Ecological and Experimental Analyses of Phytoplankton Dynamics in the Bay of Bengal

Thesis submitted to Goa University

For the degree of

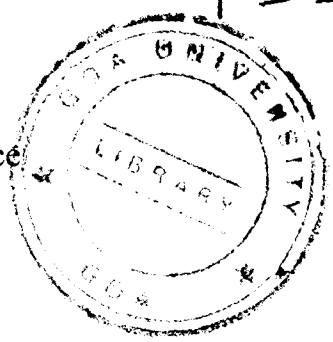
Doctor of Philosophy

in

Marine Sciences

By

Miss. Jane Theophline Paul, M. Sc.



Under the Guidance

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CERTIFICATE

This is to certify that **Ms. Jane Theophline Paul** has duly completed the thesis entitled **'Ecological and Experimental Analyses of Phytoplankton Dynamics in the Bay of Bengal'** under my supervision for the award of the degree of Doctor of Philosophy.

This thesis being submitted to the Goa University, Taleigao Plateau, Goa for the award of the degree of Doctor of Philosophy in Marine Sciences is based on original studies carried out by her.

The thesis or any part thereof has not been previously submitted for any other degree or diploma in any Universities or Institutions.

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Certified that all corrections suggested by the examiners have been incorporated.

4/12/09

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DECLARATION

As required under the University Ordinance 0.19.8 (iv), I hereby declare that the present thesis entitled '**Ecological and Experimental analyses of Phytoplankton dynamics in the Bay of Bengal'** is my original work carried out in the National Institute of Oceanography, Dona-Paula, Goa and the same has not been submitted in part or in full elsewhere for any other degree or diploma. To the best of my knowledge, the present research is the first comprehensive work of its kind from the area studied.

Jane Theophline Paul

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Dedicated To My
Beloved Parents

Table of Contents

Chapter 1

Chapter 1

General Introduction

Much before Victor Hensen, a professor at Kiel University who led the first German 'Plankton Expedition' on board the *National*, coined the term 'plankton' in 1887, there were inquisitive individuals who studied marine plankton. The first person to have studied them was, J. Vaughan Thompson, a surgeon and an amateur naturalist. Back in 1828, he collected plankton by towing a simple fine meshed net off the coast of Ireland. His studies resulted in the first description of the planktonic stages of crabs. This was followed by Charles Darwin, who also used a similar net to collect marine plankton during his voyage on the *Beagle* during 1831-1836. Later in 1847, Joseph Hooker recognized that the diatoms collected in plankton nets were plants and suggested that they played the same ecological role in the sea as green plants do on the land. The *Challenger* Expedition, 1872-76, collected samples from across the world oceans for detailed analyses. The word plankton was more critically defined in 1890 by Ernst Haeckel, and today, globally all drifting organisms are called planktons including photo-synthesizers, which are termed as 'Phytoplankton'.

'Phytoplankton', taken from the Greek word '*Phytos*'-plant and '*Planktos*'- free floating, are ubiquitous free-floating microscopic and aquatic photosynthetic organisms. They form the base of aquatic food chain and are major fixers of atmospheric carbon through the process of photosynthesis. Consisting both eukaryotic and prokaryotic species, their role in the marine food chain is of paramount importance. They are usually abundant in the top layers of the water column, in the euphotic depth.

Significance of phytoplankton

The most essential factor binding an ecosystem is the constant transfer of energy over different trophic levels. Thus, in the approach to ecosystem *vis-à-vis* trophic dynamics, we try to measure the production in terms of either biomass or organic carbon content in each trophic level.

The phytoplankton biomass is measured in terms of chlorophyll. Photosynthesis is closely linked to total chlorophyll. Chlorophyll pigments exist in several closely allied forms in algae. Chlorophylls have their maximum absorption in the red (650 to 700 nm) and in the blue-violet (ca. 450 nm) ranges of the spectrum. The effective range for all the photosynthetic pigments thus falls in the 400 to 700 nm, the "visible" range in solar radiation (Round 1973). With the help of these pigments, phytoplankton fix the inorganic carbon and convert it into organic carbon by the process of photosynthesis. The rate at which photosynthesis occurs in the ocean is termed as gross primary production and excess of gross production minus the respiration of phytoplankton is net primary production. The net production is also the amount of organic carbon made available to next higher trophic level. A considerable part of the global primary production is by marine phytoplankton (40%; Falkowski 1994) of which diatoms are the major primary producers and are thought to be responsible for up to 25% of the world's net primary productivity (Jeffrey & Hallegraeff 1990).

Two methods have been used for the measurements of primary production, viz; oxygen method and carbon isotope method. Of these, the ^{14}C method developed by Steemann Nielsen (1952) has been the method of choice to estimate photosynthesis in the open ocean because of its sensitivity and ease of use. Although the method has its advantages, there are many limitations to this method as listed out by Stickland & Parsons (1972). For example, the effects of confinement in the bottle, contamination of the sample and rapid decline of sensitive organisms cannot be determined. The bacterial uptake is significant and varies between dark and light bottles. Isotope-effect which differs with species mixture of phytoplankton, is not quantifiable. Apart from the above, the phytoplankton is always accompanied by grazing zooplankton (Banse 2002). In spite of its many limitations, it is yet the most preferred technique for measuring primary production as evident from its extensive use for productivity studies in different regions of the ocean. The results from Bermuda Atlantic Time Series (BATS) and Hawaii Ocean Time Series (HOTS) have depicted intra-, inter-annual and even inter-decadal variability in the phytoplankton standing stocks, composition and rates of production (DuRand et al 2001). Moreover, usage of the same method would facilitate direct comparison of the productivity rates both in time and space.

Primary production is the basic biological process in marine ecosystems. There are still many lacunae present in understanding the underlying physical, chemical and biological factors that determine the rates and fates of primary production in various regions of the world oceans. Recently developed methods such as the use of Fast repetition rate fluorescence (FRRF) instruments may allow greater spatial and temporal resolution of primary productivity (Sherr & Sherr 2002).

Apart from the fixation and transfer of organic carbon in the marine food web, phytoplankton is also a major factor influencing the global climate. A few examples of such biogenic gases are non-methane hydrocarbons (NMHC), volatile organohalogens (VOH), ammonia, methylamines and dimethyl sulfide (DMS). Transfer of these reactive trace gases from sea to air links oceanic sources with atmospheric pools and terrestrial environments. Thus, ecological processes involving phytoplankton are vital for the global biogeochemical cycles of halogens (Cicerone 1981), nitrogen (Gibb et al 1999a) and sulfur (Malin et al 1992). While most of these gases contribute to the ozone destruction, some aid its production (Donahue & Prinn 1990). Some of them provide aerosols for cloud formation (Charlson et al 1987; O'Dowd et al 2002). Also, recently, atmospheric scientists have reported a new and potentially important mechanism by which emissions and oxidation of isoprene- a chemical emitted by the ocean phytoplankton- may influence the formation of clouds. When oxidized, isoprene may enhance the effect of DMS by increasing the number and size of particles thus helping them to chemically attract more moisture. Previously, the impact of isoprene on (http://www.sciencedaily.com/releases/2006/11/061108155014.htm) atmospheric particulate matter was thought to be important only for terrestrial plants. Results from laboratory culture experiments (Moore et al 1994) showed that the production rates of halocarbons such as bromoform ($CHBr_3$), monochloro-dibromo methane ($CHBr_2Cl$), dibromo methane (CH_2Br_2) are dependent on type and age of phytoplankton species. The interrelation between the halocarbons and the role of phytoplankton in their release is not clearly understood. Further research on this will help predicting the levels of halocarbon emissions with better precision and help in understanding its impact on a global scale. Thus, phytoplankton studies are also useful in relating the changes occurring in their composition and structure to the changes occurring in the

environment. Such elucidations help in a better understanding of the past (paleo) climate (Taylor et al 2001).

Issues related to phytoplankton

Identifying the ecological variables that regulate phytoplankton community is essential for developing hypotheses and to broaden our understanding of pervasive environmental issues as oligotrophy, biogeography, eutrophication and harmful algal blooms. In natural conditions, environmental factors responsible for spatio-temporal variations of phytoplankton composition are nutrients, temperature, light and salinity. Since diatoms are the predominant phytoplankton in the marine environment, they require silica (Si) for their frustule's formation and, availability of dissolved Si in natural water regulates their growth (Paasche 1973). When silica is limiting, the community changes from the diatom dominated to a non-siliceous dinoflagellate community. Hence the effect of the nutrient concentrations on the phytoplankton community structure would help find out changes that occur in the phytoplankton community.

Phytoplankton release organic material due to changes occurring in environmental conditions that inhibit multiplication but still permit photo-assimilation, as in the case of nutrient limitation. Thus, nutrient status profoundly affects the amount and composition of phytoplankton exudates. In the marine environment, the dissolved organic carbon (DOC) produced mainly by phytoplankton in the euphotic zone represents one of the largest biologically reactive organic carbon pools on earth. Dissolved organic matter (DOM) in the ocean is thus the byproduct of marine primary production (Mague et al 1980; Carlson & Ducklow 1995) accounting for more than 50% of the photosynthetically fixed carbon.

A large fraction of the DOC is channeled through the microbial loop (phytoplankton DOC → bacteria → microzooplankton) in the pelagic waters. Several processes have been attributed to the production of DOM including extracellular releases/exudation by phytoplankton (Fogg 1971; Hellebust 1965; Mague et al 1980; Jensen 1983; Baines & Pace 1991) and heterotrophic bacteria (Tranvik 1994; Tanoue et al 1995; Stoderegger & Herndl 1998). Sloppy feeding (Lampert 1978), dissolution of fecal pellets, marine

snow (Alldredge et al 1993) and/or other marine aggregates, viral infection of phytoplankton and cell lysis (Fuhrman 1992) are the major causes for releasing organics from phytoplankton cells. DOM is released by the phytoplankton during all phases of growth (Myklestad 1995). However, the excretion appears to increase when the cells are entering the stationary phase of growth (Henriques-Vieira & Myklestad 1986). Healthy cells and dying/ lysing algal cells may release some fraction of organic material into their surroundings (Sharp 1977; Fogg 1983; Myklestad 1995).

The microbial loop has been shown to play a major role in the recycling of a large fraction (34–90%; Jensen 1983) of the organic carbon released from phytoplankton within the euphotic zone. Thus, an understanding of the differences in growth and metabolic activity in bacteria due to their assimilation of exudates from diatoms is important to estimate the carbon re-mineralization in the surface waters and the net DOC flux to deeper waters.

In marine ecosystems, heterotrophic zooplankton forms the major link between the autotrophic phytoplankton and phagotrophic fishes and other animals in the higher trophic levels (Li et al 2003). Reproduction, growth and mortality rates form the essential components of the zooplankton dynamics (GLOBEC 1999). These in turn affect the phytoplankton species composition and total biomass. Therefore, studies on feeding of zooplankton are important for our understanding of the ocean ecosystem dynamics. The grazing pressure on phytoplankton varies with the abundance, age and composition of zooplankton. Moreover, as mesozooplankton devour on phytoplankton cells and on microzooplankton, it is of ecological interest to evaluate the differences if any, in their consumption of actively growing, senile and moribund phytocells.

As can be discerned from above, phytoplankton studies have been going on for a long time yet various aspects related to phytoplankton diversity and ecology have to be continued for assessing their dynamics both in the short term (diel, weekly, fortnightly, monthly, seasonally and annually) and long term (inter annual, decadal and centennial) basis.

Among the two basins in the northern Indian Ocean, phytoplankton community studies in the Bay of Bengal are very few. This is despite the fact that the fish catches from the Bay contribute to over 40% of the nation's annual landings. This study was aimed at understanding the factors that control their community structure and response to a highly dynamic and unique environment in the east coast of India, the Bay of Bengal.

From literature survey provided in the next chapter, it is easily seen that most phytoplankton studies in the Bay of Bengal (BoB) have been carried out in the coastal areas and do not cover the oceanic waters. Therefore, as a part of the Bay of Bengal Process Studies (BOBPS), a study for comparative analysis of the phytoplankton between the coastal and the oceanic regions covering a ~1200 km transect from 9°N to 20°N 88°E along the Central Bay (CB) and a ~1300 km oblique transect, from 12°N to 19°N, along the Western Bay (WB) was undertaken. The seasonal or regional variations in phytoplankton characteristics of this region were not studied so far. It was conceived that phytoplankton samples from both the WB and CB collected during different seasons would help realize variations in abundance and type of phytoplankton in the Bay. Being at the base of the food chain, analyzing their composition is important to relate with types and biomass of micro and mesozooplankton. With the expansion of our understanding on physico-chemical and biological processes (Prasanna Kumar et al 2002; 2004; Madhupratap et al 2003) in the Bay, an analysis of phytoplankton composition and seasonal differences will help in realizing the influences these processes bear on autotrophic community structure. For this study, the following objectives were planned. Through intensive sampling spatio temporal variations in some of the important aspects of phytoplankton have been investigated.

- To understand species composition and seasonal differences of phytoplankton along a track each in the Central-Bay and Western Bay. The rationale behind this objective was to understand: how would the phytoplankton thrive in the northern Bay that is perennially stratified due to freshwater capping?
- To understand the relationship between nutrient concentrations and dynamics of diatom community in terms of their seasonal shifts, predominance, species diversity and succession. Since rivers are known not to bring in nutrients, a

rationale approach would be to study these aspects of phytoplankton dynamics for a better understanding.

- To understand the effect of varying concentrations of nutrients on phytoplankton growth, chl *a*, ^{14}C uptake and dissolved organic matter (DOM) formation by a select set of centric and pennate diatoms. Measurements of bacterial abundance and activity as a consequence of DOM utilization. The rationale here was to measure these parameters by setting up experiments that would help in quantitative assessment of autotrophic processes.
- To examine the effect of grazing by microheterotrophs (ciliates, tintinnids, heterotrophic nanoflagellates) and mesozooplankton individually and in combination in microcosm based studies using natural seawater from the Bay. The question planned to be addressed was, how does heterotrophic grazing affect chl *a* and, phytoplankton cell numbers?

Chapter 2

Chapter 2

Review of Literature

Introduction

The community structure and abundance of phytoplankton are usually controlled by the physical parameters: light, temperature and, availability of inorganic macronutrients: nitrate, phosphate and silica. Most species usually undergo a fairly predictable annual cycle but some species may develop suddenly forming blooms. Present in both fresh and marine waters, the phytoplankton growth and division are tightly coupled with the diel cycle (Vaulot & Marie 1999). They are represented by diverse algal groups with size ranging from 0.2 μm to several millimeters. They include diatoms, dinoflagellates, phytoflagellates, coccolithophorids, red algae, green algae and blue green algae (cyanobacteria; Table 2.1). Based on their sizes, they can be classified as micro- (200-20 μm), nano- (20-2 μm) and pico- (2-0.2 μm) phytoplankton. The first two size categories can be easily identified from long established microscopic techniques. However, the picoplankton can be detected only by fluorescence techniques such as epifluorescence microscopy and the more recent technique of flow-cytometry that played a crucial role in the discovery and identification of picoplankton (Chrisholm et al 1988). Among the 13 groups of phytoplankton found in the marine biosphere, the Diatoms and Dinoflagellates contribute to a major fraction of the phytoplankton abundance.

Diatoms

The study of Diatoms began in the 18th century. Diatoms (Greek: *Dia-* Cut, *Tom=* across) are protists belonging to the Phylum Bacillariophyta and class Bacillariophyceae. They are eukaryotic, autotrophic, microscopic, and single or chain forming cells that are widely distributed in the aquatic environment. There are approximately more than 50,000 species of diatoms (Tomas 1997). They are found in marine and fresh water, on and in sea ice and, benthic as well as planktonic in distribution. The distinct features of diatoms are the frustules. The frustule consists of two valves composed of silica fitting into each other like a pillbox. The bigger, upper valve is known as the epitheca and the smaller lower is called the hypotheca (Fig. 2.1).

Table 2.1. Different taxa of marine phytoplankton

Sr No	Class	Common Name	Example
1	Cyanophyceae	Blue-green algae	*Synechococcus*
2	Rhodophyceae	Red algae	*Rhodella*
3	Phaeophyceae	Brown seaweeds	*Kelps*
4	Cholorophyceae	Green algae	*Tetrasporales*
5	Prasinophyceae	Prasinomonads	*Micromonas*
6	Chrysophyceae	Chrysomonads Silicoflagellates	*Aureococcus* *Dictyocha*
7	Haptophyceae/ Prymnesiophyceae	Coccolithophorids Prymnesiomonads	*Emiliania* *Prymnesium*, *Phaeocystis*
8	Craspedophyceae	-	*Stylochromonas*
9	Xanthophyceae	Yellow- green algae	*Heterochloris*
10	Bacillariophyceae	Diatoms	*Coscinodiscus*, *Chaetoceros*, *Rhizosolenia*
11	Pyrrophyceae	Dinoflagellates	*Ceratium*, *Gonyaulax*, *Protoperidinium*
12	Cryptophyceae	Cryptomonads	*Cryptomonas*
13	Euglenophyceae	Euglena	*Eutreptiella*

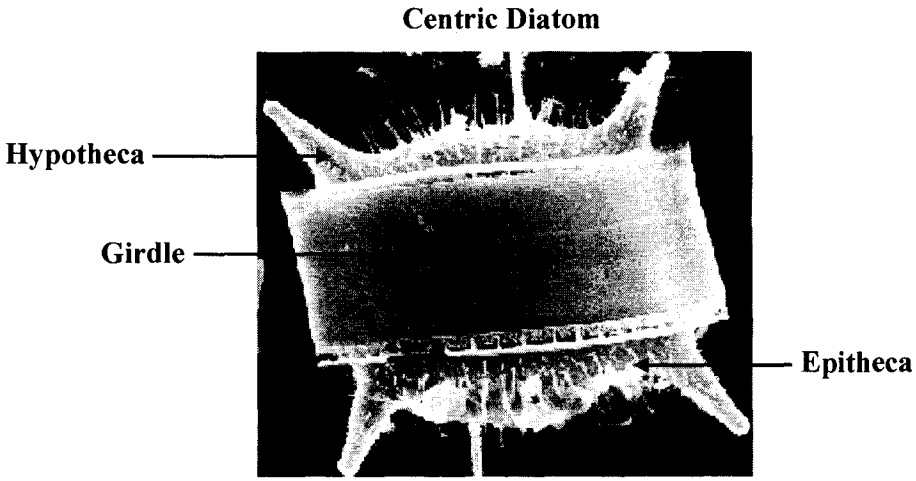


Fig. 2.1. Structure of a centric diatom

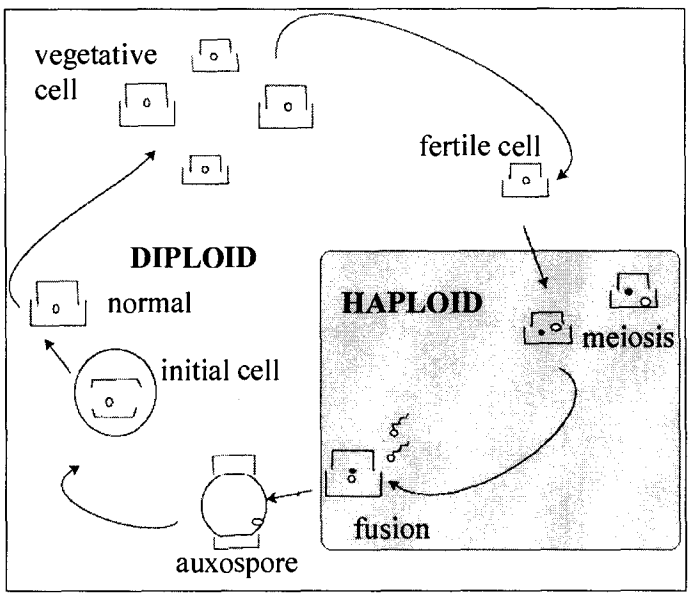


Fig. 2.2. The life cycle of diatoms

Each theca has two features- the main surface and its incurved margins termed valve and connecting bands, respectively. The two connecting bands represent incurved sides of the lid and the main body. The valve relates to the top or bottom of the box. When fitted together, the connecting band of epitheca overlaps hypotheca and the two bands remain united in the overlapping region called the girdle. The cell can be observed in two views: the valve view and the girdle view. Most diatoms appear rectangular in the girdle-view but, in the valve-view, their shapes are variable. The line connecting the middle of the two valves constitutes the pervalvar axis and the place along which the cell divides is called the valvar plane. The frustule is usually in patterns of spines, pores, channels or ribs, which are distinctive to individual species. These ornamentations are restricted to the valve position of the silica wall. Morphologically distinct varieties of diatoms occur due to structural diversity of the frustules. Reproduction in diatoms is by means of vegetative cell division. Repeated cell division results in diminutive cell size until the cell reaches a threshold point beyond which it cannot divide any further. Therefore for the cell to retain its original cell size, it forms an auxospore: a large sphere surrounded by an organic membrane, without the siliceous theca. Within this sphere, a new diatom frustule is formed and the cycle starts anew (Fig. 2.2). Most diatoms form resting spores under unfavorable conditions and germinate back with conditions becoming favorable.

The diatoms are further divided into two types (Fig. 2.3) depending upon their shape and symmetry, Centric (radial symmetry, Order Centrales) and Pennate (bilateral symmetry, Order Pennales). Pennales are further divided into Araphidineae (without a raphe system), Monoraphidineae (with one raphe system on one valve) which helps in their motility and attachment to the substrata and Biraphidineae (with two raphe systems on both valves) are completely attached to substrates. These two major taxonomic divisions also reflect major ecological differences (Round 1973).

Dinoflagellates

'Dinoflagellates' (*dinos*- whirling) form the second most abundant phytoplankton group. Belonging to the Class Pyrrophyceae, the dinoflagellates are very old eukaryotic microorganisms whose first fossil record dates back to the Silurian era, 416 to 443 million years ago. They are found from Arctic to tropical seas to estuaries as well as to

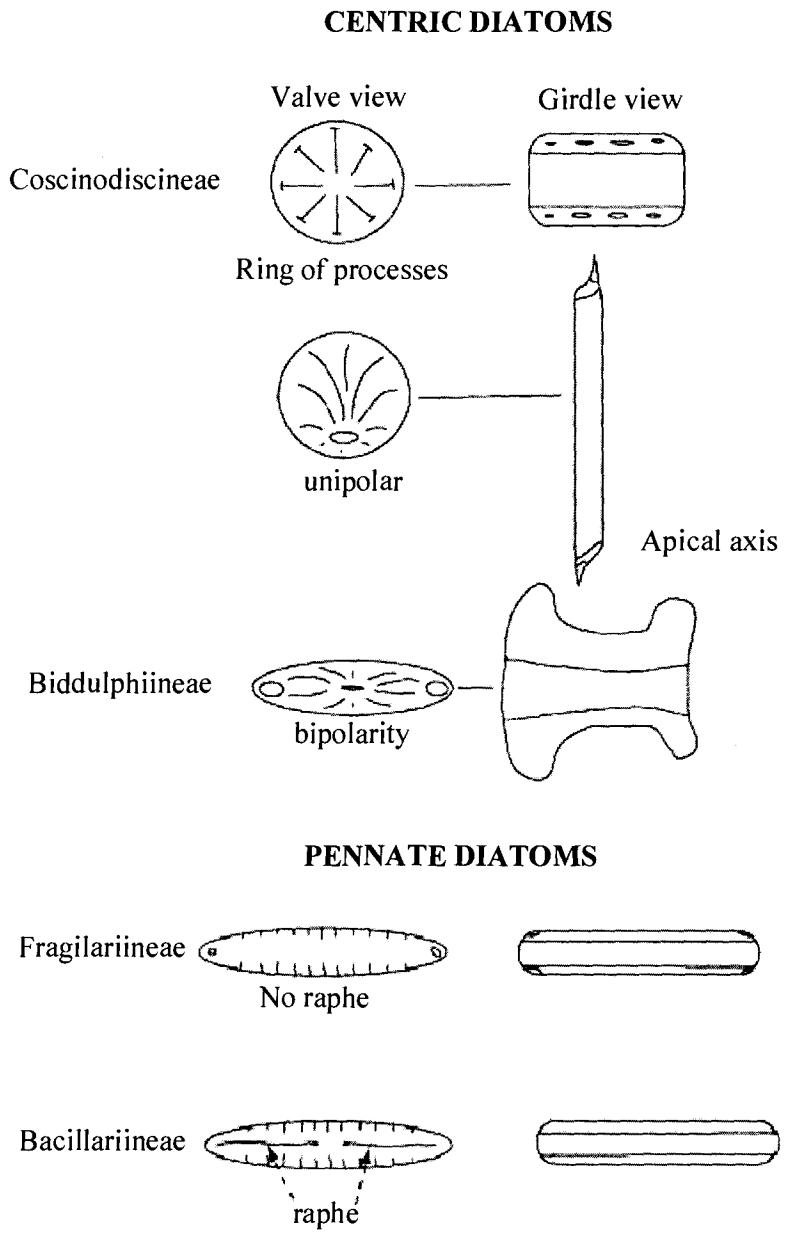
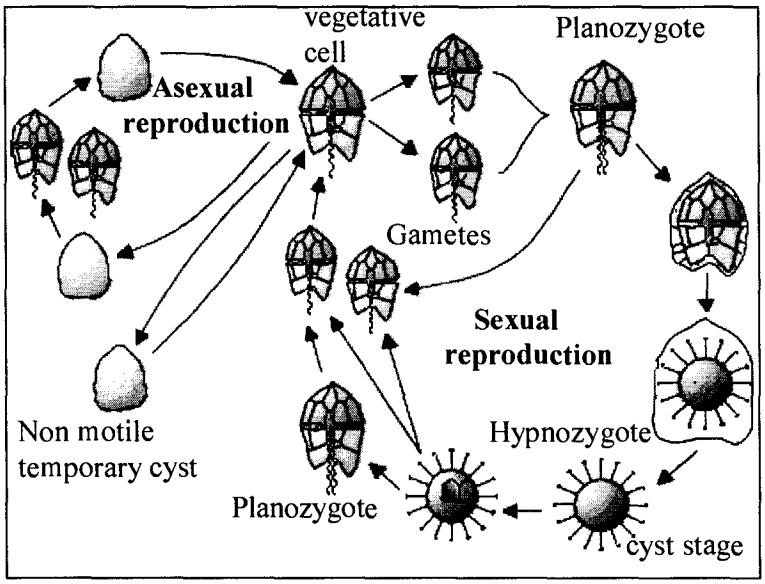


Fig. 2.3. Schematic diagrams of centric and pennate diatoms with main features (picture modified from Hasle & Syvertsen 1997)

fresh to hyper-saline waters. Majority of them are free living or benthic species while only a few are symbiotic or parasitic. Most of the free-living forms are photosynthetic and thus found in the upper euphotic zone. Not all dinoflagellates are photosynthetic; some, such as *Protoperidinium* and *Gymnodinium* can be holozoic (feed on small algae). Only few dinoflagellates are strictly autotrophic building organic material and obtaining all their energy sources by photosynthesis e.g. Zooxanthellae present in the corals. Others are mixotrophic, which also possess heterotrophic mode of nutrition (e.g. *Noctiluca scintillans*). Some dinoflagellates such as *Kofoidinium* and *Polykrikos* prey on other dinoflagellates, copepod eggs, nauplii and fish eggs. Most of the1500 to 1800 species exist singly while only a few species form chains. Unlike the diatoms that are entirely dependent on water currents for movement, the dinoflagellates show feeble independent motility due to the presence of two flagella or whip like appendages. Dinoflagellates are either walled (thecate) or naked (athecate). In all thecate forms, the cell is divided into an anterior and posterior half by a transverse groove known as girdle. The flagella are so arranged that one extends posterior from the cell and the other wraps transversely around the cell in the girdle region. Reproduction in dinoflagellates is normally asexual with the cell dividing obliquely to form two daughter cells. Binary fission of a motile or a non-motile stage can lead to rapid population under favorable conditions. Sexual reproduction although limited, also occurs in some species wherein gametes fuse to form planozygotes (2N) and these zygotes produce vegetative (1N) cells. As the conditions become unfavorable, the zygote cells form cysts. Cysts settle on the sea floor, where they can remain dormant for years (Fig. 2.4A; Lalli & Parsons 1993).

Common thecate genera include *Ceratium*, *Protoperidinium*, *Gonyaulax* in Peridiniales and *Dinophysis* in Dinophysiales. Some species, *Gymnodinium* spp are athecate in Gymnodiniales. In the thecate or armoured forms, the vesicles are filled with cross-linked cellulose sheath, forming plates. The pellicle in both groups divides into an epicone ahead of the cingulum and a hypocone in the hind of the cingulum (Fig. 2.4B). The arrangement patterns of these plates help in distinguishing the sub-groups and species. Peridiniales are mostly biconical, tapering from the cingulum toward rounded anterior and posterior ends. The plates are in two rows surrounding both epicone and hypocone. The plates may in some cases bear spines. On the other hand, the

A) Life cycle



B) Dinoflagellate

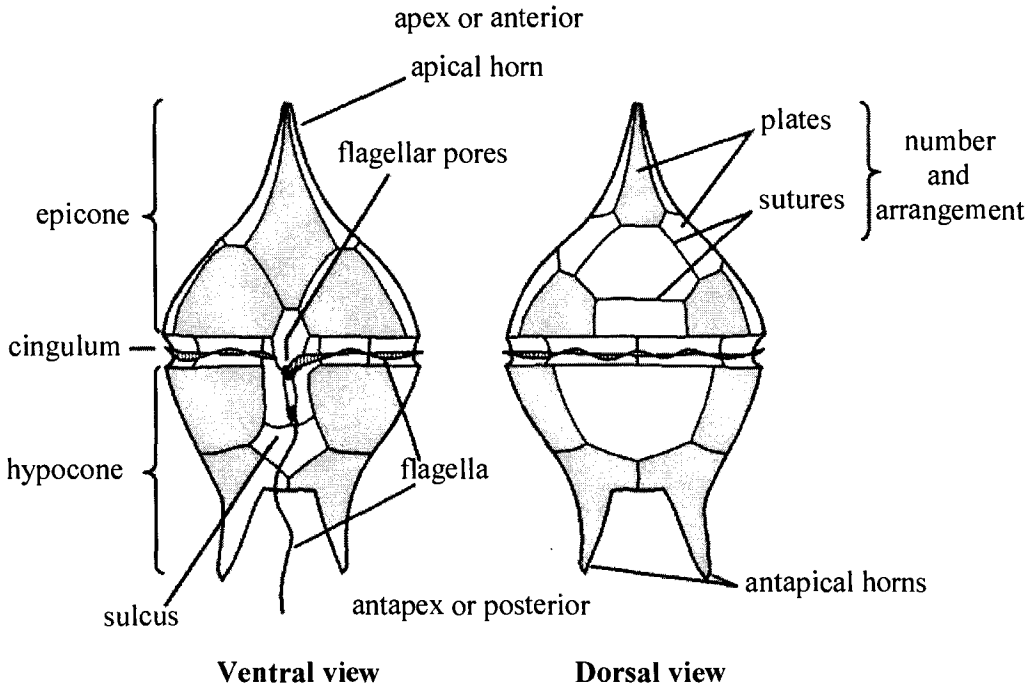


Fig. 2.4. A) Life cycle of dinoflagellates and B) Structure of a dinoflagellate (picture modified from www. tnmanning.com)

Dinophysiales have much smaller plates that are fused into anterior and posterior valves with the cingulum and sulcus bordered by thin expansions or crests arising from the edges of the grooves. The pattern again differs from species to species. Dinophysiales are mostly tropical and exclusively marine and rarely form the major constituent of the phytoplankton (Walker 1984).

Other Phytoplankton

Coccolithophores and silicoflagellates are also part of the nanoplankton other than the Diatoms and Dinoflagellates. Coccolithophorids and *Phaeocystis* belong to Prymnesiophyceae. High concentrations of DMSP and DMS are reported from the coccolithophorids and *Phaeocystis* (Barnard et al 1984; Di Tullio & Smith 1993; Van-Duyl et al 1998). Thus this group is of immense importance for production of anti-green house gas and in organo-sulphur cycles (Liss et al 1993). The outstanding feature of Coccolithophores is the presence of an external shell made up of calcareous plates called coccoliths, the shape and arrangement of which can be used for their identification. Silicoflagellates have an internal structure formed of siliceous spicules. They are small (10-250 μm) and contain yellow brown chloroplasts. They are mostly found in cold waters. Numerous species of other taxonomic divisions also make up the phytoplankton group but they are poorly known because of difficulties in collecting and preserving them.

Phytoplankton studies in the Atlantic and Pacific regions

Distribution pattern and composition of phytoplankton

Phytoplankton has been studied globally from different oceanic regimes. Marked differences exist between the phytoplankton crop and biomass of various regions resulting in a patchy distribution of phytoplankton. This could be partly due to the water movement and other factors such as concentrations of nutrients and trace metals (Raymont 1980). Generally, the oceanic regions in the temperate and high latitudes have high abundances whereas the lower latitudes and the central regions such as the oceanic gyres are low in phytoplankton abundances. In early 1930, Hentschel & Wattenburg investigated the phytoplankton crop for the upper 50 m from the South Atlantic region. They observed that the phytoplankton crop was lower in the tropical

and lower latitudes (>5000 <1000 cells L^{-1}) than the upwelling regions (>10000 cells L^{-1}). High abundance was also found in the mixed waters in the western Atlantic near the Amazon River mouth and in coastal shelf of Mexico (Zernova 1974). These were followed by many studies in the recent years (Gibb et al 2001; Yallop 2001; Lovejoy et al 2002; Marañón et al 2003) on distribution pattern and productivity of phytoplankton in the Atlantic Ocean.

The phytoplankton biomass was also reported to vary in different parts of the tropical Atlantic and, was reported to be <1 mg m^{-3} between north and south of 10° latitude (Zernova 1974). Phytoplankton biomass varied from place to place in the Atlantic having a biomass ranging from less than 0.1 to 1.6 mg m^{-3} (Gibb et al 2001). The North Atlantic had a biomass of >1 mg m^{-3}. In the Pacific regions the biomass ranged from 0.09 to 0.18 mg m^{-3} and in the Arabian Sea it ranged from 0.03 to 0.46 mg m^{-3} (Table 2.2).

Austin and Brock (1959) observed increased phytoplankton abundance in the Cromwell Counter Current which causes upwelling of nutrient rich waters in the area. Bogrov (1959) also observed high abundance in the upwelling regions near the equator in the Pacific. Zernova (1974) claimed that the distribution of phytoplankton in the Atlantic is similar to the South Pacific wherein dense phytoplankton abundance is typical in higher southern latitudes associated with higher nutrients concentrations. In recent years, numerous studies have been carried out in different regions of the Pacific on the distribution and community structure of the phytoplankton (Iriarte & Fryxell 1995; Ishizaka et al 1997; Venrick 2000; Yang 2002; Mochizuki et al 2002; Kobayashi & Takahashi 2002; Liu et al 2002). Summaries from long-term data sets (~40 years) from the Pacific regions (Parsons & Lalli 1988) indicate that the monthly chlorophyll *a* (chl *a*) concentrations did not exceed 0.4 mg m^{-3} having an annual average of less than 0.5 mg m^{-3}. However, there were also reports on sporadic increase in the concentrations of chl *a* (1-2 mg m^{-3}; Miller et al 1991). Measurements by the Canadian JGOFS group over a period of 5 years confirmed that the chl is low (<0.4 mg m^{-3}) and did not vary seasonally and annually (Boyd et al 1995; Boyd & Harrison 1999). Smaller nanoplankton (2-5 μm) dominated the biomass similar to the community structure found in the North Atlantic and the Pacific (Booth et al 1993).

Table 2.2. Reported values/ ranges of phytoplankton cell counts (PCC), chlorophyll *a* (Chl *a*) and primary production (PP) from different oceans

Area	PCC $x10^3L^{-1}$	Chl *a* (mgm^{-3})	PP (mg $Cm^{-3}d^{-1}$)	Reference
Pacific Ocean				
Northern Pacific	25[$]	0.09	2.6	[$]Venrick 1999, Pennington et al 2006
Equatorial Pacific	<2[#] - 300[$]	0.18	11.7	[$]Chavez et al 1996,[#]Kaczmarska & Fryxell 1995; Pennington et al 2006
Southern Pacific	300[$]	0.1	8.4	[$]Chavez et al 1996;Pennington et al 2006
HOTS**	--	<0.1	211*	Bienfang & Szyper 1981
Atlantic Ocean				
North Atlantic	51[$]- 462[#]	>1	>12	[$]Yallop et al 2001;[#]Savidge et al 1995; Marañón et al 2000
Equatorial	--	<0.1	<2.4	Marañón et al 2000
Southern Atlantic	7- 13[$]	>0.6	>12	[$]Piontovski et al 2003; Marañón et al 2000
BATS***	--	0.4	800*	Michaels & Knap 1996
Indian Ocean				
Arabian Sea (AS)				
Western AS	--	0.46	1332*	Barber et al 2001
Central AS	9.4 -133[$]	0.06-0.41	494*	[$]Sawant & Madhupratap 1996; Bhattathiri et al 1996
Eastern AS	13.9[$]	0.03- 0.31	577*	
Bay of Bengal (BoB)				
Western BoB	5-175	1.04	51.22	Radhakrishna et al 1978
Central BoB	>6.6	0.03-1.04	8 - 495.3	Devassy et al 1983
Eastern BoB	--	0.03	2.4-12.4	Bhattathiri & Devassy 1981

* integrated values (mg $Cm^{-2}d^{-1}$), --data not available, $,#, : denote corresponding reference. **Hawaii Ocean Time Series,***Bermuda Atlantic Time Series

The world distribution of primary production is largely similar to the distribution of phytoplankton (Koblentz-Miske et al 1970). Seasonal fluctuations in the productivity ranged from 127-318 mg C m^{-2} d^{-1} in the eastern Pacific regions throughout the year (Owen & Zietschel 1970). Malone (1971) observed the surface productivity to be higher for the nanoplankton than the net plankton in the Pacific and Caribbean oceanic and neretic regions. Generally, production in warm oceans such as the centre of major gyres is low except for upwelling and divergence areas. During the North Atlantic Bloom Experiment (NABE), production was measured to 1284 mg C $m^{-2}d^{-1}$ (Marra & Ho 1993) and averaged 1188 mg C $m^{-2}d^{-1}$; this was similar to mean production (1140 mg C $m^{-2}d^{-1}$) in the equatorial Pacific (Barber et al 1996). In the Sargasso Sea, production varied from 50 to 830 mg C m^{-2} d^{-1}, with the maxima during winter and early spring and, low levels in late spring, summer and early fall (Menzel & Rhyther 1960). Koblentz-Miske et al (1970) had earlier calculated the primary productivity to be 200 mg Cm^{-2} d^{-1} in the equatorial Pacific. However, Barber et al (1996) reported a four fold of approximately 888 mg Cm^{-2} d^{-1}. This may be because of variations in the primary production over large time as well as seasonal scales. The mean productivity for six years from the equatorial Pacific (5°N to 5°S) was estimated to be 900 mg Cm^{-2} d^{-1} (Chavez et al 1996). During a five year period as a part of the HOTS programme the primary production ranged from 125 mg C m^{-2} d^{-1} to 1055 mg C m^{-2} d^{-1} (Karl et al 1996). These changes in the rates of primary production was reported to be controlled by the chemical, physical and biological factors in the Eastern Equatorial Pacific (Chavez et al 1996), along the Western Equatorial Pacific (Mackey et al 1995; 1997) and along the Western and Central Equatorial Pacific (Le Borgne et al 1999).

Studies on nutrients and phytoplankton

Phytoplankton succession and community composition reflect the environmental conditions of the ecosystem, among which the availability of nutrients plays a significant role (Dugdale 1967; Rhyther & Dunstan 1971; Smayda 1980). If the supply of nutrients is less than the uptake by phytoplankton, nutrient concentrations decrease and limit additional growth of phytoplankton (Tilman et al 1982). Growth of algae in the aquatic ecosystems is frequently limited by the availability of nutrients and the limiting nutrient concentrations vary with season, location and phytoplankton

community structure (Fisher et al 1992). Generally, nitrogen (N) limitation prevails in most marine systems (Fisher et al 1992; Howarth 1988) except for the North Pacific Sub-tropical gyre where there is phosphate (P) limitation (Karl 1999). In the "high nutrient, low chlorophyll" Equatorial Pacific and the Southern Ocean, iron is known to limit phytoplankton productivity (Behrenfeld et al 1996; Timmermans et al 1998).

Nutrient limitation in natural phytoplankton communities is primarily identified from bioassays in which response of the phytoplankton community to N or P is measured by additions of one or both nutrients in micro/mesocosms or, inferred from elemental ratios (Havens 2000). Several bioassay experiments have been carried out to assay the concentrations of dissolved inorganic nutrients and to estimate which nutrient limits the phytoplankton growth (Tilman et al 1982; Howarth 1988). Changes in nutrient supply are often reflected in their ratios (Yin et al 2001). Thus, elemental ratios (nitrate: phosphate: silicate) from the sampling regions can be used as indicators of the status of nutrient loading and subsequently, to predict productivity (De-Pauw & Naessens 1991). The ideal elemental N:Si:P ratio for optimal phytoplankton growth has been shown to be 16:16:1 (Redfield et al 1963; Brzezinski 1985). Deviations from these molar ratios have been used to infer which nutrient would be limiting phytoplankton growth (Howarth 1988). The nutrient concentrations along with their molar ratios (N:P:Si) have been used by many authors to infer or, suggest nutrient limitations as well as changes in the phytoplankton community structure (Krom et al 1991; Dortch & Whitledge 1992; Justic et al 1995; Mochizuki et al 2002; Ortiz et al 2002; Moutin & Raimbault 2002; Bethoux et al 2002; Wang et al 2003; Ramirez et al 2005).

Studies on effect of grazing on phytoplankton

The phytoplankton species composition and biomass of phytoplankton communities depend to a great extent on the interrelationship between the phytoplankton community and the organisms belonging to the higher trophic level. In many aquatic systems zooplankton grazing is responsible for reduction/ removal of a large fraction of phytoplankton by selective grazing (Lehman & Scavia 1982). Zooplankton forms the major link between the phytoplankton and fishes and, other animals at higher trophic levels in marine ecosystems (Li et al 2003). Differential nutrient regeneration and nutrient patchiness caused by zooplankton proves to be an important mechanism by

which zooplankton affect phytoplankton (Frost 1977). Therefore, zooplankton- feeding experiments are important for our understanding of the ocean ecosystem dynamics. The importance of grazing was recognized in a number of temperate and high latitude areas in the shallow North West Atlantic waters (Riley 1946; 1947; Pratt 1965). Petipa (1973) carried out experiments on feeding rates for a variety of Pacific zooplankton, which indicated that a constant feeding rate could be maintained when maximum phytoplankton abundances occurred in the seas. Mesozooplankton grazing studies were carried out in the Pacific sector of the Antarctic Polar Front wherein the grazing pressure was more in the night than the day (Urban–Rich et al 2001).

Microzooplankton was observed to selectively graze on the smaller, fast growing phytoplankton than the dominant phytoplankton (Gaul & Antia 2001). In their serial dilution and nutrient enrichment experiments, the ratio of microzooplankton to phytoplankton biomass was inversely related to the nitrate and phosphate concentrations. Microzooplankton grazing in the Central Equatorial Pacific was observed to be balanced with the abundance of larger diatoms (Landry et al 1995 and references therein). In a separate experiment however, these authors observed that the microzooplankton grazing was still sufficient to balance growth rates of smaller phytoplankton. Very few grazing studies have been carried out in the Indian Ocean as compared to the Atlantic (Moralis et al 1991; Head et al 1999; Huskin et al 2001; Sommer et al 2004; 2005; Hale et al 2006; Olsen et al 2007; McManus et al 2007) and the Pacific regions (Dam et al 1995; Landry et al 1995; Bollens & Landry 2000; Landry et al 2003; Gaudy et al 2004).

Phytoplankton studies in Indian Ocean

Unlike Atlantic (106.2×10^6 km^2) and the larger Pacific (179.7×10^6 km^2), the Indian Ocean (74.9×10^6 km^2) is bordered in the north by landmass. As a result of land and far higher fluvial inputs, it is considered to be the most productive areas in the world oceans (Dileep Kumar et al 1992). However, Krey (1973) suggested that the Arabian Sea and the Bay of Bengal to be regions of higher proportion of dinoflagellates and coccolithophorids as compared to the diatoms.

The northern Indian Ocean is different from other oceanic regimes in terms of its geographical setting and circulation pattern. The Indian subcontinent splits the Indian Ocean into the Arabian Sea (AS) and the Bay of Bengal (BOB), two zones of vastly different hydrographical regimes. Yet, there are some similarities between these two. Both are semi enclosed basins located in the same latitude band and are connected to the Equatorial Indian Ocean in the south. Apart from this, they also have meteorological similarities in which both are faced by the changing monsoon winds (Shenoi et al 2002). The AS is a region of negative water balance where the evaporation far exceeds the precipitation and run off; consequently the upper layers are much more saline and less stratified as compared to the BoB. In the latter, excess precipitation and river runoff over evaporation lead to very low salinities and highly stratified upper layers (George et al 1994; Prasanna Kumar et al 2002).

The AS has been a cynosure of many investigations. Consequently, most of the studies that have been carried out in the Indian Ocean sector have been in the AS. Under the aegis of the Joint Global Ocean Flux Studies (JGOFS), the AS was targeted as one of the prime areas of investigations along with the Atlantic, Pacific and Southern Oceans. As a result, there is vast amount of data sets of various parameters from the AS (Burkill et al 1993; Lal 1994; Sawant & Madhupratap 1996; Latasa & Bidigare 1998; Garrison et al 1998; Liu et al 1998; Landry et al 1998; Marra et al 1998; Smith et al 1998; 2001; Smith et al 2000). Apart from the JGOFS, numerous studies have been done on the phytoplankton characteristics and primary productivity in the AS (Menon 1945; Goericke 2002; Subramanyan & Sarma 1961; Thorrington-Smith 1971; Stuart et al 1998; Satyendranath et al 1999; Tarran et al 1999). Numerous studies have helped establish the AS to be a highly productive region through open ocean upwelling and lateral advection (Barber et al 2001). Shalapyonok et al (2001) studied the phytoplankton size structure and composition in the AS using a flow-cytometer. They observed that diverse eukaryotes dominated phytoplankton carbon biomass in both the Southwest and Northeast monsoons. A study in the relationship of DOC with oxygen was observed to reflect the different biological characteristics in different zones of the AS (Rajendran et al 1993; Naqvi & Shailaja 1993; Naqvi et al 1996; Shailaja et al 2006). Recently studies on the ectoenzymatic activity in surface waters have reported the Central Indian Ocean basin to be a region of high heterotrophy (Misic et al 2006).

Of the very few studies conducted in the Northern Indian Ocean, many have focused on the hydrodynamics and hydrology (Fieux et al 1996; Schott & McCreary 2001; Jensen 2003), inorganic nutrient concentrations (Naqvi et al 1978; De Sousa et al 1981; Mantoura et al 1993; Woodward et al 1999; Naqvi 2001), and autotrophic and heterotrophic communities (Ramaiah et al 1996; Naqvi et al 1996; Veldius et al 1997). The distribution of organic matter and its biochemical constituents such as carbohydrates, proteins and lipids in the AS (Nandkumar et al 1987; Bhosle & Wagh 1989) have been well studied. Of a few grazing studies that have been carried out in the Indian Ocean most of them have been from the Arabian Sea (Landry et al 1998; Edwards et al 1999).

In comparison with the AS, the BoB has been -at best- sparsely visited/ investigated by biological oceanographers. The BoB comprises the north east part of the Indian Ocean and extends over a distance of ~2500 km between 22°N and the Equator (Berner et al 2003) enclosing the Andaman Sea surrounding the Andaman and Nicobar Islands. It represents the low salinity portion of the Indian Ocean contrary to the high saline waters of the AS. The Bay is distinguished by low saline, highly stratified surface water. The four large rivers viz: Ganges, Brahmaputra, Irrawady and Mahanadi, discharge large amounts of fresh water (ca. 1.6×10^{12} m^3 yr^{-1}; Subramanian 1993) into the Bay. The Ganga and the Brahmaputra annually bring in ~10^{12} m^3 of fresh water (Shetye et al 1996). The fresh water input and estuarine characteristics with low surface salinities is observed over a large part of the Bay. This hampers exchange processes between the atmosphere, surface and deeper water layers that consequently affect the biological and biogeochemical processes (Ittekkot et al 2003). Though the International Indian Ocean Expedition (IIOE) during 1960-65 investigated multiple aspects of the oceanography of Indian Ocean amassing volumes of data, all collected data could not be synthesized very effectively. This was clearly quoted by Babenard (1976) as: "The lack of systematic survey for the entire ocean and necessity to combine data from many years, as well as variability in time and heterogeneity in time and space, which are naturally inherent in oceanic biological parameters made the preparation of the Atlas rather troublesome". In addition, the number of cruises that were undertaken for studying the Bay of Bengal during IIOE was very few. The hydrography (La Fond 1957; Varadachari et al 1967; Rao & Jayraman 1968; Narasimha Rao et al 1986; Murty

et al 1992; Shetye et al 1996; Prasanna Kumar et al 2002), nutrient concentrations and variations (Sarma et al 1994; Naqvi 2001; Madhupratap et al 2003) and primary productivity characteristics (Radhakrishna et al 1978; Bhattathiri et al 1980; Devassy et al 1983; Madhupratap et al 2003) in the Bay have been investigated. Similar to the AS, many studies have been carried out to study the biochemical constituents such as carbohydrates, proteins and lipids in the Bay of Bengal (Bhosle et al 1981; 1992; Sreepada et al 1996; Unger et al 2005; Khodse et al 2007). However, earlier studies on phytoplankton from the east coast are by Venkataraman (1939); Subramanyan (1946); Subba Rao (1976); Devassy & Goes (1988). Subba Rao (1973) reported the extensive analyses done during 1957, 1958, 1960 and 1962 from Lawson's Bay off Vizag in the east coast. The phytoplankton composition from the Andaman waters was studied by Devassy & Bhattathiri (1981) and, Sarojini & Sarma (2001). From the near-shore environments, Panigrahy (1985), Phani Prakash & Raman (1992), Umamaheshawararao (1992), Gouda and Panigrahy (1996) have recorded the phytoplankton species composition and suggested the existence of diverse autotrophic communities. Main aspects of the phytoplankton characteristics in the three major oceans are listed in Table 2.2.

Chapter 3

Chapter 3

Hydrography, chlorophyll *a* and phytoplankton abundance

Introduction

Phytoplankton depend on their immediate environment for all requirements of nutrient salts and dissolved gases. The water current determines their distribution (Thorrington-Smith 1971). Smayda (1958) and Margalef (1961) had shown that there were processes that limited the distribution of individual species. Studies on the effect of physico-chemical parameters such as temperature (Eppley 1972), salinity (Hulburt & Rodman 1963) and nutrients on the qualitative and quantitative distribution of phytoplankton in the oceans (Fisher et al 1992; Ramirez et al 2005) have suggested species-specific optima for all these parameters.

The surface waters of the tropical and subtropical areas in the ocean usually contain low nutrients and, as a consequence, low chlorophyll *a* levels (Eppley et al 1973). However, localized or regional injections of nutrient rich waters such as mid-ocean divergences (Reid 1962), river plumes (Halim 1960), frontal zones (Yoder et al 1981), coastal upwelling zones (Barber & Smith 1981) and sub-thermocline intrusions (Yoder et al 1985) into the euphotic zone increase the standing stock of the phytoplankton.

Thorrington-Smith (1971) found that the abundance and distribution of phytoplankton are strongly influenced by the water masses along a large area on the western part in the Indian Ocean. Gomes et al (2000) observed significant influences of physical processes on phytoplankton biomass and productivity along the coastal margins of the Bay of Bengal. However, the effect of such processes on the distribution pattern of phytoplankton community during different seasons in the Bay was not studied.

A few experimental studies to discern the effect of salinity on the diatoms (Desikachary & Rao 1972; Qasim et al 1972) imply that both their growth and

photosynthetic fixation of CO_2 are affected by varying the salinity levels. With the expansion of our understanding on physico-chemical and biological processes (Ittekkot et al 2003; Prasanna Kumar et al 2002; 2004; Madhupratap et al 2003) in the Bay, an analysis of phytoplankton composition and seasonal differences would augment to realizing the influences these processes bear on autotrophic community structure.

In this chapter, the seasonal variations in chlorophyll *a* (chl *a*), phytoplankton abundance and distribution in relation to hydrography in the central bay (CB) and western bay (WB) are described.

Materials and Methods

Study Area

The Bay of Bengal (BoB) forms the eastern purlieu of the Indian sub-continent. Similar to its western counterpart, the Arabian Sea (AS), the Bay is also land-locked in the north and experiences seasonally reversing monsoons. However, it has several distinguishing features different from the AS. Annually, precipitation exceeds evaporation by almost 2 m yr^{-1} (Prasad 1997). Freshwater influx from the rivers is substantial (1.6×10^{12} m^3 yr^{-1}) compared to the AS (0.3×10^{12} m^3 yr^{-1}; Subramanian 1993). Further, there is a positive net heat flux from the atmosphere (Murty et al 2000). Surface winds are generally weak (0-10 ms^{-1}) and variable. Somewhat stronger winds (5-10 ms^{-1}) during monsoon do influence the upper circulation in the Bay. Almost perennially warmer (30°C) and low saline (<34.0) waters lead to strong stratification in the upper 50 m. All these characteristics make the BoB, a particularly unique and dynamic region.

Sampling Procedure

Water samples were collected during four cruises onboard ORV Sagar Kanya during summer monsoon (SM, from July 6 to August 2, 2001), fall intermonsoon (FIM, September 11 to October 11, 2002), spring intermonsoon (SpIM, April 10 to May 10, 2003) and northeast monsoon (NEM, November 25, 2005 to January 11, 2006 onboard FORV Sagar Sampada). Two transects were consistently

covered in these cruises, one in the central Bay along 88°E, and another along the western bay (WB, 81°-85°E, Fig. 3.1). As the shelf in the Bay is quite narrow, three of the four sampled stations along the WB were quite offshore (~1000 m). Data on salinity, temperature and nutrients at all the nine stations were collected by the physical and chemical oceanographers. They are duly acknowledged for and used with permission to study their effect on biological parameters detailed in this chapter. Water samples were collected from eight discrete depths (near surface, 10 m, 20 m and thereafter at 20 m interval till 120 m for estimating chlorophyll *a* (chl *a*) and enumerating phytoplankton cell counts (PCC).

Sample Analyses

Estimation of chlorophyll *a* (chl *a*)

Water samples collected from different depths were filtered immediately through GF/F filter papers using low vaccum. One-liter volumes of water samples from each depth were filtered on to GF/F (Whatman, UK, 0.7 μm pore size) for chl *a* estimation. All samples were filtered in low light conditions and, the filters held at 4°C overnight in 10 ml 90% acetone in polycarbonate vials for extraction. The chl *a* concentrations in terms of fluorescence strength units (FSU) were measured by flurometric method (Turner 10AU, USA) following the JGOFS Protocols (UNESCO 1994). The chl *a* concentration was converted to carbon equivalent by following Banse (1977). Since most locations sampled under BOBPS were deeper than 200 m, each mg of chl *a* concentration was equated to 50 mg C.

Phytoplankton enumeration

Water samples from each of the above depths were fixed in Lugol's iodine (1% w/v) and 3% formaldehyde and stored in dark until taken up for analyses. A settling and siphoning procedure was followed to concentrate samples from 250 ml to 10 ml (Utermohl 1958). For counting phytoplankton cells (size >5 μm) and identification of genera and species, two one-ml replicates of concentrated aliquots were transferred to a Sedgwick-Rafter plankton counting chamber and examined microscopically at 200–400X magnification. Oil immersion 100X objective on a Zeiss (Axioskop, 2plus, Germany) microscope was also made use

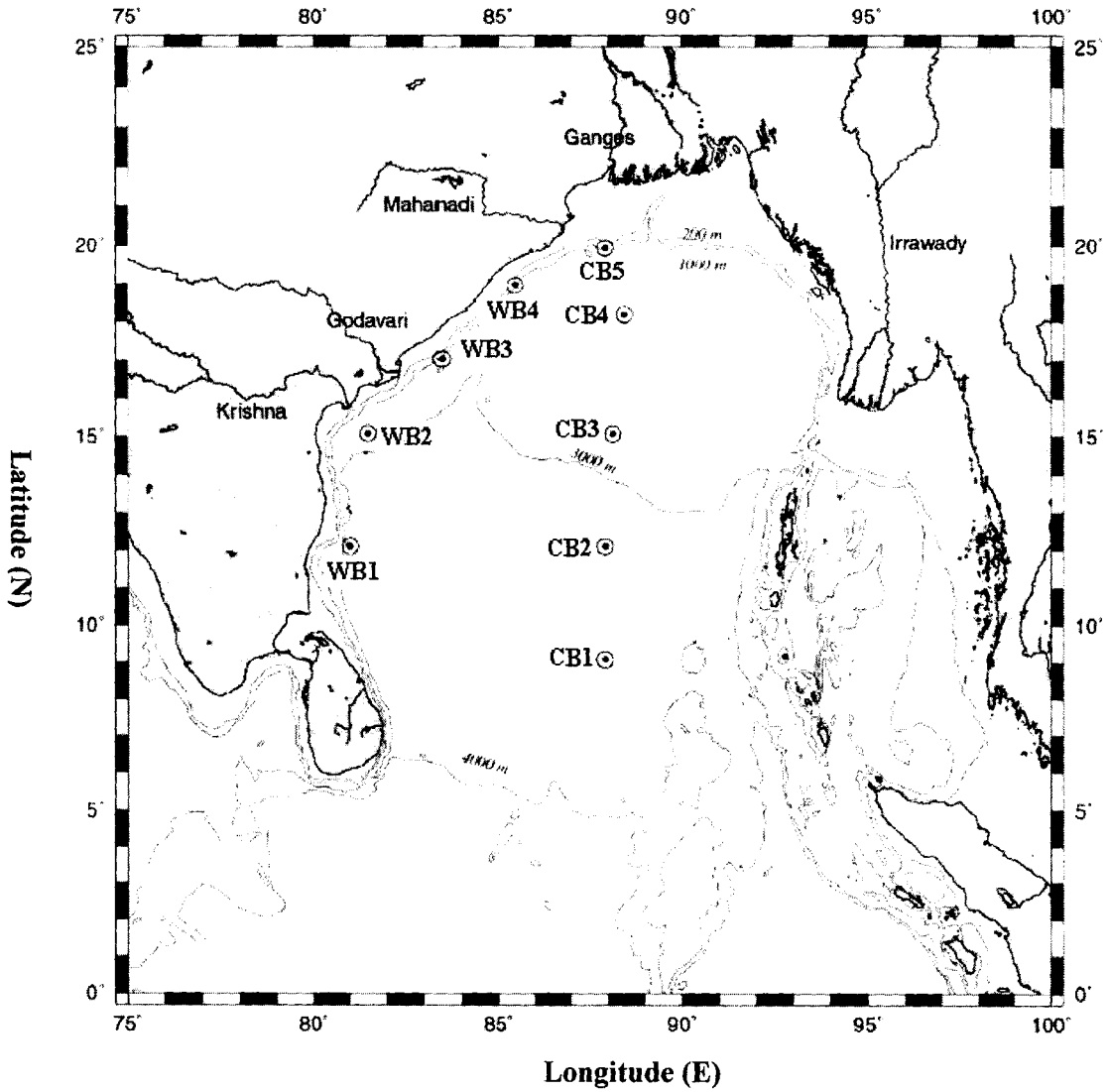


Fig. 3.1. Sampling stations along Central Bay (CB1 to CB5) and Western Bay (WB1 to WB4)

of for confirming the genera or species. Generic and species identification was done according to the various keys (Subramanyan 1946; 1961; 1968; Lebour 1978; Constance et al 1985a; 1985b; Desikachary & Ranjithadevi 1986; Desikachary & Prema 1987; Desikachary et al 1987; Tomas 1997).

Results

Hydrological Parameters

Central Bay of Bengal (along 88°E)

In SM, the sea surface temperature (SST) averaged 28°C (Fig. 3.2a). Sea surface salinity (SSS) showed a steady decrease during SM from ~34 psu at 7°N to 32 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 psu (Fig. 3.2b). Further, a strong vertical gradient in salinity in the upper 50 m that was more intense in the northern locations was evident. In that, the salinity increment in the upper 50 m was ca 1.5 psu at 7°N and 7 psu at 20°N (CB5) indicating low saline surface waters in this region. Below 50 m, the salinity was homogeneous, gradually increasing from ~34 to 35 psu. Mixed layer depth (MLD; Table 3.1, SM) calculated using density criteria (Levitus 1982) shoaled from 50 m at CB2 (12°N 88°E) to less than 4 m at CB5 (20°N 88°E).

The upper 30 m was almost devoid of nitrate (Fig. 3.2c). The shoaling of 1 μM NO_3-N isopleth to 20 m was observed at CB5. Nitracline between 50 and 100 m was prominent. Phosphate was undetectable in the top 40 m (Fig. 3.2d). Silicate distribution was similar to that of nitrate (Fig. 3.2e) except for higher silicate concentrations (>2 μM) in the surface waters in the north. Shoaling of both 28°C isotherms and 1 μM isopleth nitracline was discernible.

In FIM, the average SST was 28.70 ± 0.28°C in the CB. In the top 50 m (Fig. 3.3a) an increase of 1°C in the upper waters that are thermally homogenous was noticeable from north to south (except at CB5). Low saline surface waters (29 psu) in the northern regions (Fig. 3.3b) and, increasing SSS southwards attaining the maximum of 34 psu were prominent features. The average SSS was 31 ± 2.65 psu. Below 50 m the salinity did not vary much. MLD shoaled from 55 m at CB2

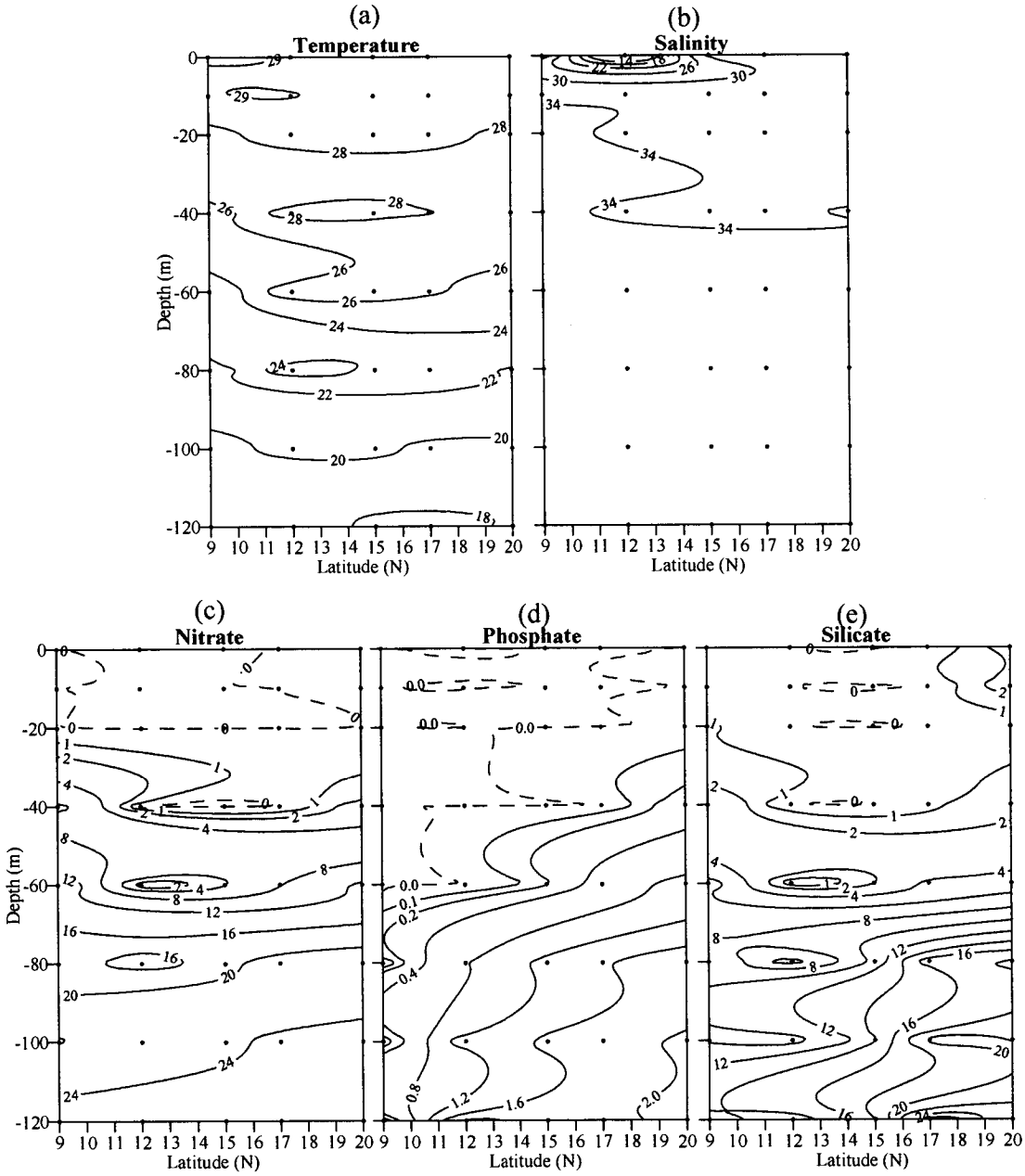


Fig. 3.2. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and e) silicate (μM) along Central Bay during summer monsoon

Table 3.1.Variations in Mixed layer depth (MLD; m) during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM) along Central Bay and Western Bay

Central Bay

Station	Season			
	SM	FIM	SpIM	NEM
CB1	12	37	14	40
CB2	51	55	12	40
CB3	29	26	31	40
CB4	13	3	41	30
CB5	4	6	33	10

Western Bay

Station	Season			
	SM	FIM	SpIM	NEM
WB1	29	30	36	40
WB2	30	6	44	20
WB3	14	5	17	52
WB4	2	7	26	30

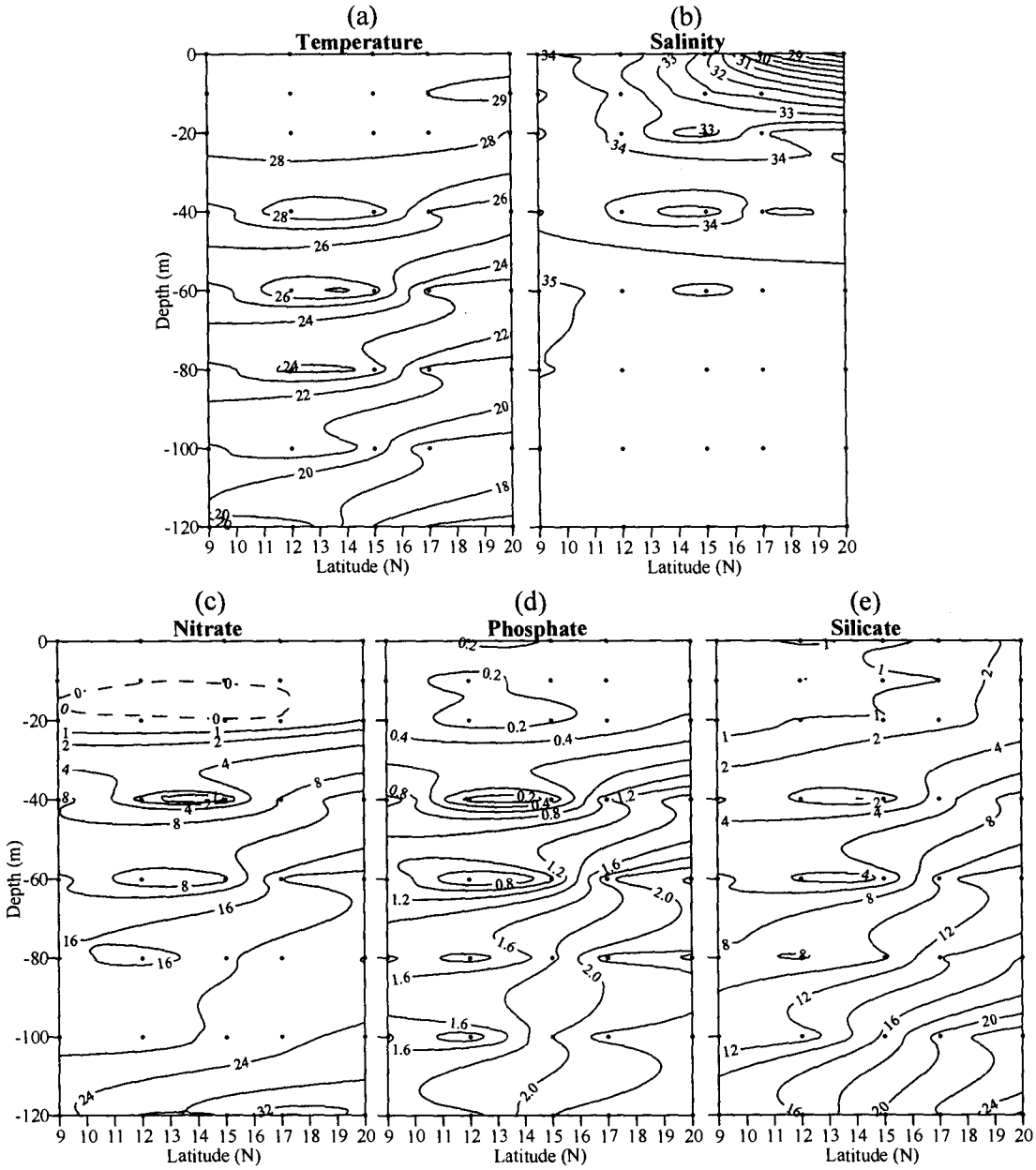


Fig. 3.3. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and e) silicate (μM) along Central Bay during fall intermonsoon

(12°N 88°E) to less than 3 m at CB4 (20°N 88°E; Table 3.1, FIM). The nitrate was below detectable levels in the top 20 m (Fig. 3.3c). However, the 1 μM nitrate isopleth was observed around 25 m. Phosphate was around 0.40 μM in the top 20 m (Fig. 3.3d) almost through out the transect. Compared to the other nutrients higher concentrations of silicate were observed in the top 30 m (Fig. 3.3e). Its surface concentrations increased from 0.5 μM in the south to 2 μM in the north similar to that observed during the SM.

