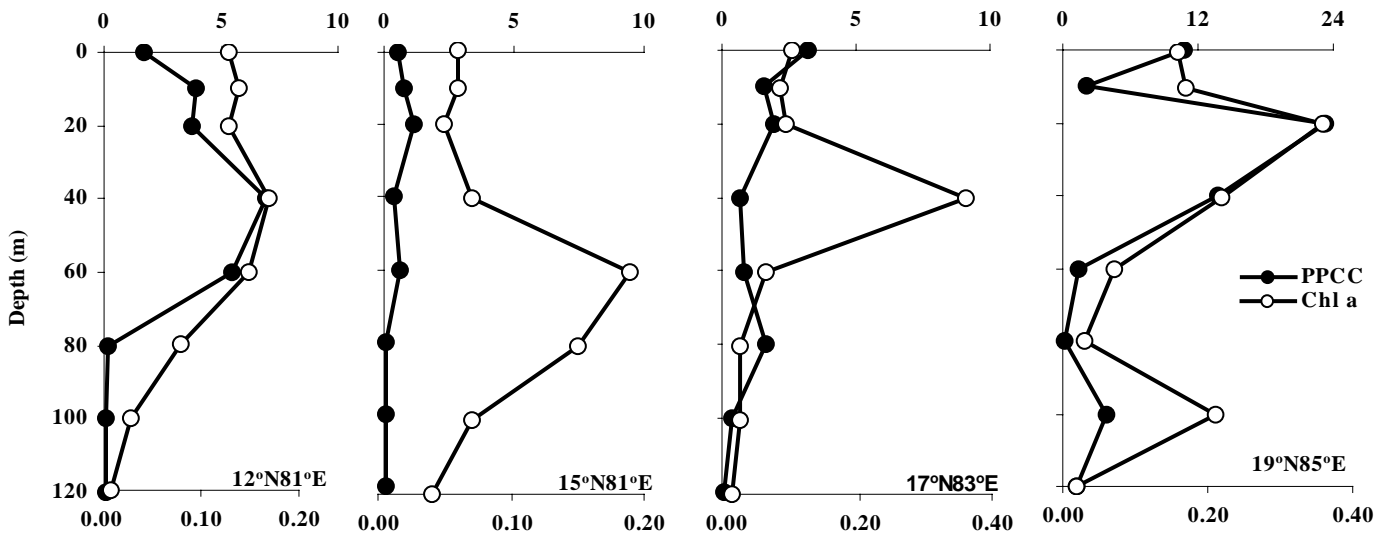


Fig 4: Abundances of phytoplankton (PPCC, cells  $\times 10^3 L^{-1}$ ) and chlorophyll *a* (Chl *a*,  $mgm^{-3}$ ) in the Central and Western Bay of Bengal during the 2001 Summer monsoon



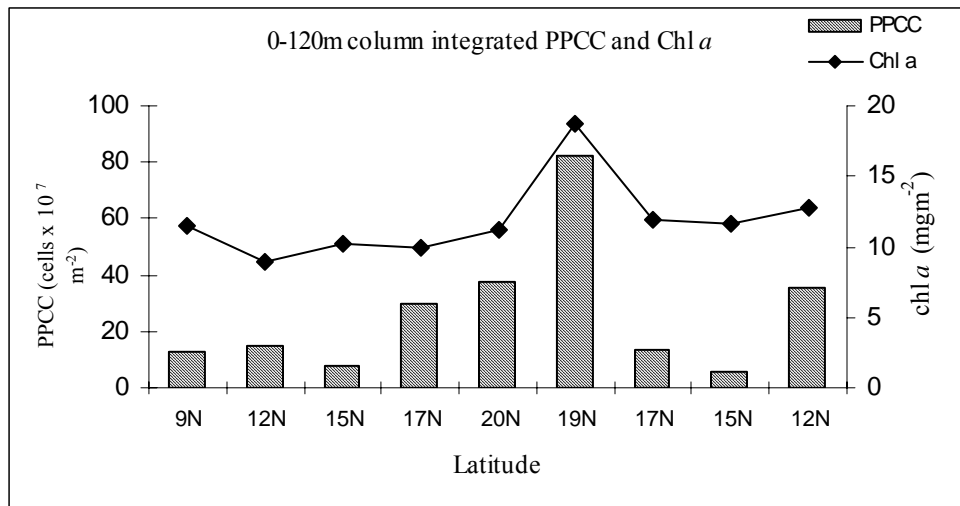


Fig 5: The 0-120m column integrated phytoplankton abundance (PPCC, cells  $\times 10^7 \text{ m}^{-2}$ ) and chlorophyll a (chl *a*, mgm $^{-2}$ ) in the Bay of Bengal during the 2001 summer monsoon.

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