In SpIM, ~10 m thin 30°C isothermal layer was observed in the south of 15°N. Further north of 15°N the isothermal layer was thicker (~30 m) and also was colder by ca. 1°C (Fig. 3.4a) in the north. The SST averaging 29 ± 0.50°C did not vary too much. From the vertical salinity structure (Fig. 3.4b) an isohaline of 33 psu of ~30 m in thickness was observed. The SSS averaged ~33 ± 0.30 psu and did not vary too much unlike FIM and SM. Also, unlike SM and FIM, the MLD deepened from 12 m at CB2 to 41 m at CB4 (Table 3.1, SpIM). With nitracline between 40 and 60 m, nitrate in the upper 60 m was in the range of 0.4-6.8 μM (Fig. 3.4c). Phosphate was undetectable in the upper 30 m at all stations (Fig. 3.4d). High concentrations of silicate (≥2 μM) were observed in the surface waters at the southern stations, which decreased to ca 1 μM in the north (Fig. 3.4e).

During NEM, the SST varied from 28.5 to 27°C decreasing towards the north (Fig. 3.5a). A distinct thermal inversion was observed in the northernmost station with relatively cold surface waters (<27°C) overlying the warm (>27°C) subsurface layers. Ranging from 32.8 to 32.63 psu, the SSS did not vary much (Fig. 3.5b). The northernmost station had a temperature of 27°C and salinity of 32.63 psu at the surface. Similar to SM and FIM, the MLD (Table 3.1, NEM) was shallow in the north (~40 m at CB1 to less than 10 m at CB5). Similar to the other seasons, the upper 50 m was devoid of nitrate (Fig. 3.5c). Throughout the transect the 1 μM NO_3-N isopleth was observed below 50 m. Unlike the other seasons 0.4 μM phosphate isopleth (Fig. 3.5d) was observed at the surface. The top 40 m had

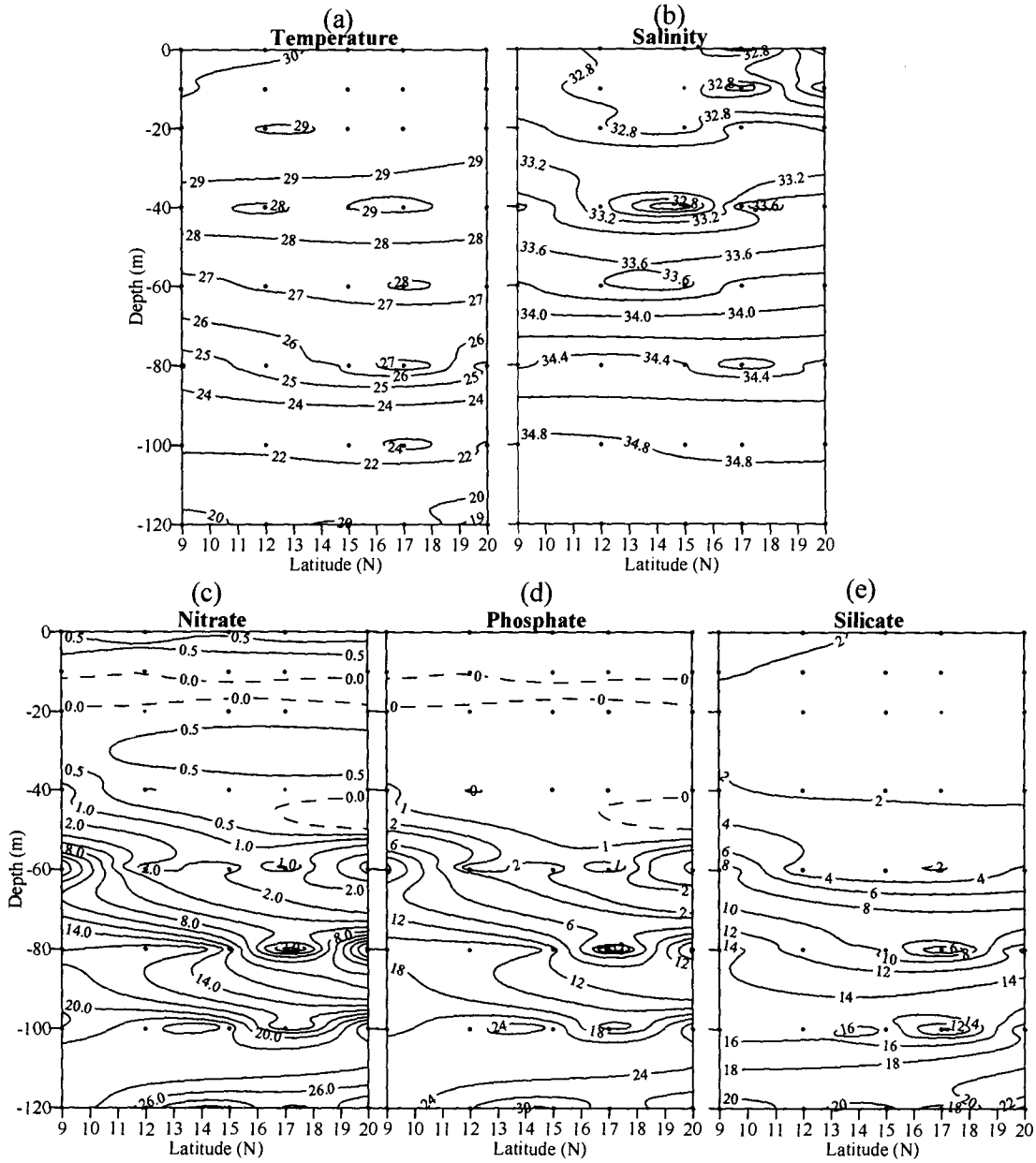


Fig. 3.4. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and e) silicate (μM) along Central Bay during spring intermonsoon

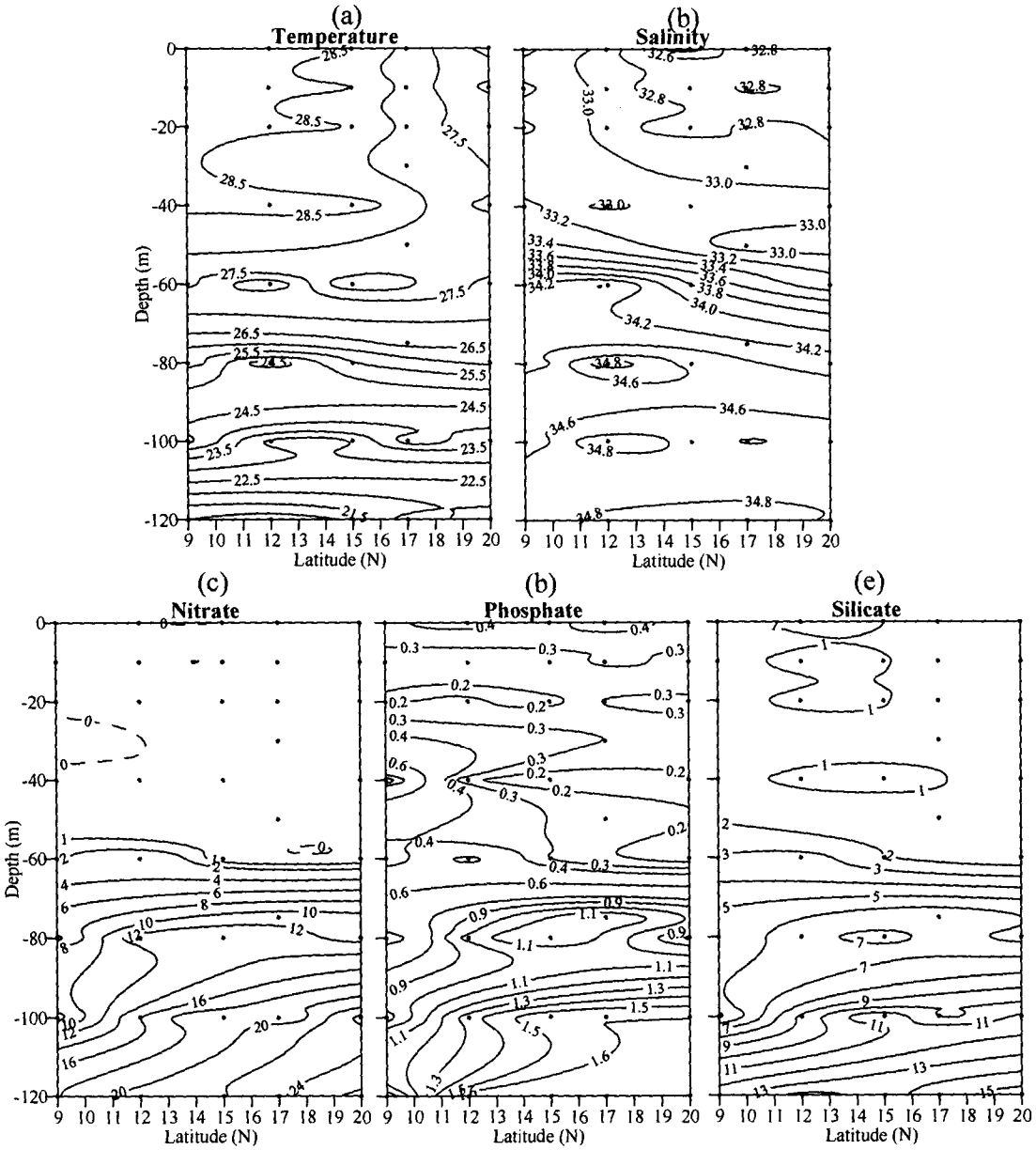


Fig. 3.5. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and e) silicate (μM) along Central Bay during northeast monsoon

high concentrations of silicate (~2 μM; Fig.3.5e) as compared to the nitrate and phosphate.

Western Bay of Bengal (WB)

In SM, the average SST of 28.9°C was higher than that in the open ocean. It ranged from 28-29°C (Fig. 3.6a). The average salinity in the surface was 33.7 psu (Fig. 3.6b) that reduced northward reaching 29.6 psu at WB4 (19°N 85°E). The MLD (Table 3.1, SM), 25 m at the southern location, shoaled to 4 m in the northernmost location, 20°N 88°E. The upper 40 m was devoid of nitrate (Fig. 3.6c) and phosphate was undetectable in this layer (Fig. 3.6d). Except for high concentrations (~4 μM) in the north, the silicate distribution (Fig. 3.6e) was similar to that of nitrate.

During FIM, the SST (Fig. 3.7a) was warmer compared to the open ocean (>30°C) except in the north where it was ~1°C cooler. The SST averaged 29.98 ± 0.54°C. The surface salinity was lower in the north (25 psu) compared to that in the south (33 psu, Fig.3.7b) averaging 29.65 ± 3.83 psu in the WB. The MLD shoaled northwards from 30 m at WB1 to <5 m at WB3 (Table 3.1, FIM). The 1 μM nitrate isopleth shoaled to 20 m in the north (Fig. 3.7c). Unlike during SM, the surface phosphate concentrations (Fig. 3.7d) ranged from 0.03 μM at WB3 in the south to 1 μM in the north (WB4). Silicate concentrations increased from 1.05 μM at WB1 to 9 μM at WB4 (Fig.3.7e).

During SpIM, SST did not vary much unlike the other seasons along WB averaging 29 ± 0.50°C. About 40 m thick isothermal (~30°C) surface layer was observed south of 16°N (Fig. 3.8a). It tapered northward to ~10 m and, was cooler by a degree. The isohalines (Fig. 3.8b) also shoaled from south to north with surface waters fresher by 0.5 psu in the north. The MLD also shallowed northwards from 44 m at WB2 to 17 m at WB3 (Table 3.1, SpIM). Surface nitrate concentrations ranging from 0.2 to 0.8 μM with the maximum observed at WB4. The 1 μM nitrate isopleth shoaled from below 40 m to less than 30 m in the north (Fig. 3.8c). Surface phosphate concentrations ranged from 0.1 in the south to <0.4

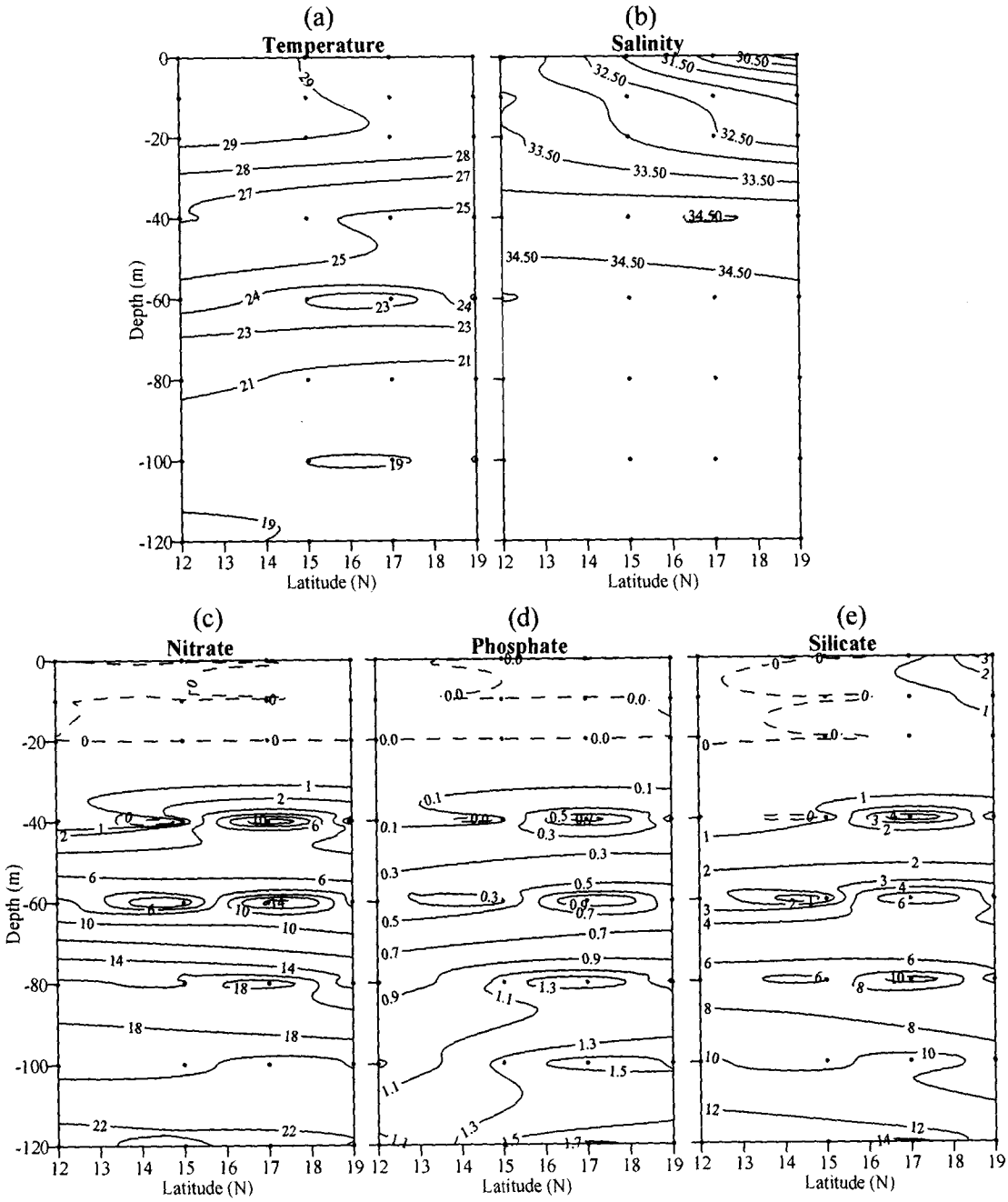


Fig. 3.6. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and, e) silicate (μM) along Western Bay during summer monsoon

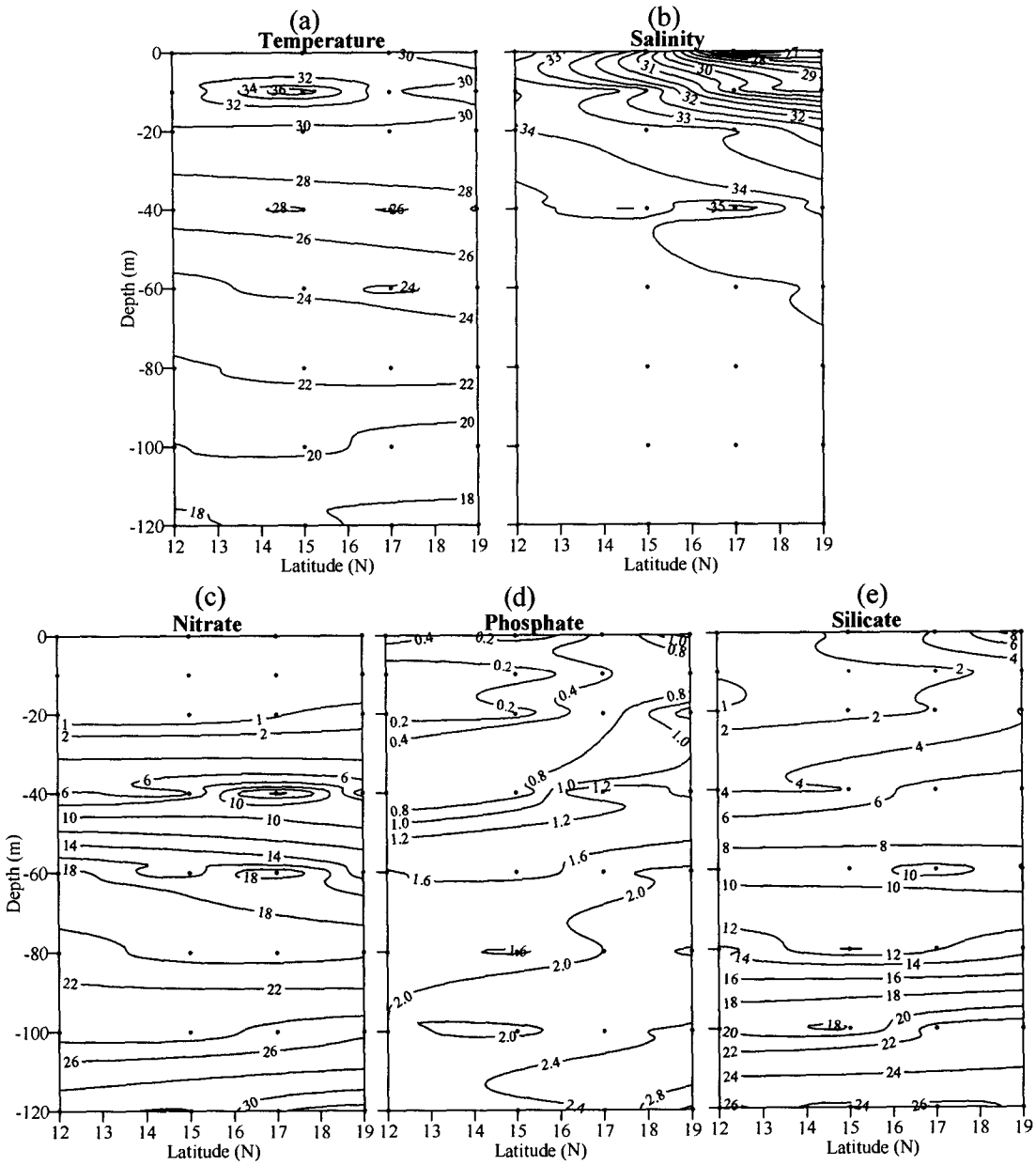


Fig. 3.7. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and, e) silicate (μM) along Western Bay during fall intermonsoon

μM in the north (Fig.3.8d). Phosphate was very low in the top 20 m (<0.1 μM) at some locations. The silicate levels (Fig. 3.8e) in the upper 30 m varied from 1.5 to 2 μM. The 1 μM nitrate and 2 μM silicate isopleths was generally located at about 60 m depth shoaled to less than 20 m towards the north.

In NEM, ~30 m thick ~26°C isothermal layer (Fig. 3.9a) north of 12°N deepened to 50 m at 17°N. However, to the north of 17°N, a distinct thermal inversion could be discerned with relatively warm (>27°C) subsurface layers. The 33 psu isohaline layer (Fig. 3.9b) was ~30 m thick in the south that deepened to ~40 m in the north. The MLD showed an oscillating pattern unlike observed in the other seasons (Table 3.1, NEM). From a depth of 40 m at WB1 it shoaled to 20 m at WB2. It deepened again at WB3 to 52 m and shoaled up to 30 m at WB4. Similar to the other seasons, the top 40 m was devoid of nitrate during the NEM as well (Fig. 3.9c). However, unlike in the other seasons, the concentration of phosphate (Fig. 3.9d) was approximately 0.2 μM in the top 30 m throughout the transect. Silicate concentration in the top 40 m (Fig. 3.9e) decreased from ~3 μM in the south to 1 μM in the north.

Biological Parameters

Central Bay of Bengal

Chlorophyll a (chl *a*)

Along CB, seasonal variation in chl *a* concentration (Fig. 3.10) was quite distinct. Its column profiles both in terms of mg m^{-2} and mg C m^{-2} are depicted in Fig. 3.11. They also showed a marked difference from station to station during different seasons.

During SM, the surface chl *a* increased from south to north. It ranged from 0.06 to 0.28 mg m^{-3} in the surface. The surface concentration from CB1 to CB5 respectively was 0.11, 0.06, 0.12, 0.13, 0.28 mg m^{-3}. The corresponding nitrate values at these stations were undetectable except at CB5 where the nitrate was 0.10 μM. Silicate in the surface layers was in measurable concentrations only at CB1 (1 μM) and CB5 (2.7 μM). These concentrations corresponded to high

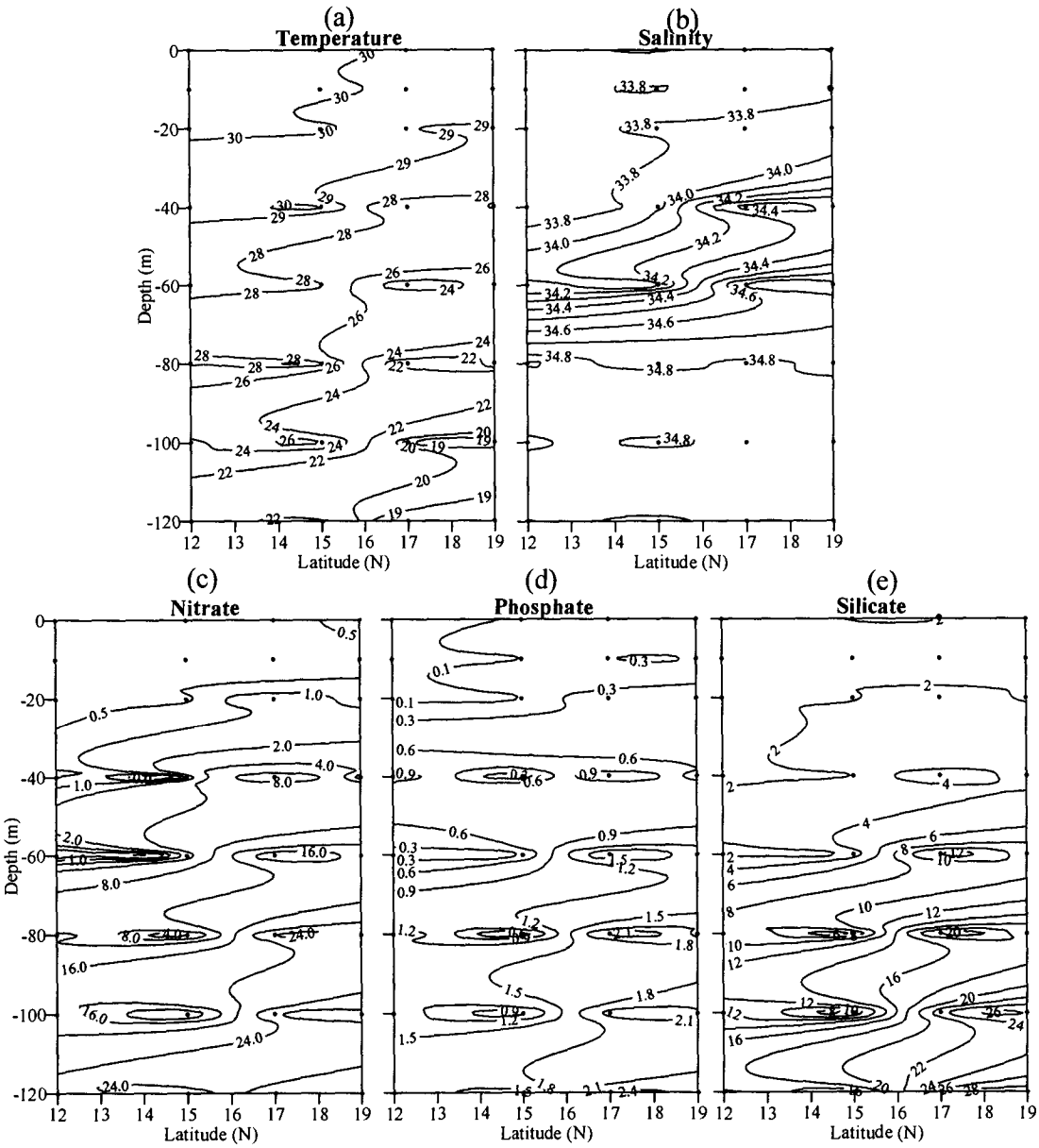


Fig. 3.8. Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and, e) silicate (μM) along Western Bay during spring intermonsoon

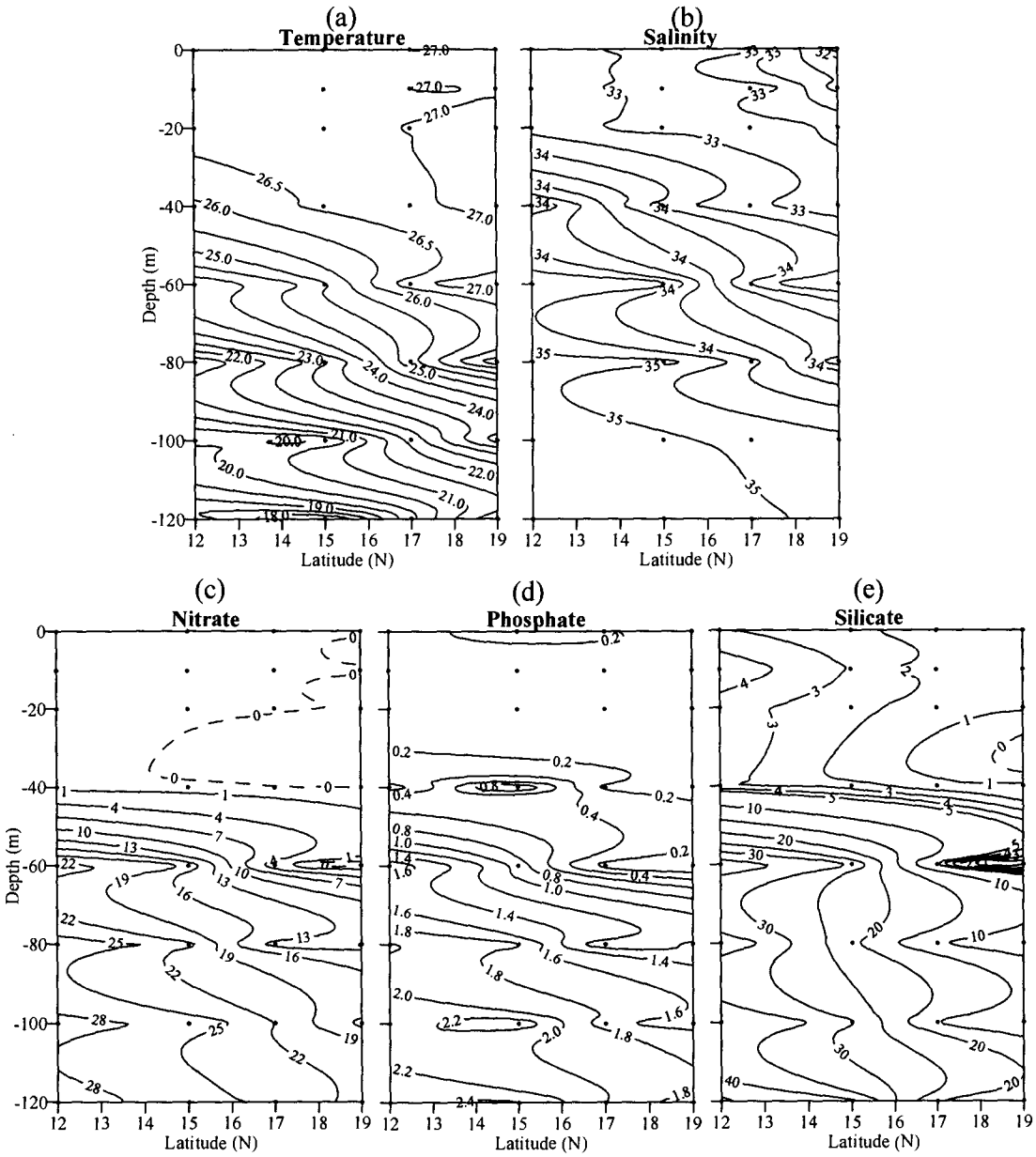


Fig. 3.9 Vertical sections of: a) temperature (°C), b) salinity (psu), c) nitrate (μM), d) phosphate (μM) and, e) silicate (μM) along Western Bay during northeast monsoon

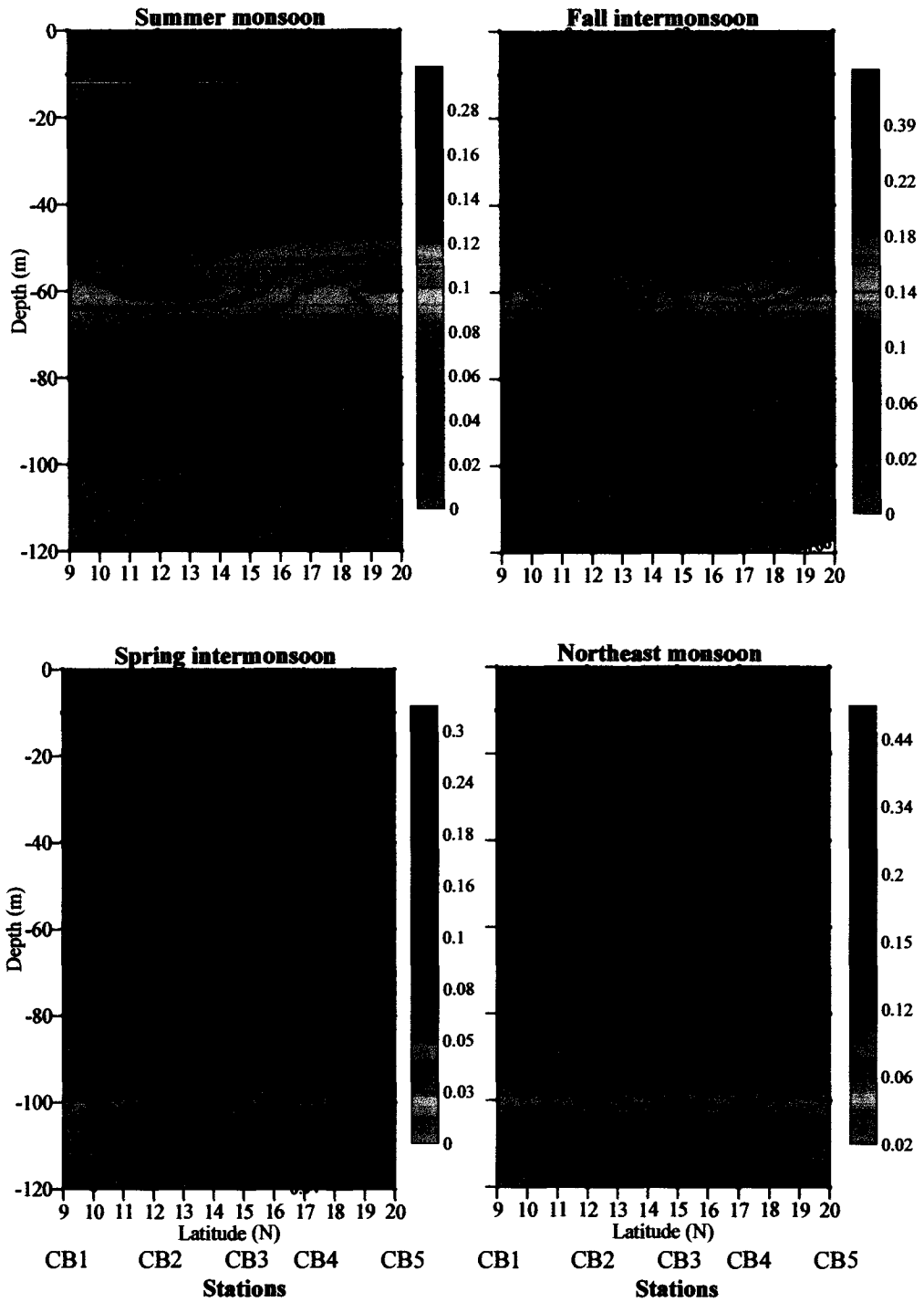


Fig. 3.10. Chlorophyll *a* concentrations (mg m^{-3}) along Central Bay during different seasons

surface chl *a* at these stations. Subsurface chlorophyll maxima (SCM) were observed at almost all the stations. The SCM were located at 40 m, 60 m, 40 m and 20 m and at the surface from CB1 to CB5 respectively. However, only at CB1 (with 9 μM NO_3 and 3.80 μM Si) and CB5 (0.10 μM NO_3 and 2.7 μM Si), the SCM corresponded to relatively high values of nitrate and silicate. In general, the SCM did not coincide with the phytoplankton abundance except at 20°N. In the 80-120 m column, it varied between 0.01 and 0.06 mg m^{-3}. The 0-120 m column integrated chl *a* ranged from 9 to 11.45 mg m^{-2} with its highs at CB1 and CB5.

During FIM, the surface chl *a* exhibited a decreasing trend from south to north. This was quite in contrast to its trend during SM. The surface concentration was 0.37, 0.16, 0.26, 0.12, 0.13 mg m^{-3} respectively from CB1 to CB5. The corresponding nitrate concentrations at these stations were undetectable at CB1 and 0.04, 0.08, 0.07, 0.11 μM at other stations. Silicate in the surface ranged from 0.4, 1.16, 0.81, 1.18, 2.28 μM respectively from CB1 to CB5 showing an increasing trend from south to north. Occurring around 40 m, 60 m, 10 m, 40 m and 40 m respectively from CB1 to CB5, the SCM corresponded to relatively high NO_3 (9.61, 5.02, 0.07, 8.77, 14.82 μM) and Si (4.25, 3.58, 1.09, 4.99, 9.28 μM). However, the SCM coincided with the phytoplankton abundance max only at 9°N and 20°N. The chl *a* during FIM ranged from 0.01 to 0.09 mg m^{-3} in 80 to 120 m. However, the 0-120 m column integrated chl *a* of 13 to 23 mg m^{-2} was higher than that in the SM with its highest at CB1.

Ranging narrowly from 0.06 to 0.11 mg m^{-3}, the surface chl *a* (CB1 to CB5 was 0.07, 0.06, 0.09, 0.11, 0.10 mg m^{-3} respectively) showed a uniform distribution from south to north during SpIM. Further, nitrate in the surface (ranging respectively from 0.4, 0.2, 0.4, 0.2, 0.2 μM from CB1 to CB5) also did not vary much. Silicate however, decreased from CB1 to CB5 and their concentrations were 2.04, 2.13, 1.90, 1.95 and 1.61 μM respectively. From CB1 to CB5, the SCM occurred around 60 m, 80 m, 80 m, 80 m and 60 m respectively and corresponded to relatively high NO_3 (15.7, 16.5, 15.3, 0.5, 6.8 μM)) and Si (10.16, 10.85, 10.29, 3.86, 4.6 μM). In general, the SCM did not coincide with

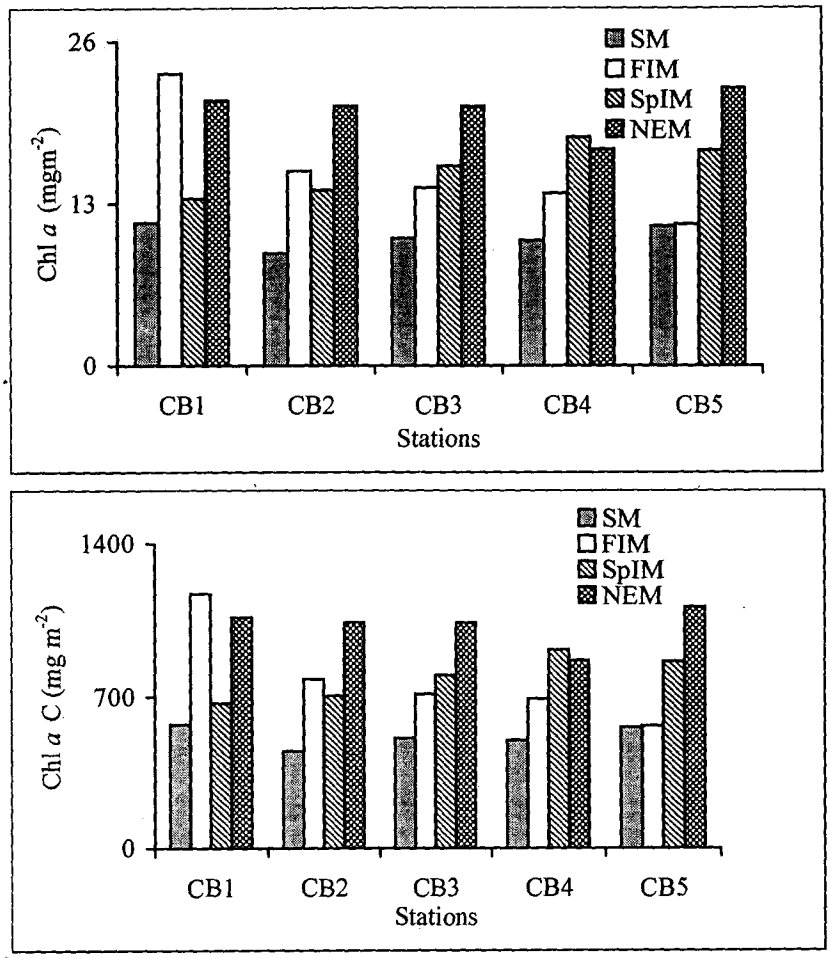


Fig. 3.11. Surface -120 m column integrated chlorophyll *a* (Chl *a*; mg m^{-2}) and chlorophyll carbon (Chl C; mg m^{-2}) along Central Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

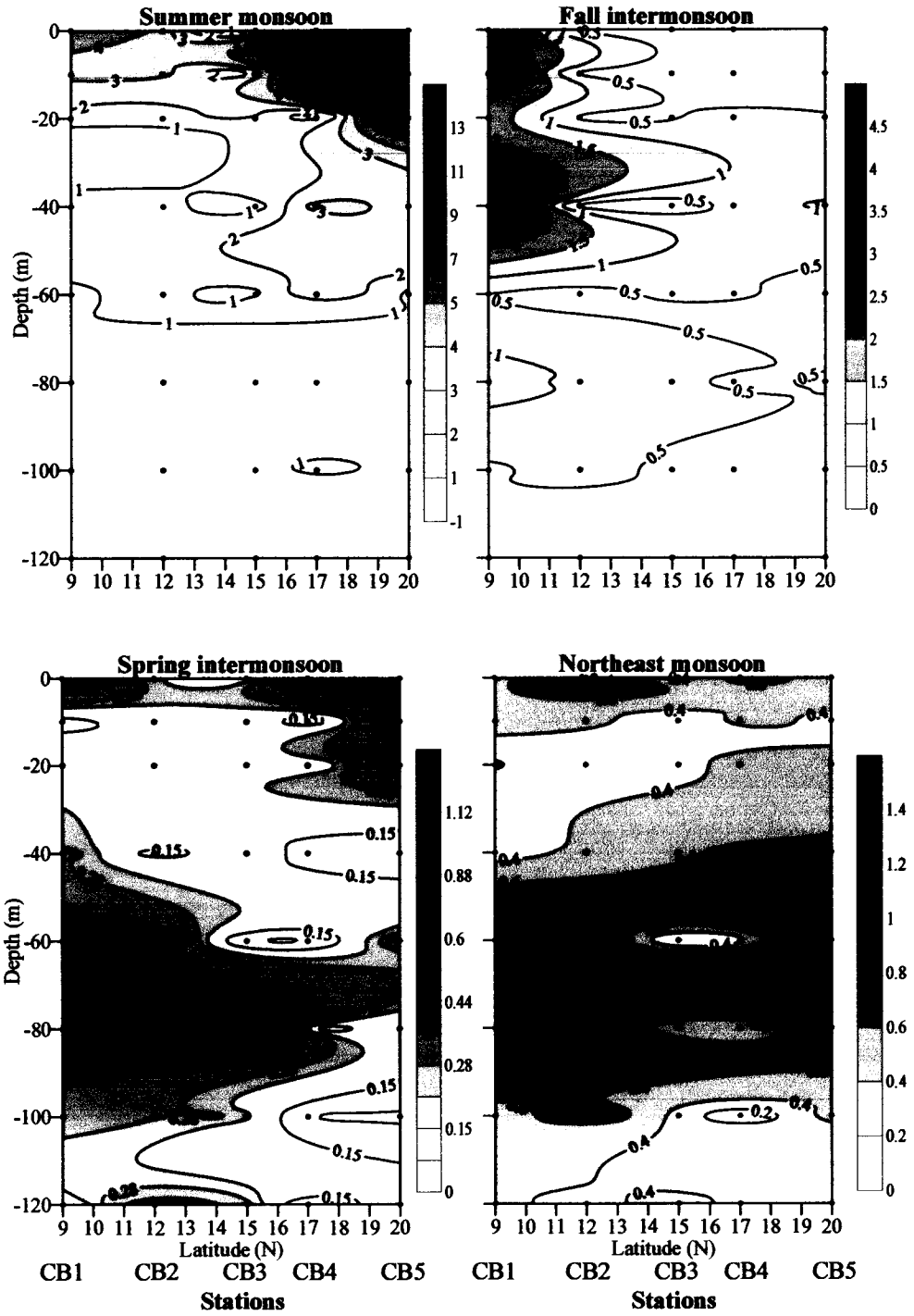


Fig. 3.12. Phytoplankton abundance (cells x $10^3 L^{-1}$) along Central Bay during different seasons

phytoplankton abundance maxima. In the 80-120 m depth, chl *a*, was in the range of 0.01-0.28 mg m^{-3}. It was higher than found in FIM and SM. The 0-120 m column integrated chl *a* ranged from 13.41 to 18.26 mg m^{-2}, increasing northwards, with its highest at CB4.

Chlorophyll *a* ranged from 0.12–0.19 mg m^{-3} in the surface samples during NEM. Its concentration was 0.15, 0.12, 0.13, 0.19, 0.13 mg m^{-3} from CB1 to CB5 respectively. The corresponding nitrate in the surface was: 0.16, not detectable (ND), ND, 0.14, 0.15 μM and silicate: 1.82, 0.56, 0.96, 1.57, 1.43 μM respectively from CB1 to CB5. The SCM occurred around 60 m at almost all the stations. At all stations, the SCM corresponded to relatively high values of NO_3 (1.69, 4.18, 0.21, 0.16, 0.2 μM)) and Si (3.64, 3.6, 1.98, 1.28, 1.24 μM). Except at CB5, the SCM did not coincide with the phytoplankton abundance maximum. The chl *a* in 80 to 120 m depth was in the range of 0.03-0.21 mg m^{-3} was higher than observed in the SM, FIM or SpIM. The 0-120 m column integrated chl *a* ranged from 17.3 to 22.2 mg m^{-2}, increasing northwards in general.

Phytoplankton cell counts (PCC)

Seasonal variations in phytoplankton abundance in terms of their cell numbers at different sampling locations along CB are depicted in Fig. 3.12 and, their 0-120 m column integrated abundance, in Fig. 3.13.

Similar to chl *a*, the surface PCC increased northwards with the highest cell counts of 13.8 x 10^3cells L^{-1} at CB5 (20°N 88°E) during SM. Mostly, PCC decreased with depth. Their 0-120 m column integrated abundance at different stations decreased from 9°N (12.6 x 10^7nos m^{-2}) to15°N (8.1 x 10^7nos m^{-2}) and, thereafter increased to 20°N (37 x 10^7nos m^{-2}). Up to 56% of total PCC were present within the MLD.

During FIM, the PCC abundance in the surface was more in the south. Their maximum surface count of (3.2 x 10^3 cells L^{-1}) was at CB1 (9°N 88°E). Further, the highest abundance (4.8 x 10^3 cells L^{-1}) was at 40 m at CB1. The PCC did register subsurface maxima depths at a few locations, unlike that in the SM. The

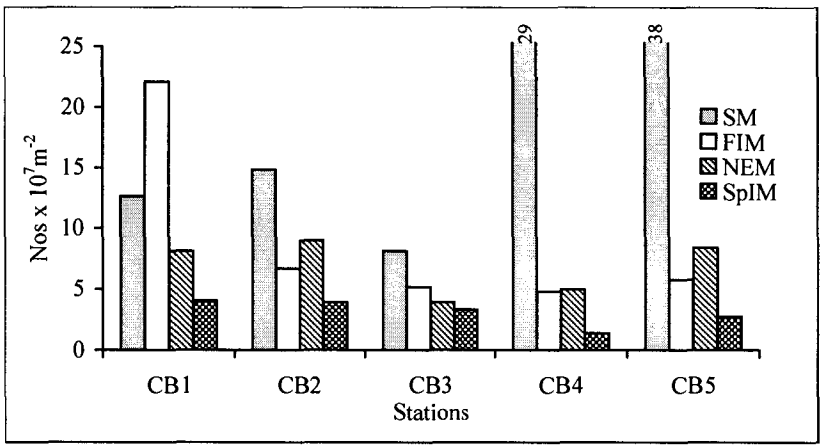


Fig. 3.13. Surface-120 m column integrated phytoplankton abundance (Nos x $10^7 m^{-2}$) along Central Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

column abundance ranged from 4.8 to 22 x 10^7 nos m^{-2} with the maximum abundance at CB1 (Fig. 3.13). Bulk (57%) of the total PCC abundance was within the MLD.

In general, PCC were low during SpIM compared to SM and FIM. During SpIM, surface PCC were more at CB1 and CB4. The highest PCC (0.8 x 10^3 cells L^{-1}) was at 100 m at CB3. The PCC mostly decreased with depth except for the subsurface maxima at CB3. Column abundance ranged from 1.4 to 4 x 10^7 nos m^{-2} with their maximum abundance at CB1. Unlike during SM and FIM, only 37% of the total PCC was within the MLD.

In NEM, surface abundance decreased north of CB2. Similar to chl *a* distribution pattern, PCC also showed an oscillating pattern of higher abundances at CB2 and CB4; lower abundances at CB1, CB3 and CB5. The PCC was the highest at CB2. The 0-120 m column abundance ranged from 3.9 to 8.9 x 10^7 nos m^{-2} with their highest at CB2 (12°N 88°E). Similar to SpIM, the PCC abundance was lower in the MLD accounting for only 37% of the total abundance.

Statistical Analyses

During SM and FIM, there was a significant negative correlation between chl *a* and salinity and, between chl *a* and nutrients. It showed a significant positive correlation with temperature (Table 3.2). In SpIM, significant negative correlation was observed with silicate only. During NEM, a significant negative correlation with salinity, phosphate and silicate was observed and a positive correlation was observed only with temperature.

The same was not the case with phytoplankton abundance. It showed a negative relation with salinity, nutrients and a positive relation with temperature in SM. None of the parameters had strong correlation with phytoplankton abundance in FIM, SpIM and NEM (Table 3.2). Phytoplankton abundance (Fig. 3.14) correlated strongly with chl *a* during SM ($R= 0.701$; $p<0.00$), FIM ($R= 0.656$; $p<0.00$) and NEM ($R= 0.406$; $p<0.01$); not during SpIM ($R= 0.178$; $p>0.272$).

Table 3.2. Spearman's Rank correlation coefficients for chl *a*, log transferred PCC versus temperature (Temp), salinity, nitrate (NO_3), phosphate (PO_4) and silicate (SiO_4) along the Central Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

Chl *a* v/s	**Parameter**									
Season	**Temp**		**Salinity**		**NO_3**		**PO_4**		**SiO_4**	
	R	*p*	R	*p*	R	*p*	R	*p*	R	*p*
SM	**0.69**	**0.00**	**-0.55**	**0.00**	**-0.76**	**0.00**	**-0.68**	**0.00**	**-0.71**	**0.00**
FIM	**0.76**	**0.00**	**-0.64**	**0.00**	**-0.79**	**0.00**	**-0.74**	**0.00**	**-0.85**	**0.00**
SpIM	0.24	0.14	-0.22	0.19	-0.25	0.12	-0.26	0.11	**-0.35**	**0.03**
NEM	**0.43**	**0.01**	**-0.33**	**0.04**	-0.31	0.06	**-0.45**	**0.01**	**-0.36**	**0.02**

Log (PCC) v/s	**Parameter**									
Season	**Temp**		**Salinity**		**NO_3**		**PO_4**		**SiO_4**	
	R	*p*	R	*p*	R	*p*	R	*p*	R	*p*
SM	**0.67**	**0.00**	**-0.77**	**0.00**	**-0.72**	**0.00**	**-0.51**	**0.00**	**-0.66**	**0.00**
FIM	0.07	0.66	0.03	0.84	-0.07	0.67	-0.10	0.53	-0.22	0.18
SpIM	-0.05	0.77	0.03	0.87	0.08	0.63	0.02	0.90	0.13	0.42
NEM	-0.09	0.58	0.12	0.46	0.06	0.70	0.02	0.88	-0.03	0.87

* significant values at $p \leq 0.05$ are in bold.

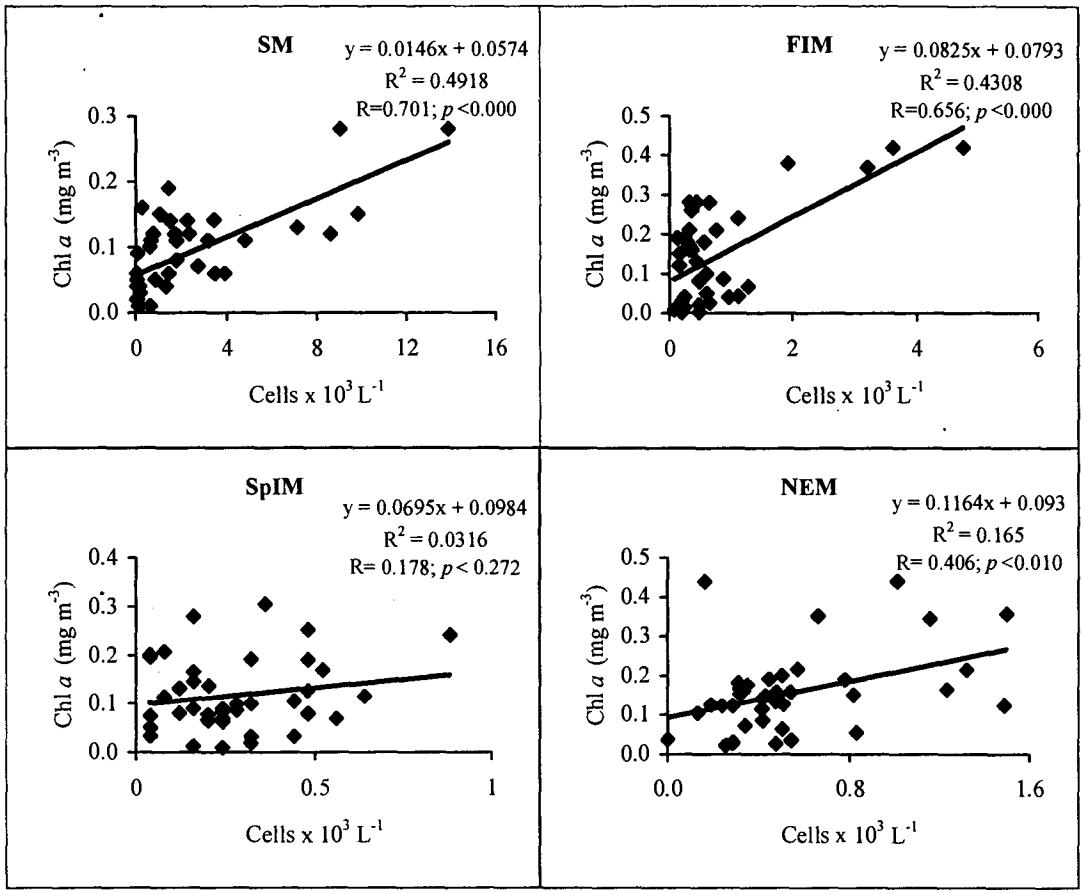


Fig. 3.14. Coefficients of regression (R^2) for phytoplankton abundance (cells x 10^3 L^{-1}) and chlorophyll *a* (chl *a*; mg m^{-3}) along Central Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

Western Bay of Bengal

Chlorophyll a (chl a)

Seasonal variations in chl *a* concentrations along WB differed from station to station (Fig. 3.15). Its column profiles also showed a marked difference during different seasons (Fig. 3.16). The column profiles are given in terms of chl mg m^{-2} and also as mg C m^{-2} in Fig 3.16.

Similar to those in CB, the surface chl *a* ranging from 0.06 to 0.16 mg m^{-3}, increased northwards during SM. Its surface concentrations were 0.13, 0.06, 0.10, 0.16 mg m^{-3} respectively at WB1-WB4. Nitrate and silicate were undetectable throughout the transect except for 4 µM silicate at the northernmost station. The SCM were observed at 40, 60, 40, 20 m from WB1 to WB4 respectively. Although as high as 14.40 µM nitrate was recorded at WB3 at the corresponding SCM depth, it was undetectable at the other stations. Silicate concentrations of 6 and 0.6 µM were recorded at WB3 and WB4 at the SCM depths. It is possible that the nutrients were exhausted by phytoplankton at these depths, hence not detected. In general, SCM did not coincide with PCC except at WB1 and WB4. The chl *a* ranged from 0.01 to 0.21 mg m^{-3} between 80 m and 120 m. This was similar to the concentrations along CB during SM. The 0-120 m column integrated chl *a* from WB1 to WB4 were 12.7, 11.65, 11.95 and 18.7 mg m^{-2}; with the highest at WB4.

During FIM, the surface chl *a* ranged from 0.14–0.77 mg m^{-3}; increasing northwards. Its surface concentration from WB1 to WB4 was 0.18, 0.14, 0.18 and 0.77 mg m^{-3} respectively. The corresponding surface nitrate and silicate concentrations were 0.21, 0.11, 0.13 and 0.22 µM and, 1.05, 2.25, 3.62 and 9.69 µM respectively. SCM were observed at 20, 40, 40 m and near surface from WB1 to WB4 respectively. At all these stations, SCM corresponded to high NO_3 (0.4, 5.36, 17.04, 0.22 µM)) and/or Si (1.07, 3.96, 7.58, 9.69 µM) concentrations. SCM coincided with PCC-maxima except at WB3. The chl *a* ranges were between 0.01 and 0.07 mg m^{-3} in the depth zone of 80-120 m. The 0-120 m column integrated chl *a* (18.7, 12.9, 18.4 and 11.28 mg m^{-2} from WB1 to WB4) increased northwards; with its highest at WB1.

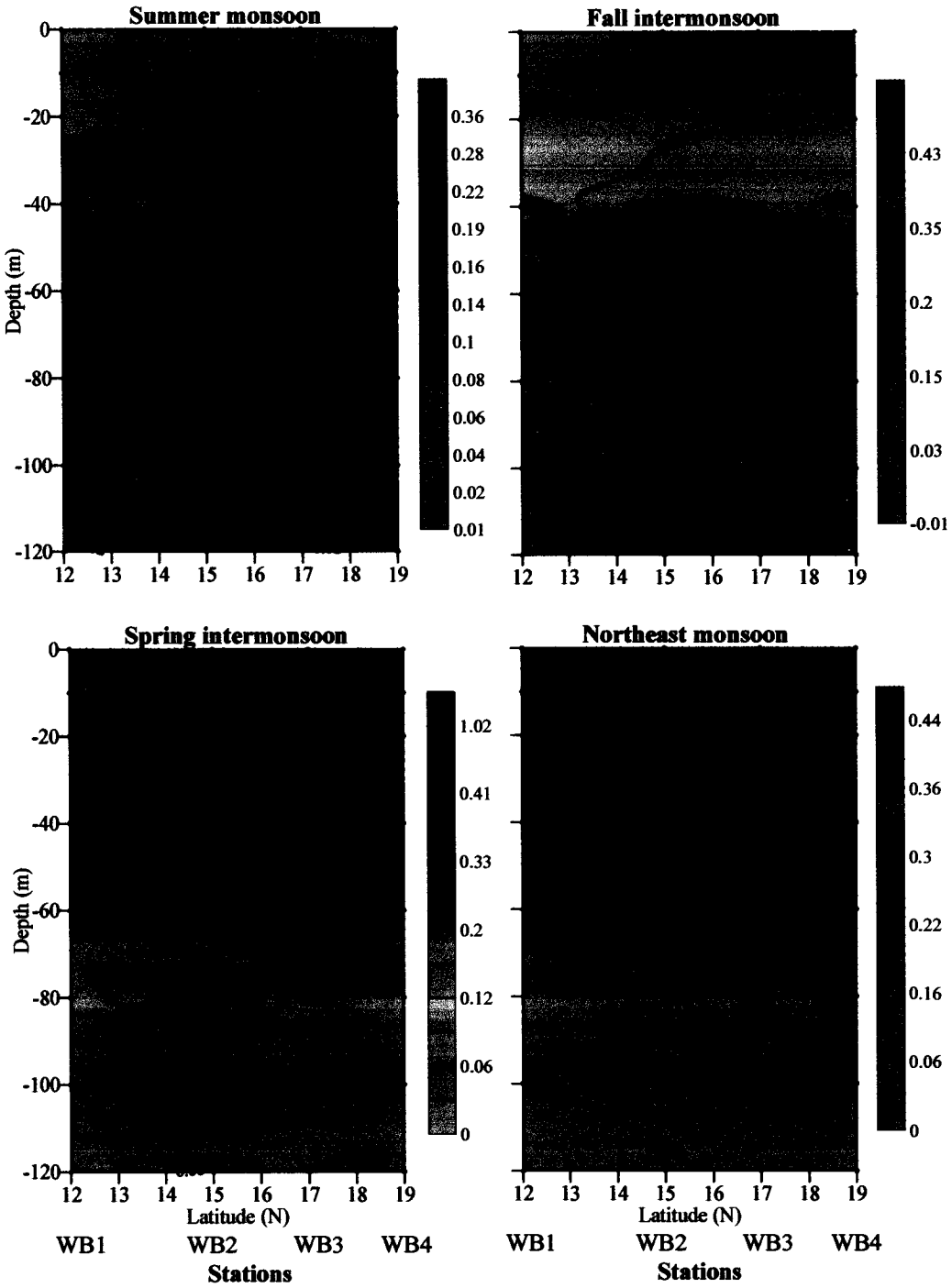


Fig. 3.15. Chlorophyll *a* concentrations (mg m^{-3}) along Western Bay during different seasons

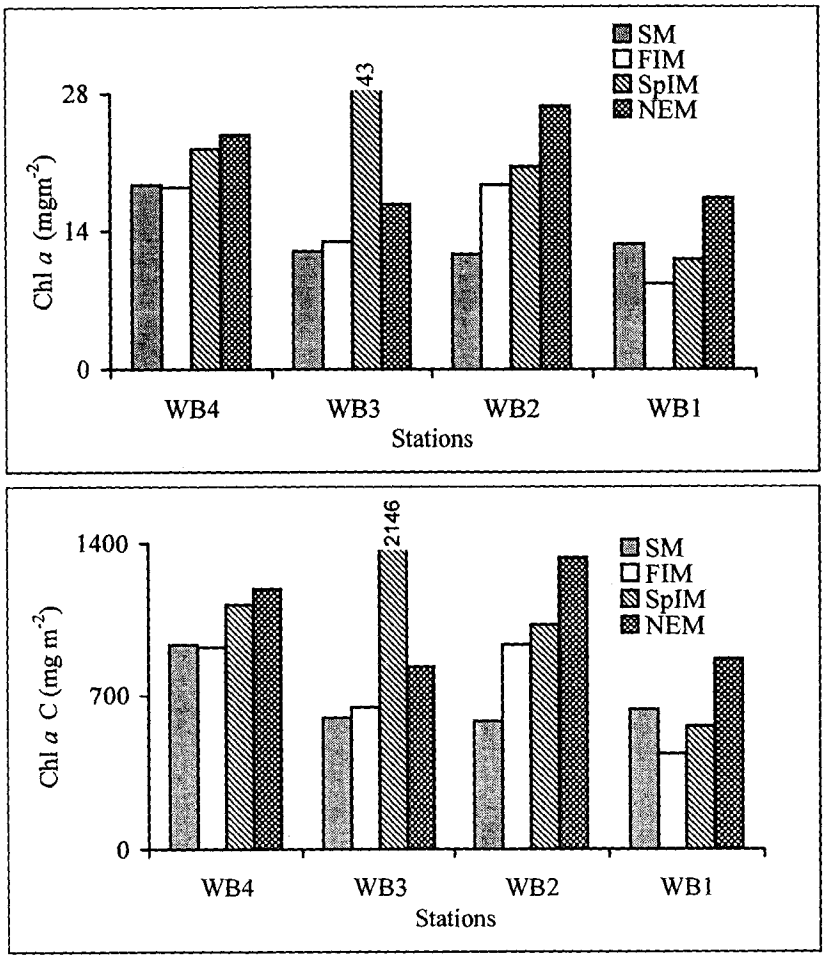


Fig. 3.16. Surface -120 m column integrated chlorophyll *a* (Chl *a*; mg m^{-2}) and chlorophyll carbon (Chl C; mg m^{-2}) along Western Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

Increasing northward, surface chl *a* concentration during SpIM was 0.06, 0.06, 0.14 and 0.21 mg m^{-3} respectively from WB1 to WB4. The surface nitrate concentrations (0.5, 0.2, 0.2, and 0.8 μM) did not vary much. Silicate concentrations from WB1 to WB4 were: 1.67, 2.02, 2.13 and 1.42 μM respectively. Located at 80 m, 80 m, 40 m and 60 m respectively from WB1 to WB4, SCM was evident at all these stations. It corresponded to relatively high NO_3 (13.3, 2.2, 14 and 12 μM)) and/or Si (9.4, 5.44, 6.3 and 7.63 μM) concentrations. However, it did not coincide with PCC-maximum except at WB3. The chl *a* ranged between 0.02 and 0.31 mg m^{-3} between 80 m to 120 m which was higher than found in SM and FIM. The 0-120 m column integrated chl *a* increased northwards (11.18, 20.51, 42.92 and 22.27 mg m^{-2} from WB1 to WB4) with its highest at WB3.

Unlike during the other three seasons, the surface chl *a* values showed an oscillating pattern during NEM with highs at WB2 and WB4 and lows at WB1 and WB3. It ranged from 0.15–0.28 (0.15, 0.28, 0.16 and 0.23 from WB1 to WB4 respectively) mg m^{-3} in the surface. The corresponding nitrate and silicate concentrations were: 0.7, 0.18, 0.04 and 0.10 μM and, 3.07, 2.41, 1.28 and 1.42 μM. SCM were at 50 m at all stations. It corresponded to relatively high values of NO_3 (123.1, 19.4, 0.01 and 0.05 μM)) and Si (37.35, 31.26, 1.11 and 1.14 μM) from WB1 to WB4. In general, it did not coincide with PCC-maxima. Between 80 m and 120 m, chl *a* was in the range of 0.005-0.05 mg m^{-3}. This concentration range was the lowest among all the seasons. The 0-120 m column integrated chl *a* was 17.4, 26.67, 16.7 and 23.8 mg m^{-2} from WB1 to WB4. These concentrations were similar to those observed along CB during NEM.

Phytoplankton cell counts (PCC)

Both the synoptic (Fig. 3.17) and 0-120 m column integrated (Fig. 3.18) PCC were higher along the WB than CB during most of the seasons sampled.

The surface PCC increased northwards from WB2 during SM. This pattern is similar to that observed along CB. The PCC decreased with depth although their subsurface maximum (23.2 x 10^3cells L^{-1}) was observed at 20 m at WB4 (19°N

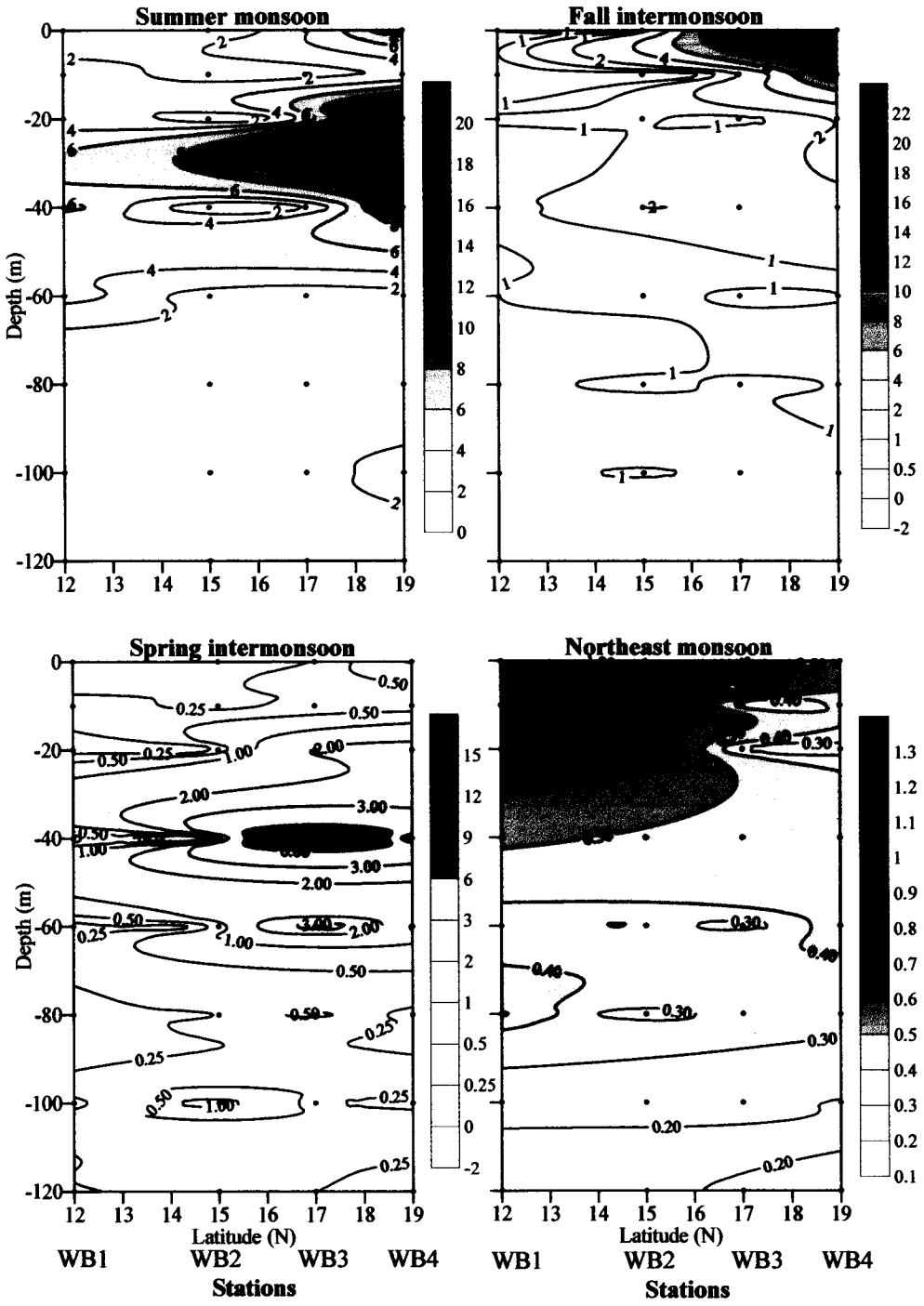


Fig. 3.17. Phytoplankton abundance (cells x $10^3 L^{-1}$) along Western Bay during different seasons

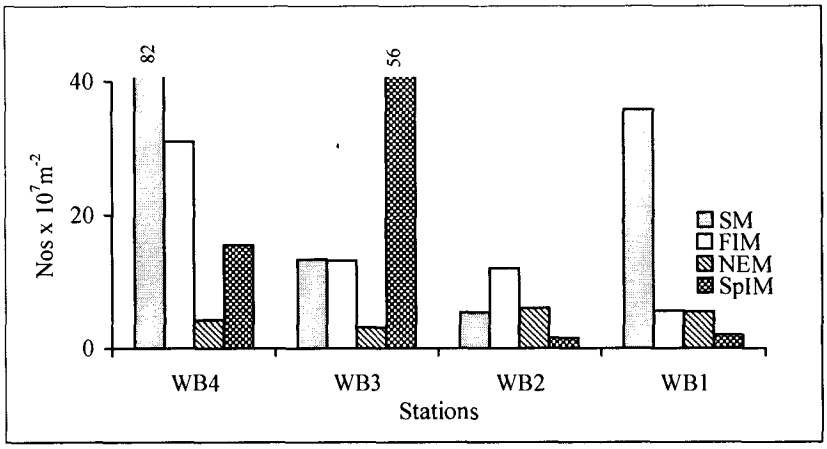


Fig. 3.18. Surface-120 m column integrated phytoplankton abundance (Nos x 10^7 m^{-2}) along Western Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

85°E). The 0-120 m column integrated counts ranged from 5.3 x 10^7 to 82.1 x 10^7 m^{-2}; with the highest counts at WB4 and, decreasing southwards thereafter. However, unlike in CB, only 29% of total PCC were within the MLD in the WB.

In contrast to CB, PCC increased northwards during FIM. Their surface abundance also increased northward with their maximum (22.76 x 10^3cells L^{-1}) at WB4. The 0-120 m column integrated counts ranged from 5.5 x 10^7 to 30.9 x 10^7 m^{-2}. As also observed along CB, 57% of the total PCC was present within the MLD.

The PCC increased towards north also during SpIM with the maximum abundance (1.08 x 10^3cells L^{-1}) again at WB4. However, the SpIM abundance was lower than that observed either during SM or FIM. The 0-120 m column integrated counts ranged from 1.5 x 10^7 to 55 x 10^7 nos m^{-2} with their maximum at WB3. Only 19% of the total PCC occurred in the MLD, akin to that seen along CB.

In the north east monsoon (NEM) only seven depths were sampled along the WB. The PCC, similar to chl *a*, showed an oscillating pattern with high abundance at WB2 (1.3 x 10^3cells L^{-1}) and WB4 (0.50 x 10^3cells L^{-1}) and lower abundance at WB1 (0.96 x 10^3cells L^{-1}) and WB3 (0.48 x 10^3cells L^{-1}). The 0-120 m column integrated counts ranged from 3.1 x 10^7 to 6.0 x 10^7 nos m^{-2} with their maximum at WB2. As much as 72% of the total PCC was present within the MLD.

Statistical Analyses

During SM, FIM and NEM, a strong negative correlation between chl *a* and salinity, as well as nutrients was evident. It correlated positively with temperature (Table 3.3). No significant relation was observed with any of the parameters during SpIM.

The PCC correlated negatively with salinity and nutrients and positively with temperature during SM and FIM. While only salinity seems to control the abundance in NEM by having a negative significant correlation with abundance.

Table 3.3. Spearman's Rank correlation coefficients for chl *a*, log transferred PCC versus temperature (Temp), salinity, nitrate (NO_3), phosphate (PO_4) and silicate (SiO_4) along the Western Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

Chl *a* v/s	**Parameter**									
Season	**Temp**		**Salinity**		**NO_3**		**PO_4**		**SiO_4**	
	R	*p*	R	*p*	R	*p*	R	*p*	R	*p*
SM	**0.68**	**0.00**	**-0.73**	**0.00**	**-0.55**	**0.00**	**-0.46**	**0.01**	**-0.52**	**0.00**
FIM	**0.71**	**0.00**	**-0.69**	**0.00**	**-0.75**	**0.00**	**-0.68**	**0.00**	**-0.72**	**0.00**
SpIM	0.08	0.67	-0.14	0.45	-0.10	0.60	-0.08	0.66	-0.16	0.37
NEM	**0.68**	**0.00**	**-0.75**	**0.00**	**-0.72**	**0.00**	**-0.64**	**0.00**	**-0.74**	**0.00**

Log (PCC) v/s	**Parameter**									
Season	**Temp**		**Salinity**		**NO_3**		**PO_4**		**SiO_4**	
	R	*p*	R	*p*	R	*p*	R	*p*	R	*p*
SM	**0.67**	**0.00**	**-0.77**	**0.00**	**-0.54**	**0.00**	**-0.54**	**0.00**	**-0.52**	**0.00**
FIM	**0.49**	**0.01**	**-0.59**	**0.00**	**-0.57**	**0.00**	**-0.49**	**0.01**	**-0.49**	**0.01**
SpIM	-0.29	0.10	0.06	0.76	0.22	0.23	0.24	0.19	0.05	0.80
NEM	0.19	0.30	**-0.48**	**0.00**	-0.20	0.28	-0.23	0.20	-0.17	0.36

* significant values at $p \leq 0.05$ are in bold.

In SpIM as observed with the chl *a* no significant relation was observed with any of the parameters.

Cell abundance (Fig. 3.19) correlated significantly with chl *a* during SM (R= 0.651; $p<0.000$), FIM (R= 0.7134; $p<0.000$), SpIM (R= 0.867; $p<0.000$) and NEM (R= 0.504; $p<0.006$).

Discussion

The biogeography of the ocean *vis a vis* that of land is more complicated due to the dynamic nature of the ocean wherein the water masses are in constant motion (Thorrington-Smith 1971). The surface physical and chemical properties of partially enclosed seas are affected by the degree of mixing of river water with the oceanic waters (Solorzano & Grantham 1975). Due to the addition of large amounts of fresh water, a strong vertical stratification is created inhibiting nutrient upliftment from the subsurface (Sprintall & Tomczak 1992; Vinaychandran et al 2002). The proportion of saline to river water also affects the water column stability and irradiance levels. In that, with more saline waters, stability is better and irradiance is deeper. Plankton is wholly dependent on their immediate environment for growth and reproduction requirements and, their subsequent distribution/dispersal. Thus, it is tangible to discern that the physico-chemical features in the Bay affect distribution and abundance/biomass (chl *a*) of phytoplankton. The large amounts of riverine influx into the BoB affect the salinity and thus stratify the top layer. Weak winds of 0-10 ms^{-1} during most part of the year are unable to break this stratified layer. As a result, SSTs are warmer than 28°C in the top 20-40 m.

The runoff also affects the chemistry of the water column through controls on the circulation and mixing thus directly influencing the distribution of the phytoplankton. Low or undetectable concentrations of nitrate in the upper 20-40 m during this investigation confirm to the extensive analyses of De Sousa et al (1981). It was discerned by their study that the nutrient input, in particular nitrate, from the river discharges is quite insignificant. Low nitrate is apparently limiting

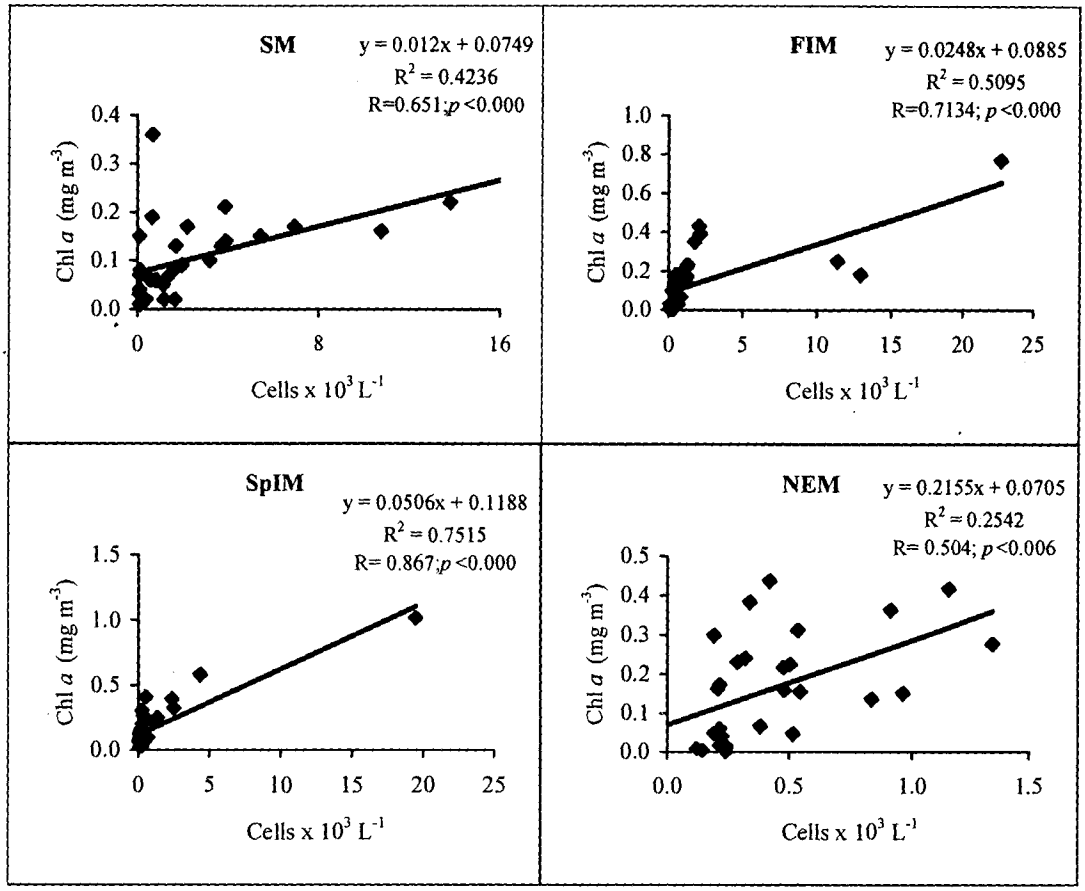


Fig. 3.19. Coefficients of regression (R^2) for phytoplankton abundance (cells x 10^3 L^{-1}) and chlorophyll *a* (chl *a*; mg m^{-3}) along Western Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

primary production in the BoB than the Arabian Sea (Naqvi et al 1978; Prasanna Kumar et al 2002).

During SM and FIM, upper 30 m is homogenous in terms of temperature profile except in areas of cold core eddies. During July to October covering SM and FIM periods of this study, the monthly river discharge of the six major rivers, viz. Ganges, Brahmaputra, Irrawady, Godavari, Krishna and Cauvery (Global runoff data center, Germany, http://grdc.bafg.de/servlet/is/2781/) dominates. The river discharge peaks in August and this voluminous river discharge is reflected in vertical salinity that showed a strong gradient (Prasanna Kumar et al 2002; 2007) in the top 30 m. Murty & Varadachari (1968) and De Sousa et al (1981) reported localized mild upwelling along the southern part of the western BoB. However, no signatures of upwelling were evident during any season at any sampling location chosen for BOBPS programme.

Earlier studies of Radhakrishna et al (1978) and Bhattathiri et al (1980) reported surface chl *a* in the ranges of 0.08-1.67 and 0.01-1.01 mg m^{-3} in the WB during summer. Similar to ranges observed during this study, recently Madhu et al (2006) reported <0.1 mg m^{-3} chl *a* in surface waters during SM. Availability of higher nitrate (1 μM) and phosphate (<0.4 μM) in the top 20 m might have led to such concentrations of chl *a* in the well-lit surface layers. However, Madhu et al (2006) did not observe any SCM as observed during SM of this study. Frequent SCM observed in this study are attributable to:(a) lack of nutrients in the top 10-30 m but, (b) their availability in excess of 0.5 μM below 30 m. The phytoplankton in the BoB appear to have adapted to low light conditions as the SCM were often deep seated and, chl *a* was often far more than that recorded from surface samples from the same location.

Usually, there is low-salinity surface layer during SM (29 psu) and FIM (25 psu), than during SpIM (33 psu). The warm surface waters and thermal stratification is a well-known feature of the BoB during SpIM. Along the WB, the SpIM SST did not differ much from that of FIM. Shetye et al (1993) observed several warm water recirculation zones in the northwestern Bay in association with the pole-

ward flow of the east India coastal current (EICC) north of 10°N during SpIM. This EICC carries nutrient poor warm water from the south. The average surface (0.09 mg m^{-3}) and column integrated (15.79 mg m^{-2}) chl *a* reported in this study during SpIM were lower than previously reported (<0.3 mg m^{-3}; Madhu et al 2006 and, 18 mg m^{-2}; Gomes et al 2000). Sengupta et al (1977) reported that rivers did not contribute to the inorganic nutrient pool of the western BoB during SpIM. Such a situation might be forcing the phytoplankton to depend on 'ideal concentrations' persisting in nitracline of ~30-70 m layer. As also observed in this study, deep-seated SCM ~50 to 80 m is apparently a common SpIM feature reported by Murty et al (2000); Gomes et al (2000) and Madhu et al (2006). Further, the SCM occurring in the nitracline are essential features of the typical tropical structure in the Atlantic (Herbland & Voituriez 1979) and in the Arabian Sea (Madhupratap et al 1996).

Inspite of low SST in the north, winter cooling during NEM 2005-06 did not lead to convective mixing. As reported by many authors (Prasanna Kumar & Prasad 1996; Madhupratap et al 1996; Jyothibabu et al 2004), the intense stratification by freshwater-lense may not allow such mixing. The NEM 2006, higher salinity and deeper isohaline and isothermal layers plus thermal inversion are also observed earlier (Shetye et al 1996; Han et al 2001; Pankajakshan et al 2002; Maheswaran 2004). This scenario contrasted the physical settings of SM and FIM sampled for this study. The average concentrations of surface and column integrated chl *a* were similar to those reported from offshore waters by Madhu et al (2006); Gomes et al (2000). Apparently, SCM were not noticeable in the earlier years during winter. In this study however, deep SCM were observed. Reasons for such SCM are already detailed above.

Strong winds over the Arabian Sea (AS) are reported to pump up subsurface nutrients by upwelling (Kuzmenko 1973) or convective vertical mixing (Prasanna Kumar & Prasad 1996) leading to strong coupling between physical and biological processes (Tarran et al 1999). Sawant & Madhupratap (1996) had earlier reported high phytoplankton abundance as a consequence of upwelling along the coastal and open ocean AS during SM. However, due to warmer

freshwater during SM, FIM and NEM as well as for reasons listed above, the weak winds over the BoB are unable to break the strong stratification. Thus, surfacing of nutrients abundant below the mixed layer will be either very poor or, none. Further, the weak coastal upwelling-if at all- in the WB is quite inconsequential for nutrient injections into the well-lit surface layer.

Salinity is known to have little influence on the distribution of phytoplankton in the open sea (Smayda 1958; Kinne 1971). This is because; its variations are too slight to bear an effect on their biogeography. Salinity fluctuations in the BoB are more than those of temperature. While distribution of euryhaline and eurythermal species of phytoplankton may not be affected by salinity and temperature fluctuations, there were strong negative correlations between chl *a* and salinity as well as between chl *a* and nutrients during SM, FIM and NEM along both transects. Such relationships imply that variations in salinity and availability of nutrients govern the phytoplankton pigment concentrations and growth. This could also be the reason for the phytoplankton to have aggregated at 40 to 80 m with stable salinity and adequate nutrients for their growth. Albeit the growth would be relatively slow owing to poorer light levels. Studies off New England and Bermuda where the salinity changes are very small (31.68 to 36.53 psu) indicated that many species of phytoplankton prefer lower salinities (Hulburt & Rodman 1963). Qasim et al (1972) observed that both growth rates of phytoplankton and photosynthesis are affected by fluctuations in salinity especially in estuaries and in estuarine like environments. The high fluctuations of salinity in the BoB present almost throughout the year give it an estuarine like characteristic. Results of this study corroborate with observations of Gomes et al (2000). In that, both phytoplankton biomass (chl *a*) and productivity are influenced by fluctuating salinity in coastal waters of BoB. Significant correlation between chl *a* and phytoplankton abundance during all four seasons along CB might also be suggesting that most chl *a* comes from phytoplankton >5 μm. The apparently poor correlation between these two parameters during SpIM along WB can be reasoned out that picoplankton (not quantified during this study), might have been the major components. In North Pacific too, high chl *a* was found during periods of low abundance of phytoplankton >5 μm (Mochizuki et al 2002).

Corresponding to depths of adequate/higher concentrations of nutrients, the SCM were observed in all seasons along both transects. Distribution of chl *a* and abundance of phytoplankton in the BoB during most part of the year are governed not only by nutrient regimes but also by physical features such as cold core eddies (Prasanna Kumar et al 2002) and Ekman pumping (Vinaychandran & Matthew 2003). During SM, FIM and SpIM, cold core eddies along CB and WB seem to facilitate surfacing the nutrients up to 20-50 m strata in the freshwater capped, stratified BoB (Prasanna Kumar et al 2002; 2004; 2007). These cyclonic cold core eddies entrain the subsurface nutrients closer to or until the bottom of stratified isohaline layer. At such subsurface depths, phytoplankton use these for growth and thus, reflect in elevated chl *a*. Eddy pumping is known to cause upward displacement of nutricline (Falkowski et al 1991; McGillicuddy et al 1998; Seki et al 2001) by injecting growth promoting nutrients into the impoverished euphotic zone thus enhancing chl *a* and phytoplankton growth (Valliancourt et al 2003).

In the NEM however, the SCM were between 40 and 60 m along both transects. Mostly, SCM were at depths with higher than 1 μM nutrients. Phytoplankton abundance at the surface along the coast during NEM could be due to more silicate apart from sufficient enough amounts of nitrate and phosphate.

In conclusion, the riverine influx and physical processes (eddies and Ekman pumping) seem to affect availability of nutrients to the phytoplankton. Distribution of phytoplankton in terms of cell abundance and biomass (chl *a*) along both transects, thus, appear to be governed by nutrient inputs. Despite their low abundance and lower PAR around 40–60 m, the phytoplankton in the BoB appear to contain higher chl *a*. Microphytoplankton apparently contribute as much as ~90% of chl *a* biomass.

Chapter 4

Chapter 4

Nutrient ratios and phytoplankton community structure

Introduction

Phytoplankton community composition and succession reflect the environmental conditions of an ecosystem, among which the nutrients and, their availability in right proportion play a significant role (Dugdale 1967; Rhyther & Dunstan 1971; Smayda 1980). When the supply is in less than required amounts, nutrients limit phytoplankton growth (Tilman et al 1982). The limiting nutrient concentrations vary with season, location and phytoplankton community structure (Fisher et al 1992). Generally, nitrogen (N) limitation prevails in most of the marine systems (Fisher et al 1992; Howarth 1988). Principally, the half-saturation constant K_s, for a limiting nutrient are greater than its ambient concentration and therefore regulate the growth of phytoplankton community. Changes in nutrient supply are often reflected in their ratios (Yin et al 2001). Thus elemental ratios (nitrate, phosphate and silicate) from water samples can be used as indicators of the status of nutrient loading or to predict productivity (De-Pauw & Naessens 1991). Nutrient limitation in natural phytoplankton communities is primarily identified from bioassays in which the response of the phytoplankton community to N or P is measured by additions of one or both nutrients in micro/mesocosms, or it is inferred from elemental ratios (Havens 2000). These ratios may be used to predict the phytoplankton abundance and assemblages. The ability to identify limiting nutrients thus becomes of considerable importance to our understanding of the ecology of phytoplankton. Moreover, measurements of elemental ratios in a given water body and their effect on the phytoplankton community can provide evidences for possible growth limitations. Therefore, the phytoplankton community structure in relation to nutrient (nitrate, phosphate and silicate) concentrations and their ratios was examined during this study.

Materials and Methods

Phytoplankton composition

Water samples from all nine stations (Chapter 3, Fig. 3.1) from each of the sampling depth were settled and concentrated from 250 ml to 10 ml. For counting phytoplankton cells (size >5μm) 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. Oil immersion 100X objective on a Zeiss (Axioskop, 2plus, Germany) microscope was also made use of for confirming the genera or species. Generic and species identification was done following various keys (Subramanyan 1946; 1961; 1968; Lebour 1978; Constance et al 1985a; 1985b; Desikachary & Ranjithadevi 1986; Desikachary & Prema 1987; Desikachary et al 1987; Tomas 1997). The cells were then calculated for one liter using the formula $x= (n \times v)/V$. Where, x= species per liter, n= numbers of cells in one ml, v= volume of concentrated sample, V= volume of sample in liters

Nutrient concentrations

Nutrient concentrations were measured by the chemical oceanographers and are made available for this study. They were measured using the auto-analyzer (SKALAR). These concentrations were used for calculating the N:P:Si ratios.

Clustering and ordination analyses

The fourth root ($\sqrt{\sqrt{}}$) transformed phytoplankton-abundance data were converted into a lower triangular similarity matrix using Bray-Curtis coefficients (Bray-Curtis 1957). These similarity matrices were then subjected to clustering. Clustering was performed using group average method (Pielou 1984). In case of clustering there are a few disadvantages such as: a) the individual loses its identity once placed in a group, b) the sequence of individuals is arbitrary and, c) only inter-group relationships are shown. Due to these disadvantages, it is prudent to employ an additional method such as non-metric multidimensional scaling (NMDS; Kruskal & Wish 1978). In NMDS, the stress values ≤ 0.05 indicate excellent similarity between the components. Thus, apart from clustering,

ordination was also done. Since both these methods are based on different assumptions (Gray et al 1988) different insights can be obtained by applying them. For evaluating species relationships, clustering and NMDS were carried out (using software Primer version 5).

Spearman's rank correlation test

Spearman's rank correlation test was performed to assess the relationship between the dominant phytoplankton group/species and various environmental component(s) that may be responsible for regulating their population. As the name suggests, the correlation is based upon assuming the variables are measured in a ranked order. Mostly this test is carried out on non-parametric data sets not showing normal distribution. The same test was applied between chlorophyll *a* and the environmental components. These tests were performed using Statsoft (software Statistica release 6.0.).

Results

Different ratios of nutrients at a given depth are plotted in Figs. 4.8; 4.9; 4.17; 4.18. The distribution of dominant species during different sampling seasons are plotted in Figs. 4.4; 4.5; 4.6; 4.7; 4.13; 4.14; 4.15; 4.16 at each depth. Using these data sets, the Spearman's rank correlation test was performed. Results below are described on the basis of these data sets.

Central Bay

Phytoplankton assemblages in the Central Bay

Generally, diatoms dominated (Fig. 4.1) followed by dinoflagellates and silicoflagellates in SM and FIM. While in SpIM diatoms, cyanobacteria and dinoflagellates dominated. Silicoflagellates were totally absent during SpIM. In NEM, the receding order of dominance was: diatoms >dinoflagellates >cyanobacteria >silicoflagellates. Among diatoms, pennales dominated in all the seasons. During FIM however, their abundance was of similar proportion to that of centric diatoms.

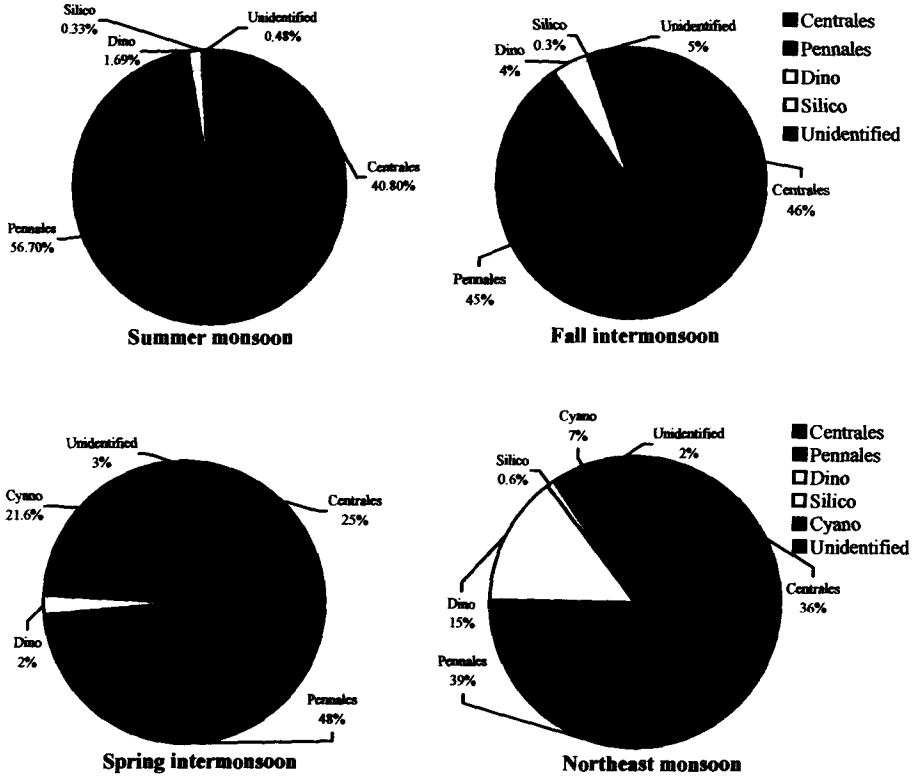


Fig. 4.1. Percent composition of centrales, pennales, dinoflagellates (Dino), silicoflagellates (Silico), cyanobacteria (Cyano) and unidentified phytoplankton along Central Bay during four different seasons

The season based cluster analysis on phytoplankton abundance revealed greater than 80 % similarity between seasons (Fig. 4.2A). Cluster I comprised of three seasons viz., NEM, FIM and SpIM. As the highest abundance was during SM, PCC did not group with other seasons. Similar pattern of phytoplankton distribution was evidenced through 2D NMDS ordination (Fig. 4.2B) method as well.

Summer Monsoon

In the SM, among the most abundant species of diatoms (Table. 4.1) were, *Thalassiothrix longissima* (20.29 %), *T. fauenfeldii* (16.21 %), *Nitzschia angularis* (8.55 %), *Thalassionema nitzschioides* (4.65 %), *Skeletonema costatum* (4.42 %), *Chaetoceros coarctatus* (3.92 %), *C. eibenii* (2.37 %), *Coscinodiscus radiatus* (3.62 %), *C. concinnus* (2.95 %), *Rhizosolenia styliformis* (2.22 %). A few genera of dinoflagellates were observed and *Ceratium furca* (0.6 %) and *Peridinium* sp (0.53 %) were abundant. *Dictyocha crux* was the only silicoflagellate found during this season.

Cluster analyses at 50 % similarity level divided 10 species (with $\geq$ 2 % contribution to total PCC) into 3 clusters and two ungrouped individuals (Fig. 4.3A). Both clusters I and III comprised of two species whereas cluster II, 4 species. *T. longissima* and *Nit. angularis* forming cluster I were absent below 80 m and they were more abundant in the southern station viz. CB1.

Though abundant at stations CB4 and CB5, *T. fauenfeldii, Ch. coarctatus, Ch. eibenii* and *R. styliformis* forming Cluster II were absent between 80 m and 100 m. While, *T. nitzschioides* and *Coscinodiscus radiatus* forming cluster III were absent in the southernmost station, CB1. The phytoplankton species distribution pattern using 2D NMDS ordination is presented in Fig. 4.3B. The stress value in this case exceeds 0.05; hence the positioning of the points in the NMDS and cluster is likely to be different. To show the similarity the points are encircled. Most of the dominant species were found to be in higher numbers in the depth of 20-40 m column (Fig. 4.4).

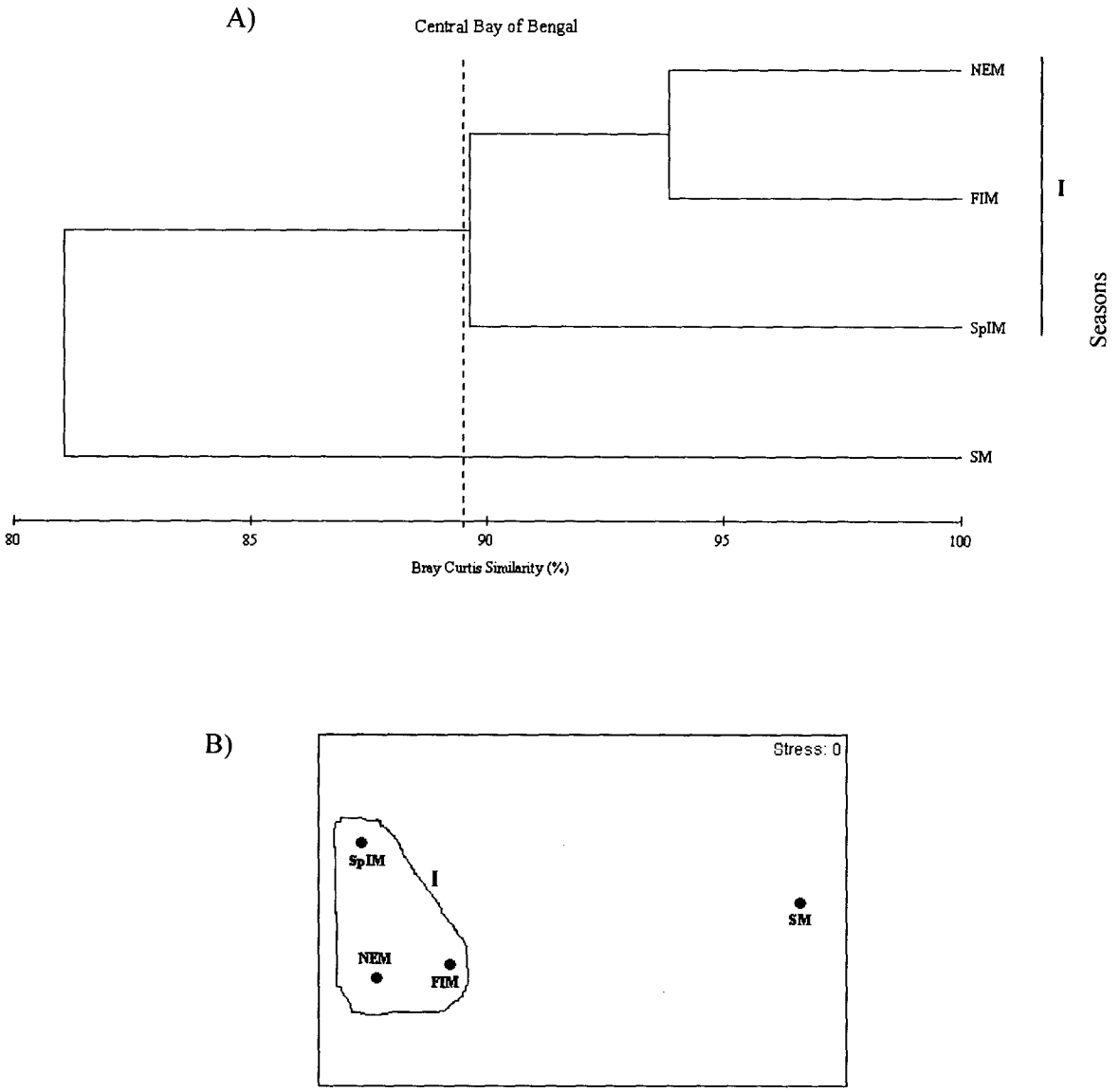


Fig. 4.2. A) Cluster dendrogram depicting similarity between seasons based on abundance of phytoplankton in the Central Bay. B) Non- metric Multidimensional scaling (NMDS) ordination based on the Bray- Curtis similarity coefficients. The season SM, did not group with other seasons.As the stress value was 0 there is still a very high similarity between the seasons as the numerical abundance was not very different

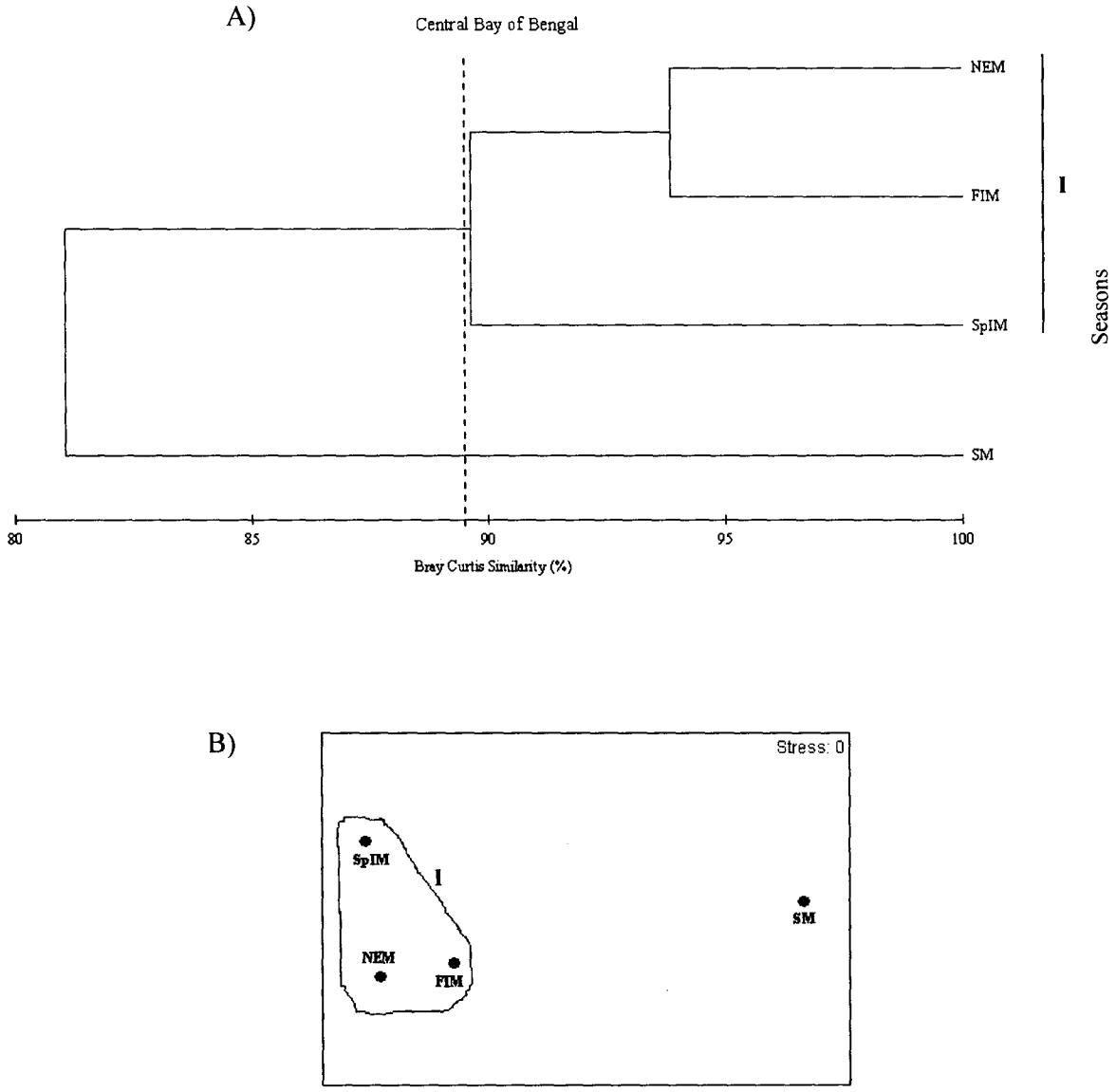


Fig. 4.2. A) Cluster dendrogram depicting similarity between seasons based on abundance of phytoplankton in the Central Bay. B) Non- metric Multidimensional scaling (NMDS) ordination based on the Bray- Curtis similarity coefficients. The season SM, did not group with other seasons.As the stress value was 0 there is still a very high similarity between the seasons as the numerical abundance was not very different

Table 4.1. Phytoplankton species composition along Central Bay (CB) and Western Bay (WB) in summer monsoon

Sr.No	Phytoplankton	CB	WB	Sr.No	Phytoplankton	CB	WB
	Centrales				**Centrales**		
1	*Actinocyclus octonarius*	--	0.31	80	*Thalassiosira antarctica*	0.05	--
2	*Asteromphalus flabellatus*	0.08	--	81	*Thalassiosira baltica*	--	0.31
3	*Bacteriastrum comosum*	0.14	0.37	82	*Thalassiosira condensata*	0.63	--
4	*Bacteriastrum delicatulum*	0.20	--	83	*Thalassiosira convexa*	0.24	--
5	*Bacteriastrum furcatum*	0.39	0.42	84	*Thalassiosira eccentrica*	0.13	--
6	*Bacteriastrum hyalinum*	0.13	0.29	85	*Thalassiosira gracilis*	--	0.14
7	*Bacteriastrum mediterranean*	--	0.07	86	*Thalassiosira gravida*	0.20	0.11
8	*Biddulphia mobiliensis*	1.07	0.46	87	*Thalassiosira lineata*	--	0.07
9	*Biddulphia granulata*	0.03	--	88	*Thalassiosira* sp	--	1.19
10	*Biddulphia longicruris*	--	0.19	89	*Thalassiosira trifulta*	0.08	--
11	*Biddulphia rhombus*	0.02	--	90	*Triceratium weissei*	--	0.05
12	*Biddulphia sinensis*	0.67	0.44		**Pennales**		
13	*Chaetoceros affinis*	0.02	--	91	*Amphora ventricosa*	0.03	--
14	*Chaetoceros bactereastroides*	0.02	--	92	*Achnanthes brevipes*	0.04	--
15	*Chaetoceros coarctatus*	3.92	4.77	93	*Fragilaria straitula*	0.23	--
16	*Chaetoceros curvisetus*	0.03	--	94	*Fragilariopsis cylindrus*	0.38	--
17	*Chaetoceros crinitus*	0.10	--	95	*Grammatophora kerguelensis*	0.05	--
18	*Chaetoceros danicus*	0.32	--	96	*Grammatophora marina*	0.13	--
19	*Chaetoceros didymus*	--	0.19	97	*Licmophora* sp	0.11	--
20	*Chaetoceros difficilus*	0.05	--	98	*Mastogloia rostrata*	0.01	--
21	*Chaetoceros diversus*	1.66	0.52	99	*Navicula directa*	0.32	0.85
22	*Chaetoceros distans*	0.08	--	100	*Navicula distans*	0.11	--
23	*Chaetoceros eibenii*	2.37	0.95	101	*Navicula fusiformes*	0.07	--
24	*Chaetoceros gracilis*	0.01	--	102	*Navicula granii*	0.11	--
25	*Chaetoceros lauderi*	0.05	--	103	*Navicula gracilis*	--	0.07
26	*Chaetoceros lorenzianus*	1.99	1.73	104	*Navicula gutata*	0.23	--
27	*Chaetoceros messanensis*	--	0.10	105	*Navicula monilifera*	0.05	--
28	*Chaetoceros socialis*	--	0.11	106	*Navicula naviculaus*	--	0.11
29	*Chaetoceros subtilis*	--	0.10	107	*Navicula pelagica*	0.54	--
30	*Chaetoceros tortissimus*	0.04	--	108	*Navicula peregrina*	--	0.21
31	*Chaetoceros peruvianus*	0.31	--	109	*Navicula radiosa*	--	0.04
32	*Climacodium biconcavum*	0.21	--	110	*Navicula rectangulata*	--	1.07
33	*Corethron criophilum*	0.03	0.06	111	*Navicula rhynchocephala*	--	0.14
34	*Coscinodiscus asteromphalus*	0.24	--	112	*Navicula* sp	0.25	0.34
35	*Coscinodiscus curvatulus*	0.65	--	113	*Navicula tuscula*	0.13	--
36	*Coscinodiscus concinnus*	2.95	1.01	114	*Navicula lyra*	0.04	--
37	*Coscinodiscus gemmatulus*	--	0.11	115	*Navicula schumanniana*	--	0.10
38	*Coscinodiscus gigas*	0.87	--	116	*Navicula vanhoeffenii*	--	0.19
39	*Coscinodiscus jonesianus*	0.01	0.06	117	*Navicula viridula*	0.04	--
40	*Coscinodiscus lewisianus*	0.83	--	118	*Nitzschia angularis*	8.55	2.28
41	*Coscinodiscus lineatus*	--	0.11	119	*Nitzschia angusta*	0.23	0.07
42	*Coscinodiscus minor*	0.41	0.15	120	*Nitzschia delicatissima*	1.85	3.61
43	*Coscinodiscus radiatus*	3.62	4.37	121	*Nitzschia fasciculate*	--	0.74
44	*Coscinodiscus rothii*	1.37	--	122	*Nitzschia fossilis*	0.08	--
45	*Coscinodiscus insignis*	0.13	--	123	*Nitzschia insignis*	--	0.14
46	*Coscinodiscus subtilis*	0.06	--	124	*Nitzschia interuptestriata*	0.30	--
47	*Coscinodiscus* sp	0.69	0.40	125	*Nitzschia longissima*	0.35	1.50

48	*Coscinodiscus superbus*	0.23	0.13	126	*Nitzschia macilentia*	0.05	--
49	*Cylindrotheca closterium*	0.08	--	127	*Nitzschia marina*	--	0.93
50	*Denticulopsis lauta*	0.22	0.19	128	*Nitzschia paradoxa*	--	0.21
51	*Denticulopsis seminae*	1.42	1.20	129	Nitzschia pelagica	--	0.15
52	*Ditylum brightwellii*	0.91	1.84	130	*Nitzschia sigma*	0.01	--
53	*Ditylum sol*	0.49	0.41	131	*Nitzschia socialis*	0.75	0.15
54	*Ethmodiscus* sp	0.08	--	132	*Nitzschia reinholdii*	0.32	--
55	*Eucampia balaustium*	0.05	--	133	*Nitzschia ventricosa*	0.01	--
56	*Eucampia zodiacus*	0.01	0.33	134	*Nitzschia* sp	0.06	0.31
57	*Hemiaulus sinensis*	0.61	0.26	135	*Synedra affinis*	--	0.97
58	*Hyalodiscus nobilis*	0.11	--	136	*Synedra tabulata*	0.05	--
59	*Hyalodiscus stelliger*	0.12	0.04	137	*Thalassionema oestrupii*	0.09	0.14
60	*Leptocylindrus minimus*	0.08	0.01	138	*Thalassionema nitzschioides*	4.65	4.92
61	*Plagiotropis lepidoptera*	0.65	--	139	*Thalassiothrix fauenfeldii*	16.21	23.55
62	*Planktoniella sol*	0.28	0.10	140	*Thalassiothrix longissima*	20.29	23.58
63	*Pleurosigma fomosum*	0.21	--		**Dinoflagellates**		
64	*Rhizosolenia alata*	0.26	0.23	141	*Amphisolenia bidentata*	0.07	--
65	*Rhizosolenia hebetata*	0.04	--	142	*Ceratium furca*	0.60	0.41
66	*Rhizosolenia imbricata*	0.06	--	143	*Ceratium trichoceros*	0.20	--
67	*Rhizosolenia robusta*	0.01	--	144	*Oxytoxum* sp	--	0.06
68	*Rhizosolenia setigera*	--	0.15	145	*Peridinium* sp	0.53	--
69	*Rhizosolenia shrubsolei*	0.01	0.11	146	*Prorocentrum micans*	0.14	0.14
70	*Rhizosolenia stolterfothii*	0.46	1.16	147	*Pseudoceratium punctatum*	--	0.63
71	*Rhizosolenia styliformis*	2.22	1.93	148	*Pyrocystis lunula*	0.15	--
72	*Rhizosolenia* sp	--	0.13		**Silicoflagellates**		
73	*Skeletonema costatum*	4.42	4.35	149	*Dictyocha crux*	0.33	--
74	*Streptotheca tamesis*	0.47	--	150	*Dictyocha speculum*	--	0.03
75	*Striatella unipunctata*	--	0.04		**Unidentified**		
76	*Surirella anceps*	--	0.06	151	Unidentified	0.40	0.37
77	*Surirella cruciata*	--	0.06	152	Unidentified1	0.05	0.07
78	*Surirella fastuosa*	0.12	0.03	153	Unidentified2	0.03	--
79	*Thalassiosira anguste-lineata*	0.02	--		**Total Cells Per Liter**	**91928**	**92993**

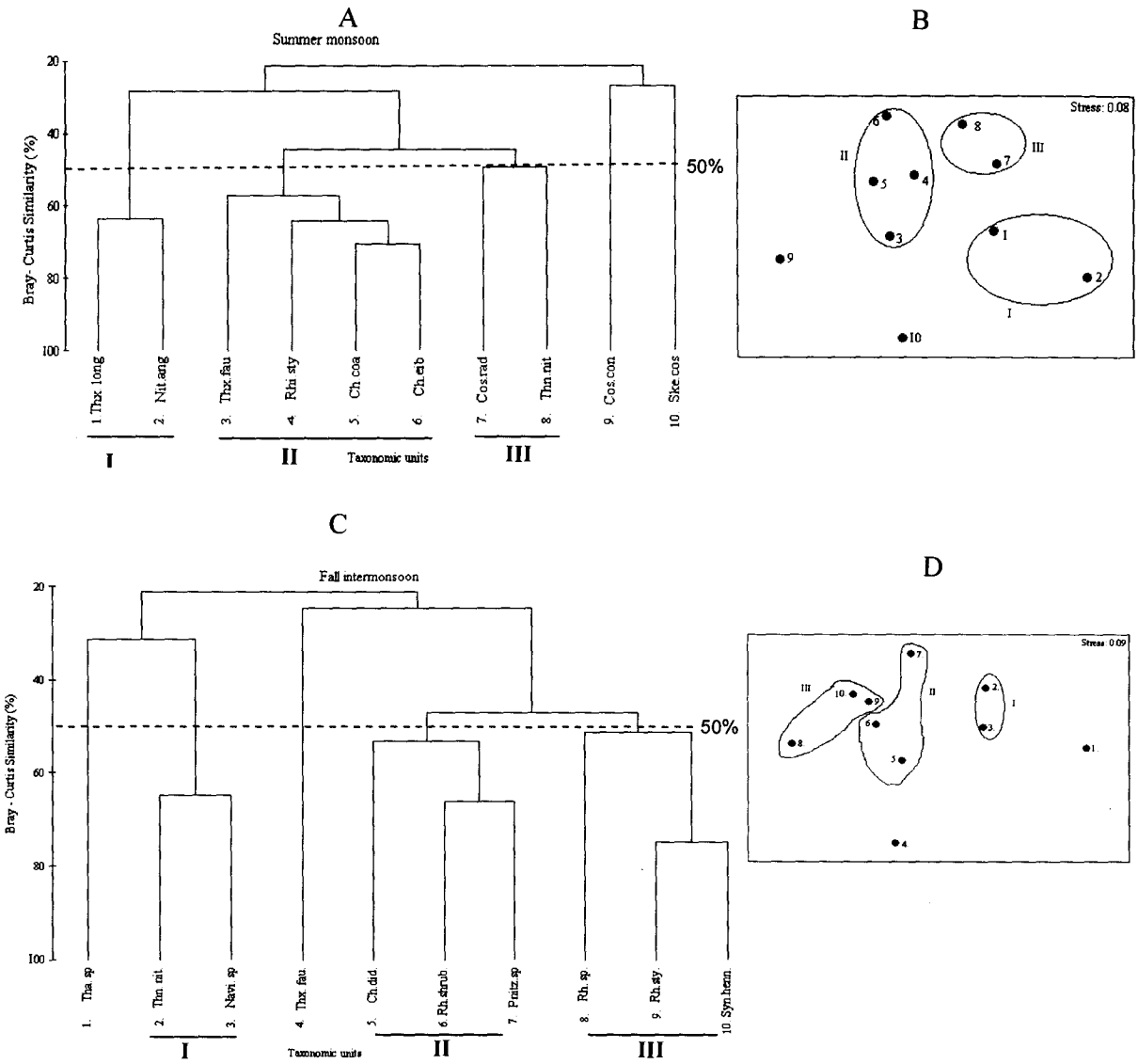


Fig. 4.3. Cluster dendrogram of major phytoplankton species (≥2%) from the Central Bay using Bray- Curtis similarity (%) and group average method. Similarity levels in A) Summer monsoon and C) Fall intermonsoon. Non-metric Multidimensional scaling (NMDS) ordination based on Bray- Curtis similarity (%) of the phytoplankton species in B) Summer monsoon and D) Fall intermonsoon

Fall intermonsoon

Thalassionema nitzschoides (12.01%), *Navicula* spp (11.61%), *Rhizosolenia* sp (2.96%), *R. styliformis* (7.42%), R. *shrubsolei* (4.86%), *Synedra hennedyana* (4.86%), *Chaetoceros didymus* (2.83%), *Pseudo-nitzschia* sp (2.56%), *Thalassiothrix fauenfeldii* (2.29%) and *Thalassiosira* sp (2.02%) were the major species in CB during this season. Among the dinoflagellates, *Oxytoxum sp* (1.2%) and *Ceratium furca* (0.4%) were the most abundant. Similar to SM, *Dictyocha crux* was the only silicoflagellate observed during this season (Table 4.2).

Cluster analyses at 50% similarity level divided species with ≥2% into 3 clusters and, just two ungrouped species (Fig. 4.3C). The 2D NMDS (Fig. 4.3D) with stress value of 0.09 implicitly suggests that clustering is in variance with NMDS. Clusters II and III comprised of three species each whereas cluster I comprised of 2 species. *Navicula* spp and *T. nitzschioides* forming cluster I and distributed all along the transect were present in high abundance even at 80 m. *Pseudo-nitzschia* sp, *Chaetoceros didymus* and R. *shrubsolei* forming Cluster II were absent below 100 m. Though abundant at CB1, *Synedra hennedyana, Rhizosolenia* sp and *R. styliformis* forming cluster III were in high abundance at CB1. Species in clusters II and III (Fig. 4.3C) were found exclusively at the upper 60 m in the southern region with higher concentrations of nutrients. Some species were seen to be concentrated in the top 40 m at CB1 when the N:Si ratio was around 1:1. This station also had high concentrations of silicate that can be attributed to the high concentration of diatoms. The two independent species that did not cluster with the others viz. *Thalassiosira* sp and *T. fauenfeldii* did not exhibit a specific pattern of distribution (Fig. 4.5).

Spring intermonsoon

During SpIM, *Trichodesmium* sp (21.61%), *Navicula* spp (31.5%), *Thalassionema nitzschioides* (3.66%), *Navicula distans* (3.3%), *Coscinodiscus sp* (5.86%), *Leptocylindrus meditteraneus* (4.03%), *Pseudo-nitzschia* sp (5.13%), *Rhizosolenia cylindrus* (2.93%), *Fragilariopsis doliolus* (2.2%) were the major species in the CB. *Oxytoxum sp* (1.47%) was the dominant dinoflagellate. No silicoflagellates observed during this season (Table 4.3).

Table 4.2. Phytoplankton species composition along Central Bay (CB) and Western Bay (WB) in fall intermonsoon

Sr.No	Phytoplankton	CB	WB	Sr.No	Phytoplankton	CB	WB
	Centrales				**Centrales**		
1	*Asteromphalus* sp	0.13	--	65	*Thalassiosira* sp	2.02	6.72
2	*Asteromphalus heptactis*	0.27	--	66	*Triceratium weissei*	--	0.06
3	*Bacteriastrum comosum*	0.67	--		**Pennales**		
4	*Bacteriastrum delicatulum*	1.35	1.20	67	*Cylindrotheca closterium*	0.27	0.06
5	*Bacteriastrum elongatum*	0.27	--	68	*Fragilaria striatula*	0.27	--
6	*Bacteriastrum furcatum*	0.67	--	69	*Fragilariopsis doliolus*	0.54	--
7	*Bacteriastrum hyalinum*	--	1.32	70	*Gyrosigma* sp	--	0.12
8	*Biddulphia sinensis*	--	1.32	71	*Licmophora* sp	--	0.30
9	*Cerataulina* sp	--	0.06	72	*Licmophora abbreviata*	--	0.24
10	*Chaetoceros affinis*	0.94	0.36	73	*Lioloma pacificum*	--	0.18
11	*Chaetoceros coarctatus*	0.94	2.10	74	*Meuniera membranacea*	--	0.66
12	*Chaetoceros compressus*	--	0.30	75	*Navicula angularis*	--	0.54
13	*Chaetoceros curvisetus*	--	9.78	76	*Navicula capitata*	0.27	--
14	*Chaetoceros decipiens*	0.54	--	77	*Navicula directa*	1.21	0.06
15	*Chaetoceros didymus*	2.83	2.58	78	*Navicula delicatula*	0.81	0.36
16	*Chaetoceros diversus*	--	0.48	79	*Navicula distans*	0.40	0.42
17	*Chaetoceros eibenii*	1.34	3.36	80	*Navicula johnsonii*	0.67	--
18	*Chaetoceros indicus*	0.40	--	81	*Navicula messanenis*	0.67	1.02
19	*Chaetoceros lorenzianus*	1.08	22.39	82	*Navicula peregrina*	0.13	--
20	*Chaetoceros messanensis*	0.13	--	83	*Navicula septentrionalis*	--	0.48
21	*Chaetoceros paradoxum*	--	2.10	84	*Navicula* sp	11.61	7.68
22	*Chaetoceros seiracanthus*	--	0.90	85	*Nitzschia angularis*	1.62	0.06
23	*Chaetoceros* sp	0.40	--	86	*Nitzschia longissima*	0.13	2.22
24	*Chaetoceros teres*	0.40	0.42	87	*Nitzschia sigma*	0.13	--
25	*Corethron criophilum*	0.27	0.24	88	*Nitzschia* sp	0.27	0.78
26	*Corethron hystrix*	0.13	--	89	*Pleurosigma* sp	--	0.06
27	*Corethron* sp	--	0.06	90	*Pseudo-nitzschia* sp	2.56	2.52
28	*Coscinodiscus centralis*	0.67	--	91	*Synedra hennedyana*	4.86	--
29	*Coscinodiscus concinnus*	0.40	0.54	92	*Synedra* sp	1.62	1.14
30	*Coscinodiscus granii*	0.13	--	93	*Synedra radians*	0.94	--
31	*Coscinodiscus gigas*	0.13	--	94	*Synedra ulna*	0.67	0.54
32	*Coscinodiscus nodulifer*	--	0.06	95	*Thalassionema nitzschioides*	12.01	3.12
33	*Coscinodiscus* sp	1.48	1.08	96	*Thalassiothrix fauenfeldii*	2.29	--
34	*Dactyliosolen* sp	0.13	--	97	*Thalassiothrix longissima*	0.67	0.66
35	*Denticulopsis seminae*	0.54	0.18	98	*Thalassiothrix vanhoeffenii*	0.40	--
36	*Ditylum brightwellii*	--	2.94	99	*Trigonium reticulum*	0.27	--
37	*Ethmodiscus* sp	0.13	--		**Dinoflagellates**		
38	*Eucampia zodiacus*	0.27	--	100	*Amphisolenia bidentata*	0.27	0.06
39	*Hemiaulus hauckii*	--	0.12	101	*Ceratium breve*	--	0.06
40	*Hyalodiscus* sp	0.13	--	102	*Ceratium dens*	0.67	0.12
41	*Hyalodiscus radiatus*	0.13	--	103	*Ceratium furca*	0.27	0.42
42	*Leptocylindrus danicus*	1.35	1.38	104	*Ceratium fusus*	0.27	--
43	*Leptocylindrus mediterraneus*	1.62	0.66	105	*Ceratium horridum*	0.13	--
44	*Planktoniella sol*	0.40	--	106	*Ceratium inflatum*	0.40	--
45	*Porosira* sp	--	0.06	107	*Ceratium keustenii*	0.13	0.12
46	*Rhabdonema punctatum*	0.13	--	108	*Ceratium kofoidii*	0.27	--
47	*Rhizosolenia alata*	1.08	--	109	*Ceratium trichoceros*	--	0.30
48	*Rhizosolenia calcar-avis*	0.27	--	110	*Clampylodiscus* sp	0.13	--

49	*Rhizosolenia cylindrus*	1.89	--	111	*Corythodinium tesselatum*	0.13	--
50	*Rhizosolenia flaccida*	0.94	0.54	112	*Dinophysis tripos*	0.13	--
51	*Rhizosolenia hiemalis*	0.13	--	113	*Noctiluca* sp	0.13	--
52	*Rhizosolenia hebetata*	0.40	--	114	*Oxytoxum* sp	0.94	0.30
53	*Rhizosolenia imbricata*	1.21	1.44	115	*Podolampas palmipes*	0.13	0.18
54	*Rhizosolenia shrubsolei*	4.86	0.12	116	*Protoperidinium pellucidum**	0.13	--
55	*Rhizosolenia styliformis*	7.42	0.24	117	*Prorocentrum micans*	0.13	--
56	*Rhizosolenia setigera*	--	0.60	118	*Pyrocystis lunula*	0.13	--
57	*Rhizosolenia* sp.	2.97	0.42		**Silicoflagellates**		
58	*Skeletonema costatum*	--	0.48	119	*Dictyocha crux*	0.27	--
59	*Stauroneis anceps*	--	0.18		**Unidentified**		
60	*Thalassiosira gravida*	--	4.20	120	Unidentified	3.64	0.84
61	*Thalassiosira lineata*	0.13	--	121	Unidentified 1	1.35	1.92
62	*Thalassiosira punctigera*	0.81	0.48	122	Unidentified 2	0.13	0.48
63	*Thalassiosira rotula*	0.40	--	123	Unidentified 3	--	0.48
64	*Thalassiosira subtilis*	0.27	--		**Total Cells Per Liter**	**29640**	**66640**

*heterotrophic dinoflagellates

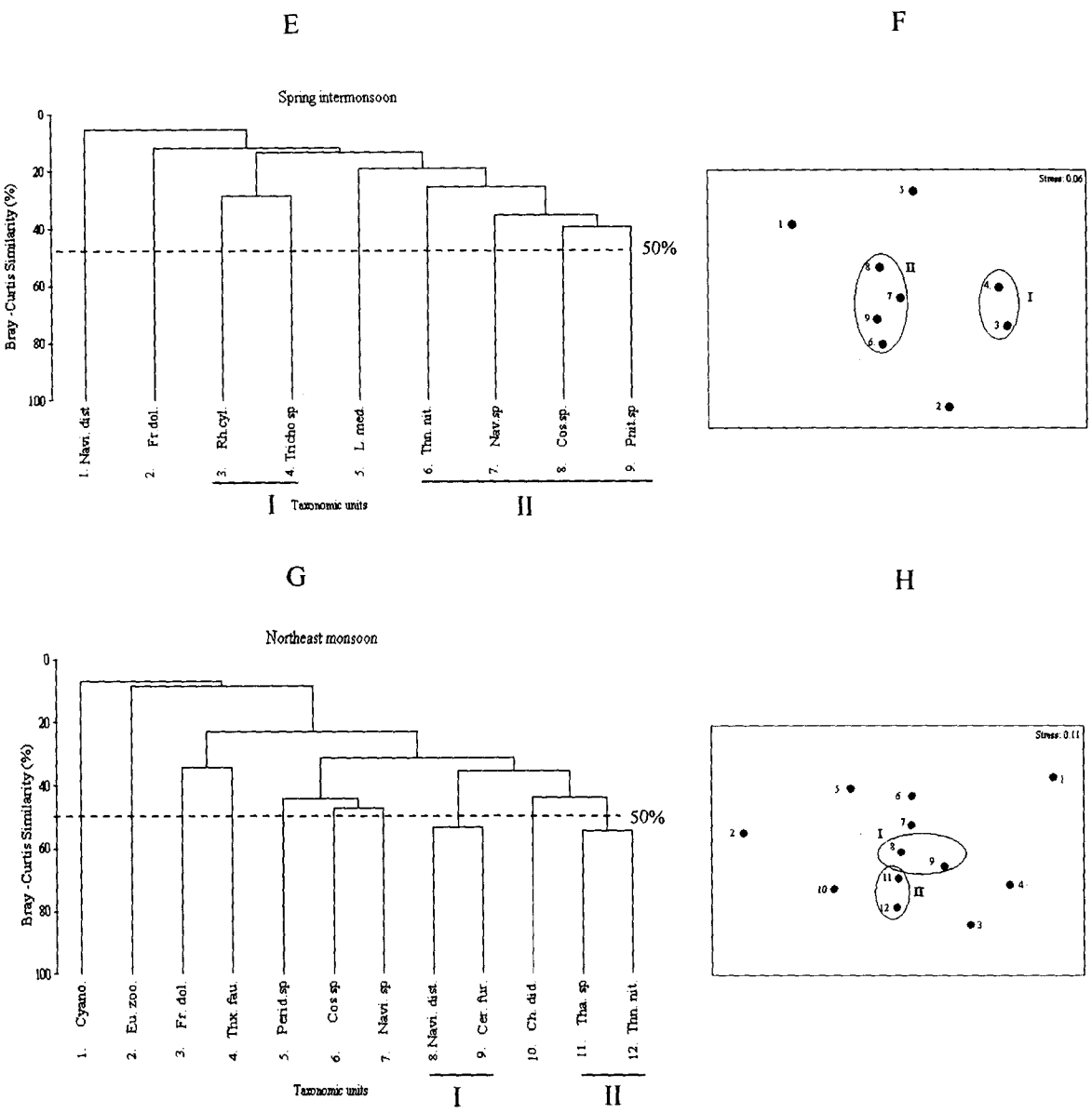


Fig. 4.3. Cluster dendrogram of the phytoplankton species (≥2%) from the Central Bay using Bray- Curtis similarity (%) and group average method. Similarity levels in E) Spring inter monsoon and G) North east monsoon. Non-metric Multidimensional scaling (NMDS) ordination based on Bray- Curtis similarity (%) of the phytoplankton species in F) Spring intermonsoon and H) Northeast monsoon

Table 4.3. Phytoplankton species composition along Central Bay (CB) and Western Bay (WB) in spring intermonsoon

Sr. No	Phytoplankton	CB	WB	Sr. No	Phytoplankton	CB	WB
	Centrales				**Centrales**		
1	*Bacteriastrum comosum*	--	6.14	36	*Rhizosolenia robusta*	--	0.32
2	*Bacteriastrum furcatum*	--	5.82	37	*Rhizosolenia* sp	--	0.11
3	*Bacteriastrum hyalinum*	--	2.80	38	*Rhizosolenia stolterfothii*	--	0.32
4	*Bacteriastrum varians*	--	1.08	39	*Rhizosolenia styliformis*	1.83	1.40
5	*Biddulphia mobiliensis*	--	1.29	40	*Stephanopyxis palmeriana*	--	2.16
6	*Biddulphia sinensis*	--	0.86	41	*Thalassiosira* sp	1.83	1.29
7	*Chaetoceros coarctatus*	0.37	1.19		**Pennales**		
8	*Chaetoceros compressus*	--	0.97	42	*Amphora ventricosa*	0.37	--
9	*Chaetoceros curvisetus*	1.10	4.74	43	*Fragilariopsis doliolus*	2.20	0.86
10	*Chaetoceros decipiens*	--	0.22	44	*Navicula directa*	1.47	--
11	*Chaetoceros didymus*	1.10	16.27	45	*Navicula distans*	3.30	0.75
12	*Chaetoceros eibenii*	0.37	1.83	46	*Navicula messanenis*	1.10	3.34
13	*Chaetoceros lorenzianus*	--	0.75	47	*Navicula* spp	31.50	10.02
14	*Chaetoceros messanensis*	--	1.83	48	*Nitzschia* spp	--	2.16
15	*Chaetoceros* sp	--	2.69	49	*Pseudo-nitzschia* sp	5.13	1.94
16	*Corethron criophilum*	--	0.22	50	*Synedra* sp	--	0.43
17	*Coscinodiscus concinnus*	0.73	1.62	51	*Synedra ulna*	--	0.22
18	*Coscinodiscus jonesianus*	--	0.22	52	*Thalassiothrix fauenfeldii*	--	0.75
19	*Coscinodiscus radiatus*	0.73	--	53	*Thalassionema nitzschioides*	3.66	1.51
20	*Coscinodiscus* sp	5.86	0.22		**Dinoflagellates**		
21	*Guinardia striata*	--	4.63	54	*Amphisolenia bidentata*	--	0.32
22	*Hemidiscus hardmanianus*	--	0.32	55	*Ceratium fusus*	--	0.32
23	*Hemiaulus hauckii*	1.47	--	56	*Ceratium trichoceros*	--	0.22
24	*Hemiaulus sinensis*	--	0.11	57	*Oxytoxum* sp	1.47	0.32
25	*Lauderia annulata*	--	0.97	58	*Podolampas palmipes*	0.73	0.11
26	*Leptocylindrus mediterraneus*	4.03	--	59	*Triceratium trichoceros*	--	0.11
27	*Leptocylindrus minimus*	0.73	1.40		**Cyanobacteria**		
28	*Leptocylindrus* sp	--	0.11	60	*Trichodesmium* sp	21.61	0.75
29	*Planktoniella sol*	--	0.22		**Unidentified**		
30	*Pleurosigma* sp	0.37	--	61	Unidentified	2.56	1.83
31	*Rhizosolenia alata*	1.47	0.11	62	Unidentified 1	--	1.08
32	*Rhizosolenia cylindrus*	2.93	4.09	63	Unidentified 2	--	0.22
33	*Rhizosolenia flaccida*	--	2.69	64	Unidentified 3	--	0.43
34	*Rhizosolenia hebetata*	--	0.22				
35	*Rhizosolenia imbricata*	--	1.08		**Total Cells Per Liter**	**10920**	**37120**

Species ≥2% of total PCC did not cluster at 50% similarity and all nine of them formed ungrouped species (Fig. 4.3E) and, 2D NMDS (Fig. 4.3F) with stress value of 0.06 suggests that clustering is in variance with NMDS. Clustering could be discerned below the 50% similarity level. For instance, *Rhizosolenia cylindrus* and *Trichodesmium* sp clustered at 30% similarity. These species were absent below 100 m and, at CB1. All four species, *T. nitzschioides*, *Navicula* sp, *Coscinodiscus* sp and *Pseudo-nitzschia* sp were absent at the surface at CB3 and CB4 and they were in higher abundance at deeper depths than surface. While *Navicula distans, Leptocylindrus mediterraneus* and *Fragilariopsis doliolus* did not exhibit a specific pattern of distribution (Fig. 4.6).

<u>*Northeast monsoon*</u>

In NEM, *Chaetoceros didymus* (5.67%), *Coscinodiscus sp* (7.85%), *Eucampia zodiacus* (2.56%), *Thalassiosira* sp (4.88%), *Fragilariolopsis doliolus* (6.52%), *Navicula distans* (7.04%), *Navicula* sp (13.42%), *Thalassiothrix fauenfeldii* (2.05%), *Thalassionema nitzschioides* (6.05%), Cyanobacteria (7.28%) were the major species along the CB. Among dinoflagellates, *Peridinium* sp (4.5%) and *Ceratium furca* (3.1%) were dominant. *Dictyocha crux* was the only silicoflagellate observed in NEM (Table 4.4). Cyanobacteria was the only group to be confined to the surface while all other dominant species was more abundant even in the subsurface waters.

Four species ≥2% of total PCC clustered in to two groups at 50% similarity. Eight major species remained ungrouped (Fig. 4.3G). The 2D NMDS (Fig. 4.3H) with stress value 0.11 suggests that clustering is quite in variance with NMDS. *Navicula distans* and *Ceratium furca* forming cluster I were absent at CB5 but present at varying depths at other locations. *T. nitzschioides* and *Thalassiosira* sp species in cluster II were more abundant in the northern stations but absent at CB3. *Chaetoceros didymus* which formed an independent group; abundant in the northern station was sparse at some stations in the south. It had closeness to cluster II; yet not part of it. The other species formed independent groups (Fig. 4.7).

Table 4.4. Phytoplankton species composition along Central Bay (CB) and Western Bay (WB) in northeast monsoon

Sr.No	Phytoplankton	CB	WB	Sr.No	Phytoplankton	CB	WB
	Centrales				**Pennales**		
1	*Bacteristrum furcatum*	0.27	1.03	32	*Nitzschia* sp	--	1.45
2	*Bacteriastrum hyalinum*	0.31	--	33	*Plerurosigma* sp	0.72	--
3	*Chaetoceros coarctatus*	0.72	--	34	*Synedra* sp	1.71	0.45
4	*Chaetoceros didymus*	5.67	5.88	35	*Thalassiothrix fauenfeldii*	2.05	0.87
5	*Chaetoceros eibenii*	1.37	1.03	36	*Thalassionema nitzschioides*	6.05	5.08
6	*Coscinodiscus granii*	0.59	0.51	37	Unidentified	0.29	1.58
7	*Coscinodiscus radiatus*	1.84	1.00	38	Unidentified1	1.53	0.48
8	*Coscinodiscus marginatus*	0.79	--		**Dinoflagellates**		
9	*Coscinodiscus* sp	7.85	11.83	39	*Amphisolenia bidentata*	0.54	--
10	*Denticulopsis seminae*	0.25	--	40	*Ceratium belone*	--	0.42
11	*Ditylium brightwellii*	0.40	1.58	41	*Ceratium furca*	3.10	--
12	*Eucampia zodiacus*	2.56	2.38	42	*Ceratium fusus*	0.50	--
13	*Guinardia striata*	0.27	2.89	43	*Ceratium macroceros*	0.14	--
14	*Hemiaulus hauckii*	1.93	--	44	*Ceratium pentagonum*	0.40	--
15	*Planktoniella sol*	0.74	--	45	*Ceratium trichoceros*	0.23	0.87
16	*Rhizosolenia alata*	--	2.06	46	*Dinophysis uracantha**	--	0.58
17	*Rhizosolenia cylindrus*	1.35	0.51	47	*Ornithocercus quadratus**	0.83	--
18	*Rhzosolenia hebetata*	0.56	--	48	*Oxytoxum* sp	1.66	6.53
19	*Rhizosolenia imbricata*	1.89	3.70	49	*Peridinium* sp	4.50	2.51
20	*Rhizosolenia shrubsolei*	--	1.22	50	*Protoperidinium* sp*	1.57	--
21	*Rhizosolenia styliformis*	1.08	0.61	51	*Podolampas palmipes*	0.49	0.93
22	*Rhizosolenia* sp	0.25	2.73	52	*Protoceratium* sp	0.25	--
23	*Thalassiosira* sp	4.88	2.12	53	Unidentified dino	0.27	--
	Pennales			54	*Triceratium* sp	0.31	--
24	*Amphora* sp	0.29	--		**Silicoflagellate**		
25	*Cylindrotheca closterium*	1.48	2.67	55	*Dictyocha crux*	0.40	1.93
26	*Fragilariopsis doliolus*	6.52	--	56	Unidentified silico	0.23	--
27	*Navicula distans*	7.04	4.41		**Cyanobacteria**		
28	*Navicula directa*	--	5.56	57	Unidentified Cyanobacteria	7.28	--
29	*Navicula* sp	13.42	19.20	58	*Trichodesmium* sp	0.22	1.54
30	*Navicula septentrionalis*	--	1.29				
31	*Nitzschia delicatissima*	0.40	0.58		**Total Cells Per Liter**	**22020**	**12440**

*heterotrophic dinoflagellates

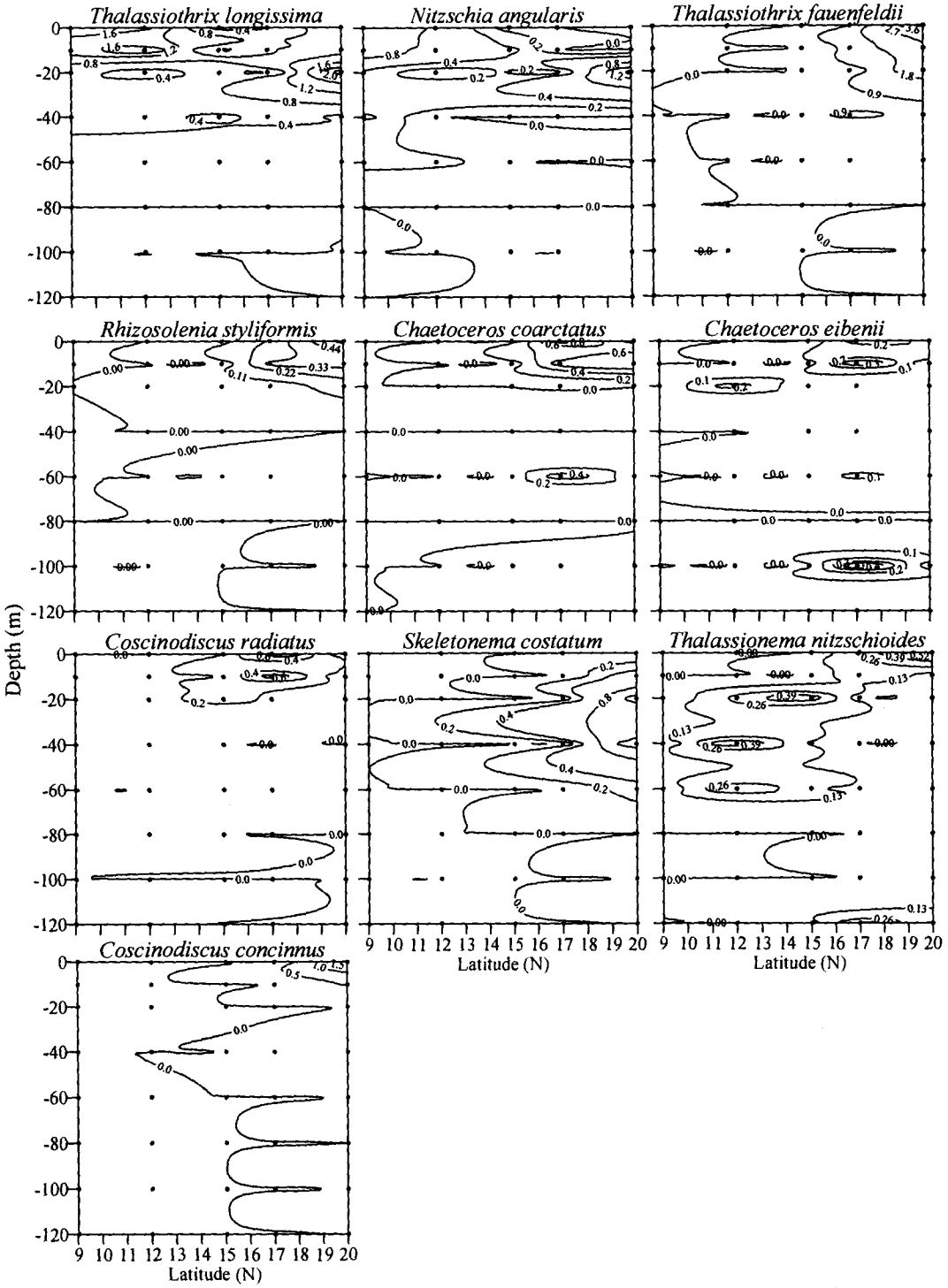


Fig. 4.4. Distribution of major species of phytoplankton along Central Bay in summer monsoon

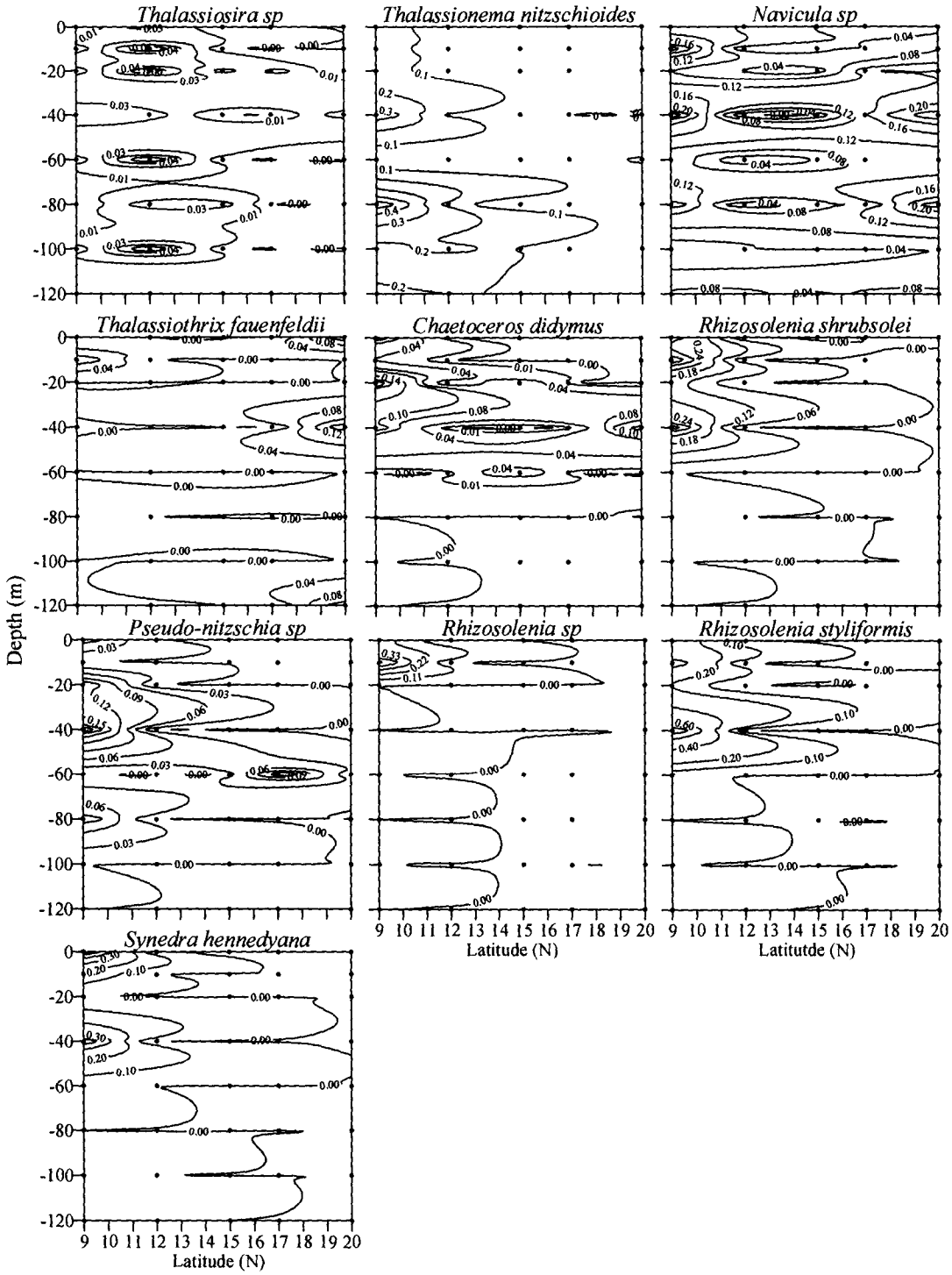


Fig. 4.5. Distribution of major species of phytoplankton along Central Bay in fall intermonsoon

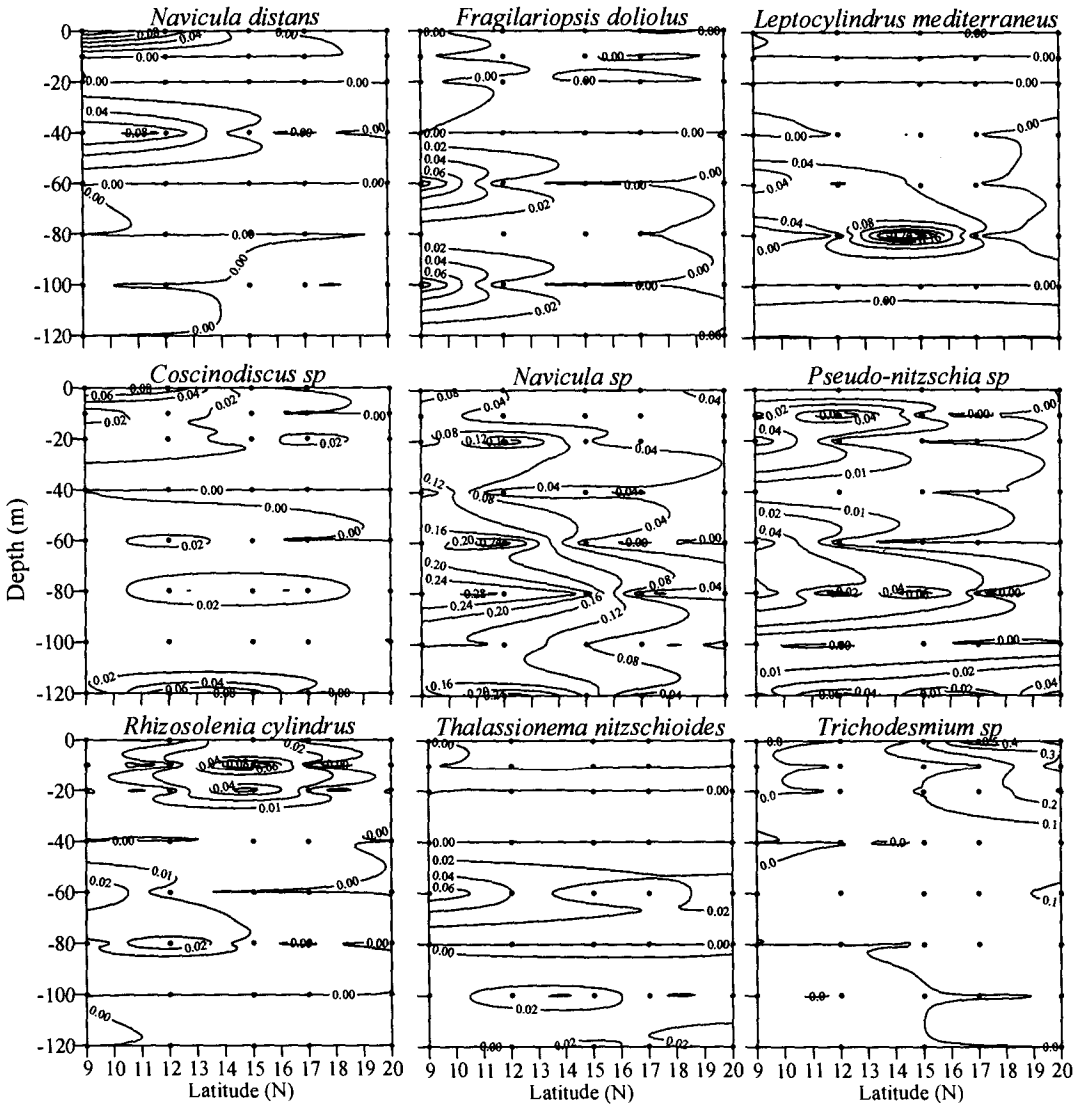


Fig. 4.6. Distribution of major species of phytoplankton along Central Bay in spring intermonsoon

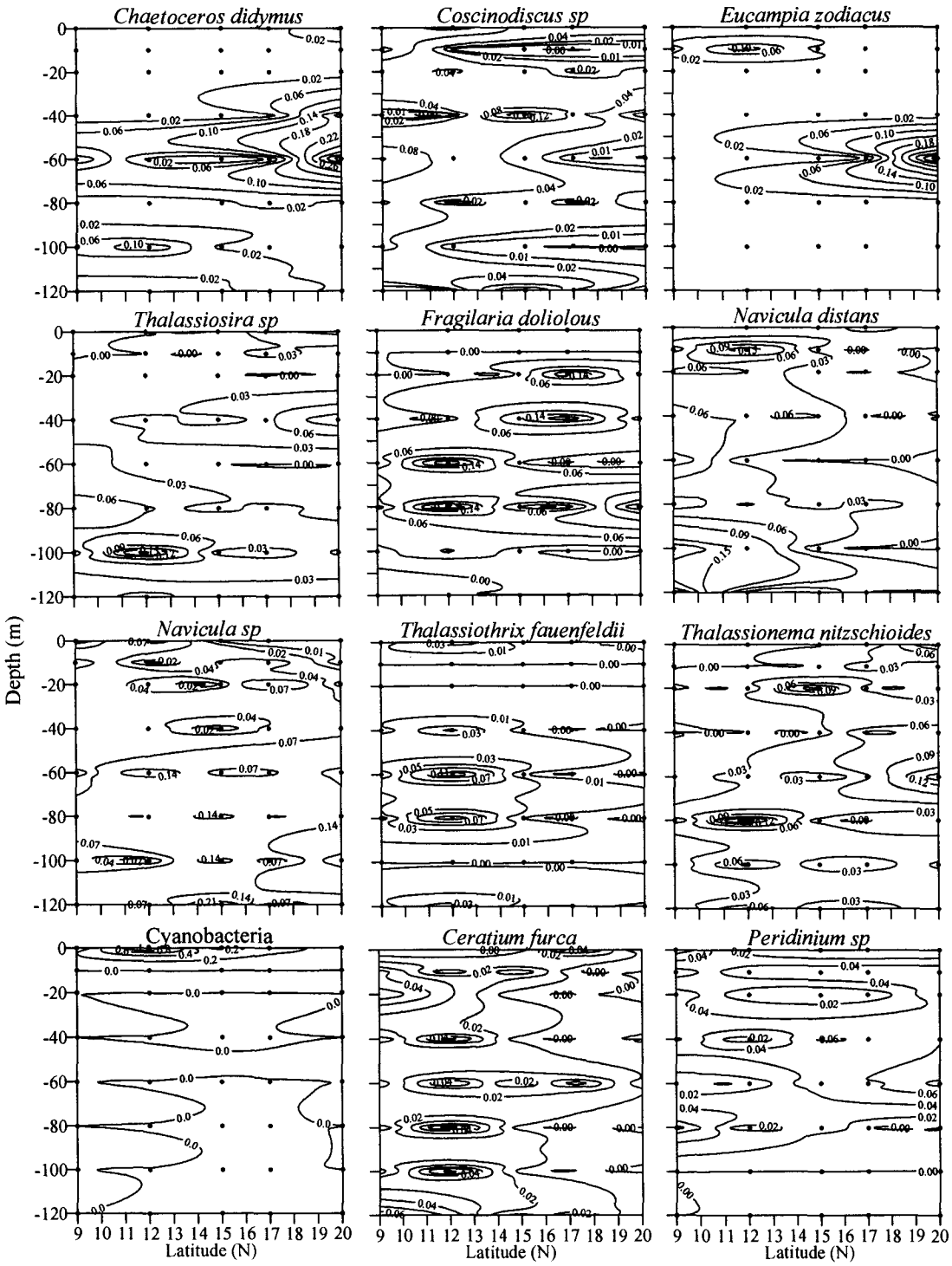


Fig. 4.7. Distribution of major species of phytoplankton along Central Bay in northeast monsoon

Nutrient Ratios

Summer monsoon (SM)

The nitrate to phosphate (N:P) ratio (Fig. 4.8a) showed a concurrent increase with depth. In general, the N:P ratio was lower than the classical Redfield ratio of 16:1 in top 60 m of the water column. The N:Si ratios in the top 40 m were generally lesser than the Redfield's 1:1 ratio throughout the transect. Also, silicate to phosphate (Si:P) ratio was always less than the Redfield ratio of 16:1 throughout the sampling depths except at CB5 where it reached greater than 16:1. The Si:P ratios ranged from 4.95 to 60.

The N:P and N:Si ratio had negative correlation with PCC (Table 4.5A) and positive correlation with Si:P ratio. The correlation of PCC was significant only with N:Si. The chl *a* was not significantly related with any of the nutrient ratios. Significant negative correlations of N:P with *Skeletonema costatum* and significant positive ones of N:P and N:Si with *Coscinodiscus radiatus* were observed. The N:Si ratio had significant negative correlation with PCC, *Thalassiothrix longissima* and *Coscinodiscus concinnus.* The Si:P ratio did not show significant relation with any of the phytoplankton species.

Fall intermonsoon (FIM)

The N:P ratio increased with depth up to 120 m (Fig. 4.8b) and was lower than 16:1 throughout the sampling depth. The N:Si ratio was also generally lower than 1:1 in the top 20 to 40 m. Thereafter, it was greater than 1 indicating nitrate enrichment. The Si:P also followed the same trend as that of N:P ratio; increasing with depth but lower than 16:1 all along the transect.

The N:P ratios did not bear significant correlation with PCC. Significant positive correlation between N:Si ratios and PCC (Table 4.5B); significant negative correlation between Si:P ratios and PCC and significant negative correlation of all the ratios with chl *a* could be seen. The N:P ratio did not have significant correlation with any major phytoplankton species. While, the N:Si ratios had significant positive correlation only with *Navicula* sp, *Pseudo-nitzschia* sp and *Synedra hennedyana.* With the other species, their correlation coefficients were

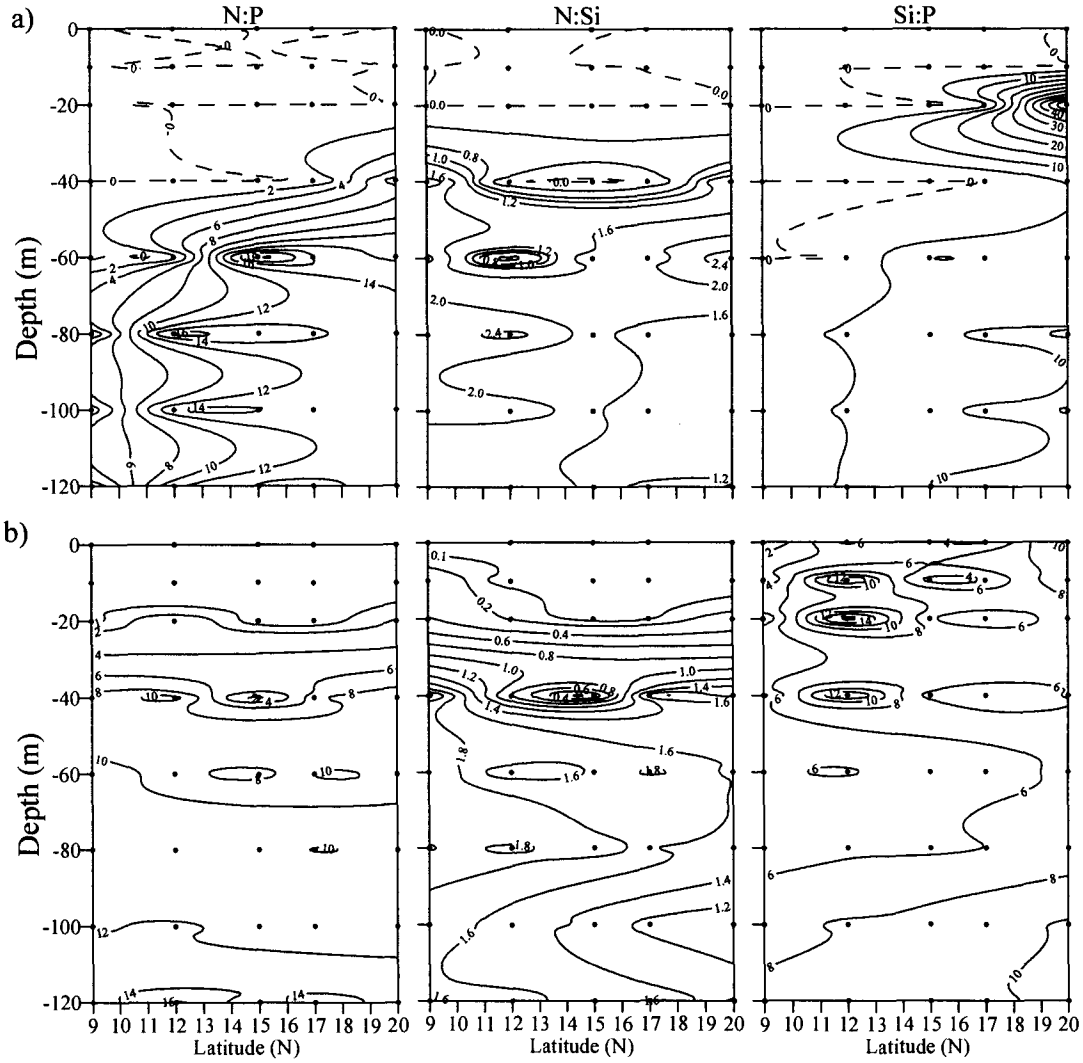


Fig. 4.8. Nitrate:phosphate [N:P], nitrate:silicate [N:Si] and silicate:phosphate [Si:P] ratios along Central Bay during (a) Summer monsoon and (b) Fall intermonsoon

Table 4.5. Spearman's Rank correlation test for log transformed phytoplankton abundance (PCC), chlorophyll *a* (Chl *a*), major dominant phytoplankton species with nitrate: phosphate (N:P), nitrate:silicate (N:Si) and silicate: phosphate (Si:P) ratios along the Central Bay in A) Summer monsoon, B) Fall intermonsoon, C) Spring intermonsoon and D) Northeast monsoon

A) Summer monsoon

Parameter	**N:P**		**N:Si**		**Si:P**	
	R	*p*	R	*p*	R	*p*
PCC	-0.16	0.55	**-0.56**	**0.00**	0.25	0.34
Chl *a*	0.08	0.75	-0.19	0.32	-0.12	0.66
Chaetoceros coarctatus	0.12	0.64	-0.08	0.69	-0.07	0.79
C. eibenii	0.17	0.51	-0.16	0.42	0.20	0.44
Coscinodiscus radiatus	**0.57**	**0.02**	**0.44**	**0.02**	-0.17	0.50
Cos. concinnus	ND	ND	**-0.39**	**0.04**	ND	ND
Nitzschia angularis	-0.41	0.10	-0.32	0.10	0.41	0.10
Rhizosolenia styliformis	-0.11	0.69	-0.32	0.10	0.28	0.28
S. costatum	**-0.55**	**0.02**	-0.08	0.68	-0.22	0.41
Thalassiothrix fauenfeldii	-0.30	0.24	-0.28	0.15	-0.14	0.60
T. longissima	-0.15	0.56	**-0.46**	**0.01**	-0.04	0.88
Thalassionema nitzschioides	0.28	0.27	-0.13	0.52	0.35	0.16

B) Fall intermonsoon

Parameter	**N:P**		**N:Si**		**Si:P**	
	R	*p*	R	*p*	R	*p*
PCC	0.04	0.79	**0.38**	**0.02**	**-0.41**	**0.01**
Chl *a*	**-0.74**	**0.00**	**-0.35**	**0.03**	**-0.56**	**0.00**
Ch. didymus	-0.20	0.22	0.07	0.66	**-0.43**	**0.01**
Rhizosolenia sp	-0.12	0.48	-0.09	0.60	-0.26	0.11
Rh. shrubsolei	-0.13	0.43	0.06	0.70	**-0.32**	**0.05**
Rh. styliformis	-0.01	0.98	0.15	0.37	**-0.32**	**0.05**
Thalassiosira sp	-0.09	0.60	-0.03	0.85	0.18	0.27
Pseudo-nitzschia. sp	0.01	0.96	**0.34**	**0.03**	**-0.36**	**0.03**
Syn. hennedyana	0.19	0.24	**0.33**	**0.04**	-0.22	0.17
Thalassionema nitzschioides	0.18	0.27	0.23	0.16	-0.11	0.50
Thalassiothrix fauenfeldii	0.08	0.62	0.00	1.00	0.04	0.79
Navicula sp	0.18	0.28	**0.41**	**0.01**	-0.24	0.14

C) Spring intermonsoon

Parameter	N:P		N:Si		Si:P	
	R	*p*	R	*p*	R	*p*
PCC	0.12	0.49	0.11	0.50	-0.16	0.33
Chl *a*	**-0.33**	**0.05**	-0.02	0.91	-0.19	0.26
*Coscinodiscus.*sp	-0.13	0.45	-0.10	0.54	-0.01	0.96
F.doliolus	0.28	0.09	0.27	0.09	-0.07	0.69
L. mediterraneus	-0.10	0.55	0.14	0.40	-0.32	0.05
Navicula sp	0.28	0.09	**0.41**	**0.01**	-0.31	0.06
Navi. distans	-0.19	0.27	-0.26	0.10	-0.02	0.89
*Pseudo-nitzschia.*sp	0.06	0.70	0.11	0.49	-0.08	0.65
Rh. cylindrus	0.20	0.24	0.14	0.40	0.19	0.26
Thalassionema nitzschioides	**0.41**	**0.01**	**0.46**	**0.00**	-0.32	0.05
Trichodesmium sp	-0.19	0.25	**-0.37**	**0.02**	**0.34**	**0.04**

D) Northeast monsoon

Parameter	N:P		N:Si		Si:P	
	R	*p*	R	*p*	R	*p*
PCC	0.14	0.39	0.17	0.29	0.08	0.63
Chl *a*	-0.28	0.09	-0.20	0.23	-0.14	0.39
Chaetoceros didymus	0.17	0.31	0.22	0.17	0.17	0.31
Coscinodiscus sp	-0.20	0.22	-0.28	0.08	0.08	0.61
Eu. zodiacus	-0.12	0.47	-0.12	0.47	-0.02	0.89
Thalassiosira sp	0.19	0.24	0.31	0.05	0.02	0.89
F. doliolous	0.09	0.59	0.17	0.31	-0.04	0.82
Navicula sp	**0.50**	**0.00**	**0.43**	**0.01**	0.31	0.05
Navi. distans	0.04	0.81	0.06	0.69	0.03	0.86
Thalassiothrix fauenfeldii	0.04	0.83	0.10	0.54	-0.14	0.39
Thalassionema nitzschioides	0.26	0.10	0.27	0.10	0.17	0.31
Cyanobacteria	-0.31	0.06	-0.26	0.12	**-0.34**	**0.03**
Ceratium furca	0.10	0.54	0.05	0.76	0.09	0.59
Peridinium sp	-0.29	0.07	**-0.34**	**0.03**	-0.04	0.83

Figures in bold indicate significant relationship at levels of shown *p*.
Refer Fig 4.8; 4.9 for different ratios at a given depth and Fig. 4.4; 4.5; 4.6; 4.7 for species distribution at each depth during different sampling seasons

not statistically significant. The Si:P ratios had significant negative correlation with some dominant species: *Chaetoceros didymus*, *Rhizosolenia styliformis*, *R. shrubsolei* and *Pseudo-nitzschia* sp.

Spring intermonsoon (SpIM)

High N:P ratio (Fig. 4.9a) was observed in the surface at CB2 and CB3 while at other stations the N:P was lower than 3 which increased with depth. The ratio of nitrate to silicate (N:Si) in the top 40 m to 60 m was in general <1:1 with no spatial variation in surface waters. N:Si ratio values increased rapidly with depth upto 80 m where it reached the maximum of >1:1 indicating an enrichment of nitrate relative to silicate at these depths. The Si:P ratio at the surface ranged from 40 to 120 and far exceeded the 16:1 ratio. This is due to almost negligible levels of phosphate as against high concentrations of silicate during this season.

None of the ratios showed any significant relation (Table 4.5C) with the PCC Only N:P ratio showed a negative significant relation with chl *a* while the other ratios were not significantly related. Among the dominant species only *Thalassionema nitzschioides* was significantly related to the N:P ratio ($R= 0.41$; $p <0.01$). The N:Si ratio had a significant positive relation with *Navicula* sp and *Thalassionema nitzschioides* while it had a significant negative relation with *Trichodesmium* sp. The Si:P had a positive significant relation only with *Trichodesmium* sp.

Northeast monsoon

The N:P ratio increased (Fig. 4.9b) with depth but it was always lower than 16:1 ratio throughout the transect. The top 40 to 60 m had the N:Si ratio less than 1 throughout the transect. The Si:P ratio increased with depth but it was lower than 16:1 throughout the sampling depth.

None of the ratios showed any significant relation with either chl *a* or PCC. The N:P ratio showed significant positive relation (Table 4.5D) with *Navicula* sp onl The N:Si ratio showed a significant positive ($R= 0.43$; $p<0.01$) and negative (R:

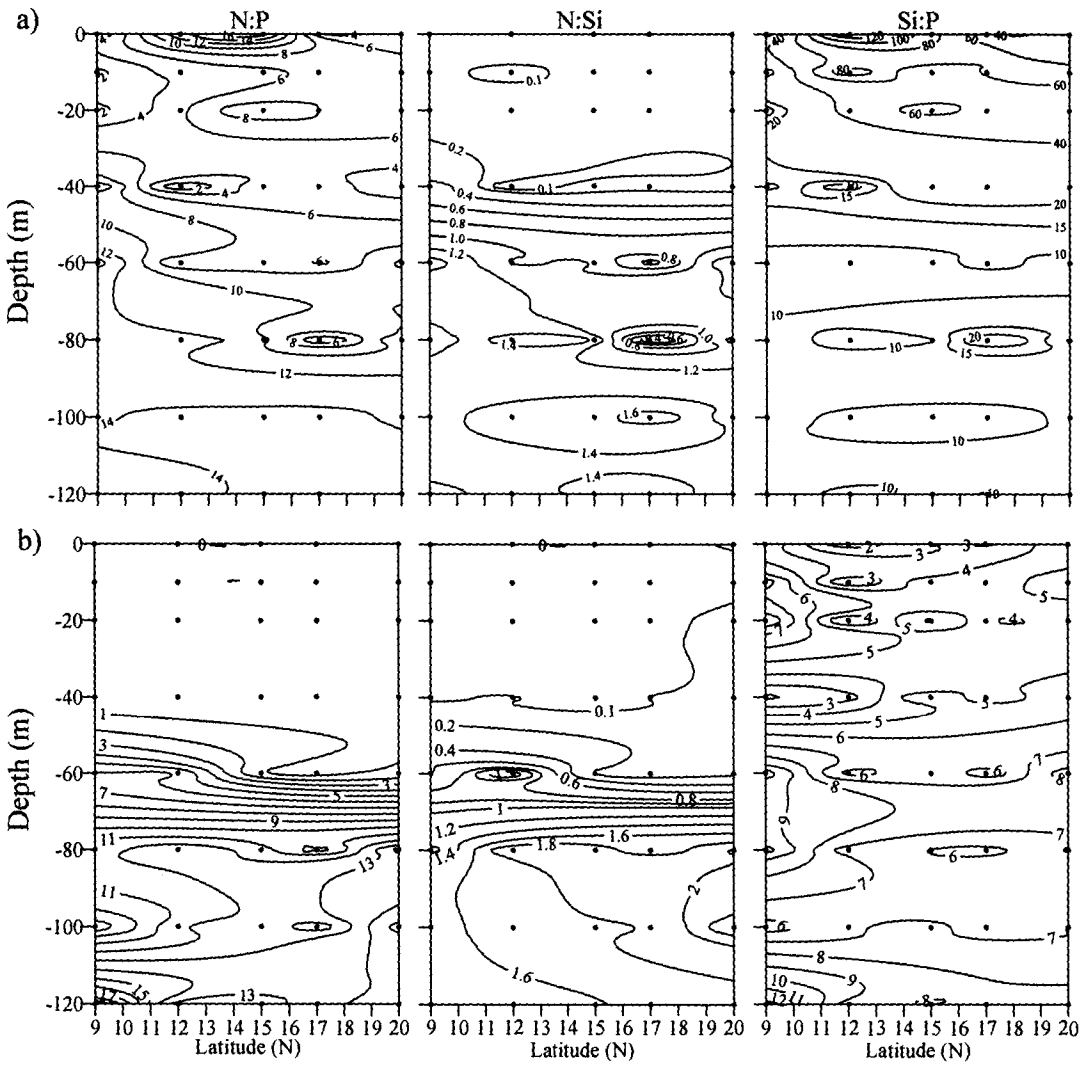


Fig. 4.9. Nitrate:phosphate [N:P], nitrate:silicate [N:Si] and silicate:phosphate [Si:P] ratios along Central Bay during (a) Spring intermonsoon and (b) Northeast monsoon

0.34; $p<0.03$) relation to *Navicula* sp and *Peridinium* sp respectively. The Si:P ratio showed a negative relationship with only the unidentified cyanobacteria.

Western Bay

Phytoplankton Assemblages along Western Bay

Generally, diatoms dominated the phytoplankton assemblages during SM and FIM. They were followed by dinoflagellates and silicoflagellates. While in SpIM, the diatoms were followed by dinoflagellates and cyanobacteria. Silicoflagellates were totally absent in SpIM. In NEM, the WB was dominated by diatoms, dinoflagellates, cyanobacteria followed by silicoflagellates. Only in SM, the pennales dominated (Fig. 4.10) while in the inter monsoon periods (FIM and SpIM) the centrales dominated. In NEM, both centrales and pennales were equal in abundance.

Cluster analysis of the sampling seasons based on phytoplankton abundance revealed greater than 75% similarity between the seasons (Fig. 4.11A). Cluster I comprised of three seasons viz. spring intermonsoon (SpIM), summer monsoon (SM) and fall intermonsoon (FIM). While northeast monsoon (NEM), was independent and did not group with the other seasons because this season was characterized with the lowest abundance as compared to the other three seasons. Similar pattern of phytoplankton distribution was evidenced through 2D NMDS ordination (Fig. 4.11B) method as well.

Summer Monsoon (SM)

In the SM, among the most abundant species of diatoms (Table 4.1) were, *Thalassiothrix longissima* (23.58%), *Thalassiothrix fauenfeldii* (23.55%), *Thalassionema nitzschioides* (4.92%), *Chaetoceros coarctatus* (4.77%), *Coscinodiscus radiatus* (4.37%), *Skeletonema costatum* (4.35%), *Nitzschia delicatissima* (3.61%) and *N. angularis* (2.28%) along the WB. A few genera of dinoflagellates observed were *Ceratium furca* (0.6%) and *Pseudoceratium punctatum* (0.6%). They were found to be abundant during SM. *Dictyocha crux* was the only silicoflagellate found in the SM.

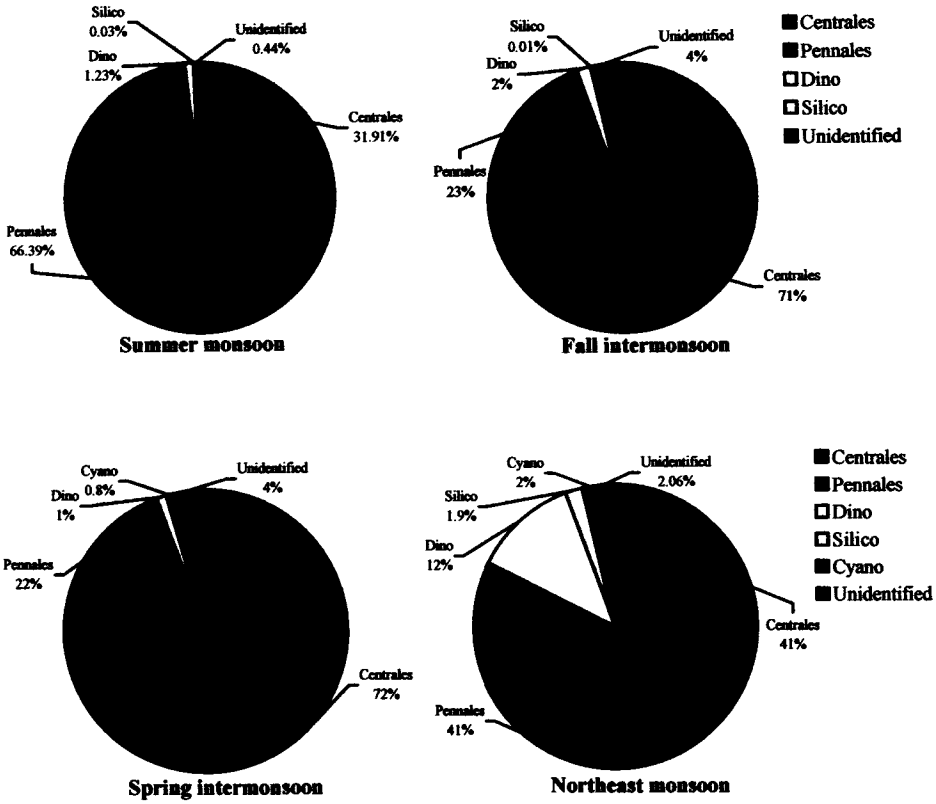
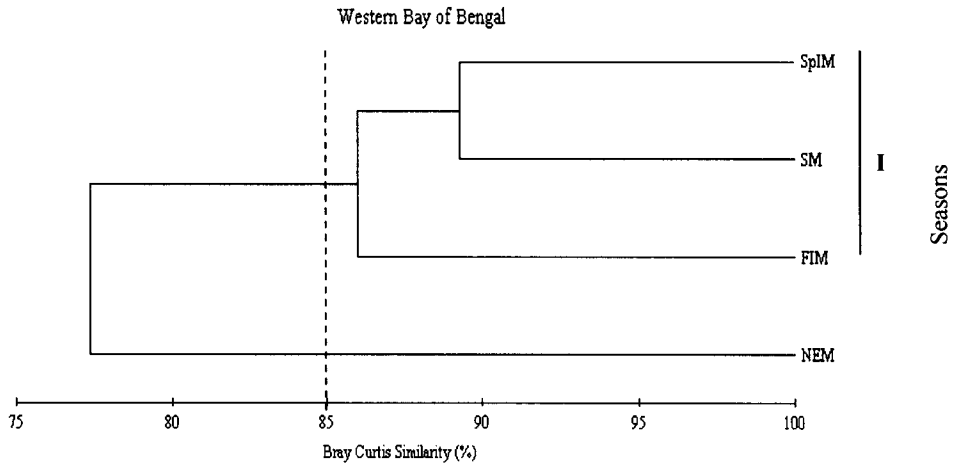


Fig. 4.10. Percent composition of centrales, pennales, dinoflagellates (Dino), silicoflagellates (Silico), cyanobacteria (Cyano) and unidentified phytoplankton along Western Bay during four different seasons

A)



B)

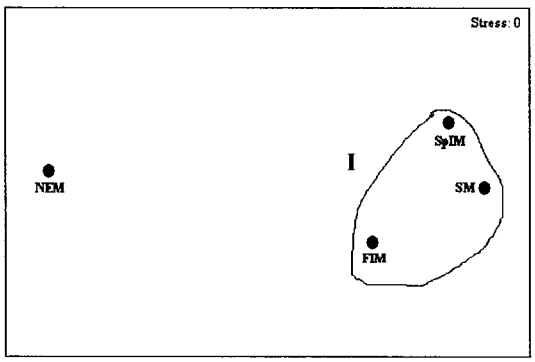


Fig. 4.11. A) Cluster dendrogram depicting similarity level in seasons based on the abundance of phytoplankton in the Western Bay and B) Non- metric Multidimensional scaling (NMDS) ordination based on the Bray- Curtis similarity coefficients. The season NEM, did not group with other seasons. As the stress value was 0 there is still a very high similarity between the seasons

Cluster analyses at 50% similarity level divided eight species (with ≥2% contribution to total PCC) into 3 clusters and one ungrouped individual (Fig. 4.12A). *Nitzschia angularis, Chaetoceros coarctatus and Skeletonema costatum* forming cluster I were absent at 80 and 120 m depth. They were abundant only at WB4 and were totally absent from the southern stations. *T. longissima* and *T. fauenfeldii* forming cluster II were absent below 60 m. While *Coscinodiscus radiatus* and *Nitzschia delicatissima* forming cluster IIA were also absent totally below 60 m. The phytoplankton species distribution pattern using 2D NMDS had a stress value of 0.01(Fig. 4.12B); suggesting that NMDS and cluster to be in great agreement. To show the similarity, the points are encircled. These species were more concentrated in the southernmost station, viz. WB1 (Fig. 4.13). They were present all through the transect but was more abundant at both WB1 and WB4. Most of the dominant species were found to be in higher numbers in the 20-40 m column (Fig. 4.13).

Fall inter monsoon (FIM)

In FIM, the most abundant species of the diatoms along the WB (Table 4.2) were, *Chaetoceros lorenzianus* (22.39%), *Chaetoceros curvisetus* (9.78%), Navicula sp (7.02%), *Thalassiosira* sp (6.72%), *Thalassiosira gravida* (4.2%), *Chaetoceros eibenii* (3.36%), *Thalassionema nitzschioides* (3.12%), *Ditylum brightwellii* (2.94%), *Chaetoceros didymus* (2.58%), *Pseudo-nitzschia* sp (2.52%), *Nitzschia longissima* (2.22%), *Chaetoceros coarctatus* (2.1%) and *C. paradoxum* (2.1%). Among dinoflagellates, *Ceratium furca* (0.4%) and *Oxytoxum sp* (0.3%) were the most abundant. Similar to the SM, *Dictyocha crux* was the only silicoflagellate found during this season.

Cluster analyses at 50% similarity level divided 13 species contributing ≥2% of total PCC into 3 clusters and three ungrouped species (Fig. 4.12C). *T. nitzschioides, Navicula* sp and *Nitzschia longissima* forming cluster I were present at all depths. They were more concentrated in the southernmost station (WB1). *Chaetoceros didymus* and *Pseudo-nitzschia* sp forming cluster II were totally absent below 40 m. They had maximum abundance in the surface at WB4. *Chaetoceros curvisetus, Ch. lorenzianus, Ch. coarctatus, Thalassiosira* sp and

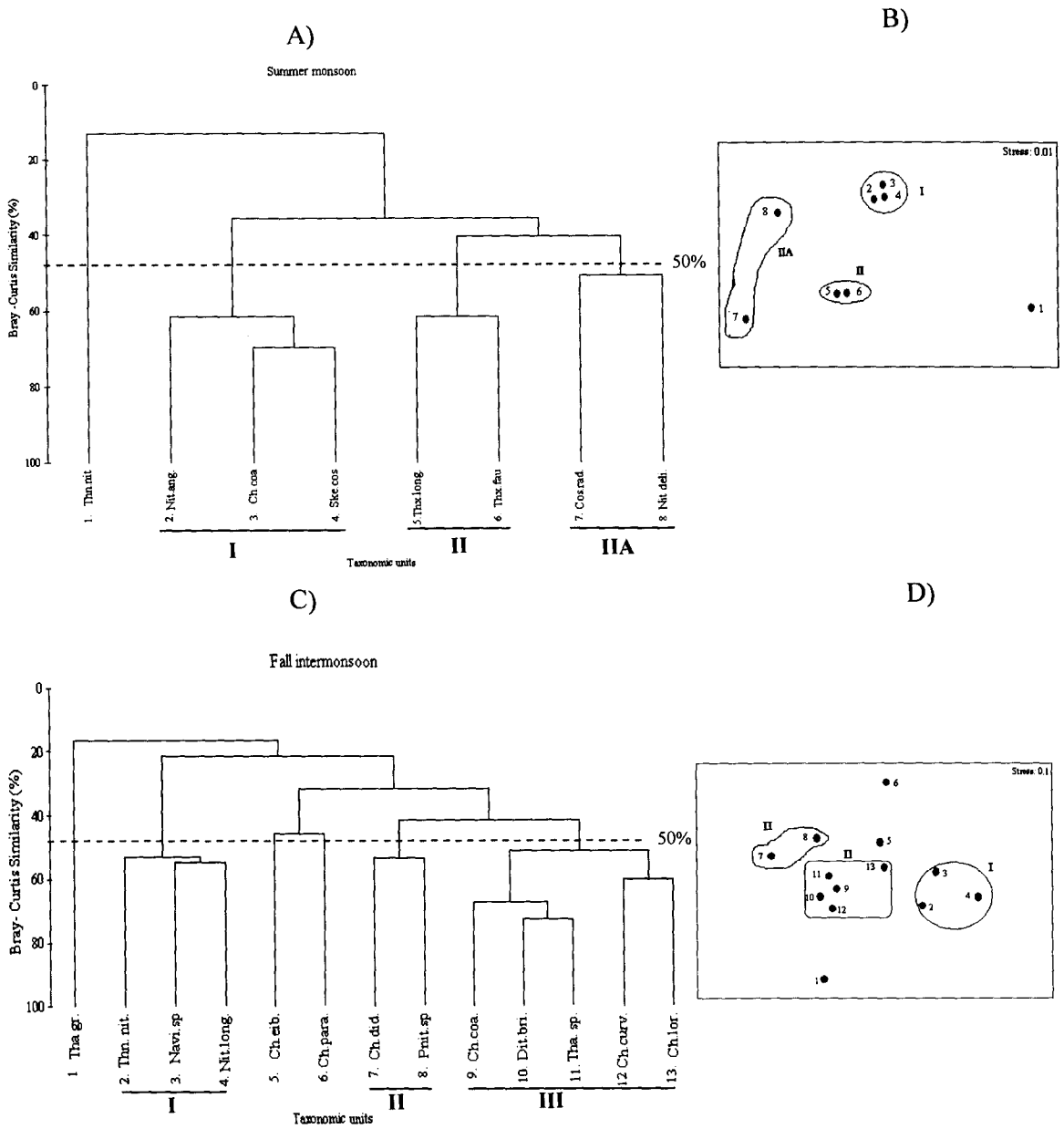


Fig. 4.12. Cluster dendrogram of major phytoplankton species (≥2%) from the Western Bay using Bray- Curtis similarity (%) and group average method. Similarity levels in A) Summer monsoon and C) Fall intermonsoon. Non-metric Multidimensional scaling (NMDS) ordination based on Bray- Curtis similarity (%) of the phytoplankton species in B) Summer monsoon and D) Fall intermonsoon

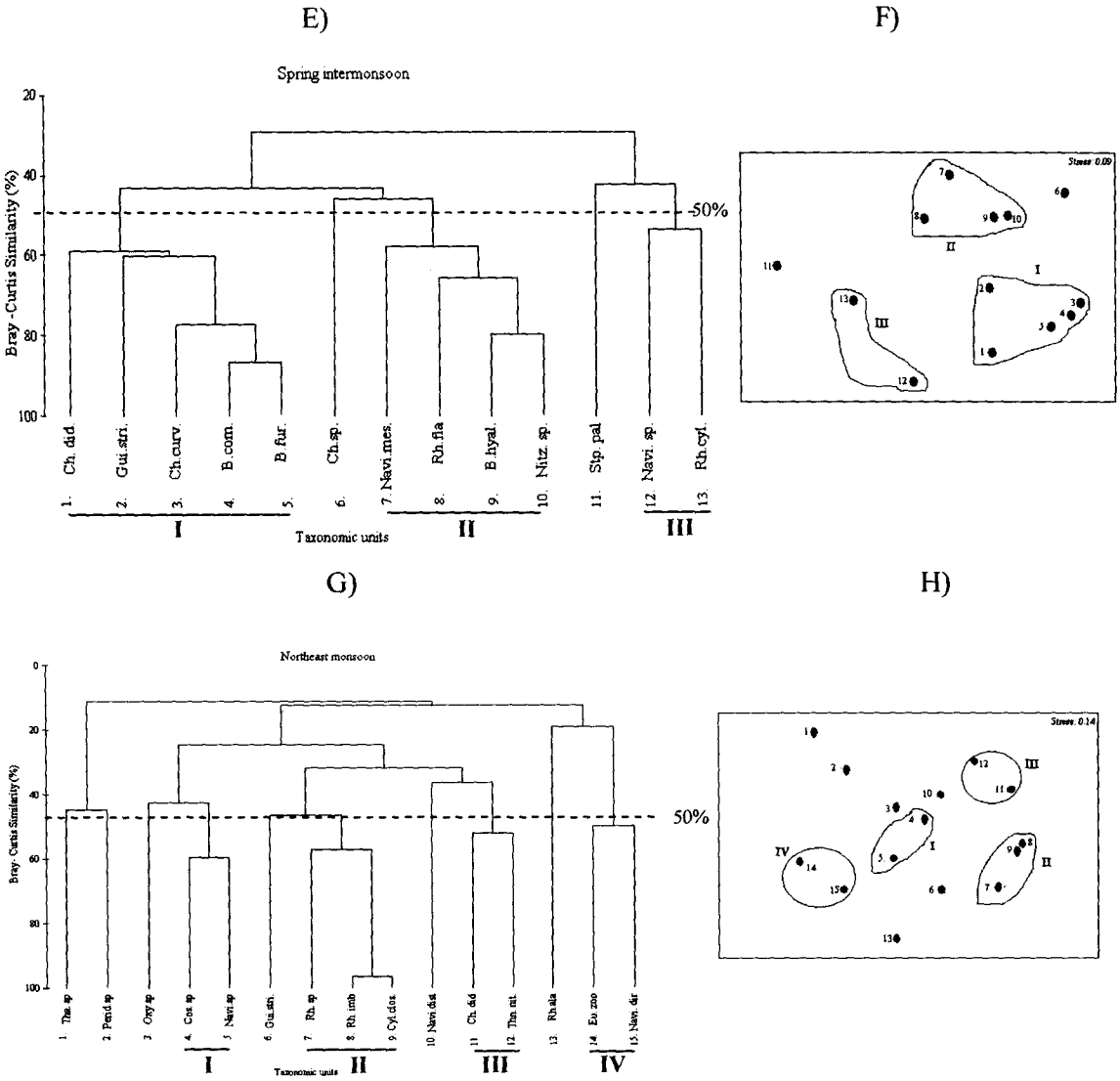


Fig. 4.12. Cluster dendrogram of the phytoplankton species (≥2%) from the Western Bay using Bray- Curtis similarity (%) and group average method. Similarity levels in E) Spring inter monsoon and G) North east monsoon. Non-metric Multidimensional scaling (NMDS) ordination based on Bray- Curtis similarity (%) of the phytoplankton species in F) Spring intermonsoon and H) Northeast monsoon

Ditylum brightwellii forming cluster III were totally absent at a depth of 120 m. They showed high abundance in the northernmost station (WB4) and were generally absent from WB1. Of the independent cluster, *Thalassiosira gravida* was present only at a depth of 10 m in WB4 and absent at other locations. *Chaetoceros paradoxum* and *Ch. eibenii* did not show a specific pattern of distribution. The 2D NMDS (Fig. 4.12D) with stress value 0.1 suggests that clustering is in variance with NMDS. Most of the dominant species were found to be in higher numbers from surf to a depth of 20 m (Fig. 4.14).

Spring inter monsoon (SpIM)

During SpIM, *Chaetoceros didymus* (16.27%), *Navicula* sp (10.02%), *Bacteriastrum comosum* (6.14%), *B. furcatum* (5.82%), *B. hyalinum* (2.8%) *Chaetoceros curvisetus* (4.74%), *Chaetoceros* sp (2.69%), *Rhizosolenia cylindrus* (4.09%), *Navicula messanensis* (3.34%), *Rhizosolenia flaccida* (2.69%), *Rhizosolenia striata* (4.63%), *Stephanopyxis palmeriana* (2.16%), *Nitzschia* sp (2.16%) were the major species in the WB. No silicoflagellates were observed (Table 4.3).

There were 3 clusters and two ungrouped species (Fig. 4.12E) from 13 species contributing ≥2% of total PCC at 50% similarity level. The 2D NMDS with stress value of 0.09 implicitly suggests that clustering is quite in variance with NMDS (Fig. 4.12F). *Bacteriastrum comosum, B. furcatum, Guinardia striata, Chaetoceros curvisetus* and *C. didymus* formed cluster I. These species were totally absent below 100 m. All the species of cluster I concentrated at a depth of 20 and 40 m depth at WB3. *Navicula messanensis, Rhizosolenia flaccida, Bacteriastrum hyalinum* and *Nitzschia* sp forming cluster II were present in high abundance at 40 m and below. They were totally absent in the 10 to 20 m depth. They were observed in high concentrations only at WB3 and were totally absent at the southernmost station. *Rhizosolenia cylindrus* and *Navicula* sp forming cluster III were found at all depths and present at most of the stations. *Chaetoceros* sp and *Stephanopyxis palmeriana* which formed independent groups did not exhibit a specific pattern of distribution (Fig. 4.15).

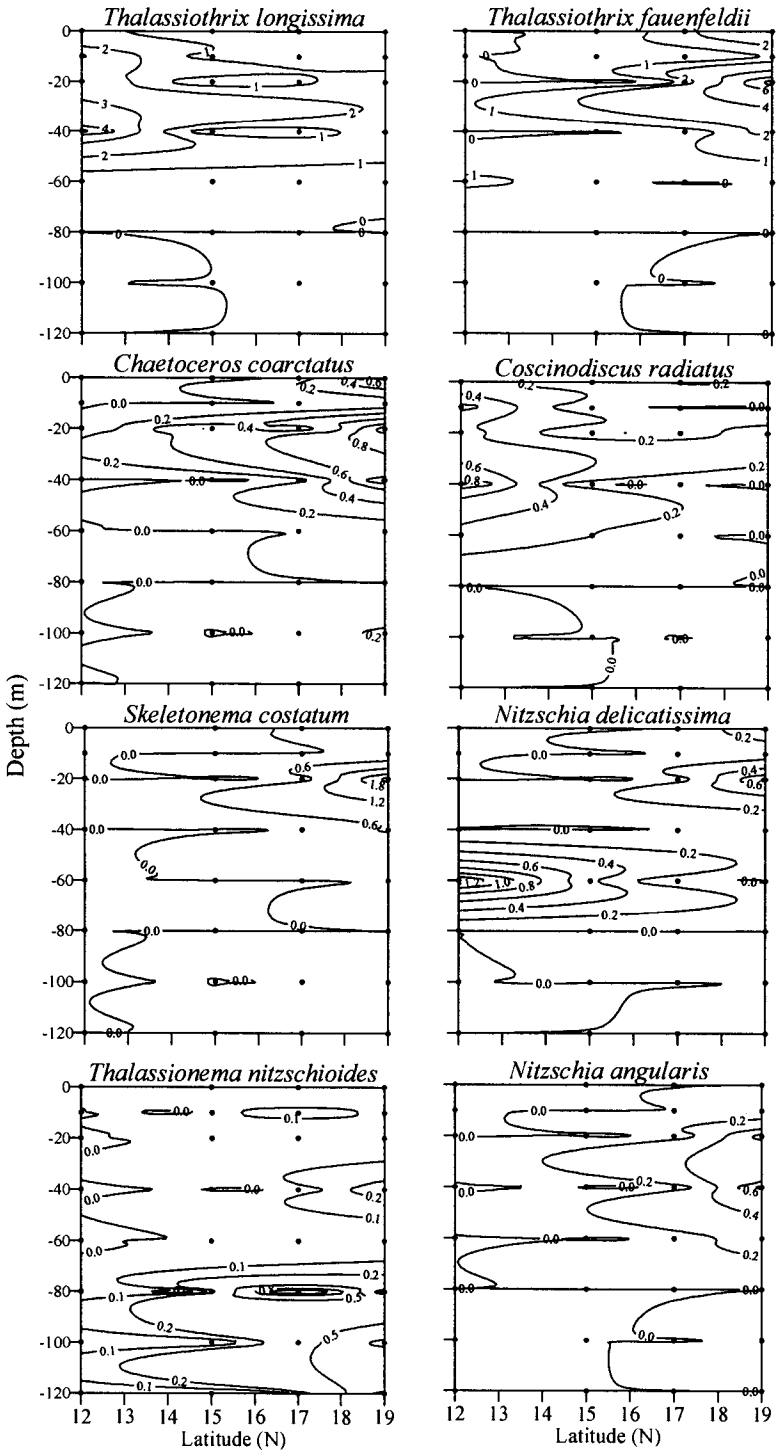
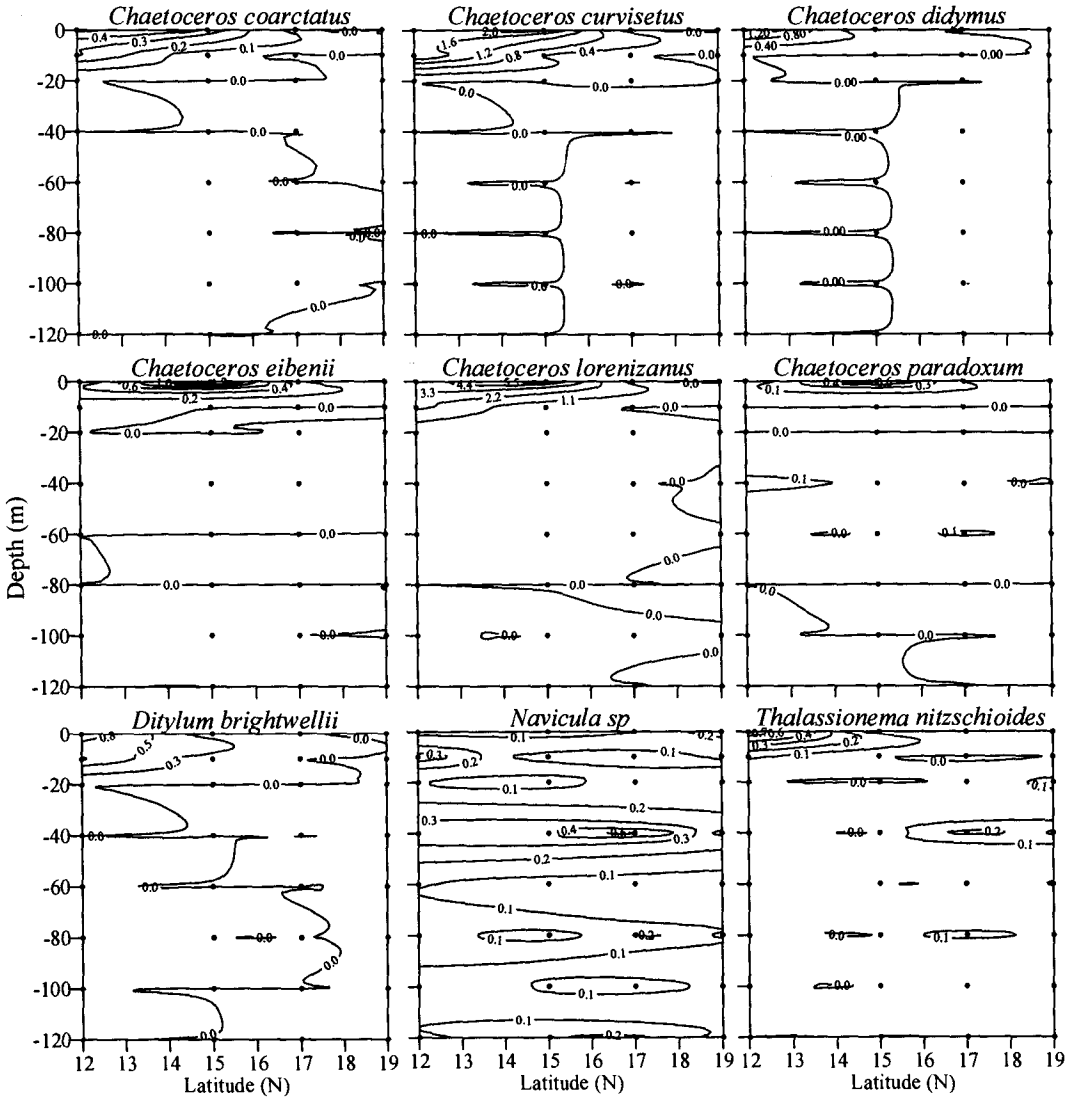


Fig. 4.13. Distribution of major species of phytoplankton along Western Bay in summer monsoon


Chaetoceros coarctatus
Chaetoceros curvisetus
Chaetoceros didymus
Chaetoceros eibenii
Chaetoceros lorenizamus
Chaetoceros paradoxum
Ditylum brightwellii
Navicula sp
Thalassionema nitzschioides
Depth (m)
0
-20
-40
-60
-80
-100
-120
12 13 14 15 16 17 18 19
Latitude (N)

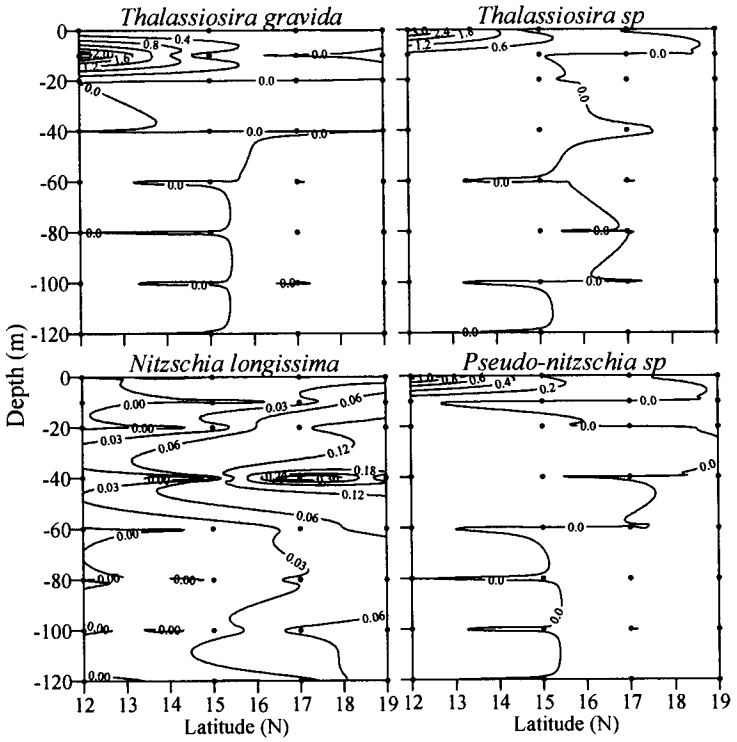


Fig. 4.14. Distribution of major species of phytoplankton along Western Bay in fall intermonsoon

North east monsoon (NEM)

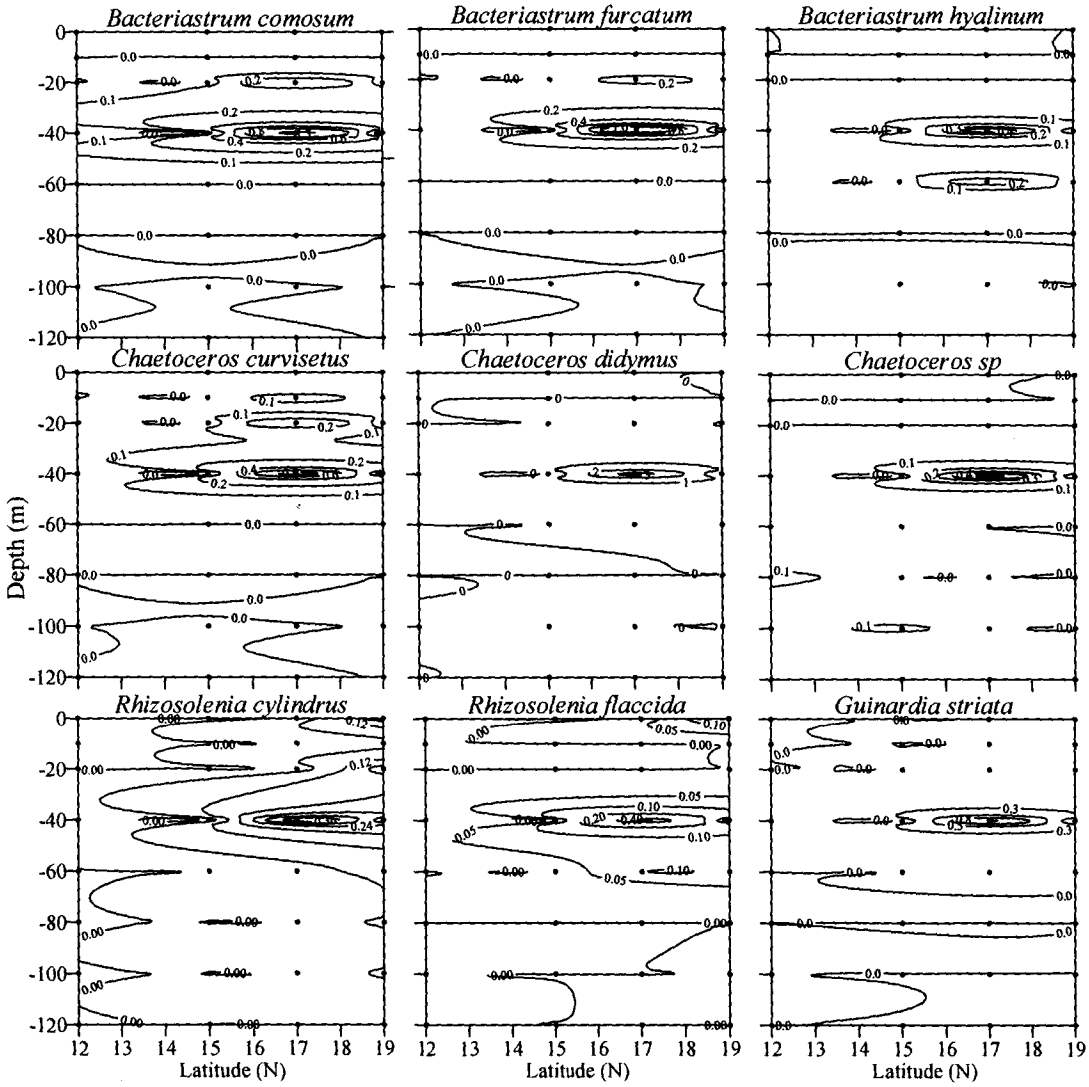
In NEM, *Navicula* sp (19.2%), *Coscinodiscus* sp (11.83%), *Oxytoxum* sp (6.53%), *Chaetoceros didymus* (5.88%), *Navicula directa* (5.56%), *Thalassionema nitzschioides* (5.08%), *Navicula distans* (4.41%), *Rhizosolenia imbricata* (3.7%), *Rhizosolenia striata* (2.89%), *Rhizosolenia* sp (2.73%), *Cylindrotheca closterium* (2.67%), *Peridinium* sp (2.51%), *Eucampia zodiacus* (2.38%), *Thalassiosira* sp (2.12%) and *Rhizosolenia alata* (2.06%) (Table 4.4) were the dominant species. *Dictyocha crux* was the only silicoflagellate found.

Fifteen species contributing ≥2% of total PCC clustered into four groups and six ungrouped species at 50% similarity level (Fig. 4.12G). The 2D NMDS (Fig. 4.12H) with stress values of 0.14 suggests that the clustering is in variance with NMDS. Two species each grouped together to form cluster I, III and IV. *Coscinodiscus* sp and *Navicula* sp forming cluster I were absent at 120 m and were in highest abundance at the surface. They did not show any specific pattern of distribution and were present at almost all stations. *Rhizosolenia* sp, *Rh. imbricata* and *Cylindrotheca closterium* forming cluster II were totally absent below 40 m and were present at all stations except WB4. Cluster III comprising of *Chaetoceros didymus* and *Thalassionema nitzschioides* were totally absent at WB3 station and below 80 m at the other stations. *Eucampia zodiacus* and *Navicula directa* forming cluster IV were absent below 80 m. They were present in high numbers at WB1; absent at stations WB3 and WB4. *Thalassiosira* sp, *Peridinium* sp. *Oxytoxum* sp, *Guinardia striata*, *Rhizosolenia* sp, *Navicula distans*, *Rhizosolenia alata* formed independent groups that did not cluster with any of the other dominant species. These species did not show any specific pattern in their distribution (Fig. 4.16).

Nutrient Ratios

Summer monsoon (SM)

The nitrate to phosphate (N:P) ratio showed a concurrent increase from 40 m to 120 m. In general, the N:P ratio was lower than the classical Redfield ratio of 16:1 throughout the water column at all station (Fig. 4.17 a) except for WB1 where it exceeded the ideal ratio of 16:1. The nitrate to silicate (N:Si) ratio in the


Bacteriastrum comosum
Bacteriastrum furcatum
Bacteriastrum hyalinum
Chaetoceros curvisetus
Chaetoceros didymus
Chaetoceros sp
Rhizosolenia cylindrus
Rhizosolenia flaccida
Guinardia striata
Depth (m)
0
-20
-40
-60
-80
-100
-120
12 13 14 15 16 17 18 19
Latitude (N)

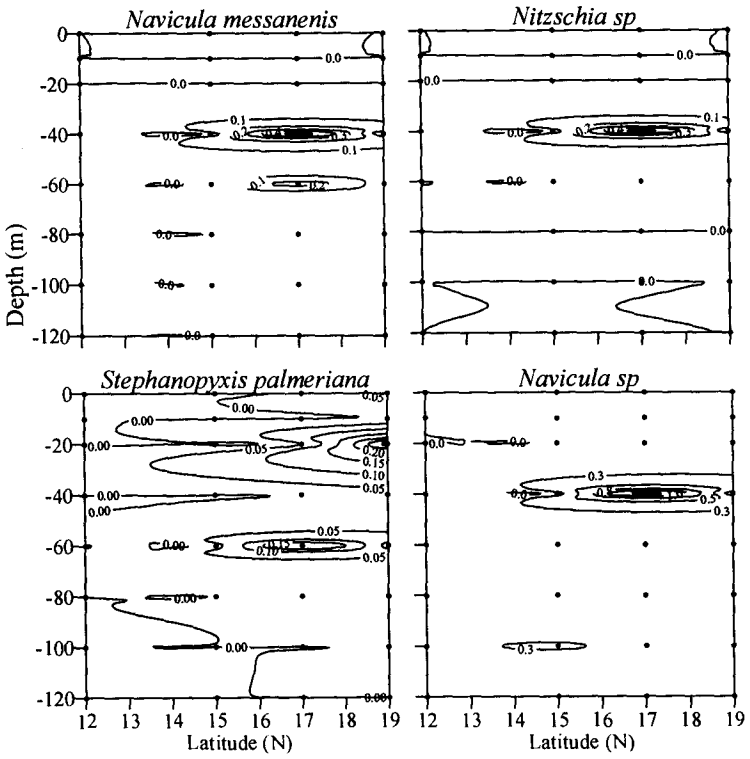


Fig. 4.15. Distribution of major species of phytoplankton along Western Bay in spring intermonsoon

top 40 m was generally lesser than the ideal 1:1 ratio and it was >1:1 at deeper depths throughout the transect indicating nitrate enrichment at these depths. The silicate to phosphate (Si:P) ratio was always less than the classical Redfield ratio of 16:1 throughout the sampling depths. None of the ratios had any significant relation with either the total phytoplankton abundance or the dominant species. Of the three ratios only the Si:P ratio had a significant negative relation with only chl *a* (Table 4.6A).

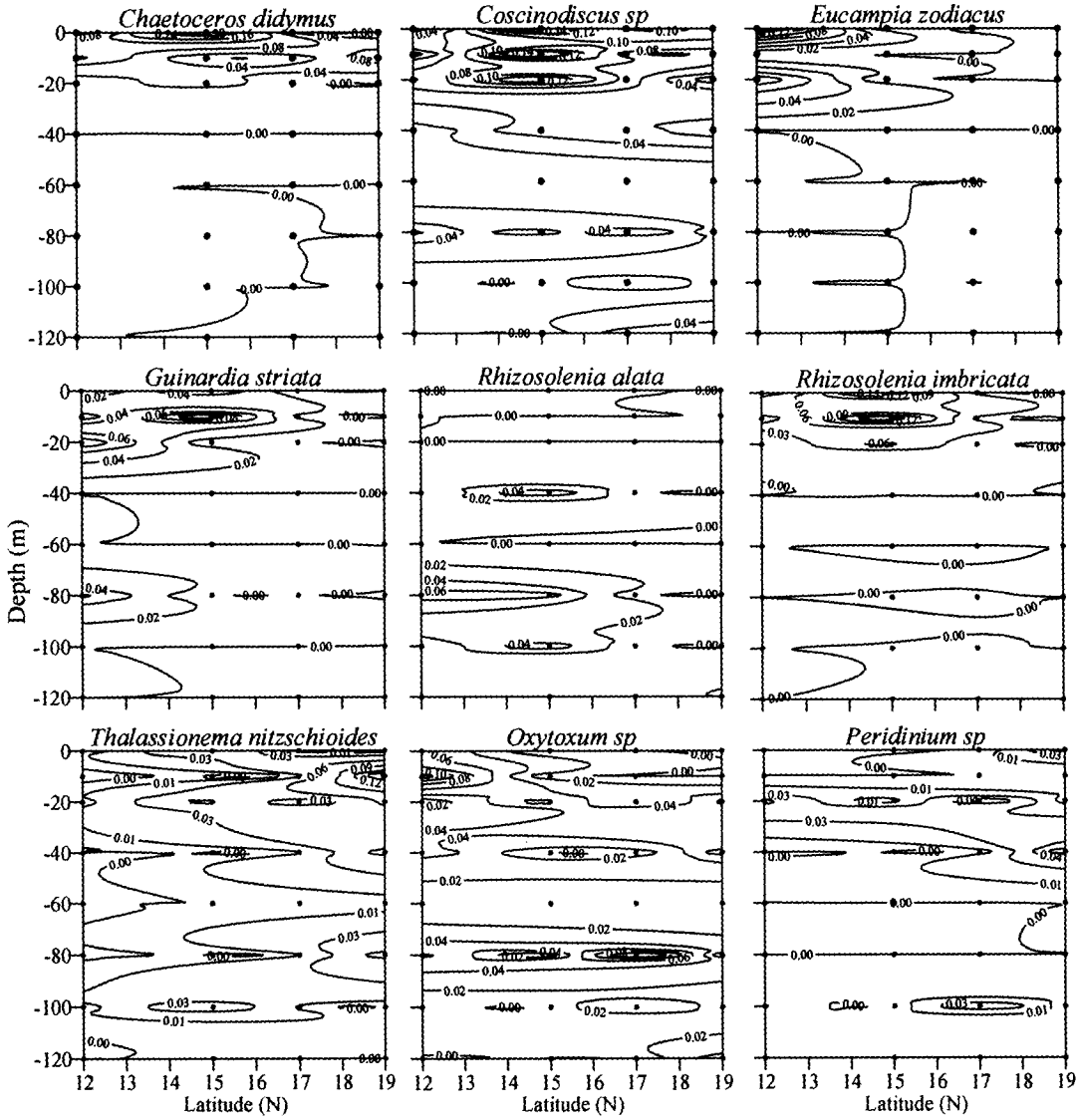
Fall inter monsoon (FIM)

The nitrate to phosphate (N:P) ratio increased with depth upto 120 m but was lower than 16:1 throughout the sampling depth (Fig. 4.17b). The nitrate to silicate (N:Si) ratio was generally lower than 1:1 in the top 20 to 40 m. Thereafter, it was greater than 1 indicating nitrate enrichment. The silicate to phosphate ratio (Si:P) did not follow any set pattern as the other ratios. In general the Si:P ratio was high at the surface and low at intermediate depths and then again increased at deeper depths. However, it was lower than Redfield ratio (16:1) at most of the stations except at the surface of WB2 where it was greater than 16:1 due to very low concentrations of phosphate as compared to silicate.

Among the three ratios, only the N:P ratio showed a significant negative relation with PCC. The N:P and N:Si ratio only had a significant negative relation with chl *a*. The N:P ratio was significant with dominant species like *Chaetoceros curvisetus*, *C. lorenzianus*, *Ditylum brightwellii*, *Thalassiosira sp* and *Pseudo-nitzschia sp*. The N:Si ratios had a negative relation with some of the dominant phytoplankton species like *Chaetoceros curvisetus* and *Pseudo-nitzschia* sp. With the Si:P ratio and the dominant phytoplankton species significant relationship was not observed (Table 4.6B).

Spring inter monsoon (SpIM)

At WB1 and WB4 in SpIM, N:P ratio in the surface was only slightly below Redfield ratio. At other stations the N:P was lower than 3 at the surface which increased with depth (Fig. 4.18a). The ratio of nitrate to silicate (N:Si) in the top 40 m to 60 m was in general <1:1 with no spatial variation in surface waters


Chaetoceros didymus
Coscinodiscus sp
Eucampia zodiacus
Guinardia striata
Rhizosolenia alata
Rhizosolenia imbricata
Thalassionema nitzschioides
Oxytoxum sp
Peridinium sp
Depth (m)
0
-20
-40
-60
-80
-100
-120
12
13
14
15
16
17
18
19
Latitude (N)

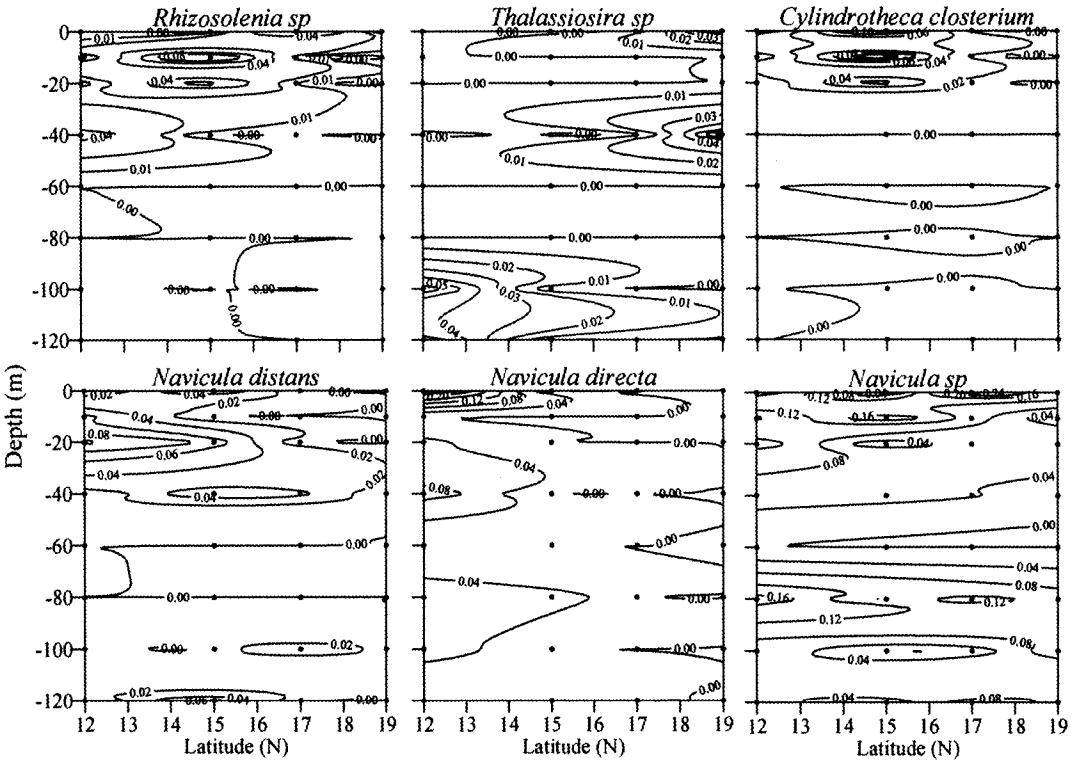


Fig. 4.16. Distribution of major species of phytoplankton along Western Bay in northeast monsoon

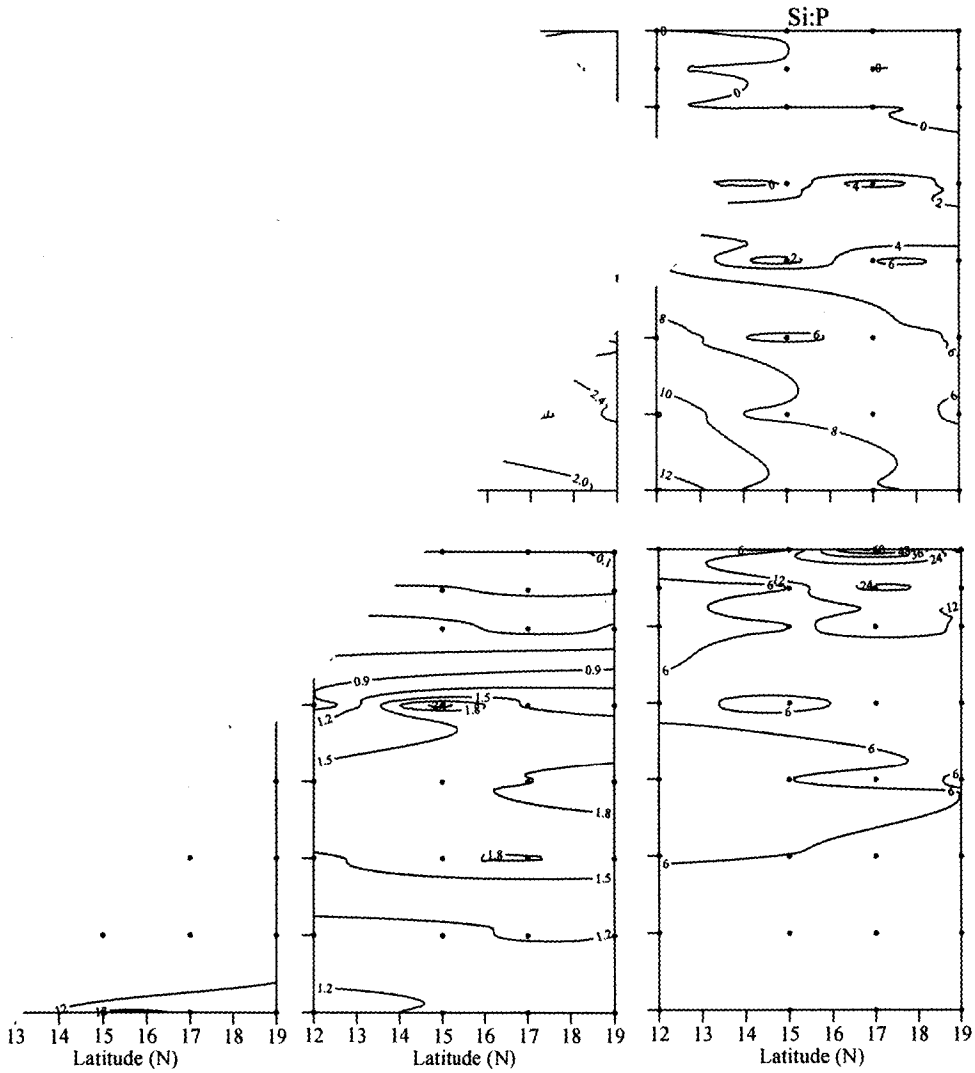


Fig. 4.17. Nitrate:phosphate [N:P], nitrate: silicate [N:Si] and silicate: phosphate [Si:P] ratios along Western Bay in a) Summer monsoon and b) Fall intermonsoon

indicating an enrichment of silicate relative to nitrate at these depths. The silicate to phosphate (Si:P) ratio had high surface values and exceeded the ideal ratio of 16:1 in the surface only at WB1 and WB2 because of high concentrations of silicate at these stations. At these two stations the values decreased with depth while at WB3 and WB4 it increased with depth.

Although not statistically significant, the N:P ratio had a negative relation and the N: Si, a positive relation with PCC and chl *a*. Only the Si:P was significantly related to both PCC and chl *a* along the WB during SpIM. N:P ratios did not show a significant relation with the other dominant species (Table 4.6C). The N:Si ratio had a significant positive relation with *Bacteriastum hyalinum, Navicula messanensis*, N*itzschia* sp and *Rhizosolenia flaccida.* The Si:P ratio had a significant negative relation dominant phytoplankton species like *Bacteriastrum furcatum, B. comosum, Chaetoceros curvisetus, C. didymus, Rhizosolenia cylindrus, R. flaccida, Guinardia striata.*

North east monsoon (NEM)

In NEM, high surface nitrate to phosphate (N:P) ratio was observed at the southernmost station (WB1) where it was greater than the ideal 16:1 ratio (Fig. 4.18b). At other stations, the N:P ratio increased with depth with the surface ratio being always lower than 16:1. At the northern stations viz., WB3 and WB4 the N:P ratio did not cross the Redfield ratio throughout the 0-120 m column indicating nitrate limitation. The N:Si ratio was less than 1 in the top 40 to 60 m throughout the transect. The N:Si ratio was >1:1 below 80 m at most of the stations along the WB indicating silica limitation. The Si:P ratio was always greater than 16:1 at all depths at southernmost station (WB1) and it was always lesser than 16:1 in the northernmost station, viz WB4. At WB2 and WB3 the intermediate depths showed greater than 16 also corroborated in the high abundance of diatoms suggesting that the silicate is not a limiting factor.

None of the ratios showed any significant relation with the PCC. The N: P and N:Si ratio only had a significant relation with chl *a*. The N: P ratio had a significant positive relation with *Navicula directa* and a significant negative

Table 4.6. Spearman's Rank correlation test for log transformed phytoplankton abundance (PCC), chlorophyll *a* (Chl *a*), major dominant phytoplankton species with nitrate: phosphate (N:P), nitrate:silicate (N:Si) and silicate: phosphate (Si:P) ratios along the Western Bay in A) Summer monsoon, B) Fall intermonsoon, C) Spring intermonsoon and D) Northeast monsoon

A) Summer monsoon

Parameter	**N:P**		**N:Si**		**Si:P**	
	R	*p*	R	*p*	R	*p*
PCC	-0.13	0.62	-0.15	0.54	-0.38	0.12
Chl *a*	-0.23	0.35	0.17	0.47	**-0.66**	**0.00**
Chaetoceros coarctatus	0.03	0.91	-0.22	0.35	-0.34	0.17
Coscinodiscus radiatus	-0.21	0.39	-0.18	0.44	-0.41	0.09
Nitzschia angularis	0.09	0.71	-0.18	0.44	-0.26	0.30
Nit. delicatissima	0.05	0.85	-0.29	0.22	-0.20	0.42
S. costatum	-0.21	0.40	-0.35	0.13	-0.21	0.40
Thalassiothrix fauenfeldii	0.45	0.06	-0.29	0.22	0.01	0.98
T. longissima	0.02	0.93	-0.16	0.51	-0.36	0.14
Thalassionema nitzschioides	-0.02	0.93	-0.02	0.92	0.27	0.28

B) Fall intermonsoon

Parameter	**N:P**		**N:Si**		**Si:P**	
	R	*p*	R	*p*	R	*p*
PCC	**-0.48**	**0.01**	-0.26	0.18	-0.33	0.09
Chl *a*	**-0.69**	**0.00**	**-0.42**	**0.03**	-0.28	0.16
Chaetoceros coarctatus	-0.31	0.11	-0.18	0.35	-0.10	0.60
Ch. curvisetus	**-0.54**	**0.00**	**-0.56**	**0.00**	0.04	0.83
Ch. didymus	-0.32	0.10	-0.32	0.10	-0.04	0.86
Ch. eibenii	-0.27	0.16	-0.29	0.14	0.13	0.52
Ch. lorenzianus	**-0.45**	**0.02**	-0.32	0.10	-0.15	0.45
Ch. paradoxum	-0.12	0.55	-0.05	0.82	0.05	0.79
Ditylum brightwellii	**-0.48**	**0.01**	-0.36	0.06	-0.17	0.38
Thalassiosira sp	**-0.42**	**0.03**	-0.15	0.44	-0.29	0.13
Navicula sp	0.14	0.47	0.18	0.36	0.02	0.93
Nitzschia longissima	0.25	0.20	0.05	0.78	0.34	0.08
Pseudo-nitzschia sp	**-0.49**	**0.01**	**-0.43**	**0.02**	-0.13	0.52
Thalassionema nitzschioides	0.03	0.89	0.10	0.63	-0.23	0.25

C) Spring intermonsoon

Parameter	N:P		N:Si		Si:P	
	R	*p*	R	*p*	R	*p*
PCC	-0.11	0.56	0.35	0.05	**-0.54**	**0.00**
Chl *a*	-0.30	0.10	0.22	0.23	**-0.51**	**0.00**
Bacteriastrum comosum	0.00	0.99	0.24	0.18	**-0.38**	**0.03**
B. furcatum	-0.12	0.51	0.16	0.38	**-0.42**	**0.02**
B. hyalinum	0.10	0.60	**0.37**	**0.03**	-0.24	0.19
*Chaetoceros*sp	0.07	0.69	0.34	0.06	-0.26	0.15
Ch. curvisetus	-0.13	0.47	0.12	0.53	**-0.44**	**0.01**
Ch. didymus	-0.07	0.73	0.27	0.14	**-0.40**	**0.03**
Navicula sp	0.10	0.59	0.29	0.11	-0.26	0.16
Navi. messanensis	0.27	0.15	**0.47**	**0.01**	-0.18	0.33
Nitzschia sp	0.10	0.58	**0.41**	**0.02**	-0.28	0.12
Rh. cylindrus	0.01	0.95	0.30	0.09	**-0.47**	**0.01**
Rh. flaccida	0.07	0.71	**0.45**	**0.01**	**-0.40**	**0.03**
Guinardia striata	-0.14	0.44	0.16	0.37	**-0.54**	**0.00**
St. palmeriana	-0.13	0.49	0.14	0.44	-0.34	0.06

D) Northeast monsoon

Parameter	N:P		N:Si		Si:P	
	R	*p*	R	*p*	R	*p*
PCC	-0.17	0.36	-0.14	0.44	-0.05	0.79
Chl *a*	**-0.69**	**0.00**	**-0.57**	**0.00**	0.04	0.86
Ch. didymus	-0.18	0.35	-0.17	0.39	0.05	0.81
Coscinodiscus sp	**-0.42**	**0.03**	-0.33	0.08	-0.21	0.29
Cylindrotheca closterium	-0.20	0.32	-0.14	0.48	0.03	0.88
Eu. zodiacus	0.22	0.27	-0.10	0.62	**0.43**	**0.02**
Guinardia striata	-0.03	0.87	-0.17	0.39	0.22	0.25
Rhizosolenia sp	-0.23	0.24	-0.18	0.35	0.17	0.39
Rh. alata	0.24	0.21	0.25	0.21	-0.13	0.52
Rh.imbricata	-0.20	0.32	-0.14	0.48	0.03	0.88
Navicula sp	0.12	0.55	0.03	0.87	0.09	0.66
Navi.distans	-0.12	0.55	-0.12	0.53	0.11	0.57
Navi. directa	**0.48**	**0.01**	0.12	0.55	**0.49**	**0.01**
Thalassiosira sp	0.04	0.83	-0.12	0.54	0.03	0.88
Thalassionema nitzschioides	-0.33	0.09	-0.16	0.42	-0.24	0.22
Oxytoxum sp	0.10	0.62	-0.02	0.94	0.24	0.22
Peridinium sp	-0.22	0.27	-0.29	0.14	0.03	0.89

Figures in bold indicate significant relationship at levels of shown *p*. Refer Fig 4.17; 4.18 for different ratios at a given depth and Fig. 4.13; 4.14; 4.15; 4.16 for species distribution at each depth during different sampling seasons

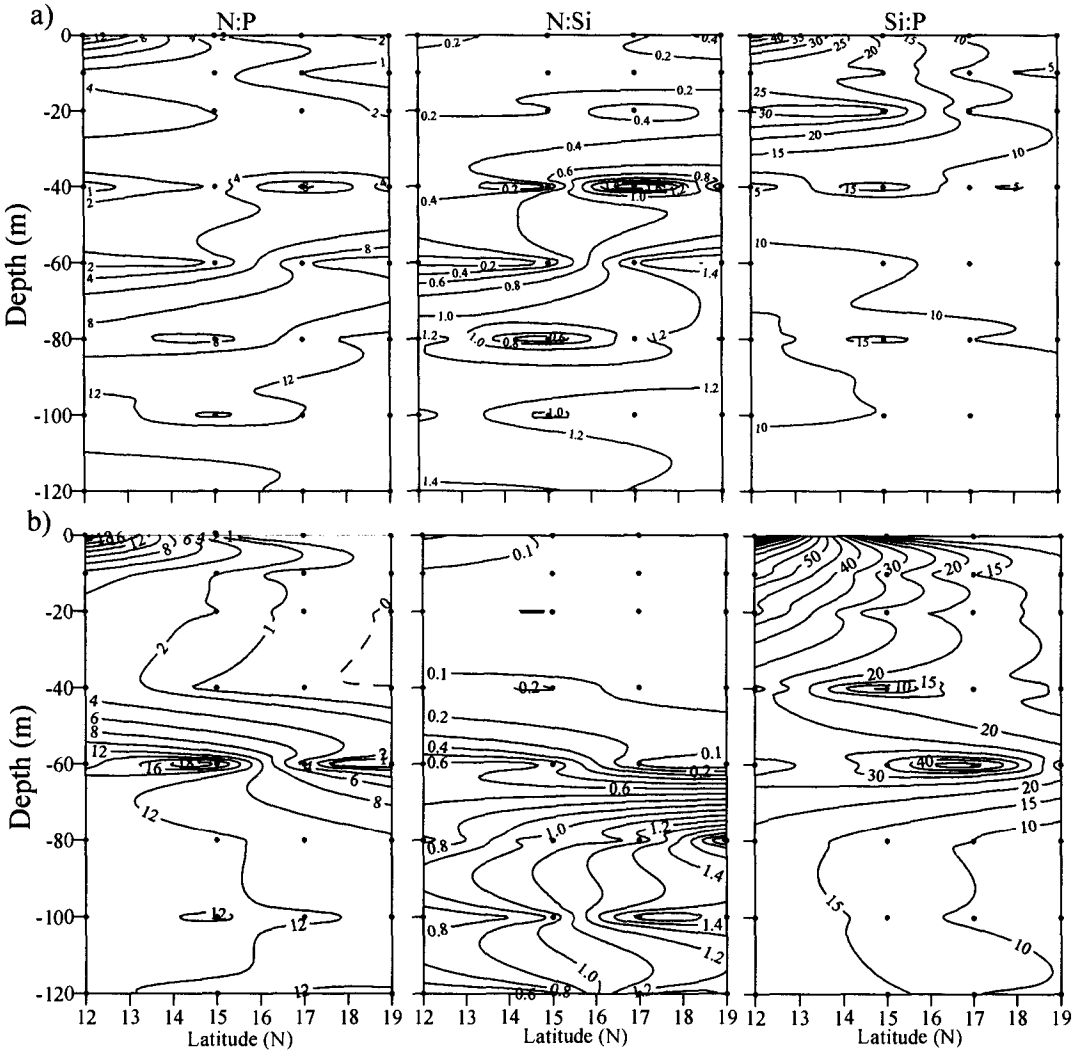


Fig. 4.18. Nitrate:phosphate [N:P], nitrate:silicate [N:Si] and silicate:phosphate [Si:P] ratios along Western Bay in a) Spring intermonsoon and b) Northeast monsoon

relation with *Coscinodiscus* sp only (Table 4.6D). None of the dominant species showed significant relationship with N:Si ratio. Dominant species like *Eucampia zodiacus* and *Navicula directa* were significantly related with Si:P ratio.

Discussion

The BoB experiences seasonal changes that are controlled by the monsoon system. Over the BoB, storms and cyclones are mostly observed during June to December (Rao 1981). Thereby, the turbulence is very high during this period (Varkey et al 1996). During SpIM, due to the low wind speeds the waters are calm (Varkey et al 1996). The discharge of the Ganges-Brahmaputra system reaches its maximum during SM, accounting to most proportions of the annual averages of sediment (1.1 x 10^9 tonnes, Milliman & Syvilski 1992) and freshwater (1000 km^3, Milliman & Meade 1983) discharges. The riverine input causes considerable variations of salinity and temperature over the entire basin with values reaching as low as 20 psu in the coastal areas during the rainy season (La Violette 1967; Varkey et al 1996; Madhupratap et al 2003; Prasanna Kumar et al 2004) causing a strong stratification in the surface layers (Shetye et al 1991; 1996).

Healthy growth of diatoms occurs when atomic N:Si:P ratio within the cells is about 16:16:1 (Redfield et al 1963; Brzezinski 1985). Deviations from these ratios due to either nutrient availability or uptake indicate nutrient-limited phytoplankton growth (Hecky & Kilham 1988; Dortch & Whitledge 1992). However, Parsons et al (1961); Healy & Hendzel (1979); Levasseur & Therriault (1987) suggested that if the ambient ratios of dissolved N:P <10 and N:Si ratio<1 it pinpointed to a potential N limitation. Harrison et al (1977) had observed that if the N:Si >1 and Si:P ratio <3 it was indicative of Si limitation. In the Bay, lower N:P and N:Si ratios along both transects during all seasons signify nitrate limiting regime in the top 40 m. High concentrations of SiO_4 (130 to 137 μmol L^{-1}; Sarin et al 1989) and PO_4 (0.3 to 3.16 μM; Datta 1999) in the freshwater delivered by the Ganges-Brahamaputra-Meghna river systems appear to be the reason for diatoms to thrive. Valsaraj & Rao (1994) also observed nitrate to be a limiting

factor for primary production in the BoB. In comparison however, the nutrient concentrations during this study are very low. Nitrate and phosphate were usually at undetectable levels and silicate concentrations were in the range of 2-4 μM. Also, higher Si:P throughout the water column suggests that Si was never at limiting levels in the BoB throughout the year.

The riverine additions to the oceans that are of greater importance to the phytoplankton are silicate and iron. The largest source of these minerals into the Bay of Bengal is from the rivers which leach the soils and transport it to the sea (Krishnaswami et al 1999). River discharges also control the distribution of phytoplankton (Peterson et al 1975). High amounts of silicate could be attributed to the abundance of diatoms observed during this study. As Furnas (1990) proposed, diatoms grow at higher rates than other algae even in oligotrophic areas. Previous studies from the Bay have also reported diatoms to be dominating (Gouda & Panigrahy1996; Panigrahi et al 2004; Umamaheswararao & Mohanchand 1988).

In the overall, composition and distribution of major phytoplankton species did not differ widely between transects. Further, the variation in abundance between seasons was low. Kibiirige & Perissinotto (2003) suggested that when the 2D NMDS plots with stress values are nearer to zero it is indicative of very high similarity between different clusters. This is clearly reflected in this study (Fig. 4B and 13B).

The WB had higher abundance than the CB. In spite of the fact that most species were distributed throughout the transect, certain species were found only in the northern or southern stations. Thus, species composition in the BoB during this study indicated north south variation. Riverine influx, especially in the head Bay, nutrient distribution and, euphotic depths that are deeper in the south appear to influence the distribution of phytoplankton.

Both phytoplankton community structure and biomass are governed by nutrient concentrations in the Bay. Egge (1998) suggested that diatom blooms would not occur if the silicate concentrations were less than 1.5 μM. The phytoplankton community becomes flagellate dominant when silicate decreased further. Therefore, high abundance of diatoms (>90%), compared to very low dinoflagellate species and abundance, is attributable to a high Si:P ratio and high concentrations of silicate (mostly >2 μM) in the BoB. Such nutrient realm appears important in supporting and sustaining a diatom dominated phytoplankton community. This can also be inferred from the high abundance of siliceous plankton reported by Rao et al (1989) in the southern BoB during summer monsoon. Moreover, as noted by Egge & Aksnes (1992), when silicate is >2 μM, there is dominance of diatoms. These findings help ascertain the preponderance of diatoms in the BoB.

Seasonal differences in the distribution of phytoplankton species in BoB are described in chapter 5. Discussion below pertains to the dominant phytoplankton species and their relationship to nutrient ratios with an emphasis on the major species recorded during different seasons. Of a few species that were abundant only in the northern regions of the BoB during SM, the abundance of *Chaetoceros* sp is noteworthy. Kobayashi & Takahashi (2002) considered this genus to be an indicator of higher nutrient concentrations in the western and central Pacific. Contrastingly, its species are also reported to be in high abundance in low nitrate waters (Collos et al 1997). When the entire study area is considered together, both these conditions of high and low nutrients were observed in the BoB. Therefore, it is speculated that *Chaetoceros* spp adapt to various nutrient regimes of the Bay and thrive. Some *Chaetoceros* spp are known to grow logarithmically (Penna et al 1999) in low N:P ratio conditions seen in the top 40 m in the BoB. *Rhizosolenia* sp and *Thalassiothrix* spp are reported to proliferate in stratified water columns (Kemp et al 2006) which, are also observed in the BoB. Thus, during SM apart from nutrients, physical factors also seem to play an important role in phytoplankton species distribution.

In FIM, when Si:P ratio is closer to 16 particularly in south, *Rhizosolenia* sp seemed to be independent of the nutrients. As its species are known to perform vertical migration in search of nitrate and then come to the surface for photosynthesis (Singler & Villareal 2005) they can in a way remain in zones of ideal nutrient levels and, depending on light levels modulate their photosynthetic rates. *Pseudo-nitzschia* sp, known to prefer nitrate replete conditions (Carter et al 2005), was higher in deeper waters (between 40-80 m) with higher nitrate levels ranging from >1 μM to 25 μM along the CB.

In SpIM, the euphotic depth extended deeper (~80 m, Kumar et al 2004) than the depths where N:P ratios were close to the Redfield ratios. The most predominant *Coscinodiscus* sp did not show any marked difference in its distribution at most of the stations along CB during this season. This is attributed to its wide temperature tolerance (Horner 2002). Another species which was dominant in SpIM was *Trichodesmium* sp which is often known to contend well in warmer water temperatures and lower nitrate concentrations (Anderson et al 1994). Many species of this genus are able to fix atmospheric nitrogen (Dugdale et al 1964; Goering et al 1966; Qasim 1970; Ramos et al 2005) and therefore form blooms in nitrate-depleted conditions, in which diatoms and dinoflagellates cannot flourish/sustain. High temperatures, calm waters and low nutrients, are prevalent in the BOB during SpIM. Thus, the ideal conditions that exist for the growth of this cyanobacterium are reflected by its high numbers in the northern regions of the CB during SpIM. Along with *Trichodesmium* sp, *Rhizosolenia* sp was also observed to be the other most abundant species in the northern most station. As mentioned earlier, this species is known to undergo vertical migration in search of nitrate. Also, some species belonging to this genus (*Rhizosolenia styliformis*) contain endosymbiotic cyanobacterium (*Richelia intracellularis*), which can fix N_2 gas (Venrick 1974; Villareal & Carpenter 1989). It has also been widely reported from warm, oligotrophic waters (Venrick 1969; 1971; Sournia 1970; Villareal 1991; 1994a; 1994b; Guillard & Kilham 1977) and eddy influenced regions (Vaillancourt et al 2003). Such species can thrive even when the waters are nitrate depleted as observed in the CB.

In NEM, some of the species seem to be controlled by the Si:P ratios and nutrient concentrations in general. Phytoplankton, chl *a* and most species were seen to be abundant at a depth of 60 to 80 m wherein the N:P, Si:P and N:Si ratios were closer to the ideal Redfield ratios and the ambient concentrations were also higher at these depths. The concentrations of *Thalassionema nitzschioides*, a cosmopolitan species (Hasle & Syvertsen 1996) surviving in wide nutrient regimes (Abrantes 1988) was observed to be concentrated in northern stations and at high numbers ~60 m.

By contrast, along the WB, hydrodynamic conditions alongside the nutrients appear to play a crucial role in the phytoplankton distribution and composition. During SM, the riverine influx is higher than the other seasons causing high salinity fluctuations. Studies from the Pacific reported complete drawdown of the nitrate by phytoplankton in waters less than 32 psu (Whitney et al 2005). This could be the reason for greater abundance and higher chl *a* in the northern regions where salinity is very low. Salinity changes -which many species cannot tolerate- are known to affect the nitrogen metabolism (Rees et al 1980; Dohler 1985). But, high concentrations of silicate aid proliferation of diatoms. *Skeletonema costatum* and *Chaetoceros* sp are known to be fast growing opportunistic species (Mozetic et al 1998) which grow fast in areas where there is constant input of nutrients and low N:P ratios (Ou et al 2007) which was evidenced in WB during this study. Occurrence of *S. costatum*, known to thrive in fluctuating salinities, in high numbers only in the northern stations ascribe to the role of salinity in controlling the distribution of this species in BoB. Near-coastal tropical regions with low salinity are reported to aid the proliferation of this species (Mitbavkar & Anil 2000; Babu et al 2001). Moreover, species like *S. costatum, Chaetoceros* spp, *Rhizosolenia* spp and *Nitzschia* spp are known to form blooms or become abundant in response to major freshwater input in the Adriatic Sea (Malej et al 1995). Thus, during SM along WB, salinity in particular and nutrients in general, seem to govern the phytoplankton species composition in the northwestern Bay.

During FIM when euphotic depth was shallow (<60 m, Kumar et al 2004), centrales dominated along the WB. *Thalassiosira* sp was abundant in the top 20 m at WB4 where Si concentrations were >9 μM. Similar to that observed in the CB, high abundance of *Pseudo-nitzschia* sp was observed at WB4 in the top 20 m (coinciding to ≥ 0.22 ≤ 2 μM of nitrate) confirming its preference to nitrate replete waters. Deeper euphotic depth of ~80m during SpIM and high nutrient concentrations appear to be beneficial for the growth of different phytoplankton such as *Ch. didymus*, *B. furcatum* and *B. comosum* at different depths. Thus, ideal light conditions and high nutrients lead to higher cell abundance of these species at different depths.

Effect of environmental parameters on phytoplankton abundance and species distribution was not clearly discernible during NEM. Notably, abundance of dinoflagellates was higher than observed during other seasons. *Cylindrotheca closterium* and *Rhizosolenia* sp known to photosynthesize at high rates under P limited conditions (Alcoverro et al 2000) were quite abundant. Hence, their occurrence and contribution to the biomass in the top 20 m in-spite of low phosphate might be important in the primary productivity in the WB.

Northern stations of this study appeared to be more conducive for centric diatoms with richer nutrients than those in the south. With generally more cell volume, it appears that centrales prefer high nutrient regions of BoB. Kobayashi & Takahasi (2002) also observed this group to show preference to high nutrient regions even within oligotrophic waters. Also, as Figueiras & Niell (1987) reported, their abundance appears to be associated with greater physical stratification observed in the northern stations during all the seasons. Pennate diatoms, the predominant constituents during this study, with higher surface to volume ratio are able to assimilate nutrients even when their concentrations are very low. Therefore, they can thrive in the Bay better than the centric ones. As evidenced during this study, pennales are preponderant in the least upwelling areas (Pace et al 1986).

In conclusion, the phytoplankton abundance particularly in the CB appears to be controlled by the ambient nutrients as indicated by their ratios. Within the community, the abundance, seasonal and geographic variations of pennales was predominantly controlled by nutrient concentrations. Seasonally, phytoplankton apparently get redistributed within the water column and, occasionally accumulate at depths to meet up their specific growth demands. Such behavior results in the predominance of certain species in specific depths and geographic locations. This is clearly seen in the BoB where different species appear to be dominant during different seasons. Their variability all along the transect is seasonally very pronounced even though some of the species seem to be ubiquitous.

Chapter 5

Chapter 5

Phytoplankton species composition and diversity

Introduction

Species diversity is a key concept in ecology. It is a concise expression of how individuals in a community are distributed within subsets of species. It is a measure of number of cohorts of identical characteristics within an assortment of various independent groups. In other words, diversity is also a measure of the degree of complexity of community structure.

Mechanisms controlling the diversity are not completely understood in most aquatic systems (Interlandi & Kilham 2001). In the overall scenario, environmental heterogeneity and incomplete mixing promote species diversity and coexistence (Ives & May 1985; Tilman 1994). Phytoplankton form the base of the food chain that drives the marine biosphere. Their distribution is regulated/controlled by physical (stratification, mixed layer depth, euphotic depth, salinity, temperature, eddies and upwelling), chemical (nutrient types and availability) and biological (grazers and their predators) factors. Such ecological underpinnings bring about changes in composition, metabolism, reproduction and growth of phytoplankton (Eppley et al 1978; Berman & Shteinman 1998; Sherman et al 1998). This is reflected in their diversity. None of the previous studies from the BoB (Venkatraman 1939; Subramanyan 1946; Menon 1945; Subba Rao 1973; Subba Rao 1976; Devassy & Bhattathiri 1981; Devassy & Goes 1988; Umamaheshwararao & Sarojini 1992; Gouda & Panigrahy 1996; Sarojini & Sarma 2001) have analyzed the phytoplankton diversity in particular from the offshore/open oceanic waters. As a part of this study the phytoplankton species diversity during different seasons has been analyzed.

Materials and Methods

Phytoplankton enumeration

Detailed descriptions of phytoplankton cell (of sizes >5 μm) counts and identification are provided in Chapters 3 and 4. Cell counts and identification were performed on as many as 72 water samples during each sampling season. Generic and species identification was done according to the various keys mentioned therein.

Species Diversity, Richness and Evenness

Shannon Weaver (Shannon & Weaver 1949) species diversity was calculated for comparing the diversity of the phytoplankton in the Bay, using the formula,

$$H` = - \sum_{i=1}^{S} Pi \log_2 Pi$$

where, S= total number of species and

Pi = proportion of the numbers of individuals of species i to the total number of individuals (Pi= ni/N). Owing to large numbers of samples analyzed during each of the sampled seasons, the total number of individuals (N) and, the numbers of individuals (n) within a species were quite large.

Species Richness (SR; Margalef 1951) is defined as the number of species recorded from a region. Higher the number of species, higher will be the richness. It is an indirect method of calculating diversity. It was determined by the formula:

$$SR = (S-1)/\log_n N$$

Species Evenness (*J'*) was calculated according to Pielou (1966)

$$J' = H'/ \text{Log}_2 S$$

Where, S= total number of species and, N= total individuals present in the sample and H' is the Shannon diversity index. Evenness is the ratio of observed diversity to maximum diversity. The latter is achieved when most species in a collection are equally abundant (Margalef 1958; Pielou 1966).

Results

Phytoplankton Composition and Distribution

Station-wise distribution of phytoplankton abundance is described in chapter 3. All the phytoplankton species observed during this study are listed transect and season-wise in Chapter 4 (Table 4.3; 4.4; 4.5). Detailed station-wise abundance and distribution are in given in Tables 5.1A and B (in CB) and Tables 5.3A and B (in WB).

Central Bay

Station-wise and seasonal distribution of phytoplankton

Along the CB, the abundance was in general the highest during SM (except at CB1; Table 5.1A). The FIM had a higher phytoplankton abundance compared to NEM and the SpIM. Among the stations, the northern stations CB 4 and CB5 had the maximum abundance and number of phytoplankton species during the SM (Table 5.1B). *Coscinodiscus* sp, *Navicula* spp and *Thalassionema nitzschioides* were the only species that were present all along the transect and in all the seasons.

Summer monsoon (SM)

The 0-120 m column abundance ranging from 126 to 378 x 10^6 m^{-2} was higher in the northern stations indicating a distinct spatial variation (Fig. 5.1A). Of the 153 species that were identified the most abundant species of them were, *Thalassiothrix longissima, T. fauenfeldii, Nitzschia angularis, Thalassionema nitzschioides, Skeletonema costatum, Chaetoceros coarctatus, C. eibenii, Coscinodiscus radiatus, C. concinnus, Rhizosolenia styliformis.* These major species (Table 5.2, SM) contributed to 69% of the total population. The northern stations CB4 and CB5 were observed to have maximum number of species, 74 and 52 respectively.

Fall inter monsoon (FIM)

The depth-integrated values showed a distinct spatial variation along the CB (Fig. 5.1A) also during FIM. With the abundances ranging from 48 to 221 x 10^6 m^{-2}, the abundance decreased northwards unlike that during SM. In all, 123 species of phytoplankton were identified. *Thalassionema nitzschioides, Navicula* spp, *Rhizosolenia* sp, *R. styliformis,* R. *shrubsolei, Synedra hennedyana, Chaetoceros*

Table 5.1A. Distribution and abundance (%) of different phytoplankton species at CB1, CB2 and CB3 stations in Central Bay during summer monsoon (SM), fall intermonsoon (FIM), northeast monsoon (NEM) and spring intermonsoon (SpIM)

Phytoplankton species	Central Bay											
	CB1				CB2				CB3			
	SM	FIM	NEM	SpIM	SM	FIM	NEM	SpIM	SM	FIM	NEM	SpIM
Diatoms	% abundance											
Centrales												
Asteromphalus heptactis	*	0.25	*	*	*	0.98	*	*	*	*	*	*
Asteromphalus sp	*	0.25	*	*	*	*	*	*	*	*	*	*
Bacteriastrum comosum	*	0.75	*	*	*	*	*	*	*	2.53	*	*
Bacteriastrum delicatulum	*	2.51	*	*	*	*	*	*	*	*	*	*
Bacteriastrum elongatum	*	*	*	*	*	1.96	*	*	*	*	*	*
Bacteriastrum furcatum	1.62	*	*	*	*	2.94	*	*	*	2.53	*	*
Chaetoceros affinis	*	1.75	*	*	*	*	*	*	*	*	*	*
Chaetoceros coarctatus	*	1.75	3.29	*	*	*	*	*	*	*	*	1.15
Chaetoceros curvisetus	*	*	*	8.34	*	*	*	*	*	*	*	*
Chaetoceros decipiens	*	1	*	*	*	*	*	*	*	*	*	*
Chaetoceros didymus	*	3.26	5.02	2.78	*	*	2.37	4.74	*	5.06	*	*
Chaetoceros diversus	*	*	*	*	1.88	*	*	*	*	*	*	*
Chaetoceros distans	*	*	*	*	*	*	*	*	*	*	*	*
Chaetoceros eibenii	*	1.25	1.32	*	2.36	*	2.24	*	*	1.27	*	*
Chaetoceros indicus	*	*	*	*	*	*	*	*	*	3.8	*	*
Chaetoceros lorenzianus	*	*	*	*	*	3.92	*	*	*	*	*	*
Chaetoceros messanensis	*	0.25	*	*	*	*	*	*	*	*	*	*
Chaetoceros teres	*	0.75	*	*	*	*	*	*	*	*	*	*
Chaetoceros tortissimus	*	*	*	*	*	*	*	*	0.65	*	*	*
Corethron criophilum	*	0.5	*	*	*	*	*	*	*	*	*	*
Corethron hystrix	*	*	*	*	*	0.98	*	*	*	*	*	*
Coscinodiscus asteromphalus	1.87	*	*	*	*	*	*	*	*	*	*	*
Coscinodiscus centralis	*	0.5	*	*	*	1.96	*	*	*	*	*	*
Coscinodiscus curvatulus	5.01	*	*	*	*	*	*	*	*	*	*	*
Coscinodiscus gigas	6.66	*	*	*	*	0.98	*	*	*	*	*	*
Coscinodiscus granii	*	0.25	1.32	*	*	*	*	*	*	*	2.72	*
Coscinodiscus lewisianus	*	*	*	*	6.02	*	*	*	*	*	*	*
Coscinodiscus marginatus	*	*	*	*	*	*	*	*	*	*	2.72	*
Coscinodiscus minor	*	*	*	*	*	*	*	*	*	*	*	*
Coscinodiscus radiatus	0.6	*	7	*	3.67	*	*	0.95	12.82	*	*	*
Coscinodiscus rothii	9.87	*	*	*	*	*	*	*	*	*	*	*
Coscinodiscus concinnus	*	0.75	*	*	*	*	*	4.74	*	*	*	*
Coscinodiscus insignis	1	*	*	*	*	*	*	*	*	*	*	*
Coscinodiscus subtilis	*	*	*	*	*	*	*	*	0.95	*	*	*
Coscinodiscus sp	0.43	1.5	11.37	2.36	0.8	3.92	3.81	11.66	2.02	*	25.08	6.9
Coscinodiscus superbus	*	*	*	*	1.72	*	*	*	*	*	*	*
Denticulopsis seminae	1	0.25	*	*	3.61	*	*	*	*	*	*	*
Ditylum brightwelli	*	*	*	*	0.45	*	*	*	1.58	*	3.51	*
Eucampia balaustium	*	*	*	*	0.35	*	*	*	*	*	*	*
Eucampia zodiacus	*	*	*	*	*	*	2.1	*	*	*	*	*
Hemiaulaus hauckii	*	*	6.26	*	*	*	*	*	*	*	*	4.6
Hemiaulus sinensis	*	*	*	*	0.35	*	*	*	*	*	*	*
Hyalodiscus radiatus	*	*	*	*	*	*	*	*	*	1.27	*	*
Hyalodiscus sp	*	0.25	*	*	*	*	*	*	*	*	*	*
Leptocylindrus danicus	*	1	*	*	*	5.88	*	*	*	*	*	*
Leptocylindrus mediterraneus	*	1	*	*	*	1.96	*	0.89	*	2.53	*	25.29
Plagiotropis lepidoptera	5.01	*	*	*	*	*	*	*	*	*	*	*
Planktoniella sol	*	*	2.64	*	1.72	*	0.59	*	0.65	3.8	*	*
Rhabdonema punctatum	*	*	*	*	*	*	*	*	*	1.27	*	*

Rhizosolenia alata	*	1.5	*	0	1.9	1.96	*	*	*	*	*	*
Rhizosolenia calcar-avis	*	0.5	*	*	*	*	*	*	*	*	*	*
Rhizosolenia cylindrus	*	3.51	4.86	0.56	*	*	*	2.37	*	*	2.56	6.26
Rhizosolenia flaccida	*	1.75	*	*	*	*	*	*	*	*	*	*
Rhizosolenia hiemalis	*	0.25	*	*	*	*	*	*	*	*	*	*
Rhizosolenia shrubsolei	*	8.77	*	*	*	*	*	*	*	*	*	*
Rhizosolenia sp	*	5.51	*	*	*	*	0.92	*	*	*	*	*
Rhizosolenia stolterfothii	*	*	*	*	*	*	*	*	0.6	*	*	*
Rhizosolenia styliformis	*	13.28	*	*	0.35	*	2.1	0	2.1	*	*	*
Rhizosolenia hebetata	*	0.5	*	*	*	*	*	*	*	*	*	*
Rhizosolenia imbricata	*	1	7.25	*	*	*	1.12	*	*	6.33	*	*
Thalassiosira antarctica	*	*	*	*	0.35	*	*	*	*	*	*	*
Thalassiosira convexa	*	*	*	*	*	*	*	*	2.92	*	*	*
Thalassiosira lineata	*	*	*	*	*	0.98	*	*	*	*	*	*
Thalassiosira punctigera	*	0.25	*	*	*	2.94	*	*	*	*	*	*
Thalassiosira rotula	*	*	*	*	*	0.98	*	*	*	2.53	*	*
Thalassiosira subtilis	*	*	*	*	*	*	*	*	*	2.53	*	*
Thalassiosira sp	*	0.25	3.13	*	*	10.78	6.9	*	*	1.27	*	6.9
Pennales												
Amphora sp	*	*	*	*	*	*	*	*	*	*	2.56	*
Achnanthes brevipes	*	*	*	*	*	*	*	*	0.65	*	*	*
Cylindrotheca closterium	*	0.5	3.13	*	*	*	2.04	*	*	*	*	*
Fragilariopsis doliolus	*	*	*	10.08	*	*	10.26	0	*	*	5.43	*
Fragilaria striatula	*	*	*	*	*	1.96	*	*	*	*	*	*
Licmophora sp	*	*	*	*	*	*	*	*	1.71	*	*	*
Navicula capitata	*	0.25	*	*	*	0.98	*	*	*	*	*	*
Navicula delicatula	*	1.25	*	*	*	*	*	*	*	*	*	*
Navicula directa	*	1.25	*	0.97	*	*	*	1.95	*	*	*	*
Navicula distans	*	0.5	15.07	3.2	*	*	8.61	5.92	*	1.27	2.72	*
Navicula gutata	*	*	*	*	*	*	*	*	3.49	*	*	*
Navicula johnsonii	*	*	*	*	*	*	*	*	*	6.33	*	*
Navicula messanenis	*	*	*	1.46	*	*	*	*	*	*	*	*
Navicula sp	*	7.27	10.21	53.06	*	6.86	8.61	51.69	*	7.59	31.79	25.98
Navicula tuscula	1	*	*	*	*	*	*	*	*	*	*	*
Navicula lyra	*	*	*	*	*	*	*	*	0.6	*	*	*
Navicula viridula	*	*	*	*	*	*	*	*	0.6	*	*	*
Nitzschia angularis	28.97	*	*	*	13.31	2.94	*	*	14.23	11.39	*	*
Nitzschia interuptestriata	*	*	*	*	1.55	*	*	*	1.31	*	*	*
Nitzschia longissima	*	*	*	*	*	*	*	*	*	1.27	*	*
Nitzschia sigma	*	*	*	*	*	0.98	*	*	*	*	*	*
Nitzschia socialis	*	*	*	*	*	*	*	*	10.08	*	*	*
Nitzschia reinholdii	*	*	*	*	1.45	*	*	*	1.81	*	*	*
Nitzschia sp	*	*	*	*	0.45	0.98	*	*	*	1.27	*	*
Pleurosigma fomosum	*	*	*	*	1.55	*	*	*	*	*	*	*
Pseudo-nitzschia sp	*	3.76	*	9.53	*	*	*	7.1	*	*	*	4.6
Synedra henndyana	*	9.02	*	*	*	*	*	*	*	*	*	*
Synedra radians	*	*	*	*	*	3.92	*	*	*	1.27	*	*
Synedra sp	*	0.75	1.07	*	*	2.94	0.53	2.37	*	2.53	*	*
Synedra ulna	*	*	*	*	*	0.98	*	*	*	*	*	*
Thalassionema oestrupii	*	*	*	*	*	*	*	*	1.31	*	*	*
Thalassionema nitzschioides	*	11.53	*	1.18	10.37	21.57	7.63	2.37	13.07	7.59	6.39	2.3
Thalassiothrix fauenfeldii	*	1	*	*	*	*	7.5	*	*	*	*	*
Thalassiothrix longissima	36.47	*	*	*	42.17	*	*	*	17.39	6.33	*	*
Thalassiothrix vanhoeffenii	*	0.75	*	*	*	*	*	*	*	*	*	*
Trigonium reticulum	*	*	*	*	*	1.96	*	*	*	*	*	*
Dinoflagellates												
Ceratium furca	*	*	3.62	*	*	0.98	5.46	*	4.14	1.27	1.76	*
Ceratium fusus	*	*	*	*	*	*	*	*	*	2.53	*	*
Ceratium horridum	*	*	*	*	*	0.98	*	*	*	*	*	*
Ceratium inflatum	*	*	*	*	*	2.94	*	*	*	*	*	*

Ceratium kofoidii	*	*	*	*	*	*	*	*	*	1.27	*	*
Ceratium macroceros	*	*	*	*	*	*	0.53	*	*	*	*	*
Ceratium pentagonum	*	*	1.81	*	*	*	*	*	*	*	*	*
Corythodinium tesselatum	*	*	*	*	*	0.98	*	*	*	*	*	*
Dinophysis tripos	*	*	*	*	*	*	*	*	*	1.27	*	*
Oxytoxum sp	*	*	1.98	6.47	*	0.98	0.92	*	*	2.53	*	*
Peridinium sp	0.5	*	6.01	*	2.49	*	1.05	*	1.91	*	8.79	*
Prorocentrum micans	*	*	*	*	*	0.98	*	*	1.08	*	*	*
Protoperidinium pellucidum	*	*	*	*	*	*	*	*	*	1.27	*	*
Protoperidinium sp	*	*	1.32	*	*	*	3.16	*	*	*	1.28	*
Podolampas palmipes	*	*	*	*	*	*	0.92	*	*	*	*	2.3
Pyrocystis lunula	*	0.25	*	*	1.1	*	*	*	*	*	*	*
Silicoflagellates												
Dictyocha crux	*	*	*	*	*	0.98	0.92	*	*	*	*	*
Unidentified	*	2.51	1.32	*	*	1.96	*	2.37	2.32	6.33	*	4.6
Unidentified1	*	2.26	*	*	*	*	*	*	*	*	2.72	*
Unidentified2	*	0.25	*	*	*	*	*	*	*	*	*	*
Cyanobacteria												
Cyanobacteria	*	*	*	*	*	*	19.72	*	*	*	*	*
Trichodesmium sp	*	*	0.99	*	*	*	*	0.89	*	*	*	9.14
Total cells per Liter	11988	15960	4856	1438	12477	4080	6084	1689	6130	3160	2504	1740

Species when not observed/ present denoted by '*'

Table 5.1B. Distribution and abundance (%) of different phytoplankton species at CB4 and CB5 stations in Central Bay during summer monsoon (SM), fall intermonsoon (FIM), northeast monsoon (NEM) and spring intermonsoon (SpIM)

Phytoplankton species	Central Bay							
	CB4				CB5			
	SM	FIM	NEM	SpIM	SM	FIM	NEM	SpIM
Diatoms	% abundance							
Centrales								
Asteromphalus flabellatus	0.31	*	*	*	*	*	*	*
Bacteriastrum comosum	0.24	*	*	*	0.19	*	*	*
Bacteriastrum delicatulum	0.73	*	*	*	*	*	*	*
Bacteriastrum furcatum	0.64	*	1.66	*	*	*	*	*
Bacteriastrum hyalinum	0.47	*	*	*	*	*	1.32	*
Biddulphia mobiliensis	3.56	*	*	*	0.27	*	*	*
Biddulphia granulata	0.11	*	*	*	*	*	*	*
Biddulphia rhombus	0.06	*	*	*	*	*	*	*
Biddulphia sinensis	0.22	*	*	*	1.55	*	*	*
Chaetoceros affinis	0.06	*	*	*	*	*	*	*
Chaetoceros bactereastroides	0.06	*	*	*	*	*	*	*
Chaetoceros coarctatus	9.98	*	*	*	3.06	*	*	*
Chaetoceros curvisetus	0.11	*	*	*	*	*	*	*
Chaetoceros crinitus	0.1	*	*	*	0.19	*	*	*
Chaetoceros danicus	0.05	*	*	*	0.77	*	*	*
Chaetoceros difficilus	0.17	*	*	*	*	*	*	*
Chaetoceros didymus	*	*	3.43	*	*	4.44	14.53	*
Chaetoceros diversus	5.15	*	*	*	*	*	*	*
Chaetoceros distans	0.28	*	*	*	*	*	*	*
Chaetoceros eibenii	6.76	*	2.88	*	0.54	1.11	*	*
Chaetoceros gracilis	0.05	*	*	*	*	*	*	*
Chaetoceros lauderi	0.17	*	*	*	*	*	*	*
Chaetoceros lorenzianus	5.55	5.56	*	*	1.2	*	*	*
Chaetoceros peruvianus	1.15	*	*	*	*	*	*	*
Chaetoceros sp	*	*	*	*	*	3.33	*	*
Clampylodiscus sp	*	1.39	*	*	*	*	*	*
Climacodium biconcavum	*	*	*	*	0.54	*	*	*
Corethron criophilum	0.1	*	*	*	*	*	*	*
Coscinodiscus centralis	*	1.39	*	*	*	*	*	*
Coscinodiscus jonesianus	0.05	*	*	*	*	*	*	*
Coscinodiscus lewisianus	0.05	*	*	*	*	*	*	*
Coscinodiscus marginatus	*	*	1.44	*	*	*	1.09	*
Coscinodiscus minor	1.24	*	*	*	0.19	*	*	*
Coscinodiscus radiatus	7.85	*	*	13.51	0.12	*	1.32	*
Coscinodiscus rothii	0.32	*	*	*	*	*	*	*
Coscinodiscus concinnus	0.31	*	*	*	7.26	*	*	*
Coscinodiscus sp	1.44	1.39	3.77	8.78	*	*	3.81	*
Corythrodinium tesselatum	*	1.39	*	*	*	*	*	*
Dactyliosolen sp	*	*	*	*	*	1.11	*	*
Denticulopsis lauta	0.82	*	*	*	*	*	*	*
Denticulopsis seminae	2.64	1.39	*	*	0.19	2.22	1.09	*
Ditylum brightwellii	0.84	*	*	*	1.3	*	*	*
Ditylum sol	0.17	*	*	*	1.12	*	*	*
Ethmodiscus sp	0.31	*	*	*	*	1.11	*	*
Eucampia zodiacus	0.05	2.78	*	*	*	*	8.55	*
Guinardia striata	*	*	*	*	*	*	1.17	*
Hemiaulaus hauckii	*	*	*	10.81	*	*	2.41	*
Hemiaulus sinensis	1.69	*	*	*	0.27	*	*	*
Hyalodiscus nobilis	*	*	*	*	0.27	*	*	*

Hyalodiscus stelliger	0.05	*	*	*	0.27	*	*	*
Leptocylindrus mediterraneus	*	4.17	*	*	*	1.11	*	*
Leptocylindrus minimus	*	*	*	5.41	0.19	*	*	*
Pleurosigma sp	*	*	0.89	*	*	*	2.49	1
Rhizosolenia alata	*	*	*	*	*	*	*	4.9
Rhizosolenia robusta	0.05	*	*	*	*	*	*	*
Rhizosolenia shrubsolei	0.05	*	*	*	*	1.11	*	*
Rhizosolenia stolterfothii	0.98	*	*	*	0.39	*	*	*
Rhizosolenia styliformis	2.96	*	1.44	*	3.11	2.22	1.17	2.9
Rhizosolenia hebetata	0.14	*	1.55	*	*	*	1.32	*
Rhizosolenia imbricata	0.22	*	*	*	*	*	*	*
Skeletonema costatum	*	*	*	*	11.19	*	*	*
Streptotheca thamensis	0.87	*	*	*	0.58	*	*	*
Thalassiosira anguste-lineata	0.06	*	*	*	*	*	*	*
Thalassiosira condensata	0.61	*	*	*	1.17	*	*	*
Thalassiosira convexa	*	*	*	*	0.12	*	*	*
Thalassiosira eccentrica	0.5	*	*	*	*	*	*	*
Thalassiosira gravida	*	*	*	*	0.51	*	*	*
Thalassiosira punctigera	*	1.39	*	*	*	1.11	*	*
Thalassiosira sp	*	1.39	6.98	*	*	1.11	5.05	*
Thalassiosira trifulta	0.28	*	*	*	*	*	*	*
Pennales								
Amphora ventricosa	0.1	*	*	*	*	*	*	*
Amphora sp	*	*	*	*	*	*	*	4.45
Cylindrotheca closterium	0.05	*	1.44	*	0.18	*	*	*
Fragilaria cylindrus	0.84	*	*	*	0.39	*	*	*
Fragilaria straitula	0.44	*	*	*	0.27	*	*	*
Fragilariopsis doliolus	*	5.56	11.52	*	*	*	5.28	*
Grammatophora kerguelensis	*	*	*	*	0.12	*	*	*
Grammatophora marina	*	*	*	*	0.34	*	*	*
Mastoglia rostrata	0.05	*	*	*	*	*	*	*
Navicula delicatula	*	*	*	*	*	1.11	*	*
Navicula directa	*	4.17	*	*	0.82	1.11	*	*
Navicula distans	*	*	4.87	*	0.27	*	1.24	*
Navicula fusiformis	*	*	*	*	0.17	*	*	*
Navicula granii	*	*	*	*	0.27	*	*	*
Navicula messanenis	*	6.94	*	*	*	*	*	*
Navicula monilifera	0.2	*	*	*	*	*	*	*
Navicula pelagica	*	*	*	*	1.36	*	*	*
Navicula peregrina	*	*	*	*	*	1.11	*	*
Navicula sp	0.22	25	10.41	9.86	0.48	28.89	15.31	27.95
Nitzschia angularis	*	*	*	*	5.11	*	*	*
Nitzschia angusta	*	*	*	*	0.58	*	*	*
Nitzschia delicatissima	2.49	*	*	*	2.96	*	1.71	*
Nitzschia fossilis	*	*	*	*	0.19	*	*	*
Nitzschia longissima	0.5	*	*	*	0.54	*	*	*
Nitzschia macilentia	0.2	*	*	*	*	*	*	*
Nitzschia sigma	0.05	*	*	*	*	*	*	*
Nitzschia socialis	0.27	*	*	*	*	*	*	*
Nitzschia ventricosa	0.05	*	*	*	*	*	*	*
Pseudo-nitzschia sp	*	5.56	*	*	*	*	*	8.91
Surirella fastuosa	0.17	*	*	*	0.19	*	*	*
Synedra radians	*	2.78	*	*	*	*	*	*
Synedra sp	*	4.17	4.65	*	*	1.11	2.49	*
Synedra tabulata	0.19	*	*	*	*	*	*	*
Synedra ulna	*	*	*	*	*	4.44	*	*
Thalassionema nitzschioides	4.6	11.11	5.87	*	2.9	7.78	9.87	5.68
Thalassiothrix fauenfeldii	17.41	*	*	*	29.04	14.44	*	*
Thalassiothrix longissima	9.99	*	*	*	15.02	*	*	*

Dinoflagellates								
Amphisolenia bidentata	0.26	2.78	*	*	*	*	2.33	*
Ceratium dens	*	1.39	*	*	*	4.44	*	*
Ceratium furca	0.05	*	3.77	*	0.78	*	*	*
Ceratium fusus	*	*	3.1	*	*	*	*	*
Ceratium keustenii	*	*	*	*	*	1.11	*	*
Ceratium kofoidii	*	*	*	*	*	1.11	*	*
Ceratium trichoceros	0.19	*	1.44	*	0.39	*	*	*
Noctiluca sp	*	*	*	*	*	1.11	*	*
Ornithoceros quadratus	*	*	*	*	*	*	3.57	*
Oxytoxum sp	*	2.78	*	*	*	2.22	4.2	*
Peridinium sp	*	*	4.43	*	*	*	5.13	*
Prorocentrum micans	*	*	*	*	0.17	*	*	*
Protoceratium sp	*	*	1.55	*	*	*	*	*
Protoperidinium pellucidum	*	*	*	*	*	*	*	*
Protoperidinium sp	*	*	1.66	*	*	*	*	*
Podolampas palmipes	*	*	1.44	*	*	1.11	*	4.45
Triceratium sp	*	*	*	*	*	*	1.32	*
Unidentified dino	*	*	*	*	*	*	1.17	*
Silicoflagellates								
Dictyocha crux	0.47	*	0.89	*	0.51	1.11	*	*
Unidentified silico	*	*	1.44	*	*	*	*	*
Unidentified	0.28	5.56	*	1.62	0.44	6.67	*	4.45
Unidentified1	0.17	*	5.98	*	*	1.11	1.09	*
Unidentified2	0.11	*	*	*	*	*	*	*
Cyanobacteria								
Cyanobacteria	*	*	11.52	*	*	*	*	*
Trichodesmium sp	*	*	*	50	*	*	*	35.3
Total cells per Liter	25017	2880	3612	740	36316	3600	5148	898

Species when not observed/ present denoted by '*'

didymus, Pseudo-nitzschia sp, *Thalassiothrix fauenfeldii* and *Thalassiosira* sp were the dominant species (Table 5.2, FIM). These species together accounted for 51% of the phytoplankton population. Unlike observed in the SM, the southern stations, CB1 and CB2 had maximum number of species, 50 and 35 respectively.

Northeast monsoon (NEM)

The abundance of phytoplankton was higher at CB2. The 0-120 m column integrated abundance was lower than those seen during SM and FIM but greater than SpIM (Fig. 5.1A). The abundance ranged from 39 to 89 x 10^6 m^{-2}. *Chaetoceros didymus, Coscinodiscus* sp, *Eucampia zodiacus, Thalassiosira* sp, *Fragilariolopsis doliolus, Navicula distans, Navicula* sp, *Thalassiothrix fauenfeldii, Thalassionema nitzschioides* and *Cyanobacteria* sp formed the dominant group contributing 67% to the total phytoplankton population (Table 5.2, NEM). Altogether 51 species were observed during this season. Similar to the SM, maximum number of species recorded from northern stations, CB4 (26 species) and CB5 (27).

Spring inter monsoon (SpIM)

Concurrent to low nutrient concentrations the phytoplankton cell counts (PCC) were lower during SpIM than other seasons (Fig. 5.1A). Their 0-120 m column abundance ranged from 14 to 40 x 10^6 m^{-2} with the maximum abundance at CB1 the southern station similar to that seen in FIM. Phytoplankton composition was quite distinct during SpIM. *Navicula* sp, *Trichodesmium* sp, *Coscinodiscus* sp, *Pseudo-nitzschia* sp, *Leptocylindrus mediterraneus, Rhizosolenia cylindrus, Thalassionema nitzschioides, Fragilariopsis doliolus* were dominant in the CB (Table 5.2, SpIM). These major species accounted for 79% of the phytoplankton population. Least number of species (27) was recorded during this season. Maximum number of species observed at CB2 (14 species) and CB3 (15).

Western Bay

Station wise and seasonal distribution of the phytoplankton

Along the WB, in stations WB1 and WB4 the phytoplankton abundance was more during the SM while in the other two stations it was higher during the FIM (Table 5.3A; 5.3B). Similar to CB, NEM and SpIM had relatively lesser abundance than the

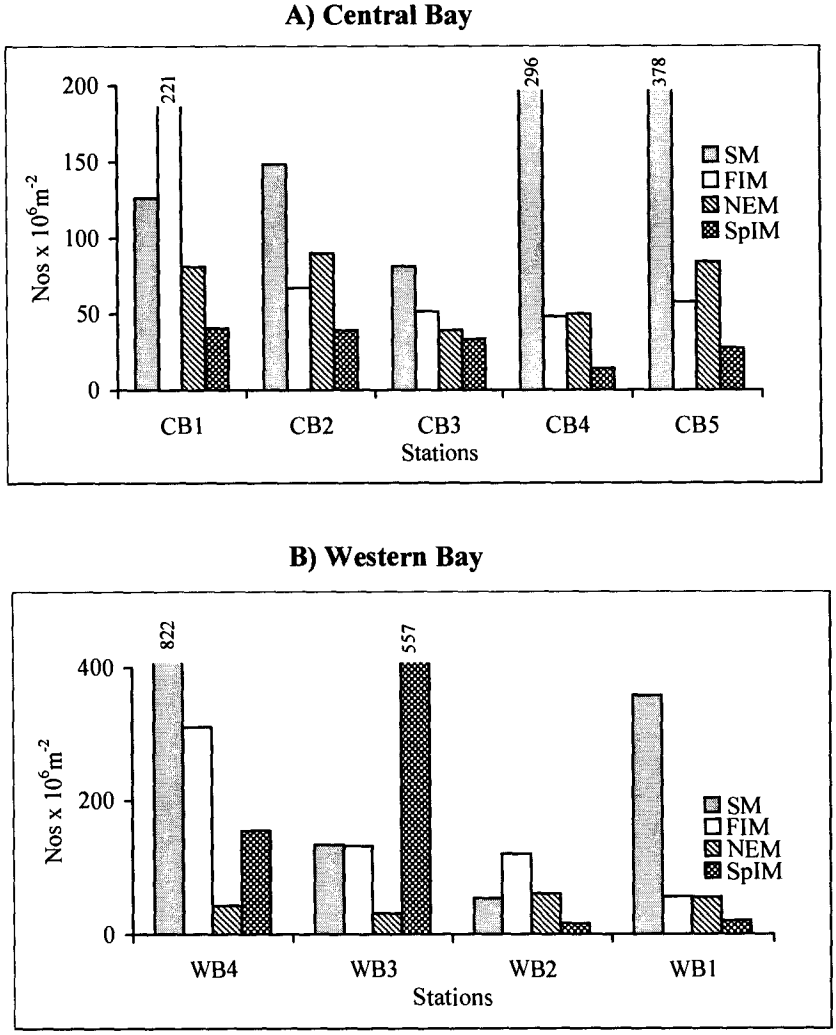


Fig. 5.1. Surface-120 m column integrated phytoplankton abundance (Nos x 10^6 m^{-2}) along A) Central and B) Western Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

other two seasons. Among the stations, northern stations WB4 had maximum abundance during SM and FIM. Similar to CB even along WB *Coscinodiscus* sp, *Navicula* spp and *Thalassionema nitzschioides* were the only species that were present all along the transect in all seasons.

Summer monsoon (SM)

Similar to the CB the 0-120 m column abundance in the SM along WB had the highest abundance in the northern stations rather than the southern stations (Fig. 5.1B). The column abundance ranged from 53 to 822 x 10^6 m^{-2}. In the SM, among the most abundant species of diatoms (Table 5.4, SM) were, *Thalassiothrix longissima, T. fauenfeldii, Thalassionema nitzschioides, Chaetoceros coarctatus, Coscinodiscus radiatus, Skeletonema costatum, Nitzschia delicatissima* and *N. angularis* along the WB forming 72% of the population. The northern stations WB3 and WB4 had the maximum number of species, 31 and 54 respectively.

Fall intermonsoon (FIM)

Unlike seen in the CB, along the WB the highest abundance was observed at WB3 and the lowest at WB1 (Fig. 5.1B). The values ranged from 55 to 309 x 10^6 m^{-2}. This was lower than SM.

In FIM, *Chaetoceros lorenzianus, C. curvisetus, C. eibenii, C. didymus, C. coarctatus, C. paradoxum, Navicula* sp, *Thalassiosira* sp, *T. gravida, Ditylum brightwellii, Pseudo-nitzschia* sp, *Nitzschia longissima,* along WB (Table 5.4, FIM) were the dominant species (>2%). These together formed 72% of the phytoplankton population. Similar to SM, northern stations WB3 (37 species) and WB4 (56) had maximum number of species.

Northeast monsoon (NEM)

In NEM, one depth was not sampled hence in place of eight depths only seven depths were used to calculate the abundance. As a result the column abundance was very less compared to the other seasons (Fig. 5.1B) and it ranged from 31 to 60 x 10^6 m^{-2} with the maximum abundance at WB2.

Table 5.2. Phytoplankton species contributing ≥2% of total counts observed in the Central Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

Season	Phytoplankton species	cells x 10^3 L^{-1}	%
SM	*Thalassiothrix longissima*	18.65	20.29
	Thalassiothrix fauenfeldii	14.90	16.21
	Nitzschia angularis	7.86	8.55
	Skeletonema costatum	3.69	4.42
	Thalassionema nitzschioides	4.06	4.01
	Chaetoceros coarctatus	3.6	3.92
	Coscinodiscus radiatus	3.32	3.62
	Coscinodiscus concinnus	2.71	2.95
	Chaetoceros eibenii	2.18	2.37
	Rhizosolenia styliformis	2.04	2.22
FIM	*Thalassionema nitzschioides*	3.56	12.01
	Navicula spp	2.76	9.30
	Rhizosolenia styliformis	2.2	7.41
	Rhizosolenia shrubsolei	1.44	4.85
	Synedra henndyana	1.44	4.85
	Rhizosolenia spp	0.88	2.96
	Chaetoceros didymus	0.84	2.83
	Pseudo-nitzschia spp	0.76	2.56
	Thalassiothrix fauenfeldii	0.68	2.29
	Thalassiosira spp	0.6	2.02
NEM	*Navicula* spp	2.19	9.85
	Coscinodiscus spp	1.74	7.85
	Cyanobacteria	1.62	7.28
	Navicula distans	1.56	7.04
	Fragilariopsis doliolus	1.45	6.52
	Thalassionema nitzschioides	1.34	6.05
	Chaetoceros didymus	1.26	5.67
	Thalassiosira spp	1.08	4.88
	Peridinium sp	1.00	4.50
	Ceratium furca	0.69	3.10
	Eucampia zodiacus	0.56	2.56
	Thalassiothrix fauenfeldii	0.46	2.05
SpIM	*Navicula* spp	3.40	31.14
	Trichodesmium spp	2.36	21.61
	Coscinodiscus spp	0.64	5.86
	Pseudo-nitzschia spp	0.56	5.13
	Leptocylindrus mediterraneus	0.44	4.03
	Navicula distans	0.36	3.3
	Rhizosolenia cylindrus	0.32	2.93
	Thalassionema nitzschioides	0.32	2.93
	Fragilariopsis doliolus	0.24	2.2

Table 5.3A. Distribution and abundance (%) of different phytoplankton species at WB1 and WB2 stations in Western Bay during summer monsoon (SM), fall intermonsoon (FIM), northeast monsoon (NEM) and spring intermonsoon (SpIM)

Phytoplankton species	Western Bay							
	WB1				WB2			
	SM	FIM	NEM	SpIM	SM	FIM	NEM	SpIM
Diatoms	% abundance							
Centrales								
Actinocyclus octonarius	1.30	*	*	*	*	*	*	*
Bacteriastrum delicatulum	*	1.02	*	*	*	*	*	*
Bacteriastrum furcatum	0.20	*	3.64	*	*	*	*	*
Bacteriastrum hyalinum	*	*	*	*	*	*	*	3.15
Chaetoceros coarctatus	*	*	*	12.76	18.60	*	*	*
Chaetoceros compressus	*	*	*	7.65	*	*	*	*
Chaetoceros curvisetus	*	*	*	*	*	2.30	*	*
Chaetoceros decipiens	*	*	*	4.08	*	*	*	*
Chaetoceros didymus	*	*	3.86	*	*	*	10.39	4.73
Chaetoceros eibenii	0.43	2.04	*	*	*	2.87	2.89	*
Chaetoceros lorenzianus	*	4.08	*	*	*	14.94	*	*
Chaetoceros messanensis	0.43	*	*	*	*	*	*	*
Chaetoceros paradoxum	*	*	*	*	*	4.60	*	*
Chaetoceros sp	*	*	*	16.33	*	*	*	6.31
Chaetoceros subtilis	0.43	*	*	*	*	*	*	*
Corethron criophilum	*	*	*	*	*	0.57	*	*
Coscinodiscus granii	*	*	*	*	*	*	1.45	*
Coscinodiscus jonesianus	*	*	*	*	*	*	*	3.15
Coscinodiscus radiatus	13.50	*	*	*	5.54	*	1.45	*
Coscinodiscus nodulifera	*	*	*	*	*	0.57	*	*
Coscinodiscus concinnus	*	*	*	*	*	0.57	*	4.57
Coscinodiscus sp	0.71	2.04	3.30	2.55	4.16	2.87	13.46	*
Ditylum brightwellii	*	*	*	*	*	*	2.71	*
Eucampia zodiacus	*	*	8.41	*	0.88	*	*	*
Guinardia striata	*	*	4.77	*	*	*	4.34	*
Hemidiscus hardmanianus	*	*	*	6.12	*	*	*	*
Leptocylindrus mediterraneus	*	*	*	*	*	1.72	*	*
Leptocylindrus sp	*	*	*	*	*	*	*	1.58
Planktoniella sol	0.43	*	*	*	*	*	*	*
Rhizosolenia alata	*	*	1.82	*	*	*	4.34	*
Rhizosolenia cylindrus	*	*	1.82	*	*	*	*	*
Rhizosolenia flaccida	*	*	*	*	*	2.30	*	*
Rhizosolenia imbricata	*	*	*	*	*	2.87	10.39	*
Rhizosolenia shrubsolei	*	*	*	*	*	*	3.43	*
Rhizosolenia styliformis	0.43	*	*	2.55	*	*	*	1.58
Rhizosolenia sp	*	*	1.59	4.08	*	*	4.61	*
Striatella delicatula	*	*	*	*	0.88	*	*	*
Surirella anceps	*	*	*	*	*	*	*	*
Stauroneis anceps	*	*	*	*	*	0.57	*	*
Thalassiosira baltica	1.30	*	*	*	*	*	*	*
Thalassiosira lineata	*	*	*	*	0.88	*	*	*
Thalassiosira punctigera	*	*	*	*	*	1.15	*	*
Thalassiosira sp	1.30	*	3.75	*	*	*	*	0.55
Triceratium weissei	0.20	*	*	*	*	*	*	*

Pennales								
Cylindrotheca closterium	*	*	*	*	*	*	7.50	*
Fragilaria doliolus	*	*	*	*	*	*	*	12.62
Navicula angularis	*	2.04	*	*	*	2.87	*	*
Navicula directa	*	*	17.61	*	*	0.57	1.63	*
Navicula delicatula	*	2.04	*	*	*	1.72	*	*
Navicula distans	*	2.04	4.89	*	*	0.57	6.14	6.31
Navicula rectangulata	2.44	*	*	*	11.16	*	*	*
Navicula sp	*	23.47	22.61	12.24	*	27.59	7.32	25.35
Navicula schumanniana	0.43	*	*	*	*	*	*	*
Navicula septentrionalis	*	8.16	*	*	*	*	*	*
Nitzschia delicatissima	6.51	*	*	*	11.11	*	1.63	*
Nitzschia longissima	*	18.37	*	*	*	10.92	*	*
Nitzschia sp	*	*	3.41	*	*	*	1.36	*
Porosira sp	*	*	*	*	*	0.57	*	*
Synedra affinis	*	*	*	*	0.88	*	*	*
Synedra sp	*	13.27	*	4.08	*	*	*	4.73
Synedra ulna	*	2.04	*	8.16	*	4.02	*	*
Thalassionema nitzschioides	0.51	12.24	*	*	2.71	8.04	4.52	5.40
Thallassiothrix fauenfeldii	7.37	*	3.07	4.08	10.30	*	*	6.31
Thallassiothrix longissima	60.48	*	*	*	28.10	*	*	*
Dinoflagellates								
Amphisolenia bidentata	*	*	*	*	*	*	*	3.71
Ceratium belone	*	*	1.48	*	*	*	*	*
Ceratium dens	*	1.02	*	*	*	*	*	*
Ceratium furca	1.57	*	*	*	1.46	2.30	*	*
Ceratium fusus	*	*	*	*	*	*	*	4.10
Ceratium keustenii	*	2.04	*	*	*	*	*	*
Ceratium trichoceros	*	*	*	2.55	*	*	*	0.55
Oxytoxum sp	*	3.06	9.09	*	*	*	1.72	3.71
Peridinium sp	*	*	1.48	*	*	*	*	*
Podolampas palmipes	*	1.02	*	*	*	0.57	*	1.58
Prorocentrum micans	*	*	*	*	3.33	*	*	*
Triceratium trichoceros	*	*	*	10.20	*	*	*	*
Silicoflagellates								
Dictyocha crux	*	*	3.41	*	*	*	*	*
Unidentified	*	*	*	2.55	*	2.30	4.43	*
Cyanobacteria								
Trichodesmium sp	*	*	*	*	*	*	4.34	*
Total cells per Litre	22084	3920	3520	980	3844	6960	4428	2536

Species when not observed/ present denoted by '*'

In NEM, (Table 5.4, NEM) *Navicula* sp, *N. directa, N. distans, Coscinodiscus* sp, *Oxytoxum* sp, *Chaetoceros didymus, Thalassionema nitzschioides, Guinardia striata, Rhizosolenia* sp, *R. imbricata, R. alata, Cylindrotheca closterium, Peridinium* sp, *Eucampia zodiacus* and *Thalassiosira* sp were the dominant phytoplankton along the WB. These contributed to 80% of the total phytoplankton abundance. Around 36 species were recorded from the WB during this season. Unlike observed in other seasons or, along the CB, maximum number of species were from the southern stations WB1 (19 species) and WB2 (20 species).

Spring intermonsoon (SpIM)

The same trend was observed in SpIM as was the case in FIM along WB. With values ranging from 15 to 557 x 10^6 m^{-2} the highest abundance was at WB3 and lowest at WB2 (Fig. 5.1B). This could be due to the presence of a cold core eddy at WB3 in all the seasons.

In contrast, the phytoplankton community showed distinct changes during SpIM (Table 5.4, SpIM) as cells of *Chaetoceros* sp, *C. didymus, C. curvisetus, Nitzschia* sp, *Navicula* sp, *N. messanensis, Bacteriastrum comosum, B. furcatum, B. hyalinum, Guinardia striata, Rhizosolenia cylindrus, R. flaccida, Stephanopyxis palmeriana* dominated the community along the WB. These together formed 66% of the phytoplankton population. Around 59 species were recorded from the WB during this season. This species number is higher than during NEM but lower than FIM and SM. Unlike in the other seasons maximum number of species was observed at WB2 (22 species) and WB3 (42 species).

Species Diversity (H'), Evenness (*J'*) and Species richness (SR)

In general H', SR and *J'* recorded higher values during FIM and SpIM than during the SM and NEM along both transects (Fig. 5.2a; 5.2b).

Central Bay

During SM, the H' ranged from 2.84 to 4.59 in the CB while *J'* from 0.70 to 0.81 and SR, from 1.63 to 6.86. The H' and the SR were the highest at CB4 and CB5. Difference in the evenness between the stations was minimal. During FIM, the diversity ranged

Table 5.3B. Distribution and abundance (%) of different phytoplankton species at WB3 and WB4 stations in Western Bay during summer monsoon (SM), fall intermonsoon (FIM), northeast monsoon (NEM) and spring intermonsoon (SpIM)

Phytoplankton species	Western Bay							
	WB3				WB4			
	SM	FIM	NEM	SpIM	SM	FIM	NEM	SpIM
Diatoms	% abundance							
Centrales								
Bacteriastrum comosum	*	*	*	1.81	0.61	*	*	*
Bacteriastrum delicatulum	*	*	*	*	*	1.96	*	*
Bacteriastrum furcatum	*	*	*	1.50	0.61	*	*	0.34
Bacteriastrum hyalinum	*	1.89	*	0.69	0.47	1.44	*	*
Bacteriastrum mediterranean	*	*	*	*	0.11	*	*	*
Bacteriastrum varians	*	*	*	0.12	*	*	*	*
Biddulphia mobiliensis	*	*	*	12.46	0.76	*	*	7.61
Biddulphia longicruris	*	*	*	*	0.31	*	*	*
Biddulphia sinensis	*	0.47	*	0.44	0.72	2.06	*	*
Cerattulina sp	*	*	*	*	*	0.10	*	*
Chaetoceros affinis	*	*	*	*	*	0.62	*	*
Chaetoceros coarctatus	1.22	2.60	*	0.19	6.35	2.47	*	*
Chaetoceros compressus	*	*	*	*	*	0.51	*	*
Chaetoceros curvisetus	*	14.66	*	4.61	*	9.99	*	*
Chaetoceros didymus	*	*	*	2.55	0.32	4.43	5.33	5.26
Chaetoceros diversus	*	0.24	*	*	0.85	0.72	*	*
Chaetoceros eibenii	*	9.69	*	0.56	1.39	0.82	*	*
Chaetoceros lorenzianus	5.16	36.64	*	0.06	1.89	19.36	*	*
Chaetoceros messanensis	*	*	*	0.31	*	*	*	0.78
Chaetoceros paradoxum	*	5.20	*	*	*	0.51	*	*
Chaetoceros seriacanthus	*	*	*	*	*	1.54	*	*
Chaetoceros socialis	*	*	*	*	0.19	*	*	*
Chaetoceros sp	*	*	*	0.19	*	*	*	*
Chaetoceros teres	*	*	*	*	*	0.72	*	*
Chrysochroilina hirta	*	*	*	*	*	*	*	0.89
Corethron criophilum	0.52	0.71	*	*	*	*	*	*
Corethron sp	*	0.24	*	*	*	*	*	*
Coscinodiscus gemmatulus	0.94	*	*	*	*	*	*	*
Coscinodiscus jonesianus	*	*	*	*	0.11	*	*	*
Coscinodiscus lineatus	0.94	*	*	*	*	*	*	*
Coscinodiscus minor	1.34	*	*	*	*	*	*	*
Coscinodiscus radiatus	2.51	*	3.09	*	1.08	*	*	*
Coscinodiscus concinnus	0.28	*	*	1.68	1.60	0.82	*	0.78
Coscinodiscus sp	*	0.24	22.89	2.49	0.10	1.03	12.38	*
Coscinodiscus superbus	*	*	*	*	0.21	*	*	*
Denticulopsis lauta	*	*	*	*	0.31	*	*	*
Denticulopsis seminae	*	0.24	*	*	1.98	0.21	*	*
Ditylum brightwelli	*	0.71	*	*	3.01	4.74	2.98	*
Ditylum sol	*	*	*	*	0.67	*	*	*
Eucampia zodiacus	*	*	*	*	0.48	*	*	*
Guinardia striata	*	*	*	0.93	*	*	*	4.47
Hemiaulus haukii	*	*	*	*	*	0.21	*	*
Hemiaulus sinensis	*	*	*	0.06	0.43	*	*	*
Hyalodiscus stelliger	*	*	*	*	0.06	*	*	*
Lauderia annulata	*	*	*	0.50	*	*	*	*
Leptocylindrus danicus	*	*	*	*	*	2.37	*	*
Leptocylindrus mediterraneus	*	1.18	*	*	*	0.31	*	*
Leptocylindrus minimus	*	*	*	0.25	0.02	*	*	0.34

Rhizosolenia alata	2.07	*	*	*	*	*	*	0.45
Rhizosolenia cylindrus	*	*	*	0.19	*	*	*	35.79
Rhizosolenia flaccida	*	*	*	0.37	*	0.51	*	3.69
Rhizosolenia hebata	*	*	*	0.19	*	*	*	*
Rhizosolenia imbricata	*	0.47	*	14.95	*	1.75	*	2.57
Rhizosolenia robusta	*	*	*	1.56	*	*	*	0.00
Rhizosolenia setigera	*	0.95	*	*	0.25	0.62	*	*
Rhizosolenia shrubsolei	*	0.47	*	*	0.19	*	*	*
Rhizosolenia stolterfothii	1.77	*	*	1.31	1.59	*	*	*
Rhizosolenia styliformis	5.23	*	*	*	2.03	0.41	2.98	1.12
Rhizosolenia sp	*	0.24	4.12	*	0.21	0.62	*	*
Skeletonema costatum	*	*	*	*	7.14	0.82	*	*
Stephanopyxis palmeriana	*	*	*	2.93	*	*	*	3.69
Striatella delicatula	*	*	*	*	*	*	*	*
Surirella anceps	*	*	*	*	0.10	*	*	*
Surirella cruciata	0.52	*	*	*	*	*	*	*
Surirella fastuosa	0.28	*	*	*	*	*	*	*
Stauroneis anceps	*	0.47	*	*	*	*	*	*
Thalassiosira gracilis	1.28	*	*	*	*	*	*	*
Thalassiosira baltica	*	*	*	*	*	*	*	*
Thalassiosira lineata	0.28	*	*	*	*	*	*	*
Thalassiosira gravida	0.94	*	*	*	*	7.21	*	*
Thalassiosira punctigera	*	0.71	*	*	*	0.31	*	*
Thalassiosira sp	*	0.47	*	*	1.44	11.33	5.17	4.70
Triceratium weissei	*	*	*	*	*	0.10	*	*
Pennales								
Gyrosigma sp	*	0.47	*	*	*	*	*	*
Licmophora sp	*	0.24	*	*	*	0.41	*	*
Licmophora abbreviata	*	0.95	*	*	*	*	*	*
Lioloma pacificum	*	0.71	*	*	*	*	*	*
Navicula angularis	*	0.47	*	*	*	*	*	*
Navicula directa	0.94	*	*	*	1.22	*	*	*
Navicula delicatula	*	*	*	*	*	0.10	*	*
Navicula distans	*	0.47	5.36	0.19	*	0.21	*	*
Navicula gracilis	0.28	*	*	*	0.06	*	*	*
Navicula membranaceae	*	*	*	*	*	1.13	*	*
Navicula messanenis	*	4.02	*	15.58	*	*	*	*
Navicula naviculaus	0.94	*	*	*	*	*	*	*
Navicula peregina	1.89	*	*	*	*	*	*	*
Navicula radiosa	*	*	*	*	0.06	*	*	*
Navicula rectangulata	0.28	*	*	*	*	*	*	*
Navicula rhyncocephala	1.28	*	*	*	*	*	*	*
Navicula sp	2.00	4.96	42.06	13.89	0.20	3.71	17.71	25.84
Navicula septentrionalis	*	*	*	*	*	*	6.27	*
Navicula vanhoeffenii	*	*	*	*	0.31	*	*	*
Nitzschia angularis	*	*	*	*	3.75	0.10	*	*
Nitzschia angusta	*	*	*	*	0.11	*	*	*
Nitzschia delicatissima	*	*	*	*	2.64	*	*	*
Nitzschia fasciculate	*	*	*	*	1.22	*	*	*
Nitzschia insignis	1.28	*	*	*	*	*	*	*
Nitzschia longissima	*	*	*	*	2.46	*	*	*
Nitzschia marina	*	*	*	*	1.52	*	*	*
Nitzschia paradoxa	1.89	*	*	*	*	*	*	*
Nitzschia pelagica	1.37	*	*	*	*	*	*	*
Nitzschia socialis	*	*	*	*	0.25	*	*	*
Nitzschia sp	0.50	0.71	*	0.37	0.42	1.03	*	*
Pleurosigma sp	*	*	*	*	*	0.10	*	*
Pseudo-nitzschia sp	*	0.95	*	0.81	*	3.91	*	*
Synedra affinis	*	*	*	*	1.52	*	*	*

Synedra nitzschioides	*	*	*	*	*	0.31	*	*
Synedra sp	*	1.42	*	*	*	*	2.19	*
Thallassionema nitzschioides	20.16	*	*	10.34	3.99	2.37	16.93	*
Thalassionema oestrupii	1.28	*	*	*	*	*	*	*
Thallassiothrix fauenfeldii	19.08	*	*	0.19	31.58	*	*	*
Thallassiothrix longissima	18.90	*	*	*	9.75	1.13	*	*
Dinoflagellates								
Amphisolenia bidentata	*	0.24	*	*	*	*	*	*
Ceratium breve	*	*	*	*	*	0.10	*	*
Ceratium dens	*	*	*	*	*	0.10	*	*
Ceratium furca	*	*	*	*	0.06	0.31	*	*
Ceratium trichoceros	*	*	2.68	*	*	0.51	2.19	*
Cylindrotheca closterium	*	0.24	*	*	*	*	*	*
Dinophysis uracanthus	*	*	*	*	*	*	2.82	*
Oxytosum sp	*	*	10.72	*	*	0.21	8.15	*
Peridinium sp	*	*	6.60	*	*	*	5.17	*
Podolampas palmipes	*	0.24	2.47	*	*	*	2.66	*
Pseudoceratium punctatum	*	*	*	*	1.03	*	*	*
Silicoflagellates								
Dictyocha crux	*	*	*	*	*	*	4.70	*
Dictyocha speculum	*	*	*	*	0.05	*	*	*
Unidentified	2.66	0.95	*	5.30	0.11	0.62	*	*
Unidentified 1	*	4.49	*	0.44	0.11	1.34	2.35	0.45
Unidentified 2	*	*	*	*	*	0.82	*	*
Unidentified 3	*	*	*	*	*	0.82	*	*
Cyanobacteria								
Trichodesmium sp	*	*	*	*	*	*	*	1.23
Total cells per Litre	10407	16920	1940	1605	56658	38840	2552	894

Species when not observed/ present denoted by '*'

Table 5.4. Phytoplankton species contributing ≥2% of total counts observed in the Western Bay during summer monsoon (SM), fall intermonsoon (FIM), spring intermonsoon (SpIM) and northeast monsoon (NEM)

Season	Phytoplankton species	cells x 10^3 L^{-1}	%
SM	*Thalassiothrix longissima*	21.93	23.58
	Thalassiothrix fauenfeldii	21.90	23.55
	Thalassionema nitzschioides	4.57	4.92
	Chaetoceros coarctatus	4.43	4.77
	Skeletonema costatum	4.04	4.35
	Coscinodiscus radiatus	4.05	4.37
	Nitzschia delicatissima	3.36	3.61
	Nitzschia angularis	2.12	2.28
FIM	*Chaetoceros lorenzianus*	14.92	22.39
	Chaetoceros curvisetus	6.52	9.78
	Navicula spp	4.68	7.68
	Thalassiosira spp	4.48	6.72
	Thalassiosira gravida	2.8	4.20
	Chaetoceros eibenii	2.24	3.36
	Thalassionema nitzschioides	2.08	3.12
	Ditylum brightwelli	1.96	2.94
	Chaetoceros coarctatus	1.4	2.10
	Chaetoceros paradoxum	1.4	2.10
	Chaetoceros didymus	1.72	2.58
	Pseudo-nitzschia spp	1.68	2.52
	Nitzschia longissima	1.48	2.22
NEM	*Navicula* spp	2.38	19.20
	Coscinodiscus sp	1.47	11.83
	Oxytoxum sp	0.81	6.53
	Chaetoceros didymus	0.73	5.88
	Navicula directa	0.69	5.56
	Thalassionema nitzschioides	0.63	5.08
	Navicula distans	0.54	4.41
	Rhizosolenia imbricata	0.46	3.70
	Guinardia striata	0.36	2.89
	Rhizosolenia sp	0.34	2.73
	Cylindrotheca closterium	0.33	2.67
	Peridinium sp	0.31	2.51
	Eucampia zodiacus	0.29	2.38
	Thalassiosira spp	0.26	2.12
	Rhizosolenia alata	0.25	2.06
SpIM	*Chaetoceros didymus*	6.04	16.27
	Navicula spp	3.12	8.41
	Bacteriastrum comosum	2.28	6.14
	Bacteriastrum furcatum	2.16	5.82
	Chaetoceros curvisetus	1.76	4.74
	Guinardia striata	1.72	4.63
	Rhizosolenia cylindrus	1.52	4.09
	Navicula messanenis	1.24	3.34
	Bacteriastrum hyalinum	1.04	2.8
	Chaetoceros spp	1.00	2.69
	Rhizosolenia flaccida	1.00	2.69
	Nitzschia spp	0.8	2.16
	Stephanopyxis palmeriana	0.8	2.16

from 3.89 to 4.69 in the CB while the evenness ranged from 0.8 to 0.93 and SR from 1.61 to 5.06. Contrast to the SM, the H', SR and *J'* were generally higher in the southern stations (CB1-CB3). During NEM, ranging from 2.2 to 4.28, the H' was lower than that recorded during SM and FIM. The *J'* ranged from 0.49 to 0.91 and the species richness ranged from 1.79 to 3.05. The H', SR and *J'* were higher in the northern stations. During SpIM, H' (1.68 to 3.35), SR (0.84 to 1.80) and *J'* (0.7 to 0.86) were higher in the southern stations (CB1-CB3).

Western Bay

The H' (2.71 to 4.01) and SR (1.64 to 4.88) were higher at WB3 and WB4 during SM. While *J'*, highest at WB2, was in the range of 0.64-0.77. During FIM, H', SR and *J'* ranged respectively from 3.34 to 4.51, 1.93 to 5.20 and 0.67 to 0.82. Again, H' and SR were higher at WB3 and WB4. While, *J'* was higher at WB1 and WB2. During NEM, H' (2.75 to 3.99), SR (1.19 to 2.28) and *J'* (0.83 to 0.92) were higher at WB1 and WB2. During SpIM, registering higher values in the intermediate WB2 and WB3, H', SR and *J'* ranged respectively from 3.41 to 4.55, 1.91 to 4.01 and 0.83 to 0.93.

Discussion

The phytoplankton composition showed a number of temperate-tropical and tropical species. Known temperate-tropical species are *Thalassiothrix fauenfeldii*, *Biddulphia longicuris*, *Chaetoceros diversus*, *C. messanenis*, *C. eibenii* and *Bacteriastrum comosum*. 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* and, *C. curvisetus* are the known temperate and/or polar/cosmopolitan species found during this study in the BoB. All the species observed during this study have been previously reported in Indian waters (Subramanyan et al 1946; 1961; 1968; Desikachary & Ranjithadevi 1986; Desikachary & Prema 1987; Menon 1945; Ilangovan 1987). Some of the phytoplankton identified from the Bay of Bengal have been photographed using the scanning electron microscope (Plates 1; 2) and light microscope (Plates 3; 4; 5). 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

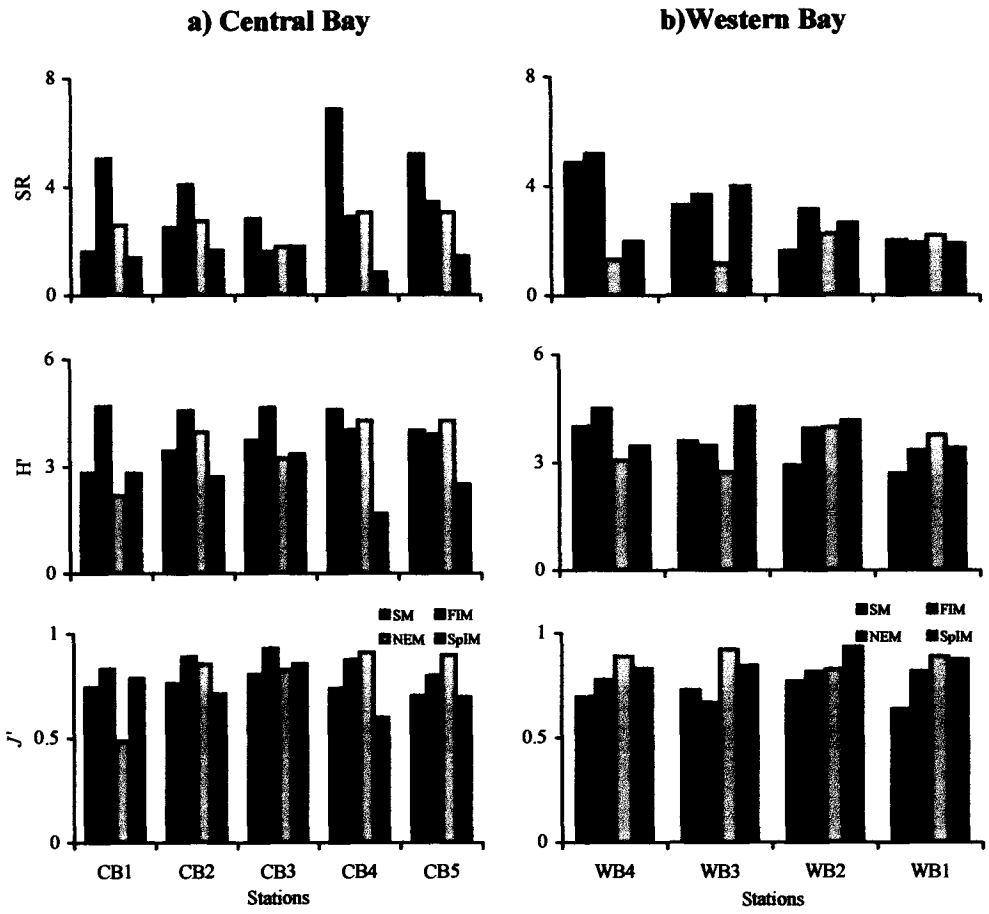


Fig. 5.2. Species richness (SR), species diversity (H') and species evenness (J') during summer monsoon (SM), fall intermonsoon (FIM), northeast monsoon (NEM) and spring intermonsoon (SpIM) at different locations in Central and Western Bay

open to the Equatorial Indian Ocean, the Arabian Sea, also to the Pacific Ocean via the Malacca Strait. Species such as *Coscinodiscus* sp, *Thalassionema fauenfeldii*, *Thalassionema nitzschioides*, *Thalassiothrix longissima*, *Navicula* spp and *Chaetoceros* sp were some of the species that were found in all the seasons in varying degrees of abundance. While species such as *Trichodesmium* sp and *Skeletonema costatum* were specific only to particular seasons and were not found in all seasons in the BoB. The occurrence of the particular species in specific seasons is due to the presence of favorable environmental and hydrographical conditions that exist at that particular time which helps in proliferation of these species.

Species composition is an important aspect of community or ecosystem ecology. A stable system is one that remains at or returns to some sort of an equilibrium when a disturbing force is applied (Conell & Souza 1983). Disturbance is often equated with environmental variability (Floder & Sommer 1999). A response of the community to this disturbance is termed as perturbation that can be detected as a significant change in a variable of a system, such as biomass or relative abundance (Conell & Souza 1983). The central North Pacific Gyre is considered to be a very stable system in terms of planktonic composition. This was supported by a decadal study on the phytoplankton composition by Venrick (1990), who reported only small, non-directional differences in the species composition. Long-term studies have found little changes in the phytoplankton species composition over time. Studies using the continuous plankton recorder (CPR) have indicated changes in the dominance structure of the plankton in the North Sea and the northeastern Atlantic Ocean (Reid et al 1975; 1977). During this study too very little variation in the phytoplankton composition was observed. In this study although the relative abundance of the species differed from season to season the composition of the community remained unchanged to a large extent, suggesting that the phytoplankton community in the BoB was a stable system with the diatoms dominating in all the seasons.

The interest in the marine biodiversity is more recent as compared to the terrestrial diversity (Ormond et al 1997). Competition, heterogeneity and predation often form the major determinants of biodiversity. In any aquatic system, phytoplankton distribution is

Scanning electron microscope photographs (Plates 1 & 2; scale bar is in μm) of a few phytoplankton species from the Bay of Bengal

Legend:

A) *Chaetoceros lorenzianus*
B) *Chaetoceros eibenii*
C) *Thalassiosira* sp
D) *Thalassiosira eccentrica*
E) *Bacteriastrum hyalinum*
F) *Biddulphia longicruris*
G) *Ditylum sol*
H) *Navicula* sp
I) *Nitzschia* sp
J) *Amphora* sp
K) *Nitzschia* spl
L) *Thalassionema nitzschioides*
M) *Ceratium furca*
N) *Peridinium* sp

Plate 1

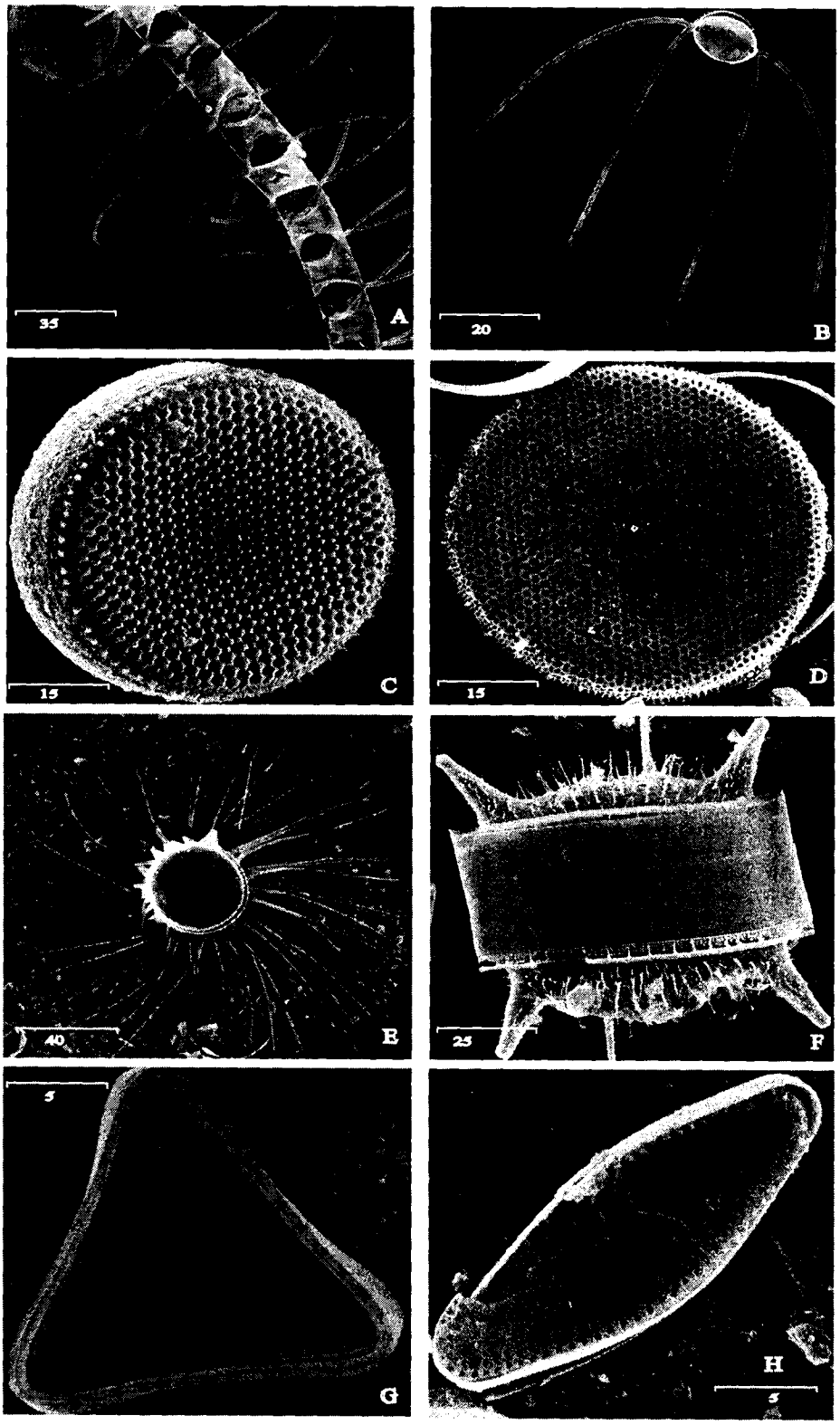
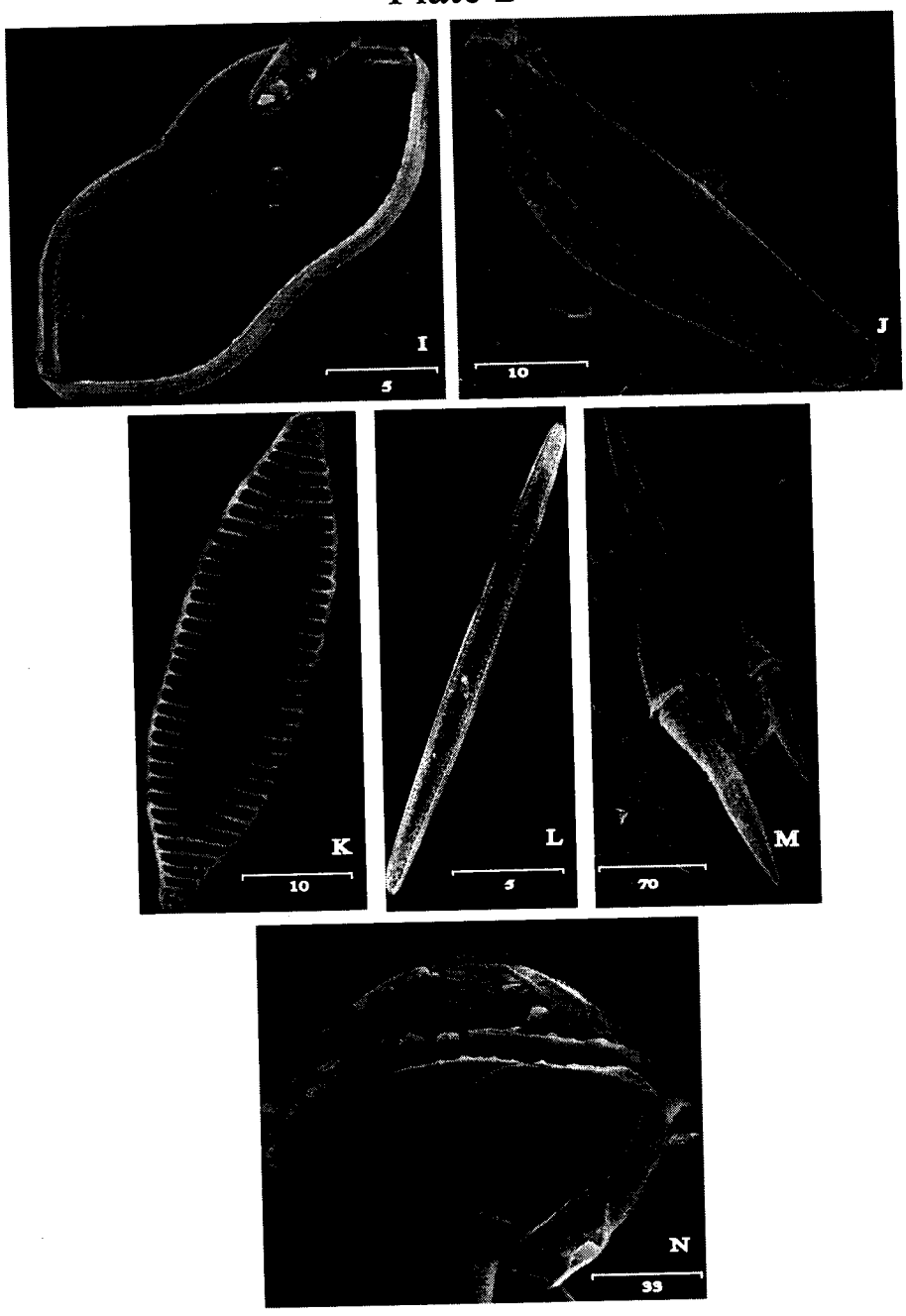


Plate 2

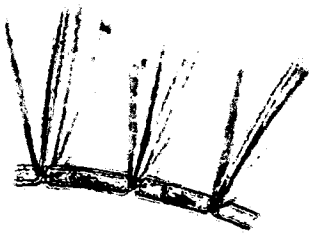


Light microscope photographs (Plates 3, 4 & 5) of a few diatom species from the Bay of Bengal

Legend:

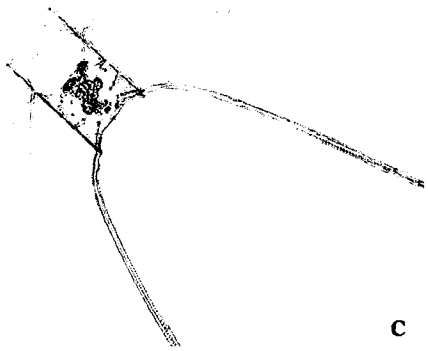
A) *Chaetoceros curvisetus*
B) *Chaetoceros coarctatus*
C) *Chaetoceros lorenzianus*
D) *Chaetoceros messanensis*
E) *Guinardia striata*
F) *Guinardia flaccida*
G) *Planktoniella sol*
H) *Striatella unipunctata*
I) *Biddulphia mobiliensis*
J) *Hemidiscus hardmanianus*
K) *Rhizosolenia imbricata*
L) *Rhizosolenia setigera*
M) *Ditylum brightwellii*
N) *Lioloma pacificum*
O) *Thalassiosira punctigera*
P) *Thalassiosira* sp
Q) *Fragilariopsis doliolus*
R) *Cerataulina* sp
S) *Meuniera membranacea*
T) *Navicula septentrionalis*
U) *Navicula* sp
V) *Thalassionema nitzschioides*

Plate 3



A

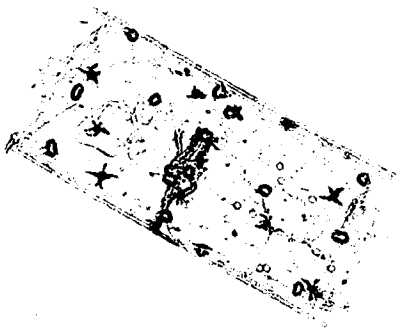
B



C

D

E



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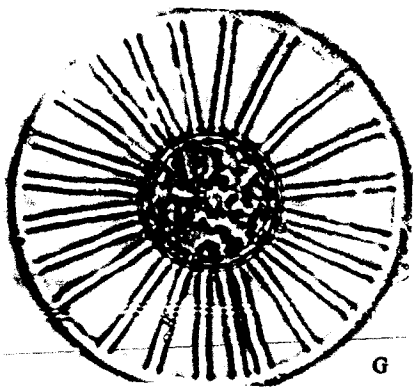

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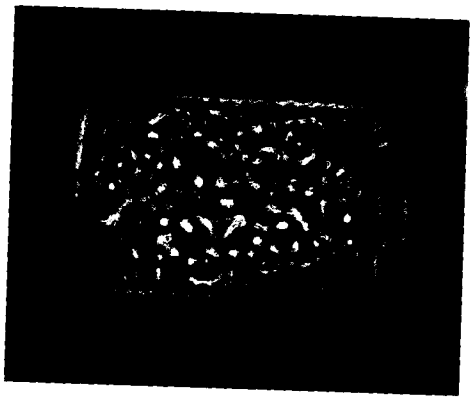

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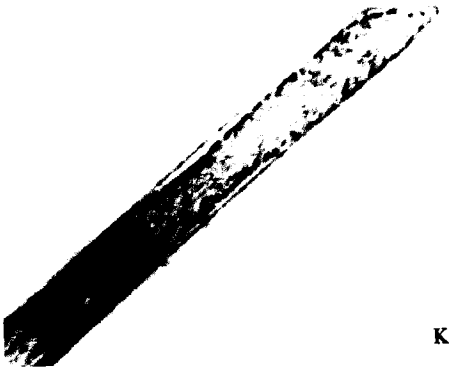

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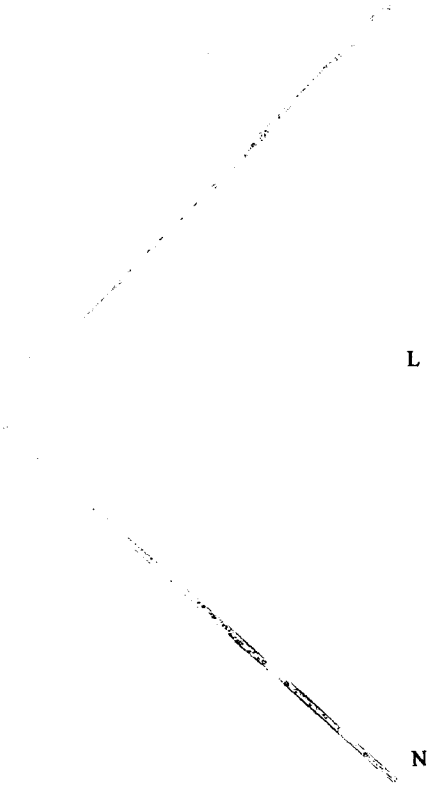

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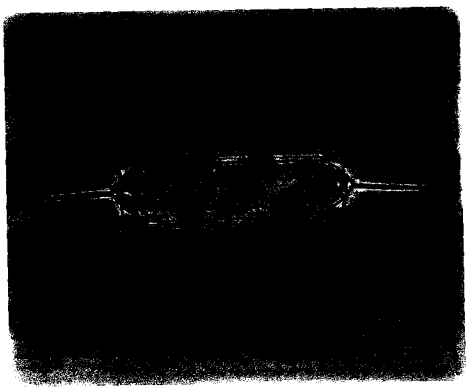

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O

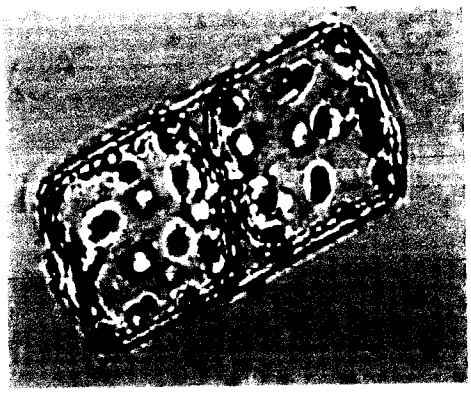
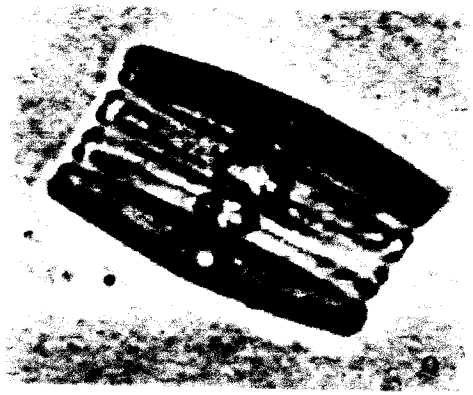
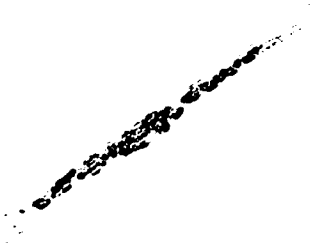


Plate 5





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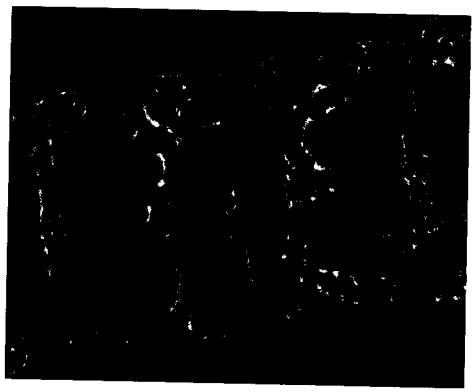
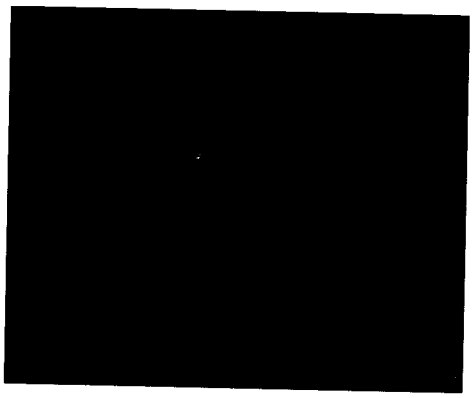
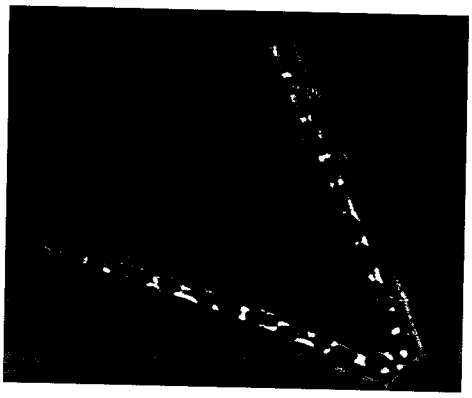


T





controlled by many physico-chemical parameters such as temperature, salinity and nutrients in the oceans. These aspects are described in Chapters 3 and 4. Phytoplankton assemblages are directly affected by turbulence and the mixing regimes, which play an important role in structuring the phytoplankton community (Thorrington- Smith 1971; Estrada et al 1987; Berman et al 1998; Arin et al 2002). Rapidly changing variables effect short-term alterations to biodiversity at different trophic levels since the life span of most planktonic organisms range from a few days to few months. Therefore, in a constant changing environment such as the marine environment dynamic changes of the biodiversity occur within the water column.

Biodiversity and community structure result from the factors of species richness and evenness. High species richness for a given area denotes the ecosystems ability to withstand natural disturbances that occur within the system. Therefore, high levels of species richness in ecosystems typically characterize these ecosystems as healthy and robust. Species richness is the simplest measure of biodiversity and, SR therefore, is directly related to diversity. Although H' and SR are positively correlated, gradients can exist along which increases in H' are accompanied by decrease in SR (Hulburt 1971). However, in all the seasons and along both transects high SR corresponded to high H' in the BoB. SR is commonly used along with other factors such as diversity index (H') and evenness (J') as a measure to determine the overall health of different biological ecosystems. An ecosystem where all the species are represented by the same number of individuals has high evenness closer to 1. In an ecosystem where some species are well represented and others are not, the evenness will be closer to 0. During all the seasons the J' averaged >0.7 suggesting that the most of the phytoplankton species was relatively well represented in the BoB. Overall, the highest evenness was observed in the NEM and the lowest during SM along the WB. This was due to high numbers of *Thalassiothrix longissima* and *Thalassiothrix fauenfeldii* which formed 23% each during SM which affected the evenness.

During SM and NEM, the H' was higher in the northern stations in CB. In the intermonsoons, it was generally higher in the southern stations. The higher H' and SR in the CB during all seasons *vis a vis* WB could be attributed to higher environmental instabilities in coastal regions than oceanic waters. Such dynamics appears to affect

only diversity not the abundance along the WB. This is reflected in higher evenness of the species along the WB suggesting that most of the species were present in higher numbers. Along WB however, the diversity was higher in the northern stations during SM and FIM and, higher in the southern stations during NEM and SpIM. Interestingly, during SpIM, the WB had higher H', SR and total number of species than CB. This could be due to the presence of *Trichodesmium* sp in high numbers 21% of the population in the CB in this season. Blooms of *Trichodesmium* sp are a common feature along both coasts of India during SpIM (Devassy 1983; PhaniPrakash & Raman 1992; Jyothibabu et al 2003). High numbers of *Trichodesmium* sp are known to deter the growth of the other phytoplankton (Ramos et al 2005). Its abundance in CB during SpIM could be responsible for lowered species diversity in this region. Similarly, the lower H' during NEM 2005-06 can be attributed to sizable numbers of *Trichodesmium* sp and unidentified cyanobacteria in the total phytoplankton population.

Kricher (1972), De Jong (1975) and Ilangovan (1987) reported that increase in diversity is a function of increasing species numbers, environmental heterogeneity, incomplete mixing of waters. The higher H' in the northern stations, 20°N and 19°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-lense over the high saline waters. Apart from such influences, low concentrations of nutrients are also known to promote species diversity (Tilman 1994; Huisman et al 1999; Raymont 1980). In spite of many rivers emptying into the BoB, the amount of nitrate and phosphate brought in by the rivers is insignificant (De Sousa et al 1981; Prasanna Kumar et al 2002; also discussed in previous Chapters). Previous studies in the BoB have reported very low concentrations of NO_3, PO_4 and SiO_4 even near river mouths (Rajendran et al 1980; De Sousa et al 1981). However, in the present study >1 μM of silica was observed in the northern Bay, such high silicate values are conducive for dominance of diatoms in the phytoplankton assemblages and could be responsible for high contribution of diatoms to the PCC in the BoB. While environmental instabilities are reported to lower species diversity (Thorrington- Smith 1971), increased nutrient concentrations, in particular of silicate, appear to favor diatom preponderance and species diversity in the Bay.

The hydrography of the BoB governed by the monsoons and the riverine influx has characteristically different features temporally in each of the season. Therefore such changes in the hydrology are bound to influence the phytoplankton species composition and diversity. The least abundant species constituted the bulk of the phytoplankton composition along both CB and WB suggesting that they are responsible for the diversity differences in the BoB. More diverse species assemblages were reported from the equatorial upwelling regions as compared to the warm pool regions in the Pacific however no diversity indices were reported from this region (Kobayashi & Takahashi 2002). Low diversity index of 0.69 in April and highest in June (3.49) have been reported from the southern Black Sea (Türkoğlu & Koray 2002). While Huang et al (2004) reported higher diversity (H'= 2.47) and evenness (J'= 0.57) in the rainy season as compared to dry season (H'= 2.01; J'= 0.54) in the Pearl River estuary.

Previous studies on species diversity were in the Vellalar estuary in the BoB which reported a diversity index ranging from 3.3 to 4.3 (Chandran 1985; Ilangovan 1987) which was similar to the values reported in this study. In comparison, phytoplankton diversity remains fairly high in the AS during SpIM, SM and NEM (Sawant & Madhupratap 1996; Raghukumar & Anil 2003). Of the 157 taxa identified in the FIM, 86 belonged to diatoms (Tarran et al 1999). However, picoplankton was reported to be the dominating form during the FIM in the AS (Tarran et al 1999). The most abundant species in the offshore AS during SpIM, were *Nitzschia serriata* and *Chaetoceros* spp (Sawant & Madhupratap 1996); unlike *Navicula* sp and *Trichodesmium* sp dominant in the BoB in SpIM. As there are no data available for FIM from the offshore AS for comparison, it is likely that there would be differences in species composition and abundance as well. Similar to the observations during this study, phytoplankton production and cell counts during SpIM were low in the AS and, waters along both the margins have higher phytoplankton abundance compared to their open ocean regions.

Although the BoB is considered to be less productive than the AS, their phytoplankton species diversity is quite comparable during SpIM. The Bay is distinctly diatom dominated with a minor proportion of species from dinoflagellates and silicoflagellates. Since phytoplankton form the base of the food web, any losses in biomass production necessarily decreases in biomass at next higher trophic levels eventually leading to

losses in the fishery yield. Thus, it is imperative to study the species diversity and species composition to estimate the fertility of the environment. Furthermore, the BoB being a sink for biogenic material (Ramaswamy et al 1997; Gauns et al 2005), phytoplankton species composition do play an important role in this process.

Through this study, distinct seasonal differences in phytoplankton composition despite a lack of noticeable differences in diversity indices are highlighted. While it is apparent that species diversity is influenced by hydrochemistry and physical settings, it is suggested from this first-time detailed analysis that there is non-competitive coexistence of diverse phytoplankton groups in the nitrate limiting regimes of the BoB.

Chapter 6

Chapter 6

Phytoplankton growth under altered nutrient ratios

Introduction

Aside from being a major source of autochthonous particulate organic matter (POM), phytoplankton are important source of dissolved organic matter (DOM) in marine ecosystems. Extracellular release of this DOM is a natural physiological process in healthy as well as stressed phytoplankton cells (Sharp 1977). Up to 50% of carbon fixed by them is released in the dissolved form by direct exudation and cell-lysis from sloppy feeding, ageing and/or viral infection (Azam et al 1983; Ducklow 1993; Nagata 2000). However, such release of dissolved organic carbon (DOC) varies in different stages of life of the phytoplankton. It is ~2 to 10% of photosynthetic carbon during rapid growth increasing up to 60% in a stationary phase (Myklestad 2000).

Chen & Wangersky (1996) suggest that both quantity and quality of photosynthetic extracellular release are influenced by the physiological state of the dominant algal species in a given ecosystem. Also, studies by Mykelstad (1977); Obernesterer & Herndl (1995); Granéli et al (1999) suggest that organisms which are stressed due to low concentrations of nutrients release higher percentage of DOC that may not be immediately oxidized. Any imbalance between growth and photosynthesis caused by nutrient deficiency can induce or accelerate the exudation process (Myklestad 1977; Fogg 1983; Lancelot 1983; Myklestad et al 1989). Both, *in situ* concentrations and, fate of DOM is determined by the bacterial uptake and conversion of this DOM to their cell components for their subsequent growth. Such transformation to POM is dependent on the physiological state of heterotrophic microbial (bacteria, ciliates, nanoflagellates among other microfauna) community, its composition and, the chemistry (for instance, lability and/or recalcitrance) of DOM (Moriarty & Bell 1993). This conversion of DOM to POM by the heterotrophic microbial community short-circuits the conventional food-chain and forms the basis of the "microbial loop" (Azam et al 1983). The microbial loop has been shown to play a major role in recycling of a large fraction (34-90%, Jensen 1983) of DOC released from phytoplankton within the euphotic zone. The rate of biotransformation of the DOM varies with the source and composition of

the DOM (Azam 1998). Algal exudates represent the main component of the labile fraction and more bio-available than some other DOM sources (Norman & Li 1995). Since DOM forms a major sink of organic carbon, the estimation of turnover rates of DOM is extremely important in understanding the fate of organic carbon both on regional and global scale.

Several studies, mostly from Atlantic and Pacific regions, have been carried out for assessing the production of dissolved carbohydrates by marine phytoplankton (Antia et al 1963; Guillard & Hellebust 1971; Eberlein et al 1983; 1985; Biddanda & Benner 1997) and their consumption by marine heterotrophs (Burney et al 1979; Liebezeit et al 1980; Ittekot et al 1981; Eberlein et al 1983; Burney 1986; Gomes et al 1991; Fajon et al 1999; Carlson et al 2002). In this respect studies from the northern Indian Ocean are few while many of them have focused only on effects of hydrodynamics (Fieux et al 1996; Schott & McCreary 2001), inorganic nutrient concentrations (Naqvi et al 1978; De Sousa et al 1981; Woodward et al 1999; Naqvi 2001) on biological productivity. Studies on distribution of organic matter, its biochemical constituents such as carbohydrates, proteins and lipids in the Arabian Sea and Bay of Bengal are available (Bhosle et al 1981; Bhosle & Wagh 1989; France-Lanord & Derry 1994; Sreepada et al 1996; Bhosle et al 1998; Unger et al 2005; Khodse et al 2007). Rajendran et al (1993); Naqvi & Shailaja (1993); Naqvi et al (1996); Shailaja et al (2006) suggest that the relationship of DOC with oxygen reflects on the biological characteristics in different zones of the Arabian Sea. Misic et al (2006) analyzed ectoenzymatic activity in surface waters in the Central Indian Ocean Basin and suggested the region to be net heterotrophic. One of the primary questions asked for this study was: how would the BoB phytoplankton assemblages, that apparently experience perennial shortage of ideal N:P:Si Redfield ratios, respond when nutrients are spiked up to (and above) the near-ideal ratios. To obtain data as a means for addressing this question, microcosm experiments with altered nutrient concentrations were set up. The following aspects were studied. 1) Effect of varying N: P ratios on both natural phytoplankton community; and as a consequence: 2) variation in the concentrations of chl *a*, DOM and rates of primary productivity during the experimental period; 3) uptake rates of DOC through estimations of bacterial abundance and production. While these microcosm experiments were conducted onboard, laboratory analyses were also done

by setting up experiments with unialgal cultures of a centric and a pennate diatom. This was done to understand how individual species contribute to the formation of DOM and how bacteria may alter its fate.

Materials and Methods

Experimental set up

Ship-board

Three sets of experiments were conducted to study the effect of varying nutrient concentrations on certain parameters of phytoplankton at three locations in the BoB. Experiment 1 was set up drawing water from 10 m at 9°N 88°E (Open Bay 1 [OB1]). Different concentrations of nutrients were added to achieve LNR [lower nutrients ratio], RFR [Redfield nutrients ratio] and HNR [higher nutrients ratio). Natural seawater control with no-added nutrients [NAN] was also maintained. Similarly, experiment 2 was at 20°N 88°E (Open Bay 2 [OB2]) and experiment 3 at 15°N 83°E (Western Bay [WB]) with similar nutrient alterations. Subsurface waters (<10 m) were collected using a 30 L Go Flo bottles. The water was passed through 200 μm mesh bolting silk to exclude mesozooplankton and other particulate matter. Triplicates of this prescreened water were transferred in to 2 L Nalgene bottles. As shown in Table 6.1, each set of three bottles was spiked with sodium nitrate and sodium dihydrogen orthophosphate to get N: P ratios a): less than [LNR], b): equal [RFR] to and c): greater than [HNR] Redfield ratios. Silicate was not added since silicate was not the limiting factor in the BoB (Chap-5). All 3 experiments lasted for a period of 10 days at onboard temperature (26°C) under 12:12 hour light (1000 lux= ~200 μE): dark cycle.

Laboratory

Water collected at 7°N, 87°E location in the Bay and passed through 200 μm mesh bolting silk were brought to the NIO and, experiments with similar nutrient alterations as done for the shipboard experiments were set up in the laboratory to monitor the effect of changed N:P ratios on cultures of a centric diatom, *Melosira* sp (NAN, LNR, RFR and HNR) and a pennate diatom, *Amphora* sp (NAN, LNR, RFR and HNR). These experiments also lasted for 10 days at room temperature (27°C) under the similar12:12 hour light (1000 lux = ~200 μE): dark cycle.

Table 6.1. Experimental set up for the study of phytoplankton growth, chlorophyll *a*, primary production, DOM formation, bacterial abundance and production in no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Microcosm	**Concentrations**			
	Nitrate (μM)	Phosphate (μM)	Silicate (μM)	N/P ratio
NAN	ambient	ambient	ambient	ambient
LNR	5	1	ambient	5
RFR	5	0.3	ambient	16
HNR	10	0.5	ambient	20

Sampling

Sub-samples from each experimental bottle were drawn on day 0, 4, 7 and day 10 for measuring nutrient concentrations, chlorophyll *a* (chl *a*), phytoplankton cell counts (PCC), primary productivity (PP), bacterial abundance (BA) and dissolved organic carbon (DOC). Bacterial production (BP) was done only for the open ocean experiment and the laboratory experiment on day 0, day 4, day 7 and day 10. For this, filtrate with $DO^{14}C$ produced as a consequence of autotrophic production during incubation was used. Three 10 ml sub-samples of filtrate from LNR treatment were transferred into polycarbonate tubes. To ensure abundant bacterial numbers, 1 ml seawater with 0.2 x 10^6 ml^{-1} bacterial cells was added into each tube and thymidine uptake of bacteria measured. Also, the PP filtrates from LNR bottles with unialgal cultures were used for measuring thymidine uptake.

Before sampling, all the microcosms were swirled for mixing the contents. To minimize removal of samples from the microcosms, filtrates of chl *a* were used for DON and DOP analyses. For these analyses, 50 ml filtrate passed through pre-ashed GF/F filters was transferred into plastic bottle, poisoned with mercuric chloride and, frozen at -20°C until analyzed. DON and DOP were analyzed by following the protocol of Raimbault (1999).

Analyses of different parameters

Nutrients

On each sampling day, 100 ml sub-sample from each Nalgene bottle was collected in clean plastic bottles and frozen at -20°C until analyses. Nutrients (NO_3-N, PO_4-P and SiO4-Si) were analyzed using a SKALAR autoanalyser following the procedures given in Grasshoff et al (1983).

Chlorophyll *a* (Chl *a*)

From all ship-board experiments, 250 ml of water samples from different microcosms were collected for chl *a* measurements. From cultures, 50 ml sub-samples were used. Details of chl *a* measurements are in chapter 3.

Phytoplankton cell counts (PCC)

The detailed procedure for PCC is given in chapter 3. Sub-samples of 100 ml water from the ship-board experiments and, 50 ml from culture experiments were collected for PCC. All of them were fixed immediately after sampling with Lugol's iodine (1% w/v) and 3% formaldehyde and, stored in dark until taken up for analyses. The species composition was also enumerated as detailed in chapter 4.

Primary production

Primary production (PP) was measured by ^{14}C technique following JGOFS protocols (UNESCO 1994). Fifty ml sample from each treatment was taken into three 300 ml capacity polycarbonate (Nalgene, USA) bottles (2 light, 1 dark). One ampoule of $NaH^{14}CO_3$ (Board of Radiation and Isotope Technology, Mumbai; Specific Activity 185kBq) was diluted with four ml of distilled water. Aliquots of 300 µL were dispensed into each bottle. All bottles were incubated on the deck for four hours. Contents of each bottle were filtered through 25 mm GF/F filters for retaining the phytoplankton. Filters were taken individually in to scintillation vials and exposed overnight to fumes of 0.5N HCl. After adding scintillation cocktail, ^{14}C radioactivity incorporated into phytoplankton cells was measured in a scintillation counter (Wallac 1409 DSA, Perkin Elmer, USA). Radioactivity measured as disintegration per minute (dpm) was converted to daily productivity rates using the following equation:

$$\text{Production (mg Cm}^{-3}\text{d}^{-1}) = (\text{SDPM/V}) * (\text{W} * 0.25 \times 10^{-3}) / \text{TDPM}) * (1.05/\text{T})$$

where: SDPM = DPMs in sample, V = volume of filtered sample (liters); TDPM = Total ^{14}C DPMs, W = DIC concentration in samples (approx 25000 mg Cm^{-3}), 0.25×10^{-3} = conversion of pipette volume to liters, 1.05 = correction for the lower uptake of ^{14}C compared to ^{12}C , T = time (days).

Bacterial abundance

The water samples (10 ml aliquots) were fixed with 0.22 µm pre filtered formaldehyde (final concentration of 3.7%) and stored at 4°C in dark as per JGOFS Protocols (UNESCO 1994) until taken up for microscopy. The method given in Parsons et al (1984) was followed for enumerating bacterial counts. Two milliliter of appropriately

diluted samples were stained with acridine orange (100 µL, final concentration 0.01%) for 3 mins, filtered onto 0.22 µm black Nuclepore filters, mounted on glass slides using fluorescent-free oil and observed under 100X oil immersion objective of a Nikon E400 epifluorescence microscope (Nikon Corporation, Japan). The slides were viewed using a blue excitation (450-490 nm) filter coupled with 510 nm beam splitter and a 520 nm emission filter. Bacterial cells in ca. 25 microscopic fields were counted, mean cell numbers per field calculated and used for estimating total abundance by using the relationship detailed in Parsons et al (1984). Bacterial abundances were used to calculate carbon biomass using a conversion factor of 11 fg C $cell^{-1}$ (Garrison et al 2000).

Bacterioplankton productivity

The bacterial productivity was measured by following the method described in JGOFS Protocols (UNESCO 1994). Rates of methyl-^{3}H- thymidine incorporation, which in turn aid estimating bacterial production, were measured to assess the uptake of DOM formed by phytoplankton. As mentioned above, aliquots of 10 ml ^{14}C filtrate from the LNR bottles were transferred into three 20 ml-capacity polycarbonate vials. An aliquot of 50 µl working solution of 59 nmole of tritiated ^{3}H (Specific Activity 18000 m ci/m mole; Board of Radiation and Isotope Technology, Mumbai) was added to all five vials and incubated for one hour in dark. Formaldehyde (100 µl; 0.22 µm-filtered) was added to stop ^{3}H-uptake. Zero-time blanks were also run for obtaining adsorption-corrections. Samples were filtered through 0.22 µm cellulose acetate filters (25 mm, Millipore India Ltd, Bangalore) and rinsed alternately with 2 ml cold trichloroacetic acid (10%) and 2 ml cold ethanol (96%). The filters were stored in 8 ml scintillation vials in moisture-free condition. Five ml of scintillation fluid (Cocktail-W, Spectrochem, Mumbai) was added a day prior to radio-assaying in a scintillation counter (Wallac 1409 DSA, Perkin Elmer, USA). Tritiated thymidine incorporated (TdR, picomole l^{-1} h^{-1}) was calculated using the formula:

$$TdR = (DPMs - DPMb) / (SV \times T \times SA \times 2.22)$$

Where, DPMs – disintegrations per minute of the sample on the filter, DPMb – Disintegrations per minute of the blank on the filter, SV = Sample volume in litres, T = Incubation time in hours, SA = Specific activity (m Ci m $mole^{-1}$).

The Bacterial Production (BP) was estimated using a mean oceanic conversion factor of 2.17×10^{18} cells $mole^{-1}$ thymidine incorporated (Ducklow 1993).

Estimation of Dissolve Organic Matter (DOM)

Dissolved organic matter (DOM) in seawater is measured by two methods: high temperature combustion (HTC; Fitzwater & Martin 1993) and wet chemical oxidation (WCO; Nydahl 1978; Valderrama 1981; Raimbault & Slawyk 1991). In this study, the DOC, DON and DOP were analyzed as components of DOM Henceforth these components are referred collectively as DOM unless specified. Forty milliliters of samples from each treatment were filtered through GF/F papers and the filtrates collected separately in 60 ml polycarbonate bottles. Since the analysis was not performed immediately, the samples were poisoned with 1 ml of saturated mercuric chloride (final concentration of 20 $\mu g\ ml^{-1}$) and stored at -20°C until analyses. Aliquots (10 ml) of samples were transferred into acid washed Pyrex Duran bottles with Teflon lining. Before oxidation, 50 µL of 5N sulphuric acid was added to the samples for removal of inorganic carbon. Immediately thereafter, 5 ml of oxidation reagent comprising a mixture of disodium tetraborate (Merck 6308) and potassium peroxodisulfate (Merck 5092) were dispensed to each bottle. The oxidizing reagent was freshly prepared in an amber coloured glass bottle to protect from direct sunlight as detailed in Raimbault et al (1999). After the addition of the oxidizing reagent to the samples, bottles were tightly closed and placed in an autoclave for digestion. Digestion was performed at 120°C (1 bar) for 45 minutes. After cooling to room temperature, this assay mixture was analyzed for nitrate (DON) and phosphate (DOP) using a SKALAR autoanalyser following the procedures given in Grasshoff et al (1983).

For estimation of dissolved organic carbon (DOC), samples were filtered individually through ashed GF/F filters and the filtrate was stored in polycarbonate bottles at -20°C until analyses. Samples were analyzed using HTCO (High Temperature Catalytic Oxidation) with platinum catalyst in a Shimadzu TOC-5000 (precision, 5%) analyzer. Standards were run daily before sample analyses using deionised water (DIW) blank and four concentrations (100 µM-300 µM) of an acid potassium hydrogen phthalate solution. Three to five sub samples were taken from each standard and sample when the precision of analyses was satisfactory (R^2 ranging from 0.989 to 0.999). The readings

were accepted only when the coefficient of variations of five replicate measurements of each seawater sample was <5%. The system and instrument blanks were determined using UV oxidized milli Q water. The acidified samples were homogenized and inorganic carbon was removed by purging a stream of carbon-dioxide free air through the samples just before the analyses.

DOC utilization rates

The DOC utilization rates by bacteria were calculated for the experiment at OB1 and the laboratory experiments using the following formula adapted from Kirchman et al (1991).

DOC utilization rates ($\mu g\ C\ L^{-1}d^{-1}$) = [DOC/ (BGR*BC)]

Where, BGR= {(BP/BA)*0.9} (0.9= growth rate constant)

BC is the carbon in μg derived from the AODC from each treatment on the day of sampling

DOC utilization rates $cell^{-1}$ were also calculated. For this, DOC were divided by AODC on the day of sampling were used. Since the bacterial numbers increased substantially in all the microcosms, it was assumed that most cells (i.e., all of the AODC) were metabolically active and therefore used for an understanding of the DOC turnover per cell per day.

Results

Ship-board experiments

Experiment at OB1 (9°N 88°E)

Nutrients

Silicate concentration in the seawater was >1 μM but nitrate and phosphate concentrations were quite low or undetectable. With time, nitrate and phosphate decreased rapidly than silicate (Fig. 6.1).

Biological Parameters

The decrease in the nutrient concentrations did not result in the increase in phytoplankton growth and/or chl *a*. In different microcosms, concentration of chl *a* on day 0, varied from 0.19 to 0.23 mg m^{-3}. These concentrations decreased with time in all

Table 6.2. Day wise variations in different parameters in the experiment conducted at Open Bay 9°N 88°E in microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Parameter	Day	Microcosm			
		NAN	LNR	RFR	HNR
Nitrate (μM)	0	0.00	3.66	3.09	6.63
	4	0.19	4.15	3.64	9.19
	7	0.00	4.46	4.03	9.12
	10	0.02	3.42	3.17	9.13
Phosphate (μM)	0	0.16	0.94	0.39	0.50
	4	0.28	0.87	0.38	0.65
	7	0.21	1.00	0.49	0.63
	10	0.15	0.88	0.51	0.62
Chl *a*	0	0.19 (5.99)	0.21(6.30)	0.23 (6.93)	0.19 (5.66)
(Chl C, mg C m^{-3})	4	0.05 (1.50)	0.07 (1.99)	0.05 (1.50)	0.05 (1.50)
	7	0.05 (1.50)	0.06 (1.72)	0.05 (1.50)	0.05 (1.50)
	10	0.02 (0.54)	0.02 (0.54)	0.03 (0.76)	0.02 (0.54)
PCC	0	0.40	0.60	0.70	0.66
cells x 10^3 L^{-1}	4	0.22	0.12	0.20	0.10
	7	0.13	0.09	0.27	0.22
	10	0.11	0.18	0.22	0.30
BA (BC, μg)	0	2.5 (27.9)	2.4 (26.1)	2.2 (24.2)	2.8 (30.3)
cells x 10^9 L^{-1}	4	7.0 (77.8)	4.9 (53.3)	6.6 (72.3)	2.6 (28.9)
	7	3.8 (41.6)	5.3 (58.1)	6.1 (66.8)	5.9 (64.8)
	10	2.2 (24.4)	6.7 (73.2)	4.9 (54.5)	6.9 (75.9)
PP (BP)	0	1.52	2.00 (7.11)	2.38	2.09
(mg C m^{-3} d^{-1})	4	0.85	1.7 (8.43)	1.55	1.00
	7	0.35	1.44 (5.42)	0.98	0.60
	10	0.22	0.79 (5.00)	0.49	0.25
DOM (DOC, μM)	0	194 (180)	232 (201)	146 (118)	188 (152)
	4	249 (218)	175 (116)	155 (122)	225 (140)
	7	131 (131)	140 (110)	162 (128)	253 (144)
	10	100 (100)	101 (101)	122 (93)	123 (96)

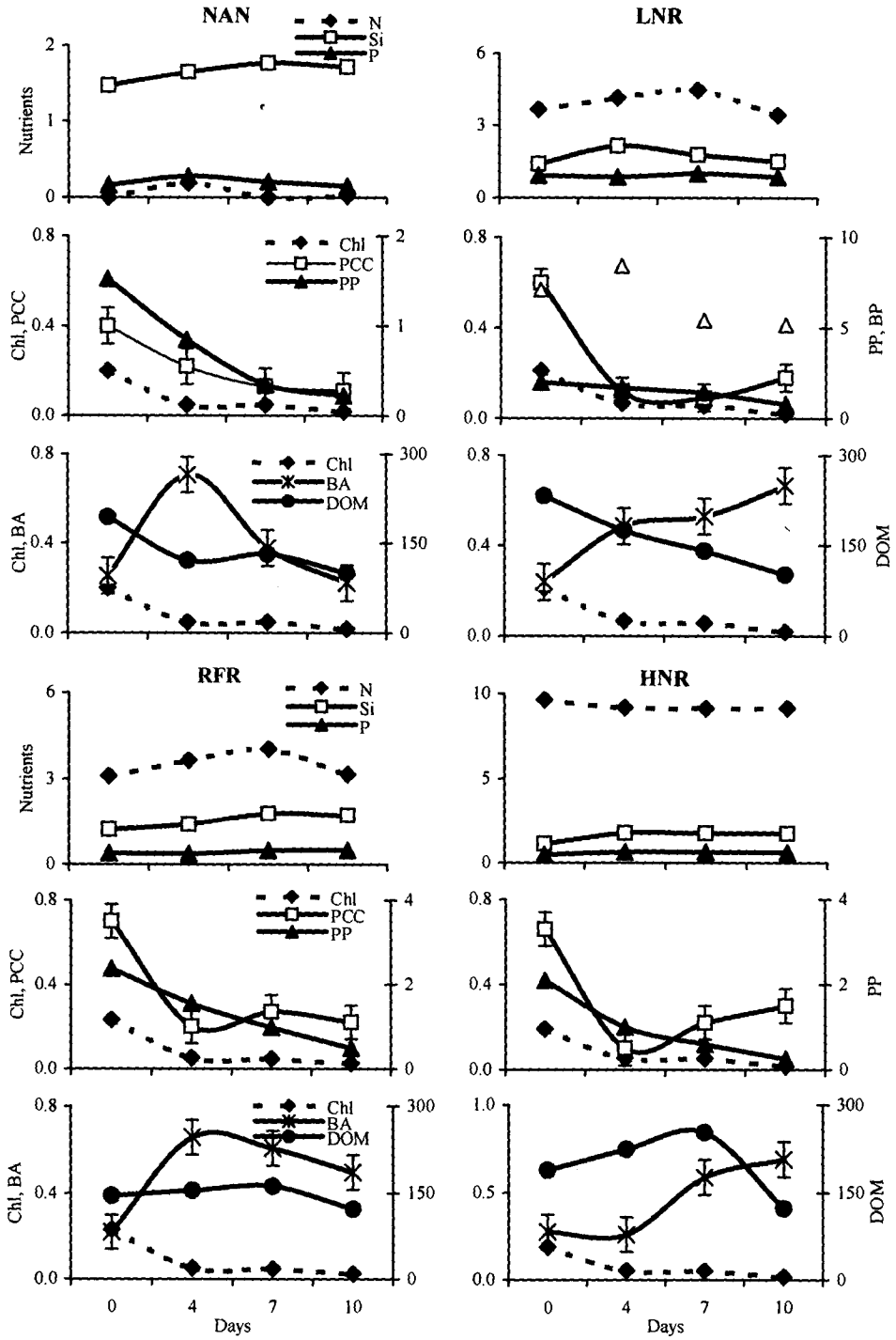


Fig. 6.1. Variations in chemical and biological characteristics under altered nutrient regimes: no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) high nutrient ratio (HNR) in a shipboard experiment at 9°N 88°E. Units are: nutrients;μM, chl a; mg m^{-3}, PCC; cells x 10^3 L^{-1}, PP/BP; mg C m^{-3} d^{-1}, BA; cells x $10^{10}L^{-1}$ and DOM;μM. Error bars denote standard deviations

Table 6.3. Phytoplankton species (Cells L^{-1}) that dominated after day 7 in different microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR) in the experiment conducted at Open Bay 9°N 88°E

Microcosm	**Phytoplankton species**	**Cells L^{-1}**
NAN	*Licmophora* sp	110
	Navicula distans	130
LNR	*Chaetoceros didymus*	180
	Thalassiosira sp	90
RFR	*Coscinodiscus radiatus*	90
	Licmophora sp	110
	Thalassiosira sp	90
	Navicula sp	110
	Nitzschia delicatissima	90
HNR	*Rhizosolenia* sp	110
	Navicula sp	100
	Synedra sp	110
	Amphisolenia bidentata	100

the microcosms to as low as ~ 0.02 mg m^{-3} on the last day. Notably, the reduction in chl *a* was rapid in LNR and slow in others. The PCC averaged to 0.597 x 10^3 L^{-1} on day 0. The PCC also decreased over time barring minor differences in microcosms with LNR and HNR. Further, decline in PCC coincided with decrease in PP in all the microcosms. The bacterial abundance (BA) ranged from 2.2 to 2.8 x 10^9cells L^{-1} on day 0. It increased with time in the LNR and the HNR microcosms while in NAN and RFR the bacterial abundance peaked on day 4 and decreased thereafter. On day 0, the PP ranged from 1.52 to 2.38 mg C $m^{-3}d^{-1}$ and decreased to a mean value of 0.44 mg $Cm^{-3}d^{-1}$ on day 10. Bacterial production measured only from LNR also followed the same pattern as that of PP. The DOM concentration varied from 146 to 232 μM on day 0 and decreased to ~100 μM on day 10. This decrease generally coincided with the increase in the bacterial abundance (Table 6.2; Fig 6.1). The phytoplankton species composition was quite different from the one seen during the regular sampling (Chapter 5). The phytoplankton species that became dominant by day 7 or day 10 in either NAN, LNR, RFR or HNR are listed in Table 6.3.

Experiment at OB2 (20°N 88°E)

Nutrients

In the seawater used for altering the nutrient concentrations, silicate was almost always > 4 μM but nitrate and phosphate concentrations were quite low ~0.3 μM (Table 6.4). Nitrate and phosphate decreased quite rapidly (Fig. 6.2) to <0.02 μM by day 10.

Biological Parameters

In contrast to the observation at OB1, the decrease in the nutrient concentrations corresponded to increase in chl *a* and phytoplankton growth. Concentration of chl *a*, varied from 0.35 to 0.52 mg m^{-3} on day 0. Its concentrations increased rapidly in all nutrient altered microcosms to as high as ~3.43 mg m^{-3} on the last day. The increase in chl *a* was rapid in RFR from day 7 to day 10 (0.33 to 3.43 mg m^{-3}). The PCC averaged to 17.55 x 10^3 L^{-1} on day 0. The PCC decreased on day 4 and, thereafter, increased in all the nutrient amended treatment. However, in NAN, PCC decreased from day 7 to day 10. The changes in the PCC coincided with chl and PP in all bottles. The BA ranged from 0.16 to 0.18 x 10^9cells L^{-1} on day 0. Bacterial abundance increased with

Table 6.4. Day wise variations in different parameters in the experiment conducted at Open Bay 20°N 88°E in microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Parameter	Day	Microcosm			
		NAN	LNR	RFR	HNR
Nitrate (μM)	0	0.30	6.88	3.04	11.5
	4	2.04	7.58	4.59	4.51
	7	0.05	7.08	6.76	7.54
	10	0.02	1.28	1.47	4.62
Phosphate (μM)	0	0.30	0.31	0.6	0.56
	4	0.06	0.42	0.29	0.31
	7	0.07	0.18	0.18	0.08
	10	0.04	0.09	0.06	0.01
Chl *a*	0	0.52 (15.63)	0.35 (10.57)	0.47 (14.10)	0.49 (14.55)
(Chl C, mg C m^{-3})	4	0.25 (7.50)	0.25 (7.50)	0.35 (10.57)	0.38 (11.53)
	7	0.26 (7.83)	0.44 (13.32)	0.33 (9.89)	0.62 (18.67)
	10	0.22 (6.51)	1.74 (52.17)	3.43 (102.97)	2.85 (85.53)
PCC	0	11.77	22.40	20.30	15.72
cells x 10^3 L^{-1}	4	7.21	9.90	15.00	7.52
	7	7.81	11.94	11.31	10.77
	10	2.07	100.20	106.25	36.80
BA (BC, μg)	0	0.16 (1.72)	0.17 (1.80)	0.17 (1.90)	0.18 (1.95)
cells x 10^9 L^{-1}	4	0.15 (1.69)	0.18 (1.93)	0.12 (1.33)	0.13 (1.39)
	7	0.19 (2.10)	0.17 (1.80)	0.17 (1.90)	0.14 (1.58)
	10	0.21 (2.27)	0.17 (1.80)	0.31 (3.45)	0.31 (3.45)
PP	0	1.33	1.14	1.08	2.25
(mg C m^{-3} d^{-1})	4	0.94	2.25	1.55	2.40
	7	0.63	3.24	2.09	2.63
	10	0.54	2.92	2.95	5.43
DOM (DOC, μM)	0	121 (108)	125 (103)	124 (92)	146 (99)
	4	130 (126)	135 (92)	130 (112)	145 (122)
	7	155 (123)	156 (126)	149 (138)	145 (118)
	10	170 (127)	191 (161)	131 (130)	139 (103)

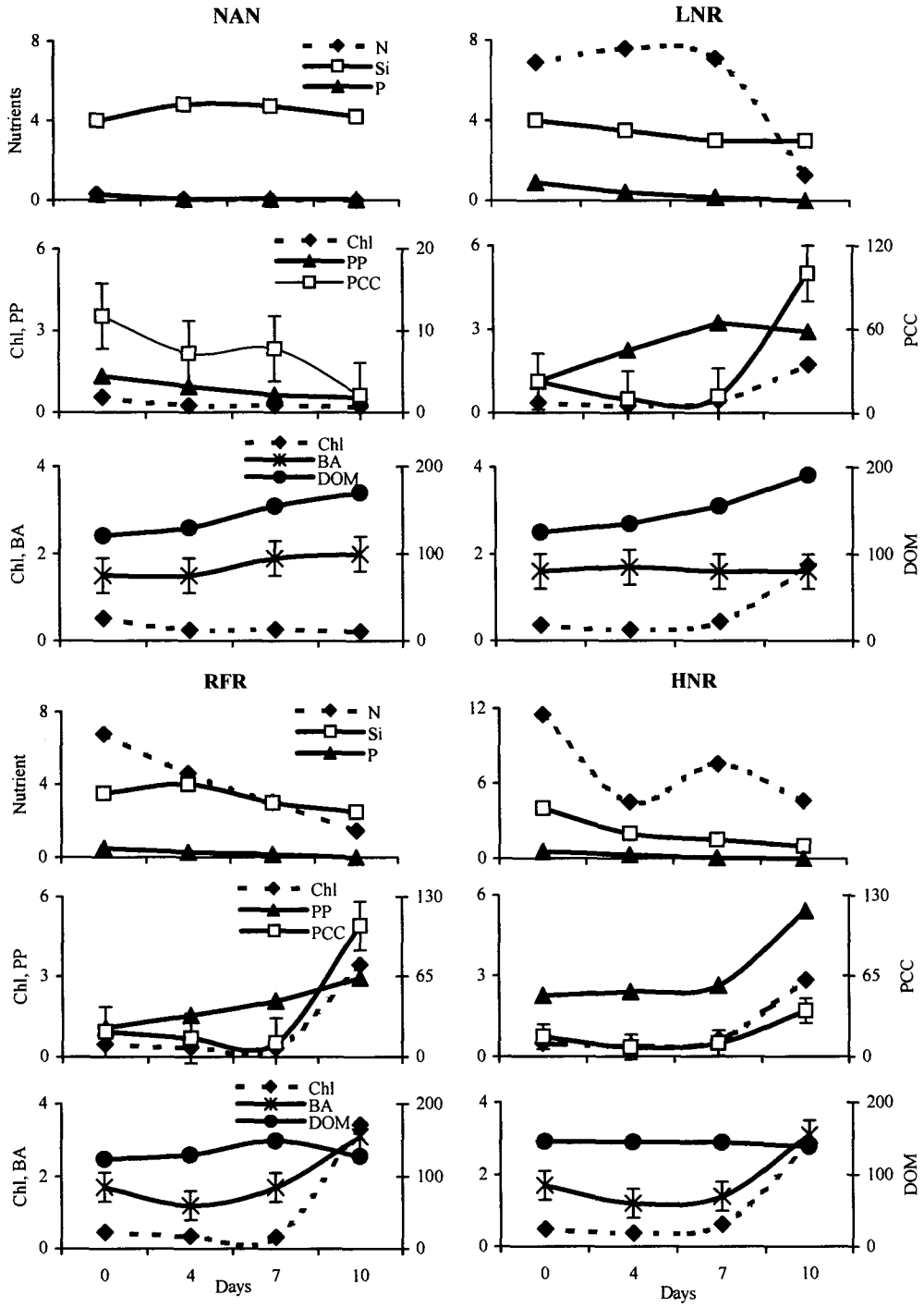


Fig. 6.2. Variations in chemical and biological characteristics under altered nutrient regimes: no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR), high nutrient ratio (HNR) in a shipboard experiment at 20°N 88°E. Units are: nutrients; μM, chl *a*; mg m^{-3}, PCC; cells x 10^3 L^{-1}, PP; mg C $m^{-3}d^{-1}$, BA; cells x $10^{10}L^{-1}$ and DOM; μM. Error bars denote standard deviations

Table 6.5. Phytoplankton species (Cells L^{-1}) that dominated after day 7 in different microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR) in the experiment conducted at Open Bay 20°N 88°E

Microcosm	Phytoplankton species	Cells L^{-1}
NAN	*Chaetoceros coarctatus*	270.00
	Chaetoceros didymus	270.00
	Chaetoceros peruvianus	190.48
	Ditylium brightwellii	190.48
	Rhizosolenia sp	190.48
	Mastoglia rostrata	190.48
	Navicula sp	1142.86
	Thalassionema nitzschioides	2476.19
	Thalassiothrix fauenfeldii	3047.62
	Dictyocha crux	190.48
LNR	*Bacteriastrum hyalinum*	519.23
	Biddulphia sp	173.08
	Chaetoceros eibenii	346.15
	Chaetoceros peruvianus	100.00
	Coscinodiscus sp	346.15
	Ditylium brightwellii	692.31
	Guinardia striata	1730.77
	Hemiaulus hauckii	519.23
	Rhizosolenia styliformis	173.08
	Skeletonema costatum	100000
	Thalassiosira sp	173.08
	Navicula distans	346.15
	Navicula sp	346.15
	Pseudo-nitzschia sp	1211.54
	Thalassionema nitzschioides	1730.77
	Dictyocha crux	173.08
RFR	*Bacteriastrum hyalinum*	538.45
	Biddulphia sinensis	134.61
	Rhizosolenia setigera	673.06
	Skeletonema costatum	1480.73
	Cylindrotheca closterium	134.61
	Navicula distans	403.84
	Navicula sp	403.84
	Trichodesmium sp	269.22
	Dictyocha crux	134.61
HNR	*Biddulphia* sp	192.31
	Ditylium brightwellii	576.94
	Guinardia striata	1346.18
	Rhizosolenia setigera	576.94
	Rhizosolenia sp	192.31
	Rhizosolenia styliformis	192.31
	Skeletonema costatum	9166.67
	Strianella unipunctata	192.31
	Thalassiosira sp	192.31
	Cylidrotheca closterium	192.31
	Navicula distans	384.62
	Navicula sp	384.62
	Pseudo-nitzschia sp	1346.18
	Thalassionema nitzschioides	2692.37

time in all bottles (Table 6.4; Fig 6.2). The rate of increase of bacteria was more in RFR and HNR as compared to LNR.

On day 0, PP ranged from 1.08 to 2.25 mg C $m^{-3}d^{-1}$. It increased by day 10 to 2.95 mg $Cm^{-3}d^{-1}$ in RFR and to 5.43 mg $Cm^{-3}d^{-1}$ HNR. It decreased marginally from day 7 in LNR and NAN. The DOM concentration varied from 121 to 146 μM on day 0 and increased to ~157 μM by day 10. The phytoplankton species composition was quite different from the one seen during the regular sampling. The phytoplankton species that became dominant by day 7 or day 10 in either NAN, LNR, RFR or HNR are listed in Table 6.5.

Western Bay Experiment (15°N 83°E)

Nutrients

Although silicate was >4 μM in the waters collected for experimental use, nitrate and phosphate concentrations were >1 μM. This is in contrast to their open ocean concentrations. Nitrate and phosphate decreased more rapidly than silicate (Table 6.6; Fig. 6.3) during the experimental period.

Biological Parameters

Concomitant with decreases in the nutrient concentrations, there were increases chl *a* and PCC in RFR and HNR. The increase in chl *a* was more in HNR from day 7 to day 10 (0.10 to 0.29 mg m^{-3}). The PCC averaged to 2.46 x 10^3 L^{-1} on day 0. The PCC began increasing from day 7 and day 10 in all but LNR nutrient amendments. The BA with 1.07 x 10^9 cells L^{-1} on day 0 increased with time in all microcosms till day 7 and decreased thereafter in LNR and HNR (Table 6.6; Fig 6.3). The rate of increase was more in RFR. PP ranged from 1.02 (HNR) to 2.19 (in LNR) mg C $m^{-3}d^{-1}$ on day 0 and rose to 1.87 mg $Cm^{-3}d^{-1}$ by day 10 in HNR. In other amendments, it decreased marginally from day 7. DOM concentrations were in the range of 121-199 μM on day 0. An increase in DOM was seen only in NAN and LNR. The phytoplankton species that became dominant by day 7 or day 10 in all microcosms are listed in Table 6.7.

Table 6.6. Day wise variations in different parameters in the experiment conducted at Western Bay 15°N 83°E in microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Parameter	Day	Microcosm			
		NAN	LNR	RFR	HNR
Nitrate (μM)	0	2.00	8.28	8.31	14
	4	1.66	7.21	8.00	9.11
	7	1.27	6.91	6.17	8.13
	10	0.82	2.75	2.54	7.69
Phosphate (μM)	0	1.06	2	1.3	1.43
	4	0.44	0.52	1.03	0.15
	7	0.23	0.29	0.23	0.23
	10	0.04	0.21	0.04	0.01
Chl *a*	0	0.20 (6.12)	0.24 (7.28)	0.30 (8.90)	0.24 (7.28)
(Chl C, mg C m^{-3})	4	0.08 (2.50)	0.09 (2.76)	0.10 (3.06)	0.13 (3.94)
	7	0.08 (2.50)	0.05 (1.47)	0.10 (3.06)	0.10 (3.06)
	10	0.15 (4.53)	0.21 (6.15)	0.28 (8.35)	0.29 (8.69)
PCC	0	1.35	3.15	4.15	1.17
cells x 10^3 L^{-1}	4	1.10	0.55	0.60	0.26
	7	0.45	0.75	1.76	0.68
	10	0.24	0.30	1.92	1.04
BA (BC, μg)	0	1.05 (11.52)	1.08 (11.9)	1.08 (11.9)	1.1 (12.2)
cells x 10^9 L^{-1}	4	9.26 (101.9)	1.58 (17.3)	1.0 (11.1)	1.30 (14.3)
	7	1.38 (15.2)	8.3 (91)	1.93 (21.2)	1.95 (21.5)
	10	1.02 (11.2)	6.91 (76)	5.97 (65.6)	1.21 (13.4)
PP	0	1.36	2.19	1.71	1.02
(mg C m^{-3} d^{-1})	4	1.17	1.50	1.30	1.00
	7	0.85	1.08	0.79	0.98
	10	0.54	0.95	0.63	1.87
DOM (DOC, μM)	0	199 (131)	121 (108)	128 (117)	123 (110)
	4	133 (133)	101 (101)	97 (97)	99 (99)
	7	96 (87)	107 (93)	111 (91)	304 (97)
	10	138 (89)	254 (94)	94 (90)	102 (91)

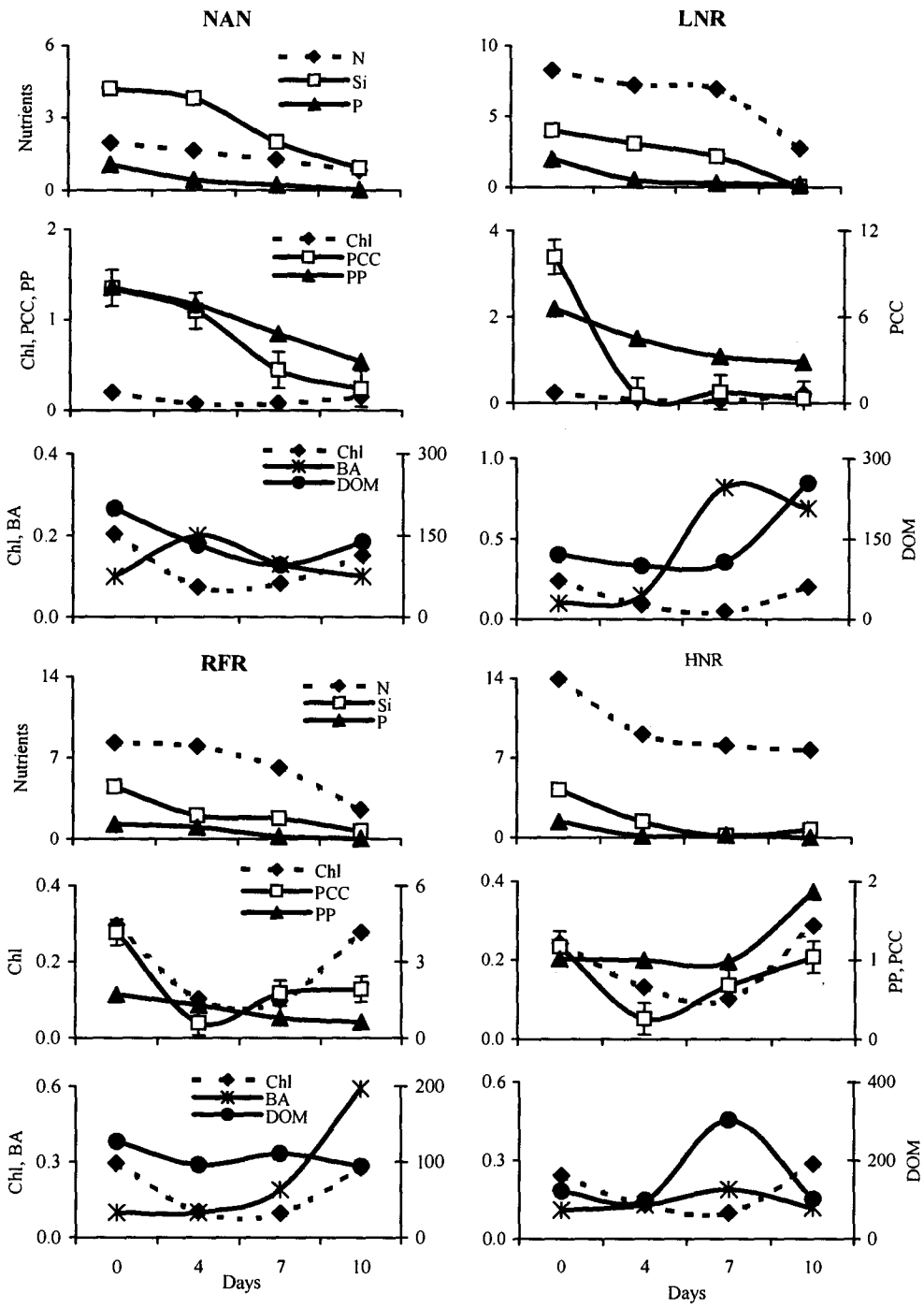


Fig. 6.3. Variations in chemical and biological characteristics under altered nutrient regimes: no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR), high nutrient ratio (HNR) in shipboard experiment at 15°N 83°E. Units are: nutrients; μM, chl a; mg m^{-3}, PCC; cells x 10^3 L^{-1}, PP; mg C $m^{-3}d^{-1}$, BA; cells x $10^{10}L^{-1}$ and DOM; μM. Error bars denote standard deviations

Table 6.5. Phytoplankton species (Cells L^{-1}) that dominated after day 7 in different microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR) in the experiment conducted at Open Bay 20°N 88°E

Microcosm	Phytoplankton species	Cells L^{-1}
NAN	*Chaetoceros coarctatus*	270.00
	Chaetoceros didymus	270.00
	Chaetoceros peruvianus	190.48
	Ditylium brightwellii	190.48
	Rhizosolenia sp	190.48
	Mastoglia rostrata	190.48
	Navicula sp	1142.86
	Thalassionema nitzschioides	2476.19
	Thalassiothrix fauenfeldii	3047.62
	Dictyocha crux	190.48
LNR	*Bacteriastrum hyalinum*	519.23
	Biddulphia sp	173.08
	Chaetoceros eibenii	346.15
	Chaetoceros peruvianus	100.00
	Coscinodiscus sp	346.15
	Ditylium brightwellii	692.31
	Guinardia striata	1730.77
	Hemiaulus hauckii	519.23
	Rhizosolenia styliformis	173.08
	Skeletonema costatum	100000
	Thalassiosira sp	173.08
	Navicula distans	346.15
	Navicula sp	346.15
	Pseudo-nitzschia sp	1211.54
	Thalassionema nitzschioides	1730.77
	Dictyocha crux	173.08
RFR	*Bacteriastrum hyalinum*	538.45
	Biddulphia sinensis	134.61
	Rhizosolenia setigera	673.06
	Skeletonema costatum	1480.73
	Cylindrotheca closterium	134.61
	Navicula distans	403.84
	Navicula sp	403.84
	Trichodesmium sp	269.22
	Dictyocha crux	134.61
HNR	*Biddulphia* sp	192.31
	Ditylium brightwellii	576.94
	Guinardia striata	1346.18
	Rhizosolenia setigera	576.94
	Rhizosolenia sp	192.31
	Rhizosolenia styliformis	192.31
	Skeletonema costatum	9166.67
	Strianella unipunctata	192.31
	Thalassiosira sp	192.31
	Cylidrotheca closterium	192.31
	Navicula distans	384.62
	Navicula sp	384.62
	Pseudo-nitzschia sp	1346.18
	Thalassionema nitzschioides	2692.37

time in all bottles (Table 6.4; Fig 6.2). The rate of increase of bacteria was more in RFR and HNR as compared to LNR.

On day 0, PP ranged from 1.08 to 2.25 mg C $m^{-3}d^{-1}$. It increased by day 10 to 2.95 mg $Cm^{-3}d^{-1}$ in RFR and to 5.43 mg $Cm^{-3}d^{-1}$ HNR. It decreased marginally from day 7 in LNR and NAN. The DOM concentration varied from 121 to 146 μM on day 0 and increased to ~157 μM by day 10. The phytoplankton species composition was quite different from the one seen during the regular sampling. The phytoplankton species that became dominant by day 7 or day 10 in either NAN, LNR, RFR or HNR are listed in Table 6.5.

Western Bay Experiment (15°N 83°E)

Nutrients

Although silicate was >4 μM in the waters collected for experimental use, nitrate and phosphate concentrations were >1 μM. This is in contrast to their open ocean concentrations. Nitrate and phosphate decreased more rapidly than silicate (Table 6.6; Fig. 6.3) during the experimental period.

Biological Parameters

Concomitant with decreases in the nutrient concentrations, there were increases chl *a* and PCC in RFR and HNR. The increase in chl *a* was more in HNR from day 7 to day 10 (0.10 to 0.29 mg m^{-3}). The PCC averaged to 2.46 x 10^3 L^{-1} on day 0. The PCC began increasing from day 7 and day 10 in all but LNR nutrient amendments. The BA with 1.07 x 10^9 cells L^{-1} on day 0 increased with time in all microcosms till day 7 and decreased thereafter in LNR and HNR (Table 6.6; Fig 6.3). The rate of increase was more in RFR. PP ranged from 1.02 (HNR) to 2.19 (in LNR) mg C $m^{-3}d^{-1}$ on day 0 and rose to 1.87 mg $Cm^{-3}d^{-1}$ by day 10 in HNR. In other amendments, it decreased marginally from day 7. DOM concentrations were in the range of 121-199 μM on day 0. An increase in DOM was seen only in NAN and LNR. The phytoplankton species that became dominant by day 7 or day 10 in all microcosms are listed in Table 6.7.

Table 6.6. Day wise variations in different parameters in the experiment conducted at Western Bay 15°N 83°E in microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Parameter	Day	Microcosm			
		NAN	LNR	RFR	HNR
Nitrate (μM)	0	2.00	8.28	8.31	14
	4	1.66	7.21	8.00	9.11
	7	1.27	6.91	6.17	8.13
	10	0.82	2.75	2.54	7.69
Phosphate (μM)	0	1.06	2	1.3	1.43
	4	0.44	0.52	1.03	0.15
	7	0.23	0.29	0.23	0.23
	10	0.04	0.21	0.04	0.01
Chl *a*	0	0.20 (6.12)	0.24 (7.28)	0.30 (8.90)	0.24 (7.28)
(Chl C, mg C m^{-3})	4	0.08 (2.50)	0.09 (2.76)	0.10 (3.06)	0.13 (3.94)
	7	0.08 (2.50)	0.05 (1.47)	0.10 (3.06)	0.10 (3.06)
	10	0.15 (4.53)	0.21 (6.15)	0.28 (8.35)	0.29 (8.69)
PCC	0	1.35	3.15	4.15	1.17
cells x 10^3 L^{-1}	4	1.10	0.55	0.60	0.26
	7	0.45	0.75	1.76	0.68
	10	0.24	0.30	1.92	1.04
BA (BC, μg)	0	1.05 (11.52)	1.08 (11.9)	1.08 (11.9)	1.1 (12.2)
cells x 10^9 L^{-1}	4	9.26 (101.9)	1.58 (17.3)	1.0 (11.1)	1.30 (14.3)
	7	1.38 (15.2)	8.3 (91)	1.93 (21.2)	1.95 (21.5)
	10	1.02 (11.2)	6.91 (76)	5.97 (65.6)	1.21 (13.4)
PP	0	1.36	2.19	1.71	1.02
(mg C m^{-3} d^{-1})	4	1.17	1.50	1.30	1.00
	7	0.85	1.08	0.79	0.98
	10	0.54	0.95	0.63	1.87
DOM (DOC, μM)	0	199 (131)	121 (108)	128 (117)	123 (110)
	4	133 (133)	101 (101)	97 (97)	99 (99)
	7	96 (87)	107 (93)	111 (91)	304 (97)
	10	138 (89)	254 (94)	94 (90)	102 (91)

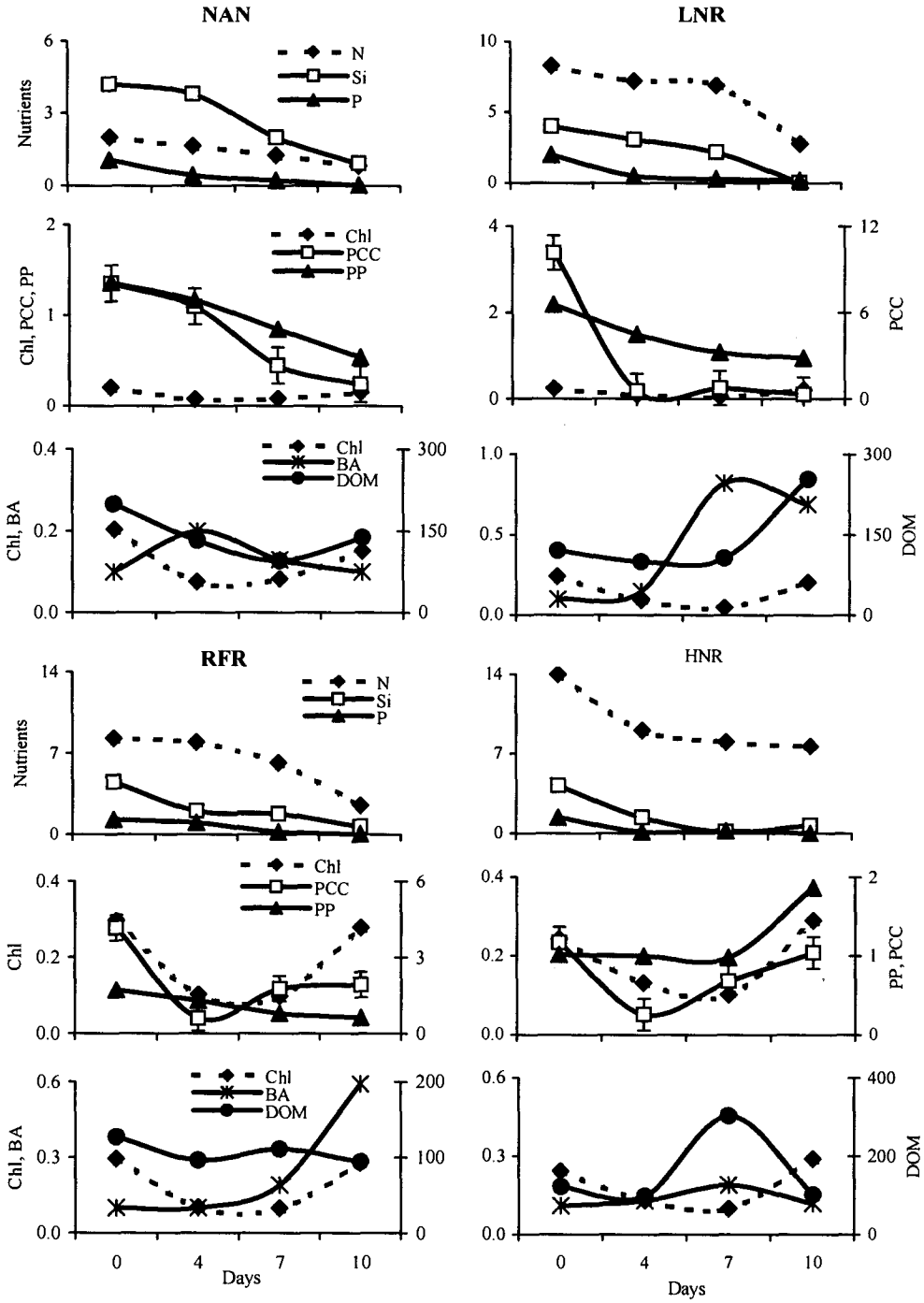


Fig. 6.3. Variations in chemical and biological characteristics under altered nutrient regimes: no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR), high nutrient ratio (HNR) in shipboard experiment at 15°N 83°E. Units are: nutrients; μM, chl a; mg m^{-3}, PCC; cells x 10^3 L^{-1}, PP; mg C $m^{-3}d^{-1}$, BA; cells x $10^{10}L^{-1}$ and DOM; μM. Error bars denote standard deviations

Table 6.7. Phytoplankton species (Cells L^{-1}) that dominated after day 7 in different microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR) in the experiment conducted at Western Bay 15°N 83°E

Microcosm	Phytoplankton species	Cells L^{-1}
NAN	*Coscinodiscus* sp	80
	Thalassiosira sp	80
	Navicula sp	180
	Navicula sp1	90
	Pyrophacus sp	80
LNR	*Coscinodiscus* sp	100
	Guinardia striata	150
	Rhizosolenia setigera	150
	Navicula distans	150
	Nitzschia delicatisima	150
	Pyrophacus sp	150
RFR	*Chaetoceros didymus*	1080
	Coscinodiscus sp	120
	Coscinodiscus marginatus	320
	Thalassiosira sp	360
	Navicula sp	160
	Navicula distans	160
	Ceratium furca	120
	Orinothoceros sp	120
HNR	*Chaetoceros didymus*	400
	Chaetoceros messanensis	80
	Coscinodiscus sp	80
	Coscinodiscus marginatus	170
	Thalassiosira sp	340
	Navicula sp	160
	Navicula sp1	80
	Peridinium sphaericum	170

Laboratory Experiment

Experiment with *Melosira* sp

Nutrients

In the seawater collected from BoB and used for the unialgal experiments, the concentrations silicate nitrate and phosphate respectively were :> 4 μM, >1 μM and > 0.23 μM. During the experiment, nitrate and phosphate decreased faster than silicate (Fig. 6.4), similar to the observations in the experiments done on-board.

Biological Parameters

Akin to most observations from the on-board experiments, decreasing nutrient concentrations corresponded to increases in chl *a* and PCC (Table 6.8). The chl *a* concentrations increased in all the microcosms to as high as ~11.17 mg m^{-3} by day 10. Such increase was rapid in HNR from day 7 to day 10 (2.55 to 8.61 mg m^{-3}). The PCC also increased from day 7 to day 10 in all microcosms. In NAN, it decreased with time. Changes in PCC mostly coincided with chl *a* in all microcosms. The BA averaged 12.5 x 10^9 cells L^{-1} on day 0. It increased with time in LNR, RFR and NAN. On day 0, PP was 1.38 to 3.44 mg C $m^{-3}d^{-1}$ in different bottles. Increase in PP was observed in all the microcosms. It increased to 31 mg $Cm^{-3}d^{-1}$ on day 10 in LNR and HNR. In this experiment, BP was measured only from LNR bottle. It increased from day 0 to day 7. DOM concentration varied from 298 to 335 μM on day 0 and was lower at an average of 239 μM on day 10 (Table 6.8; Fig. 6.4).

Laboratory Experiment

Experiment with *Amphora* sp

Nutrients

The same seawater used for experiments with centric diatom was used (Table 6.9; Fig. 6.5).

Biological Parameters

While responses of this species to changing nutrient concentrations were similar to that of the *Melosira* sp as described above, there were differences in certain biological parameters. For instance, chl *a* was in the range 3.37-7.28 mg m^{-3} on day 0 in different

Table 6.8. Day wise variations in different parameters in the laboratory experiment conducted with centric diatom in microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Parameter	Day	Microcosm			
		NAN	LNR	RFR	HNR
Nitrate (μM)	0	1.83	6.18	6.33	12.46
	4	0.92	2.99	3.67	10.36
	7	0.66	2.27	1.65	7.44
	10	0.47	1.68	1.17	5.89
Phosphate (μM)	0	0.23	0.83	0.45	0.55
	4	0.17	0.41	0.33	0.31
	7	0.16	0.41	0.16	0.27
	10	0.14	0.47	0.21	0.21
Chl *a*	0	1.30 (38.9)	1.55 (46.4)	2.13 (63.9)	1.49 (44.8)
(Chl C, mg C m^{-3})	4	0.91 (27.2)	0.96 (28.8)	2.46 (73.9)	0.93 (28)
	7	1.10 (32.9)	3.74 (112.3)	5.94 (178.2)	2.55 (76.6)
	10	1.83 (54.9)	8.50 (255.1)	11.17 (334.9)	8.61 (258.4)
PCC	0	2.40	2.19	2.17	2.20
cells x 10^3 L^{-1}	4	1.80	1.26	3.10	0.21
	7	0.50	1.76	4.74	3.82
	10	0.39	28.95	26.90	24.78
BA (BC, μg)	0	12.2 (134.3)	13.8 (151.6)	11.3 (123.9)	12.5 (137.8)
cells x 10^9 L^{-1}	4	12.5 (137.6)	13.8 (151.6)	12.0 (132.9)	13.0 (143.3)
	7	13.9 (153.3)	13.9 (153.3)	13.3 (146.4)	21.8 (239)
	10	18.2 (199.9)	16.8 (184)	18.7 (205.2)	16.9 (186)
PP (BP)	0	2.63	3.44 (4.17)	3.19	1.38
(mg C m^{-3} d^{-1})	4	4.70	12.38 (5.49)	29.64	4.84
	7	3.65	21.26 (5.87)	24.20	8.50
	10	1.50	31.00 (5.50)	26.00	31.00
DOM (DOC, μM)	0	302 (259)	335 (298)	298 (261)	332 (311)
	4	275 (222)	275 (221)	290 (248)	297 (222)
	7	254 (157)	255 (213)	279 (207)	255 (219)
	10	226 (203)	246 (212)	233 (203)	252 (219)

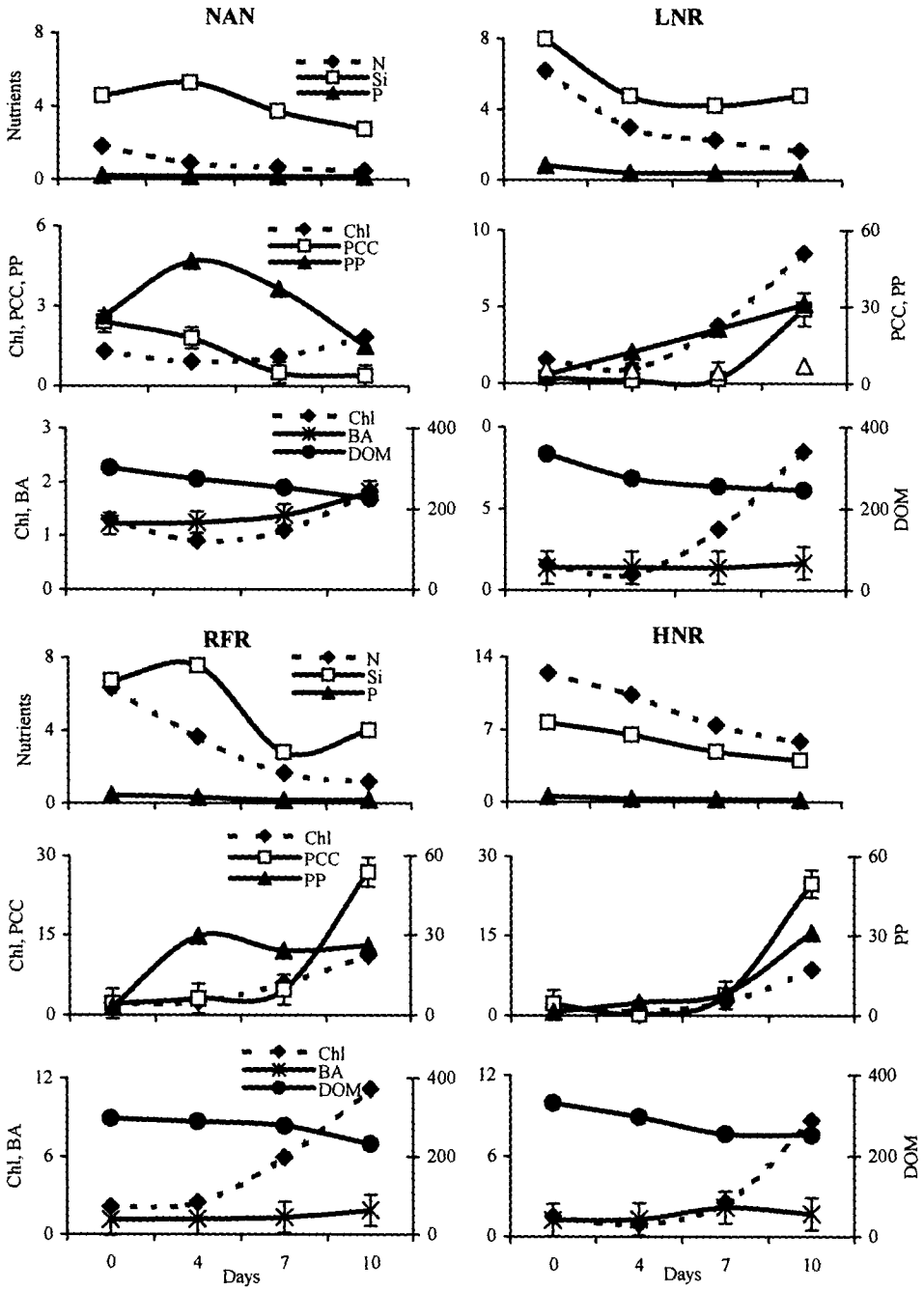


Fig. 6.4. Variations in chemical and biological characteristics under altered nutrient regimes: no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR), high nutrient ratio (HNR) in laboratory experiment with uni algal culture of a centrale. Units are: nutrients; μM, chl *a* ; mg m^{-3}, PCC; cells x 10^3 L^{-1}, PP/BP; mg C m^{-3} d^{-1}, BA; cells x $10^{10}L^{-1}$ and DOM; μM. Error bars denote standard deviations

microcosms. Its increase was rapid in HNR after day 7 (6.93 to 9.44 mg m^{-3}). PCC averaged to 2.27 x 10^3 L^{-1} on day 0 that increased from day 4 to 7 in the LNR and RFR. In the NAN, it decreased till day 7 and in HNR it increased after day 4. The BA which was in the range of 7.8 x 10^9 cells L^{-1} on day 0, increased with time in all microcosms including NAN. On day 0, PP ranged from 3.93 to 7.36 mg C $m^{-3}d^{-1}$. It was 5.43 mg $Cm^{-3}d^{-1}$ on day 7 in RFR. In LNR and HNR, it increased to 10.15 and 2.30 mg $Cm^{-3}d^{-1}$ respectively by day 10. The BP measured only from LNR, increased until day 4 and decreased thereafter. DOM decreased with time in NAN and HNR and showed an increase after day 7 in LNR and RFR (Table 6.9; Fig. 6.5).

Statistical analyses

Correlation coefficients were calculated between each of the different parameters analyzed from the experiments. Appropriate relationships between dependent and independent variables are furnished below.

In the experiment at OB 1 (9°N 88°E), DOM had a significant negative correlation with BA (R= -0.999, $p<0.01$) in LNR. Chl *a* correlated negatively with nitrate (R= -0.9724; $p<0.03$) in HNR. In the experiment at OB2 (20°N 88°E) also, chl *a* (R= - 0.9967; $p<0.003$) and PCC (R= - 0.9690; $p<0.03$) had a significant negative relationship with nitrate. In HNR, a strong correlation was observed between chl *a* and PP (R= 0.9942; $p<0.01$) and, PP was inversely related to DOM (R= -0.9975; $p<0.003$). In NAN, no significant relation was observed between any of the parameters. In the experiment at WB, only PCC and PP were positively correlated (R= 0.9800; $p<0.020$) in NAN while no significant relationship was observed in any of the experimental settings *viz.*, LNR, RFR or HNR.

In the laboratory experiment with *Melosira* sp, no significant correlation was observed between any parameters from LNR. A strong negative correlation (R= -0.9991; $p<0.01$) was seen between BA and DOM suggesting DOC utilization by bacteria. Chl *a* correlated positively with PP (R= 0.9633; $p<0.04$) in HNR. While with the pennate diatom, *Amphora* sp, chl *a* had a positive correlation with nitrate (R= 0.9723; $p<0.03$). In general, none of the nutrients bore significant correlation with either chl *a* or PP in

Table 6.9. Day wise variations in different parameters in the laboratory experiment conducted with pennate diatom in microcosms with no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR) and high nutrient ratio (HNR)

Parameter	Day	Microcosm			
		NAN	LNR	RFR	HNR
Nitrate (μM)	0	1.83	6.18	6.33	12.46
	4	0.92	2.99	3.67	10.36
	7	0.66	2.27	1.65	7.44
	10	0.47	1.68	1.17	5.89
Phosphate (μM)	0	0.23	0.83	0.45	0.55
	4	0.17	0.41	0.33	0.31
	7	0.16	0.41	0.16	0.27
	10	0.14	0.47	0.21	0.21
Chl *a*	0	3.74 (112)	7.28 (2.18)	5.03 (151)	3.37(101)
(Chl C, mg C m^{-3})	4	1.02 (30)	4.71(141)	6.97(209)	3.38 (101)
	7	0.51 (15)	3.39 (102)	7.52 (226)	6.93 (208)
	10	0.19 (6)	3.84 (115)	3.62 (108)	9.44 (283)
PCC	0	2.55	1.26	1.85	3.43
cells x 10^3 L^{-1}	4	0.48	0.37	1.25	1.87
	7	0.42	3.13	2.22	1.99
	10	0.37	7.28	1.85	13.50
BA (BC, μg)	0	7.3 (80.80)	7.0 (77.35)	8.7 (96.34)	7.7 (84.26)
cells x 10^9 L^{-1}	4	8.4 (91.80)	7.6 (83.95)	8.9 (97.88)	7.7 (84.26)
	7	11.3 (123.98)	8.6 (94.62)	9.1 (99.80)	12.7 (139.52)
	10	13.0 (142.97)	9.3 (103.25)	13.0 (142.97)	16.9 (186.15)
PP (BP)	0	7.36	5.30 (4.67)	5.13	3.93
(mg C m^{-3} d^{-1})	4	1.12	3.00 (6.28)	2.51	1.50
	7	0.52	0.97 (5.40)	5.43	1.83
	10	0.23	10.15 (4.75)	0.08	2.30
DOM (DOC, μM)	0	243 (221)	331 (295)	343 (310)	2586 (231)
	4	237 (205)	265 (189)	275 (175)	235 (179)
	7	232(208)	217 (195)	215 (191)	217 (169)
	10	228 (191)	228 (188)	234 (197)	211 (180)

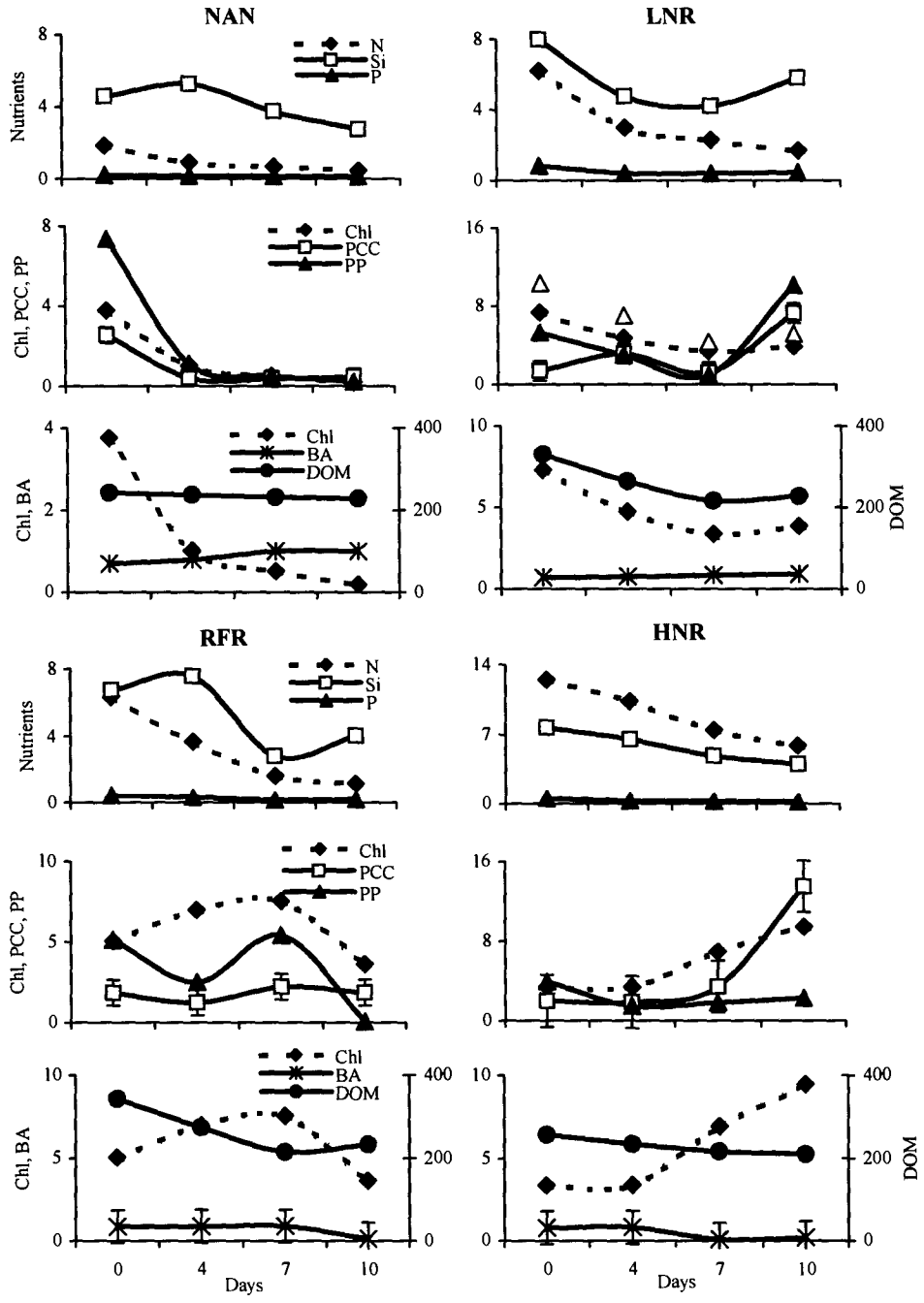


Fig. 6.5. Variations in chemical and biological characteristics under altered nutrient regimes: no added nutrients (NAN), low nutrient ratio (LNR), Redfield ratio (RFR), high nutrient ratio (HNR) in laboratory experiment with uni algal culture of a pennale. Units are: nutrients; μM, chl *a*; mg m^{-3}, PCC; cells x 10^3 L^{-1}, PP/BP; mg C m^{-3} d^{-1}, BA; cells x $10^{10}L^{-1}$ and DOM; μM. Error bars denote standard deviations

RFR and HNR. The BA was negatively correlated with DOM (R= -0.9651; $p<0.04$) in NAN.

Discussion

Effect of nutrients on growth of phytoplankton

The ratio of inorganic Nitrate to Phosphate compounds in the BoB is usually lower than the Redfield ratio (Chapter-4) suggesting that the nitrate could limit the production of phytoplankton (Naqvi et al 1978). Extensive field sampling in the BoB in summer monsoon (Prasanna Kumar et al 2002; 2004; Madhupratap et al 2003), fall intermonsoon, northeast monsoon and spring intermonsoon (Chapter 4) has implicitly brought out that concentrations of nitrate and phosphate are quite low in the surface and sub surface waters. In lieu of large influx of riverine discharges that affects the salinity and nutrient gradients, three contrasting locations were chosen for onboard experiments. Two open ocean stations one in the south (OB1- 9°N 88°E) with lower impact of the freshwater and, the other in the north (OB2- 20°N 88°E) with higher influence of riverine influx and, the third one along the western transect were chosen. Notably, the response of phytoplankton in terms of abundance and growth was different at these locations. The phytoplankton community in the OB1 did not show noticeable differences when nutrients were added. Similarly, phytoplankton did not respond to the nutrient enrichments at WB where higher nutrient concentrations were observed during the NEM (Nitrate ~2 μM, Phosphate ~1.06 μM and Silica ~4 μM). At OB2, the growth response was significant. This is an important and contrasting observation. Though there is voluminous riverine discharge into this region, such influx is believed to bring in no or at best minimal amounts of inorganic nutrients (Prasanna Kumar et al 2002; 2004). Such increase in phytoplankton growth in terms of increased chl *a*, PCC and DOM in response to nutrients enrichments is important to suggest that the flora in the northern Bay respond quickly to increased nutrient availability. As already detailed in Chapter 4, the phytoplankton numbers were low at OB2 during low nutrient times of FIM, NEM and SpIM. But, their abundance and productivity were elevated during FIM and SM despite poorer concentrations of nitrate and phosphate (owing mostly to their assimilation). From the in situ and experimental observations, it is inferred that phytoplankton assemblages in the northern Bay adapt to feast and famine situations,

rather swiftly. In that, they either proliferate as soon as the nutrients are available or, wait until right conditions prevail for their growth. This can also be inferred from the high diversity seen during the SM when seawater concentrations of nutrients were low (Jane et al 2007).

The nutrient enrichment elicited varying response from diatoms of different morphology. The centric diatoms showed an exponential growth on the last day of the experiment. Among these, the dominant species *Skeletonema costatum* contributing to almost 99% in the LNR had a significant positive relation with nitrate ($R= 0.427$; $p<0.02$) signifying that this species responds to nutrient availability rather speedily. As described in chapter 4, this species is preponderant in the northern locations of the Bay where the N:P ratio was lower than RFR and, the top 50 m in particular had very low concentrations of nitrate during summer monsoon (Jane et al 2007). Also, it has been previously reported to respond to nitrate enrichment experiment (Carter et al, 2005). Also at low N:P ratios this species is reported to grow at logarithmic phase (Penna et al 1999). In this study too, its abundance was maximal in LNR though it grew well in all three nutrient ratios at OB2.

Environs with higher nutrients benefit the growth of centrales with low surface to volume ratio. However, once these nutrients reach below threshold levels, the centrales were unable to sustain the same growth rate as observed in some of the bottles. This was unlike the pennales having higher surface to volume ratio that not only persisted in the experimental incubations but also proliferated. Conversely, in the bottles of lab experiments the centric (*Melosira* sp) and pennate (*Amphora* sp) diatom attained a similar growth pattern. This is implicit that they compete for the same nutrients when grown together and the species with a lower threshold limit for nutrients out-grows the other species. This could be one of the reasons for the different growth peaks observed in the onboard experiments and the dominance of pennate diatoms over the centrals. As proposed by Lalli & Parsons (1997) and observed during this study, these species specific differences in the growth rates and responses in nutrient altered situations allow for a greater diversity in the phytoplankton composition.

Many studies have shown that phytoplankton growth (Sakka et al 1999; Gobler & Sañuado-Wilhelmy 2001), biomass (Graziano et al 1996; Caron et al 2000) and species composition (Berdalet et al 1996; Carlsson & Granéli 1999; Duarte et al 2000) are controlled by nutrients. However there is no general consensus whether it is nitrate or phosphate that is limiting. South Central Pacific is traditionally considered to be nitrate limited (Dufour & Berland 1999) while the western and eastern Mediterranean Sea is considered to be phosphate limited (Thingstad & Rassoulzadegan 1995; Thingstad et al 1998; Zohary & Robarts 1998; Diaz et al 2001). Until recently phytoplankton growth in the North Atlantic was considered to be nitrate limited (Graziano et al 1996). Nowadays it is reported to be due to P-limitation (Ammerman et al 2003; Vidal et al 2003). Subtropical North Pacific is known to change from nitrate to phosphate limitation seasonally (Karl et al 1995). Other authors have demonstrated that a combination of several nutrients limits marine phytoplankton growth (Sakka et al 1999). This being the first experiment conducted with nutrient enrichment in the BoB, it is clearly evidenced that phytoplankton growth response differs from region to region in the generally nutrient limiting regimes of the Bay. The hydrodynamic shifts are too strong in the northern Bay *vis a vis* the other two spots where experiments were carried out during this study. Since a swift and robust response was seen in terms of elevated chl *a*, PCC, PP and DOM formation, it is proposed that phytoplankton assemblages in the northern Bay alter their metabolic functioning to suite the seasonal shifts in hydrography and nutrient chemistry.

Effect of nutrients on DOC formation

The DOC varies according to the age and physiological condition of phytoplankton community (Mykelstad 1977). While exponential growth phase of phytoplankton occurs mostly when nutrients are available at an ideal RFR, it is hard to sustain this phase for longer than, at best, a few days. Usually, it reaches a stationary/minimal growth phase even if one of the essential nutrients become limiting (Raymont 1980). High amounts of DOC were recorded under nitrate limiting (LNR) and nutrient sufficient (RFR) conditions in all the experiments. As also demonstrated by Decho (1990), this is a clear indication that the DOC production increases during nutrient (especially N) limiting conditions. Apparently, phytoplankton exude more of their photosynthates including polysaccharides (Granéli et al 1999) when nutrients become

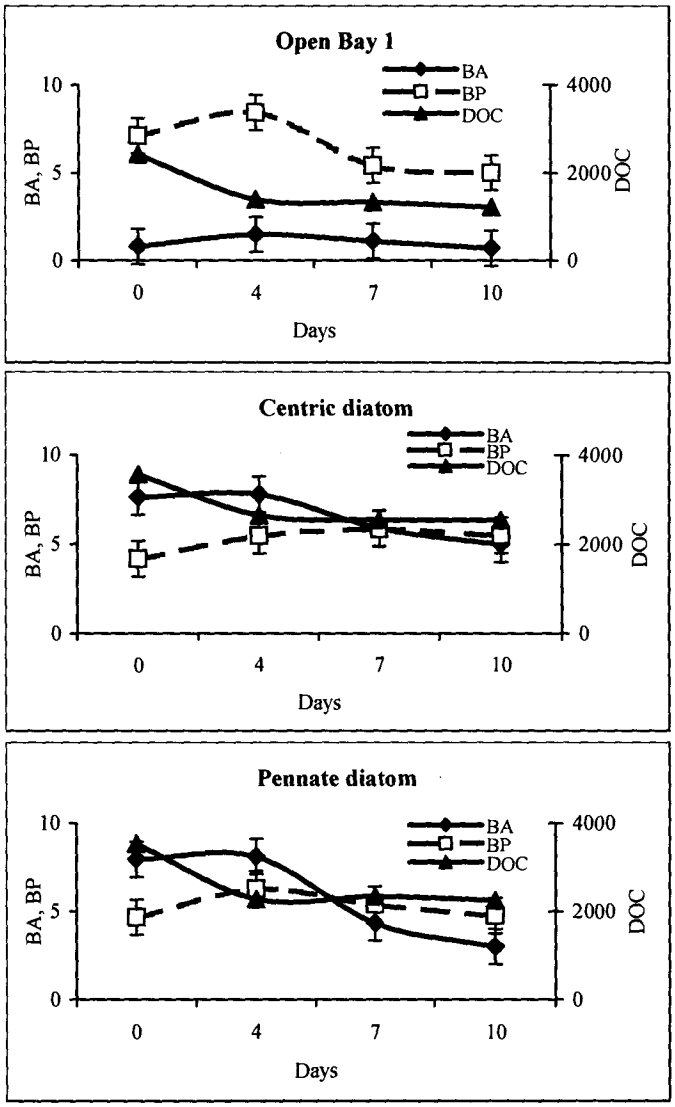


Fig. 6.6. Bacterial production (BP, μg C $L^{-1}d^{-1}$), bacterial abundance (BA, cells x 10^9 L^{-1}) and dissolved organic carbon (DOC, μg L^{-1}) in open Bay 1 (9°N 88°E) and with centric and pennate diatom. Error bars denote standard deviations

deficient, thereby contributing to increased DOC in the surrounding medium. Previous studies conducted in the Adriatic Sea reported highest amounts of polysaccharides under P- deficient conditions (Granéli et al 1999). Further as also observed in this study, DOC production/formation is rapid under nutrient limitation and when phytoplankton community is in its declining growth phase (Mykelstad 1977; Norman et al 1995; Guerrini et al 1998; Fajon et al 1999).

DOC utilization

Many well documented laboratory experiments (Amon & Benner 1996; Fajon et al 1999; Goto et al 2001) as well as field studies (Lancelot & Billen 1984; Sell & Overbeck 1992; Ducklow et al 1999; Weiss & Simon 1999; Descy et al 2002) recognize that a large fraction of photosynthetically produced carbon passes through DOM to heterotrophic bacteria. Nearly all DOM is consumed by bacteria (Azam & Hodson 1977). Thus, degradation rates of the DOM can also be calculated from the bacterial production using tritiated thymidine (Fuhrman & Azam 1982; Kirchman et al 1991). By following similar method, it was evidenced during this study that there is a strong relationship between DOC production and its uptake by bacteria. As is clear from the on-board and uni-algal culture experiments, increase in the BP as well as BA is attributable to their utilization of DOC formed as a consequence of phytoplankton growth and metabolism. Bacterial utilization of DOC is clearly observed during this study. A marked increase in bacterial abundance corresponded to a decrease in the DOC fraction in all the experiments (Fig. 6.6). The DOC utilization rates were observed to range from 183 to 378 $\mu g\ C\ L^{-1}\ d^{-1}$ in the OB1, while in the microcosms of pennate and centric diatoms, it ranged from 403 to 950 $\mu g\ C\ L^{-1}\ d^{-1}$. It was up to a tune of 26% (overall range 15-26%) of total DOC available in the laboratory experiments while in the OB1 it was around 28% (overall range 13-28%). These rates in general are comparable to those determined by Kirchman et al (1991). The corresponding per cell turnover of DOC is also depicted in the figure (Fig. 6.7). Within the microcosms, bacteria do release their own DOC over time (Nalewajko & Lean 1972; Dunstall & Nalewajko 1975; Iturriaga & Zsolnay 1981). Such extracellular, bacterial DOC is suggested to be largely refractory (Tranvik 1998). Thus, assimilable DOC in the ecosystems with low inputs from autotrophic production might get depleted over time.

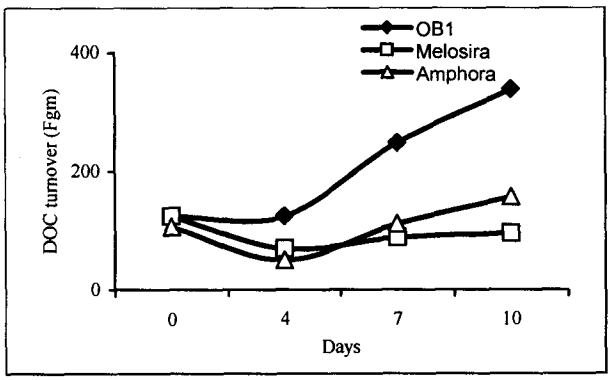


Fig. 6. 7. Percell turnover of DOC (femtogram) calculated for open Bay 1 (OB1), centric diatom (*Melosira* sp) and pennate diatom (*Amphora* sp)

This can also be inferred from both ship-board and unialgal culture experiments. In that, neither the BGR rose exponentially nor the DOC reached the zero levels with increasing duration of incubation. Therefore, it is likely that the TOC in the open waters of the Bay may have more refractory proportions than supposed by earlier studies of Azam et al (1994). From the observed utilization rates, it is suggested that the assimilation efficiency of carbon is much lower than 30%; falling in the range of 3.25-22%. This means that the respiration rates are higher and growth rates are poorer. Indirectly it also means that the refractile proportion of DOC in the Bay may be much higher than previously suggested 90% for the Arabian Sea (Azam et al 1994). Thus, this study has provided the data on DOC utilization rates of bacteria in the BoB for the first time and adds up to infer the major role bacteria play in recycling DOC.

The presence of high bacterial abundance in the BoB compared to the Arabian Sea (Gauns et al 2005; Khodse et al 2007) would help in faster recycling of the assimilable DOC in the surface waters. This would in turn sustain the microbial loop in this system and/or aid forming aggregates enabling faster sedimentation in the Bay. Exudates from phytoplankton and also mesozooplankton may also be important for the transfer of organic matter to the deep in the form of numerically abundant, small sized (<20; Kumar et al 1998) transparent exoploymer particles (TEP; Kumar et al 1998; Ramaiah et al 2000) in the BoB (Kumar et al 1998). From the first measurements of DOM production and utilization in this study, it is evident that there is substantial daily production of DOM. While only a fraction is sufficient enough to meet the bacterial growth demands, a question that persists is what fraction of this DOM is assimilable and what fraction not.

Conclusions

The ratio of inorganic nitrate to phosphate compounds in the BoB is usually lower than the Redfield ratio suggesting possible nitrate limitation. The nutrients experiments conducted in the BoB during NEM suggest zonal differences within the BoB. Changes in the nutrient concentration affect the phytoplankton directly and as a consequence both the bacterial and other microheterotrophic communities. This would be affecting the composition and quantity of the organic matter in the BoB and also play a major role in the export of the carbon to the deep.

Chapter 7

Chapter 7

Zooplankton grazing control on phytoplankton

Introduction

Energy supplied to the higher trophic levels is transferred through 2 main pathways: the herbivorous grazing food chain from larger phytoplankton to mesozooplankton and the microbial food web which involves the smaller phytoplankton, bacteria, protists to higher trophic levels (Uitto et al 1997). It is well known that zooplankton forms the major link between the primary producers (phytoplankton) and tertiary producers (fishes and other animals at higher trophic levels) in the marine ecosystems (Li et al 2003). Reproduction, growth and mortality rates form the essential components of the zooplankton dynamics (GLOBEC Implementation Plan 1999). Of these, the first two parameters are directly influenced by feeding. Therefore, studies on feeding of zooplankton are important for our understanding of the ocean ecosystem dynamics. Previously, it was considered that only a minor part of the carbon is available to higher trophic levels via microbial food web (Ducklow et al 1986; Wikner et al 1990). The emphasis of research on the grazing impact of mesozooplankton on phytoplankton has usually been on larger taxa. However, in recent times, more and more studies have indicated that smaller copepods often play an important role than the larger animals in terms of grazing pressure on phytoplankton (Moralis et al 1991; Harris & Tranter 1991; Dam & Peterson 1993; Zhang et al 1995). Many mesozooplankton (copepods, cladocerans and rotifers) are known to be largely omnivorous (Stoecker & Egloff 1987; Wiadnyana & Rassoulzadegan 1989; Stoecker & Capuzzo 1990). These feed on protists (microzooplankton) of a wide size range that consume smaller phytoplankton and bacteria. Therefore, the energy transfer from the microbial loop to higher trophic levels can be greater than previously reported (Uitto et al 1997). Grazing experiments from the Indian Ocean (Landry et al 1998; Edwards et al 1999) are fewer than those from the Atlantic (Moralis et al 1991; Head et al 1999; Huskin et al 2001; Sommer et al 2004; 2005; Olsen et al 2007; McManus et al 2007) and Pacific regions (Dagg 1993; Dam et al 1995; Bollens & Landry 2000). Grazing studies from the Bay of Bengal are none so far. In order for assessing the grazing pressure of micro and mesozooplankton on phytoplankton and bacteria experiments were set up on-board during the NEM.

Table 7.1. Microcosm experimental set up for analyzing the effect of grazing by mesozooplankton (ZP) and microzooplankton (MZP) on phytoplankton and bacteria under nutrient enrichment

Experimental set up	Microcosm						
	C	**M1**	**M2**	**M3**	**ZP1**	**ZP2**	**ZP3**
200 μM passed SW (L)	5	5	2.5	1.25	5	5	5
GF/C FSW* (L)	0	0	2.5	3.75	0	0	0
ZP (biomass)	0	0	0	0	1/4[@]	1/8[@]	1/16[@]
MZP (dilution %)	0	0	50	75	0	0	0

The concentrations of nutrients added were, nitrate: (N =5 μM as $NaNO_3$), phosphate (P= 0.3 μM as $Na_2H_2PO_4$) and silicate (Si= 5 μM Na_2SiO_4). The same designation of experiments is used in all the graphs. Nutrients were not added into microcosms designated as C. *FSW-filtered seawater. [@]The ¼ , 1/8 and 1/16 biomass respectively corresponded to 147, 86 and 67 individuals L^{-1} in the microcosms at OB1; 460, 280 and 67 individuals L^{-1} at OB2 and, 920, 745 and 370 individuals L^{-1} at WB

Microcosm experiments were set up to cover different regions of the Bay of Bengal as described in the previous chapter.

Materials and Methods

Experimental set up

Grazing experiments were carried out onboard in microcosms each with a capacity of 5 liters at three locations at 9°N 88°E (Open Bay 1 [OB1]), 20°N 88°E (Open Bay 2 [OB2]) and at 15°N 83°E (Western Bay [WB])). Each experiment included two sub sets. In one the effect of microzooplankton (MZP) grazing on phytoplankton by using the dilution technique (Landry & Hasset 1982) was conducted. In the other, mesozooplankton (ZP) grazing effect was studied by adding ZP (Calbet & Landry 1999). These experiments were carried out for 7 days.

Prior to the cruise all the experimental bottles, tubing and other experimental materials were soaked in 1N HCL overnight and then washed thoroughly with de-ionized water. These were also washed thoroughly between each use on board. For each experiment, seawater was collected from <10 m using a 30 L GO-Flo bottle. It was passed through 200 μM mesh piece and filled in 20 liter clean carbouys to be used in the experiments. As much as 20 L was then filtered under low vaccum through GF/C (poresize~1.2 μm) filters and was used as dilution medium. Natural seawater was diluted to achieve: no dilution (meaning only 200 μM passed sea water [a]), 50% dilution (equal volumes of [a] above + GF/C passed sea water [b]) and 75% dilution (25% of [a] + 75% of [b]) in 5 L bottles in the first three microcosms (Table 7.1) to study the effect of microzooplankton grazing on phytoplankton present in undiluted natural seawater that passed through 200 μm bolting silk. Nitrate (as $NaNO_3$) at 5μM, silicate (as Na_2SiO_4) at 5 μM and phosphate (as $Na_2H_2PO_4$) at 0.3 μM were added to six of the microcosms. The last bottle was filled with undiluted natural seawater without added nutrients to provide a control for the effects of nutrient enrichment on phytoplankton growth. Mesozooplankton was collected by a 10 min oblique tow in the upper 10 m using a 200 μm mesh Bongo net. A Flow meter was attached to the net to determine the volume of water filtered. The collections were carefully poured into a clean container and zooplankton that was collected was divided equally using a Folsom Splitter. Three

microcosms containing 200 μm passed seawater were added either1/4, 1/8 or 1/16 volume of the mesozooplankton. About 1/4 of the mesozooplankton sample was preserved with 4% buffered formalin for identification and enumeration. The microcosms were at ship-board temperature of ~26°C which matched with the ambient temperatures of the Bay at the time of sampling. A 12-hour light: 12 hour dark cycle was maintained with an illumination of 1000 lux (~200 μE). Samples for nutrients, chl *a*, phytoplankton abundance, bacterial abundance, mesozooplankton and microzooplankton were collected on day 0, 2, 4 and 7 for requisite analyses.

Analyses of different parameters

Nutrients

On all sampling days 100 ml sample from each microcosm was collected into clean pre washed plastic bottles and frozen at -20°C until taken up for analyses. The nutrients were analyzed using a SKALAR autoanalyser following Grasshoff et al (1983).

Chlorophyll *a* (Chl *a*)

Four hundred milliliter of water samples from different microcosms were collected on all sampling days and filtered immediately through GF/F filter papers using low vaccum. Chlorophyll measurements are the same as described in the previous chapters.

Phytoplankton enumeration

Samples of 100 ml volumes were collected from different microcosms on day 0, 2, 4 and 7 and fixed with Lugol's iodine (1% w/v) and 3% formaldehyde. They were then stored in dark until analyses. The detailed analytical procedure is as given in chapter -3.

Bacterial abundance

The water samples (10 ml aliquots) were fixed with 0.22 μm prefiltered formaldehyde (final concentration of 3%) and stored at 4°C in the dark as per JGOFS Protocols (UNESCO 1994) until slide preparation. Bacterial enumeration following acridine orange direct counts (AODC) was carried out according to Parsons et al (1984). Detailed description is given in Chapter 6.

Microzooplankton abundance (MZP)

Water samples of 100 ml volumes were preserved with Lugol's iodine and brought back to the lab. After settling the MZP for a day or two in a long cylinder, the samples were concentrated to less than 10 ml by siphoning out water only. This was achieved by covering one end of the tube with 10 μm mesh piece. One ml of the concentrated sample was then counted using the Sedgewick- Rafter slide. All the intact microzooplankton cells on the slide were counted and identified.

Mesozooplankton abundance (ZP)

One hundred milliliters of the samples were taken out on all sampling days and preserved with formalin for enumerating the mesozooplankton. They were counted using a Bogrov- chamber in the lab. The zooplankton was identified upto group level.

Estimation of Zooplankton Grazing Impact on Chlorophyll *a*

The Grazing impact of both the ZP and MZP was calculated using the formula of Landry and Hassett (1982).

$$\text{Grazing impact} = \frac{\ln \text{chl } a_F - \ln \text{chl } a_I}{\text{incubation time in days between sampling}}$$

where, F and I are final and initial concentrations of chlorophyll *a*. To differentiate the grazing of MZP from that of ZP+MZP together, the average values of grazing impact in MZP microcosms were subtracted from ZP+MZP microcosms. This way it was possible to derive the ZP grazing impact also.

Results

OB1 Experiment (9°N 88°E)

Nutrients

In general, the concentration of nutrients wasn't very different between the microcosms. Nitrate decreased over days in all the bottles (Fig. 7.1A; 7.1B). The silicate increased marginally and phosphate decreased in the first three microcosms without added mesozooplankton. In the bottles with added mesozooplankton however, phosphate concentrations increased as days went by (Fig. 7.1B).

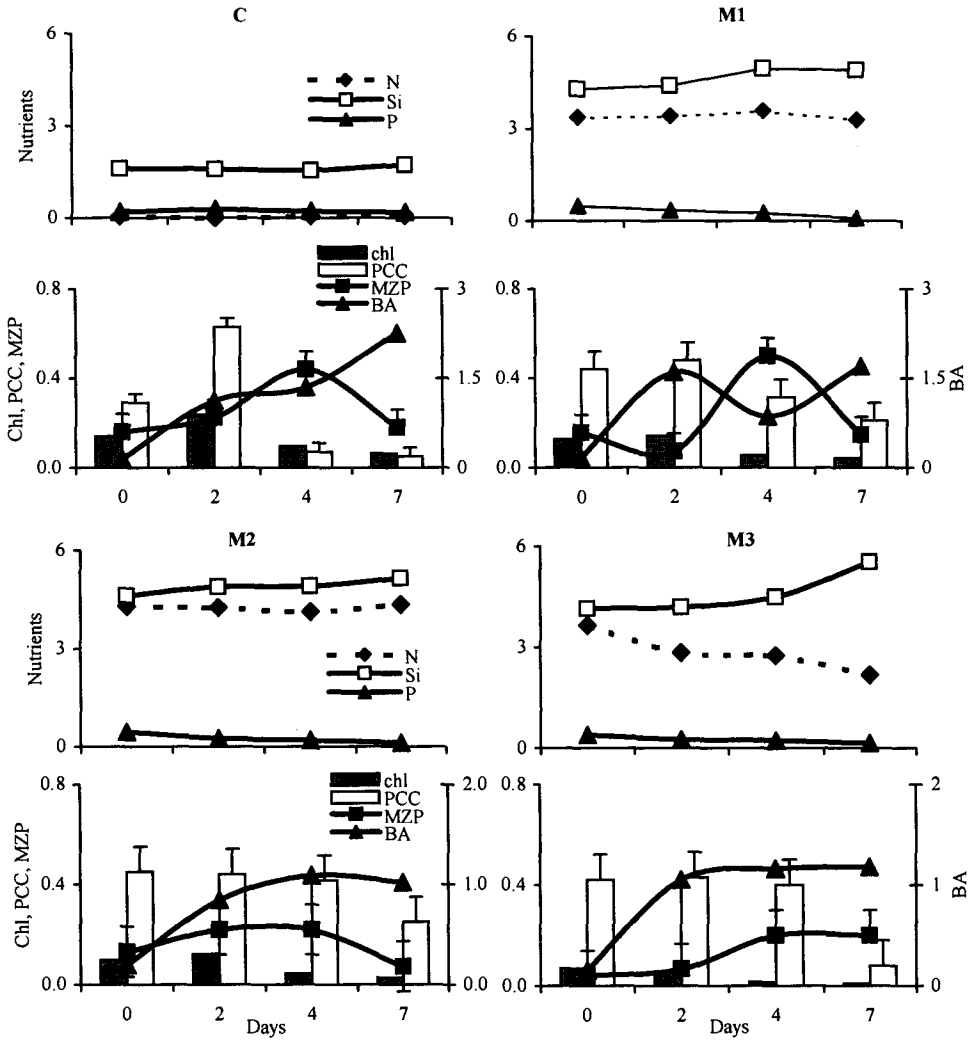


Fig. 7.1A. Effect of microzooplankton (MZP) grazing on different biological parameters under altered nutrient concenterations in microcosms M1-M3 set up at 9°N 88°E. Units are nutrients (μM), chlorophyll *a* (chl, mg m^{-3}), phytoplankton abundance (PCC, Nos x 10^3 L^{-1}), bacterial abundance (BA, Nos x 10^{10} L^{-1}) and microzooplankton (MZP, Nos x 10^3 L^{-1}). Legends on the left side also hold good for the graphs on the right side. Error bars denote standard deviations

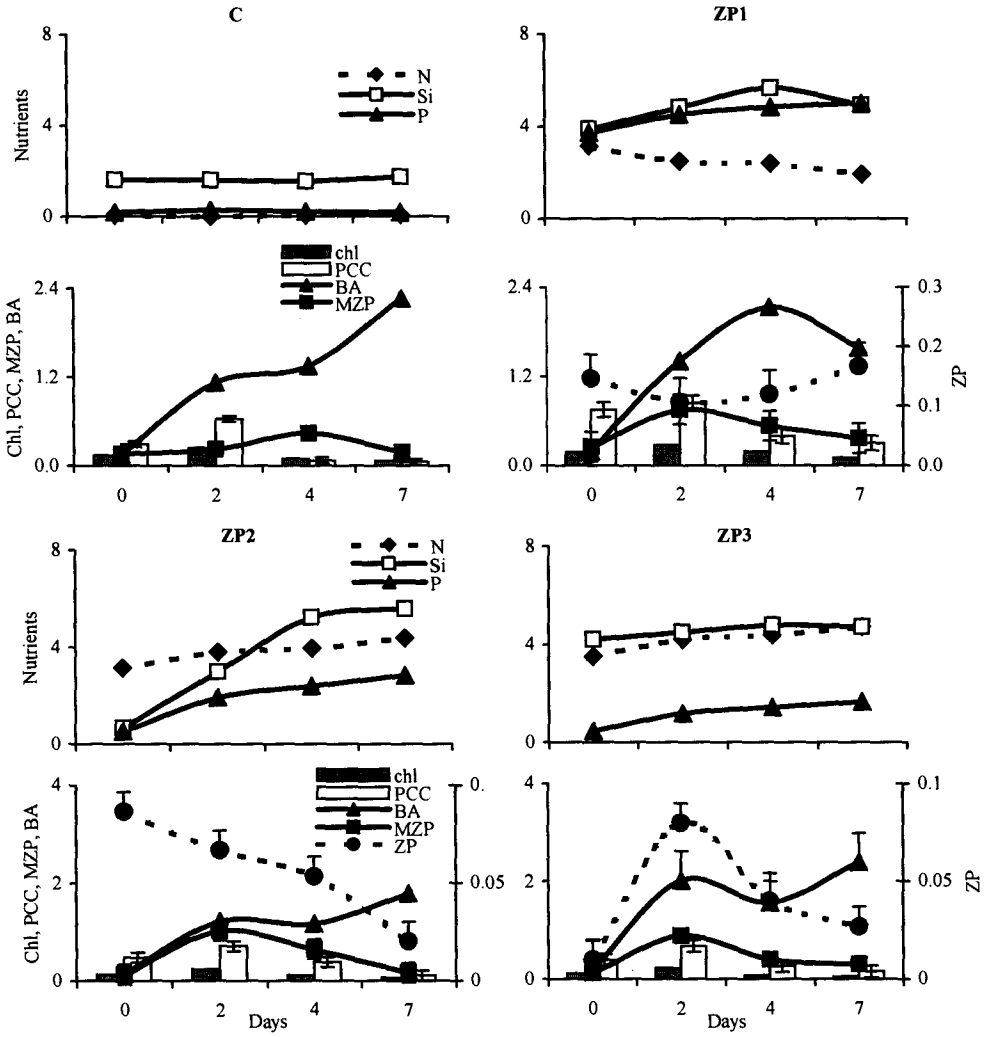


Fig. 7.1B. Effect of mesozooplankton and microzooplankton grazing on different biological parameters for the grazing experiment conducted at 9°N 88°E. Units of expression are nutrients (μM), chlorophyll *a* (chl, mg m^{-3}), phytoplankton abundance (PCC, Nos x 10^3 L^{-1}), bacterial abundance (BA, Nos x 10^{10} L^{-1}), microzooplankton (MZP, Nos x 10^3 L^{-1}) and mesozooplankton (ZP, Nos x 10^3 L^{-1}). Legends on the left side also hold good for the graphs on the right side. Error bars denote standard deviations

Biological Parameters

The chlorophyll *a* (chl *a*) concentrations (Fig. 7.1A) increased by day 2 in all the microcosms. Microcosms with added mesozooplankton (ZP) had higher chl *a* concentration than others (Fig. 7.1B). Phytoplankton cell counts (PCC) decreased from day 2 in the microcosms containing the ZP. In microcosms with microzooplankton (MZP), PCC decreased continuously in M2 while in M1 and M3 it decreased after day 2 and 4 respectively. On day 0, the phytoplankton composition consisted of the following species *Chaetoceros* sp, *Licmophora* sp, *Mastoglia rostrata*, *Navicula* sp, *N. distans*, *Synedra* sp, *Thalassionema nitzschioides*, *Oxytoxum* sp and *Dicytocha crux* in the different microcosms. While the species observed on day seven are listed in Table 7.2. The bacterial abundance increased with days in all microcosms with minor aberrations.

The MZP peaked at different times in each microcosm. The dominant were the ciliates followed by the *Protoperidinium* sp in all the microcosms (Table 7.3). In that, the MZP increased in abundance until day 4 and decreased thereafter in the control, M1 and M2. In M3, containing 75% dilution of 200 μM passed seawater, the increase in MZP abundance was gradual. Mostly, peaking on day 2 and then decreasing, the MZP abundance was high in all the three microcosms with added ZP (Fig. 7.1B). The ZP abundance increased marginally during the 7-day period in the microcosm with 147 individuals added on day 0 in the ZP1 microcosm. Although the microcosm ZP2 had lower numbers (86) than ZP1, their abundance decreased with days in ZP2. However, in ZP3 which had the lowest added 67 individuals, ZP counts increased by day 2 and decreased thereafter suggesting that phytoplankton in microcosm ZP3 could support them only during the initial period. This can also be inferred from the decreases in chl *a* and PCC. Copepods formed the dominant group in the ZP composition followed by invertebrate eggs, copepod nauplii, polychaetes and chaetognaths (Table 7.4). The number of copepod nauplii increased until day 4. In the microcosm ZP1which had the highest added individuals of zooplankton, the increase in their numbers corresponded to the decrease in the MZP, PCC and chl *a*. While in ZP2, with lower numbers of added ZP, chl *a*, PCC, MZP and ZP showed an increase on day 2 decreased gradually thereafter. The decrease in chl *a* was maximum in microcosm ZP3 with the least number of added ZP individuals. In the control, the increase of MZP in the microcosm

Table 7.2. Phytoplankton species composition on day 7 in different microcosms in grazing experiment conducted at 9°N 88°E

Phytoplankton species	**Microcosm**						
	C	**M1**	**M2**	**M3**	**ZP1**	**ZP2**	**ZP3**
Amphora sp	*	40	*	*	*	*	*
Coscinodiscus granii	*	*	*	40	*	*	*
Coscinodiscus sp	*	40	*	*	255	110	95
Navicula distans	*	*	*	*	45	*	30
Navicula sp	*	*	120	*	*	*	30
Peridinium sp	*	90	130	*	*	*	*
Triceratium weissei	45	*	*	*	*	*	*
Dictyocha crux	*	40	*	*	*	*	*
Dictyocha speculum	*	*	*	40	*	*	*
Total cells L^{-1}	45	210	250	80	300	110	155

'*' denotes not detected

Table 7.3. Microzooplankton (MZP) composition on different days and microcosms in experiment conducted at 9°N 88°E

Microcosm	Day	Nos L^{-1}	MZP Group#						
			1	2	3	4	5	6	7
C	0	160	160	*	*	*	*	*	*
	2	225	113	*	*	*	*	*	113
	4	440	440	*	*	*	*	*	*
	7	180	120	*	*	*	60	*	*
M1	0	156	*	*	156	*	*	*	*
	2	73	*	*	*	73	*	*	*
	4	500	100	300	*	*	100	*	*
	7	180	120	*	*	*	60	*	*
M2	0	132	132	*	*	*	*	*	*
	2	220	147	*	*	73	*	*	*
	4	220	110	110	*	*	*	*	*
	7	73	73	*	*	*	*	*	*
M3	0	40	40	*	*	*	*	*	*
	2	67	67	*	*	*	*	*	*
	4	200	200	*	*	*	*	*	*
	7	200	67	133	*	*	*	*	*
ZP1	0	250	125	125	*	*	*	*	*
	2	750	750	*	*	*	*	*	*
	4	533	400	*	*	*	*	133	*
	7	367	367	*	*	*	*	*	*
ZP2	0	130	*	*	*	125	*	*	*
	2	1013	788	225	*	*	*	*	*
	4	640	480	*	160	*	*	*	*
	7	160	80	*	80	*	*	*	*
ZP3	0	125	*	*	125	*	*	*	*
	2	875	875	*	*	*	*	*	*
	4	400	400	*	*	*	*	*	*
	7	300	300	*	*	*	*	*	*

#1: Ciliates, 2: Protoperidinium, 3: Strombidinium, 4: Tintinnid,
5: Orinithoceros, 6: Unidentified, 7: Radiolarians. '*'denotes not detected

Table 7.4. Mesozooplankton (ZP) composition in different microcosms on different days in experiment conducted at 9°N 88°E

Microcosm	Day	Nos L^{-1}	ZP Group#				
			1	2	3	4	5
ZP1	0	147	53	67	*	67	20
	2	107	27	80	*	*	*
	4	120	53	40	27	*	*
	7	166	120	13	33	*	*
ZP2	0	86	13	73	*	*	*
	2	66	13	40	13	*	*
	4	53	26	27	*	*	*
	7	20	*	20	*	*	*
ZP3	0	67	67	*	*	*	*
	2	80	*	40	40	*	*
	4	40	*	40	*	*	*
	7	27	20	7	*	*	*

#1: Copepods, 2: Invertebrate eggs, 3: Copepod nauplii, 4: Polychaetes, 5: Chaetognaths. '*'denotes not detected

corresponded to the decrease in PCC and BA on day 4. By day 7, decrease in MZP corresponded to increase in the BA.

OB2 Experiment (20°N 88°E)

Nutrients

The concentrations of nitrate, phosphate and silicate did not vary much with increase in days in the microcosms with the MZP. An increase in concentrations of all three nutrients was observed in the ZP added microcosms (Fig. 7.2A; Fig. 7.2B).

Biological Parameters

The chl *a* (Fig. 7.2A; Fig. 7.2B) decreased in four of the seven microcosms by day 4 or 7 (except in control, M1 and ZP2). Higher concentration of chl *a* (and PCC) was observed in all the bottles except for M2 and M3. In the bottles with added mesozooplankton (ZP1, ZP2 and ZP3) a decrease in PCC was observed on day 2 and, thereafter not much variation in PCC was seen. On day 0, the phytoplankton composition consisted of the following species *Bacteriastrum furcatum*, *Ceratium trichoceros*, *Chaetoceros coarctatus, C. compressus*, *C. didymus*, *C. eibenii*, *C. peruvianus*, *Cylindrotheca closterium*, *Denticulopsis seminae*, *Ditylium brightwellii*, *Guinardia striata*, *Hemiaulaus hauckii*, *Licmophora* sp, *Leptocylindrus mediterraneus*, *Navicula* sp, *N. distans*, *Nitzschia* sp, *Pseudo-nitzschia* sp, *Rhizosolenia* sp, *R. hebetata*, *R. imbricata*, *R. setigera*, *Skeletonema costatum*, *Synedra* sp, *Thalassionema nitzschioides*, *Thalassiothrix fauenfeldii*, *Thalassiosira* sp in the different microcosms. While the species that remained by day seven are listed in Table 7.5.

Bacterial abundance increased by day 2 in M2, M3 and ZP2 and decreased thereafter. In bottle ZP3, the bacterial counts were less on day 2 but increased by day 4 to reach their peak.

The MZP peaked at different times in each microcosm. The dominant were the ciliates in all the microcosms (Table 7.6). The MZP decreased until day 2 and increased by day 4 and thereafter decreased in the M1, M2 and M3 microcosms by day 7. The highest

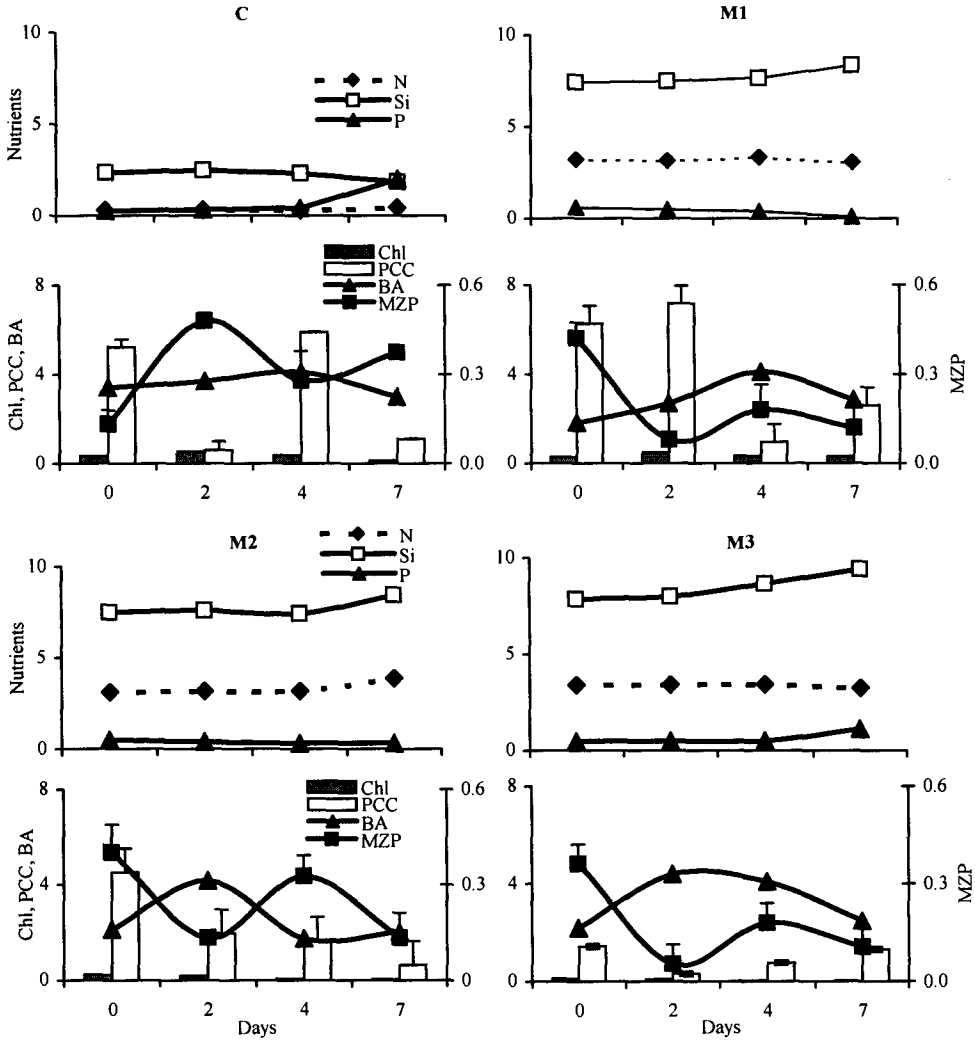


Fig. 7.2A. Effect of microzooplankton (MZP) grazing on different biological parameters under altered nutrient concenterations in microcosms M1-M3 set up at 20°N 88°E. Units are nutrients (μM), chlorophyll *a* (chl, mg m^{-3}), phytoplankton abundance (PCC, Nos x 10^3 L^{-1}), bacterial abundance (BA, Nos x 10^{10} L^{-1}) and microzooplankton (MZP, Nos x 10^3 L^{-1}). Legends on the left side also hold good for the graphs on the right side. Error bars denote standard deviations

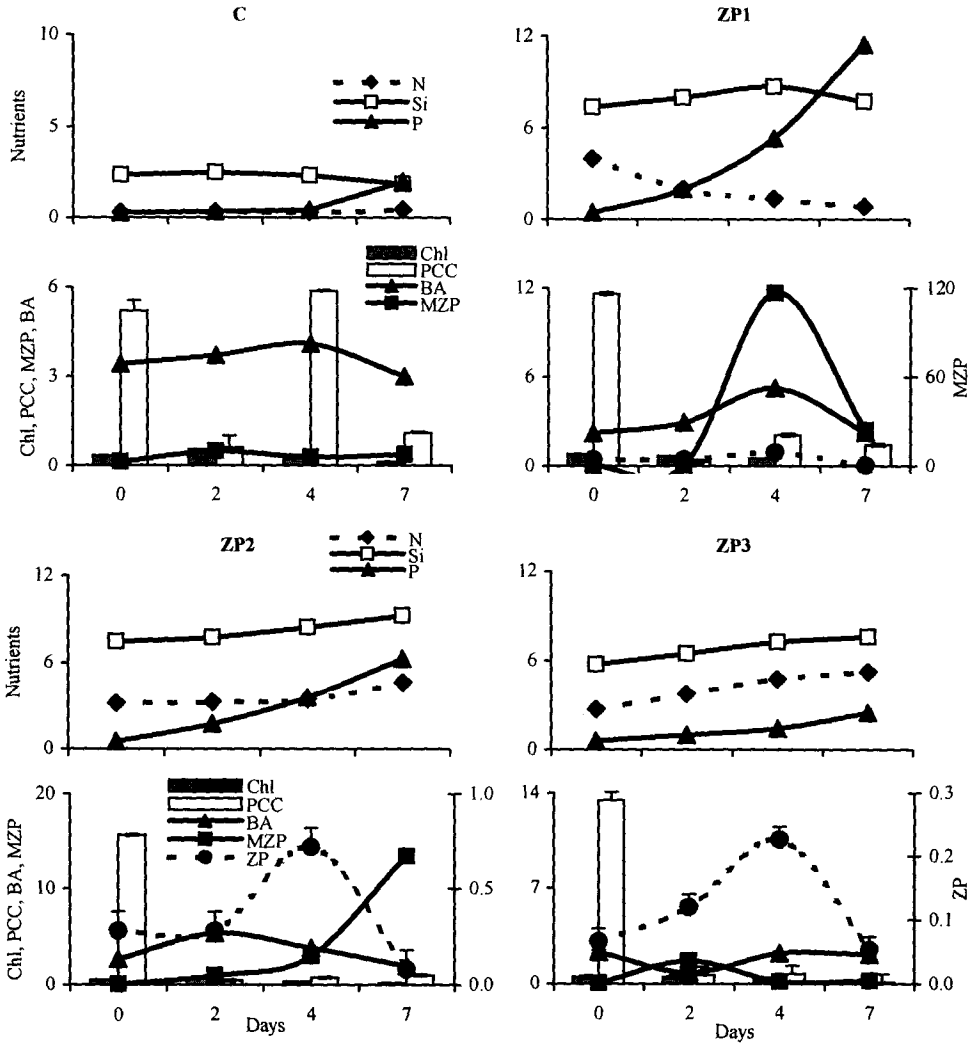


Fig. 7.2B. Effect of mesozooplankton and microzooplankton grazing on different biological parameters for the grazing experiment conducted at 20°N 88°E. Units of expression are nutrients (μM), chlorophyll *a* (chl, mg m^{-3}), phytoplankton abundance (PCC, Nos x 10^3 L^{-1}), bacterial abundance (BA, Nos x 10^{10} L^{-1}), microzooplankton (MZP, Nos x 10^3 L^{-1}) and mesozooplankton (ZP , Nos x 10^3 L^{-1}). Legends on the left side also hold good for the graphs on the right side. Error bars denote standard deviations

Table 7.5. Phytoplankton species composition on day 7 in different microcosms in grazing experiment conducted at 20°N 88°E

Phytoplankton species	**Microcosm**						
	C	**M1**	**M2**	**M3**	**ZP1**	**ZP2**	**ZP3**
Bacteriastrum furcatum	110	*	40	*	*	*	*
Biddulphia sinensis	*	*	*	*	130	*	*
Chaetoceros coarctatus	*	390	*	*	*	*	*
Chaetoceros didymus	110	650	280	390	260	330	*
Chaetoceros eibenii	*	130	40	390	*	*	*
Chaetoceros peruvianus	*	*	40	*	*	*	*
Chaetoceros curvisetus	*	*	*	520	*	*	*
Coscinodiscus sp	*	*	*	*	390	*	*
Cylindrotheca closterium	*	130	*	*	*	*	*
Ditylium brightwellii	*	*	40	*	*	*	*
Licmophora sp	*	*	40	*	*	*	*
Leptocylindrus mediterraneus	*	*	40	*	*	*	*
Navicula directa	*	130	*	*	*	*	*
Navicula distans	*	260	*	*	*	*	*
Navicula sp	*	130	*	*	390	660	110
Peridinium sp	*	130	*	*	*	*	*
Podolampas palmipes	*	*	40	*	*	*	*
Pseudo-nitzschia sp	*	130	*	*	*	*	*
Rhizosolenia imbricata	*	130	*	*	*	*	*
Skeletonema costatum	550	*	*	*	*	*	*
Synedra sp	110	*	80	*	130	*	*
Thalassionema nitzschioides	110	130	*	*	*	*	*
Thalassiosira sp	*	130	*	*	130	*	*
Triceratium reticulatum	110	130	*	*	*	*	*
Total cells L^{-1}	1100	2600	640	1300	1430	990	110

'*' denotes not detected

Table 7.6. Microzooplankton (MZP) composition on different days and microcosms in experiment conducted at 20°N 88°E

Microcosm	Day	Nos L^{-1}	MZP Group#						
			1	2	3	4	5	6	7
C	0	133	*	*	*	133	*	*	*
	2	480	*	*	480	*	*	*	*
	4	280	*	93	*	187	*	*	*
	7	370	*	160	*	*	160	53	*
M1	0	420	180	180	*	60	*	*	*
	2	80	*	80	*	*	*	*	*
	4	180	120	*	*	60	*	*	*
	7	120	*	*	*	120	*	*	*
M2	0	400	132	*	*	201	*	67	*
	2	133	*	133	*	*	*	*	*
	4	327	47	93	*	140	*	*	47
	7	133	67	67	*	*	*	*	*
M3	0	360	60	*	*	180	60	60	*
	2	53	*	53	*	*	*	*	*
	4	180	*	180	*	*	*	*	*
	7	107	*	*	*	107	*	*	*
ZP1	0	67	*	*	*	*	*	*	67
	2	360	*	*	360	*	*	*	*
	4	116667	116667	*	*	*	*	*	*
	7	24200	21067	3067	*	67	*	*	*
ZP2	0	60	*	*	*	*	60	*	*
	2	960	*	*	900	60	*	*	*
	4	3000	3000	*	*	*	*	*	*
	7	13440	12240	1200	*	*	*	*	*
ZP3	0	60	60	*	*	*	*	*	*
	2	1680	*	*	1680	*	*	*	*
	4	180	180	*	*	*	*	*	*
	7	240	120	120	*	*	*	*	*

#1: Ciliates, 2: Unidentified, 3: Eulotides, 4: Protperidinium, 5: Strombidinium, 6: Radiolarian, 7: Tintinnid. '*' denotes not detected

Table 7.7. Mesozooplankton (ZP) composition in different microcosms on different days in experiment conducted at 20°N 88°E

Microcosm	Day	Nos L^{-1}	ZP Group#							
			1	2	3	4	5	6	7	8
ZP1	0	460	320	127	*	*	13	*	*	*
	2	460	267	194	*	*	*	*	*	*
	4	933	573	347	*	13	*	*	*	*
	7	67	40	27	*	*	*	*	*	*
ZP2	0	280	160	67	*	*	13	27	*	13
	2	280	147	133	*	*	*	*	*	*
	4	720	560	40	67	53	*	*	*	*
	7	80	80	*	*	*	*	*	*	*
ZP3	0	67	40	27	*	*	*	*	*	*
	2	120	53	27	27	*	*	*	13	*
	4	227	213	*	*	13	*	*	*	*
	7	53	53	*	*	*	*	*	*	*

#1: Copepods, 2: Invertebrate eggs, 3: Copepod eggs, 4: Copepod nauplii, 5: Chaetognaths, 6: Decapod, 7: Salp, 8: Siphonophore. '*' denotes not detected

abundance of MZP was observed in ZP1. In microcosms, ZP3, ZP1 and ZP2, the MZP peaked respectively by day 2, day 4 and day 7.

The ZP abundance increased from 460 individuals L^{-1} on day 0 to 933 L^{-1} in ZP1 by day 4 in ZP1 (Table 7.7). In the ZP2 and ZP3, the ZP abundance peaked on day 4 and in general decreased thereafter. Their peaks coincided with the microzooplankton high in ZP1. Copepods were the dominant group followed by invertebrate eggs, copepod eggs, copepod nauplii, chaetognaths, decapod, salps and siphonophore. Copepod nauplii were observed only on day 4 (Table 7.7).

In the microcosm ZP1 the ZP, MZP, PCC, chl *a* and BA increased up to day 4 and decreased then on. Decrease in chl *a* was maximum in ZP1 compared to other microcosms. While in ZP2, the increase in the ZP numbers corresponded to decrease in the BA on day 4. By day 7, decrease in the ZP and BA abundance corresponded to increase in the MZP and PCC. In ZP3, the increase in ZP numbers corresponded to decrease in MZP while the PCC and BA increased.

Western Bay Experiment (WB, 15°N 83°E)

Nutrients

Nitrate decreased after day 4 in Control and M1. However, in all other microcosms, it decreased with time. Silicate concentrations did not vary much. The phosphate concentration that did not vary much in the MZP microcosms (Fig. 7.3A) increased with time in the microcosms with added ZP (Fig. 7.3B).

Biological Parameters

The chl *a* peaked on day 2 and decreased thereafter in M1, M2, ZP3 and Control. In ZP1 it peaked on day 2 and again on day 7. While, in M3 and ZP2 a gradual decrease with increase in days was observed. The PCC in M1 and M2 peaked on day 2 and decreased thereafter. With the exception of M3, in the rest of the microcosms, the abundance decreased on day 2 and then increased slightly on the last day. The phytoplankton composition in different microcosms on day 0 consisted of the following species *Bacteriastrum furcatum*, *Chaetoceros didymus*, *C. eibenii*, *C. messanenies*,

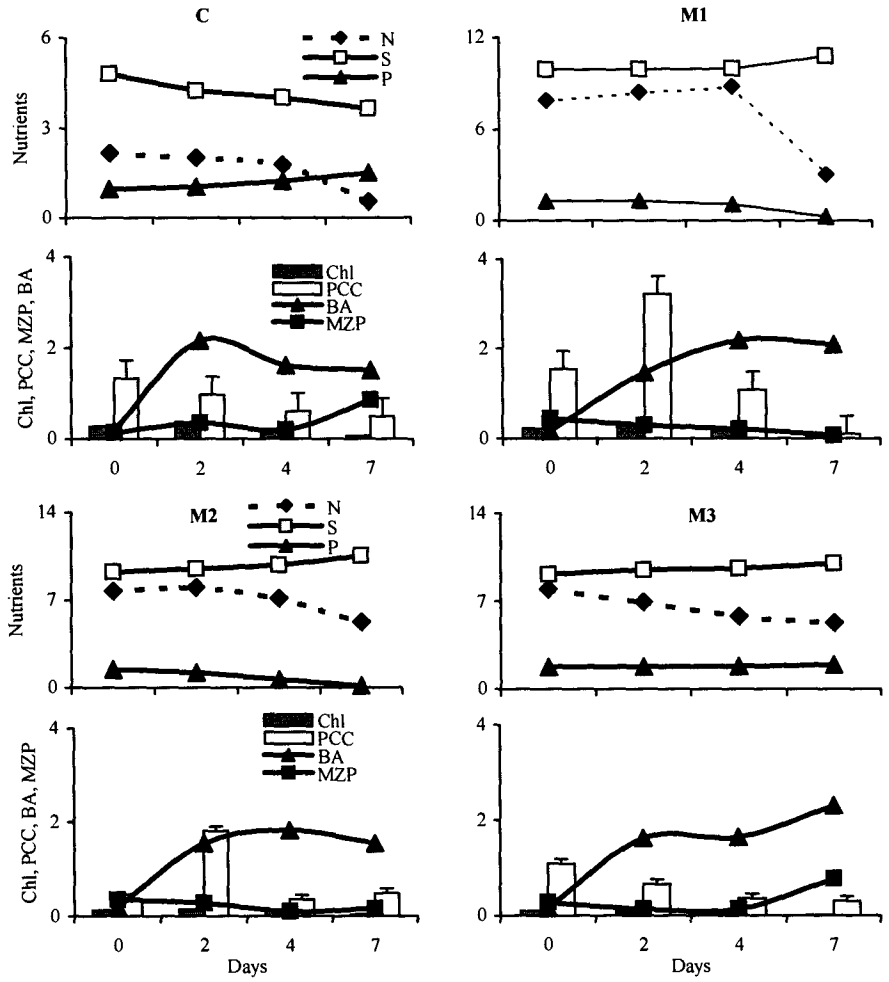


Fig. 7.3A. Effect of microzooplankton (MZP) grazing on different biological parameters under altered nutrient concenterations in microcosms M1-M3 set up at 15°N 83°E. Units are nutrients (μM), chlorophyll *a* (chl, mg m^{-3}), phytoplankton abundance (PCC, Nos x 10^3 L^{-1}), bacterial abundance (BA, Nos x 10^{10} L^{-1}) and microzooplankton (MZP, Nos x 10^3 L^{-1}). Legends on the left side also hold good for the graphs on the right side. Error bars denote standard deviations

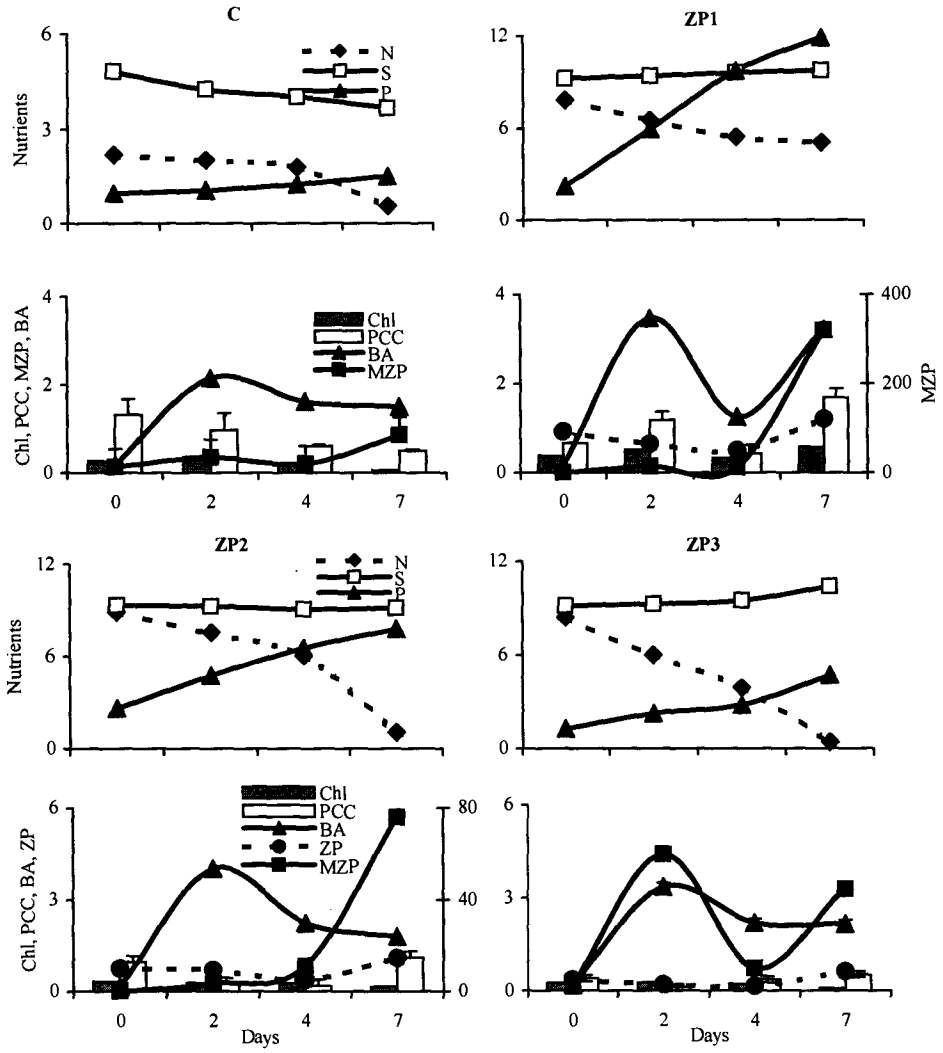


Fig. 7.3B. Effect of mesozooplankton and microzooplankton grazing on different biological parameters for the grazing experiment conducted at 15°N 83°E. Units of expression are nutrients (μM), chlorophyll *a* (chl, mg m^{-3}), phytoplankton abundance (PCC, Nos x 10^3 L^{-1}), bacterial abundance (BA, Nos x 10^{10} L^{-1}), microzooplankton (MZP, Nos x 10^3 L^{-1}) and mesozooplankton (ZP, Nos x 10^3 L^{-1}). Legends on the left side also hold good for the graphs on the right side. Error bars denote standard deviations

Coscinodiscus sp, *Ditylium brightwellii*, *Navicula* sp, *Rhizosolenia alata*, *R. imbricata*, *R. setigera*, *Synedra* sp and *Thalassionema nitzschioides*. While the species that remained by day seven are listed in Table 7.8.

The BA gradually increased in C, M1, M2 and M3. In the bottles wherein the mesozooplankton were added in different concentrations the bacterial abundance peaked on day 2 and decreased thereafter in bottles ZP2 and ZP3. In ZP1 with the highest numbers of added mesozooplankton (920 individuals L^{-1}), the BA peaked on day 2 and day 7. These peaks coincided with the decrease in PCC in ZP2 and ZP3 microcosms.

The MZP composition was similar to that observed in the previous two experiments with the ciliates dominating (Table 7.9). Their counts in M1 and M2, decreased with increasing duration. In bottle M3 and control, the MZP counts peaked by day 7. The MZP abundance peaked by day 7 also in ZP1 and ZP2. A secondary peak in their counts was seen observed on day 7 in bottle ZP3.

The ZP abundance increased by day 7 in all the ZP added microcosms. The high counts of ZP coincided with the high counts of MZP in all microcosms. The ZP composition was dominated by copepods followed by copepod eggs, other invertebrate eggs, copepod nauplii, polychaetes, siphonophores and chaetognaths (Table 7.10). Only PCC and BA showed an increase on day 2 while the ZP decreased till day 4 in microcosm ZP1, though all parameters showed increases by day 7. In ZP2, BA increased on day 2 and decreased thereafter. This decrease corresponded with the increase in ZP and MZP. The PCC however, also increased by day 7 suggesting that the MZP fed mostly on bacteria. The same was also true for ZP3 by day 7.

The ZP grazing impact in percent terms was different at different locations in the Bay (Table 7.11). At OB1, grazing both by MZP and ZP was very intense by day 2 indicating rapid decline in chl *a* as well as PCC. With the decline in chl *a*, the grazing percent also decreased. Though large numbers of copepods and ciliates were present on day 7, they may have been supported by bacteria (Table 7.3; Fig. 7.1A; 7.1B). This could mean that both MZP and ZP rely mostly on bacteria when the chl *a*

Table 7.8. Phytoplankton species composition on day 7 in different microcosms in grazing experiment conducted at 15°N 83°E

Phytoplankton species	**Microcosm**						
	C	**M1**	**M2**	**M3**	**ZP1**	**ZP2**	**ZP3**
Chaetoceros didymus	210	*	*	*	*	*	*
Coscinodiscus sp	*	*	*	100	140	*	*
Navicula sp	70	*	*	*	*	*	*
Peridinium sp	*	*	120	*	140	*	*
Peridinium sphaericum	70	*	*	*	*	*	*
Rhizosolenia imbricata	*	100	*	*	*	*	*
Rhizosolenia setigera	*	*	*	100	*	*	*
Synedra sp	*	*	*	100	*	*	*
Thalassionema nitzschioides	*	*	240	*	980	1100	520
Thalassiosira sp	140	*	120	*	420	*	*
Total cells L^{-1}	490	100	480	300	1680	1100	520

'*' denotes not detected

Table 7.9. Microzooplankton (MZP) composition on different days and microcosms in experiment conducted at 15°N 83°E

Microcosm	Day	Nos L^{-1}	MZP Group#				
			1	2	3	4	5
C	0	140	*	140	*	*	*
	2	350	140	*	70	70	70
	4	200	200	*	*	*	*
	7	850	750	*	*	100	*
M1	0	450	450	*	*	*	*
	2	300	120	60	120	*	*
	4	210	70	*	140	*	*
	7	80	80	*	*	*	*
M2	0	350	140	140	70	*	*
	2	280	140	*	140	*	*
	4	100	100	*	*	*	*
	7	160	120	40	*	*	*
M3	0	280	*	280	*	*	*
	2	140	140	*	*	*	*
	4	140	70	*	70	*	*
	7	770	770	*	*	*	*
ZP1	0	140	140	*	*	*	*
	2	14250	14250	*	*	*	*
	4	12000	11950	*	50	*	*
	7	320000	320000	*	*	*	*
ZP2	0	120	60	*	60	*	*
	2	3280	3280	*	*	*	*
	4	11200	11200	*	*	*	*
	7	76000	76000	*	*	*	*
ZP3	0	180	*	90	*	90	*
	2	4410	4410	*	*	*	*
	4	720	640	*	80	*	*
	7	3290	3290	*	*	*	*

#1: Ciliates, 2: Radiolarian 3: Protperidinium, 4: Strombidinium, 5: Ornithoceros. '*' denotes not detected

Table 7.10. Mesozooplankton (ZP) composition in different microcosms on different days in experiment conducted at 15°N 83°E

Microcosm	Day	Nos L^{-1}	ZP Group#						
			1	2	3	4	5	6	7
ZP1	0	920	850	*	25	35	5	*	5
	2	645	635	*	*	10		*	*
	4	500	490	*	10	*	*	*	*
	7	1210	1100	100	*	10	*	*	*
ZP2	0	745	640	*	60	45	*	*	*
	2	700	575	*	65	60	*	*	*
	4	390	230	150	10	*	*	*	*
	7	1065	1055	*	*	10	*	*	*
ZP3	0	370	335	*	25	*	5	5	*
	2	205	160	25	20	*	*	*	*
	4	145	140	*	5	*	*	*	*
	7	630	630	*	*	*	*	*	*

#1: Copepods, 2: Copepod eggs, 3: Invertebrate egg, 4: Copepod nauplii, 5: Polychaetes, 6: Siphonophore, 7: Chaetognath. '*' denotes not detected

Table 7.11. Grazing impact on chl *a* by microzooplankton (MZP) and zooplankton (ZP) at Open Bay 1 (OB1), Open Bay 2 (OB2) and Western Bay (WB)

Station	Day	% of chl *a* grazing by	
		MZP	ZP
OB1	2	2.95	26.91
	4	-55.19	17.89
	7	-13.73	-4.00
OB2	2	0.65	0.80
	4	-38.14	15.96
	7	-67.00	-64.00
WB	2	3.53	0.11
	4	-20.87	9.48
	7	-39.45	29.45

concentrations become very low. At OB2 however, such clear pattern in grazing pressure was not seen. The maximum removal of chl *a* was by day 4. Since it did not show any increase later, it is inferable that the MZP feed mostly on bacteria. In the WB the grazing pressure by the ZP was maximum by day 7 while that of the MZP was on day 2. Although large-sized diatoms dominated in all microcosms, the calculated MZP grazing percent accounted for 0.65-3.53% of chl *a* disappearance.

Discussion

From the present set of experiments, it is discernible that changes in nutrient concentrations affect phytoplankton directly (and the bacterial community indirectly). Thereby, secondary trophic levels are affected. In the experiment at OB1, increase in PCC was observed only in ZP added microcosms while the ones having the MZP such an increase was not imminent. This increase in PCC could be attributed to the re-supply of nutrients in particular, ammonia and urea by the zooplankton excretion (Lehman & Sandgren 1985; Sterner 1986; 1990). This is also corroborated by the sharp increase in the phosphate concentrations in the bottles with added ZP. However, a close coupling between phytoplankton growth and the MZP grazing at the OB1 was observed ($R= 0.4869$; $p<0.02$) and WB ($R= 0.77$; $p<0.003$). This suggests that microzooplankton grazed on phytoplankton and the MZP increase reflected on their growth in the microcosms set up at these stations using the seawater collected from ~10 m at these stations. In mesocosm experiment carried out in the coastal waters of Denmark, a good correlation was observed between MZP and PCC (Schlüter 1998).

At OB1, the phytoplankton standing stock was sufficient to support the mesozooplankton biomass, at least initially. This can be taken for a top-down control. In that, when the sufficient phytoplankton are available, the ZP graze and, their growth in terms of increased number of individuals can occur. While the results from the on-board, microcosm experiments are insufficient to draw conclusive inferences, they are certainly indicative that ZP does exert a strong control on phytoplankton growth. When the added numbers of individuals of ZP were more, the decrease in PCC was rather rapid. With less numbers of added ZP individuals to microcosms with similar initial PCC and chl *a*, the latter did show some increases before finally decreasing. In the ensuing period, the ZP numbers showed an overall increase as a consequence of their

reproduction. This can be ascertained by the increased number of copepod eggs and naupliar stages mostly seen after day 4 or, by day 7. In the other two experiments at OB2 and WB, the initial standing stock of the phytoplankton could not sustain the ZP beyond day 2. From this observation it is suggested that the grazing control is quite strong. As Sterner & Hessen (1994) suggest food quality (species composition) than the food quantity may have limited the ZP growth due to which not much changes in their abundance were observed on the second day.

The worldwide daily ZP grazing is reported to vary regionally, inter- annually and seasonally but falling in the broad range of 0.10–18% (Dagg 1993; Dam et al 1995). From the daily differences of chl *a* in the microcosm experiments set up at different locations in BoB of this study, it is deducible that the ZP grazing was in the range of 0.11-29% (meaning, 0.29 times the amount of chl *a* consumed from the previous sampling day). Increases of ZP and MZP individuals in numbers when chl *a* and PCC declined firm up the fact that bacteria are fed up on by these groups. While the very high negative grazing pressures are apparently artifacts. For working out the grazing pressure in terms of % differences in chl *a*, its concentration from previous sampling day is subtracted from the day of sampling. If there was an increase in chl *a* on the last sampling day, the grazing % values became negative. Barring such artifacts, the mesozooplankton grazing impact in the BoB appears to be larger when compared to 0.5-7.7% daily ZP grazing along the equatorial Pacific (Zhang et al 1995). Thus, the phytoplankton alone may be insufficient to meet up the daily food requirements of ZP. This would suggest that apart from the direct consumption of phytoplankton, the ZP would have to feed on MZP (Gaudy et al 2004). This is reflected by the positive and significant correlation of ZP with MZP at OB2 ($R= 0.667$; $p<0.02$) and WB ($R= 0.638$; $p<0.03$). Detrietal matter plus bacteria that colonize the moribund and decaying particulates (that also include molts, feces, ZP carcasses, etc) can also serve as food for ZP. This can also be suggested from the predominance of omnivorous ZP groups observed in the experiments, especially after day 4 or later. Head et al (1999) also concluded that the ZP grazers have a smaller impact on phytoplankton biomass. These authors suggested that microzooplankton and detritus to be the major component of ZP diet.

When the phytoplankton abundance is low, clearance rate of ciliates by copepods was higher (Fessenden & Cowles 1994) suggesting microzooplankton as an important component of copepod diet. Further, MZP are known to contribute significantly to the diet of ZP even in the presence of large phytoplankton (Stoecker & Capuzzo 1990; Gifford 1991; Froneman et al 1996). In this study, copepods and ciliates became dominant with the progression of time in most microcosms. A decrease in copepods during day 2 to 4, in many microcosms may be due to their confinement without changing the waters in which the waste accumulation may have been a constraint. However, some omnivorous ZP groups and their nauplii did survive the experimental duration. It is well known that bacteria are the major diet of most MZP (see below). From the overall picture of the observations during this study, and from the significant positive relation between the MZP and the ZP in the northern and coastal regions, it is inferred that the microheterotrophs are crucial in the ecology, growth, reproduction and recruitment of mesozooplankton in the Bay.

Ciliates became dominant in dilution experiments of McManus & Ederington-Cantrell (1992); Ruiz et al (1998). These authors indicated that MZP maybe important grazers of the phytoplankton in the estuarine like marine regions. However, in the northern Bay that receives a huge influx of freshwater, no clear and significant ($R= 0.048$; $p<0.88$) relationship was observed between PCC and MZP. This could be due to the dominance of larger phytoplankton such as *Thalassiothrix longissima* and *Rhizosolenia* sp as compared to the nanophytoplankton which the protists prefer (Landry et al 2000). Further, from the observed strong coupling between bacteria and microzooplankton (which was dominated by the ciliates in this study), direct predation on bacteria by ciliates, is likely. This was also suggested by Børsheim (1984) and Turley et al (1986).

The MZP such as ciliates abound in the low chlorophyll seasons and regions in the oceans and are apparently sustained by bacteria (Cole et al 1988; Gauns et al 1996; Ramaiah et al 1996; Landry et al 1998). The Arabian Sea mesozooplankton stable biomass paradox was also suggested to be due to the importance of bacteria in operating the microbial loop (Madhupratap et al 1996). In many regions of the world oceans having low concentrations of chlorophyll bacterial carbon often exceeds phytoplankton carbon (Furham et al 1989). Unlike in the nutrient rich waters (Gasol et

al 1997), heterotrophic bacteria are also known to be generally more important in low productive waters, similar to those of BoB. As explained above, the substantial increases of bacterial abundance in the microcosms could be due to ZP which contributes to the increase in particulate organic matter. With this increase of bacteria, the MZP are major beneficiaries. In that ZP contribution to organic carbon help bacteria proliferate. And, as Blomqvist et al (2001) suggest, the changeover from phytoplankton (the basal food-resource) to bacterioplankton as their food as a result of labile organic carbon input from ZP. Large riverine influx with higher organic flux (Ittekot et al 1991; Prasanna Kumar et al 2002; 2004; Madhupratap et al 2003; Jane et al 2007 and references therein) makes an ideal place for high growth of bacteria. Regions similar to the BoB such as the northern Baltic Sea and the Gulf of Bothnia having a high influx of freshwater (Bergulund et al 2007) have a bacterial based food web to a large extent. In many pelagic systems allochthonous dissolved organic carbon (ADOC) supports bacterial growth and, the pelagic food web (Rolff & Elmgren 2000; Pace et al 2004; Sandberg et al 2004). This dissolved organic matter is then made available to higher trophic levels (via the microbial loop; Bergulund et al 2007), i.e., to mesozooplankton (Rolff & Elmgren 2000).

Observations of Gauns et al. 2005; Fernandes et al (submitted) along with this study indicate higher bacterial biomass along the western Bay of Bengal almost through out the year. Such high bacterial abundance along the coastal region is probably supported by allochthonous dissolved organic carbon brought in by the rivers.

Chapter 8

Chapter 8

Summary

The Bay of Bengal, in the eastern margin of the Indian sub-continent, similar to the Arabian Sea, is also a land locked marine ecosystem. Also, it experiences seasonally reversing monsoon currents that dynamically alter the hydrochemistry and biological community processes. Unlike the Arabian Sea, the Bay experiences excess precipitation over evaporation. Also, the cloud cover, low saline freshwater lense and terrigenous loads through discharges by some of the worlds' major rivers make the Bay biologically less productive. Besides, the strong stratification as a consequence of low saline tongue plus the usually weak winds (barring cyclone events) are not conducive for either coastal or offshore upwelling. Thus riverine influx and associated physical processes seem to affect the availability of nutrients to the phytoplankton. All these differences make the BoB a particularly unique and scientifically interesting region.

Intensive sampling to study the spatio-temporal variations in some of the important aspects of phytoplankton was investigated during this study. Species composition, seasonal differences of phytoplankton along the Central Bay and Western Bay were studied to understand their responses to hydographic settings in the northern Bay that is perennially stratified due to freshwater capping.

The relationship between nutrient concentrations and dynamics of diatom community in terms of their seasonal shifts, predominance, species diversity and succession was also assessed.

Experiments were set up for quantitative assessments of autotrophic processes with a view to understand the effect of varying concentrations of nutrients on phytoplankton growth and production and dissolved organic matter (DOM) formation. Measurements of bacterial abundance and activity as a consequence of DOM utilization were also carried out.

The impact of grazing by microheterotrophs (ciliates, tintinnids, heterotrophic nanoflagellates) and mesozooplankton individually and in combination in microcosm was studied to address how heterotrophic grazing affects chl *a* and phytoplankton cell counts.

Thus, ecology, spatio-temporal variability and vertical distribution (0-120 m column) of phytoplankton in the Bay of Bengal (BoB) were investigated for this study. Sampling was carried out seasonally from pre-decided locations along Central Bay (CB) and Western Bay (WB). During all the cruises, standard protocols were followed for sampling and the many analyses pre-planned for this study. The main parameters analyzed were chl *a*, phytoplankton abundance and species composition of microphytoplankton >5 μm. Onboard and laboratory experiments were set up for measuring the production of dissolved organic matter, grazing impacts and bacterial production and abundance in altered nutrient regimes. This is an extensive, first time detailed investigation on phytoplankton that systematically covered four different seasons and sampled open ocean and western margin of the inadequately understood Bay of Bengal though lying adjacent to the Indian sub-continent, which enjoys a formidable share of its fish resources.

Following are some of the major observations related to phytoplankton

- Subsurface chl *a* maxima (SCM) were the most common features during all the seasons along both transects. In the overall, chl *a* concentrations were higher during NEM than those observed in the SM, FIM or SpIM. Frequent SCM observed in this study can be attributed to the lack of nutrients in the top 10-30 m and their availability in greater quantities in deeper waters within the photic zone where light intensities are adequate for phytoplankton growth.

- Phytoplankton in the BoB appear to be adapted to low-light conditions. The average concentrations of surface and column integrated chl *a* were similar to previous reported concentration from offshore waters. Although, SCM was not reported in earlier years during winter, in this study, deep

SCM were observed. Significant correlation between chl *a* and microphytoplankton abundance during all seasons along CB suggests that most chl *a* comes from phytoplankton >5 μm in size. During all the seasons, chl *a* concentrations were higher in the WB. Though, seasonal variability in chl *a* concentration was not pronounced between locations on either transects.

- In the CB, phytoplankton abundance appeared to be controlled by the ambient concentrations of nutrients. Abundance of pennales in particular, was predominantly controlled by nutrient concentrations. In the case of centrales, physical processes such as stratification (and salinity, though feebly) also appeared to bear an influence on their distribution.

- Microphytoplankton apparently contributes as much as ~90% of chl *a* biomass. Predominance of certain phytoplankton species in specific depths and geographic locations has been observed in the BoB.

- The abundance of phytoplankton in surface and 0-120 m column was higher along the WB than in the CB. The PCC decreased with depth excepting the SCM depths in all the seasons.

- On a seasonal scale, mostly diatoms dominated. Usually the abundance of dinoflagellates and silicoflagellates followed during SM and FIM. While in SpIM, the order of dominance was, diatoms, cyanobacteria and dinoflagellates. Silicoflagellates were totally absent during SpIM. In NEM, diatoms were dominant in the CB; followed by, dinoflagellates, cyanobacteria and silicoflagellates.

- Among diatoms, pennales were dominant during most of the seasons except FIM wherein their % abundance equaled the centric diatoms. As far as the number of species is concerned, centrales was higher than pennales.

- Diatom dominance can be attributed to high concentrations of silicate. North-south variations in phytoplankton species composition were more pronounced than between the CB and WB.

- As a whole, the phytoplankton species composition in the Bay of Bengal has a wide mix of species belonging to various bio-geographical realms. A number of temperate-tropical and tropical species were recorded during this study. Some of the temperate-tropical species are *Thalassiothrix fauenfeldii, Biddulphia longicuris, Chaetoceros diversus, C. messanenis, C. eibenii* and *Bacteriastrum comosum.* While *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* and, *C. curvisetus* are the known temperate and/or polar/cosmopolitan species found during this study in the BoB.

- Larger environmental instabilities along the WB appear to cause higher species diversity (H') and species richness (SR) in the CB during SM, FIM and NEM. Only in SpIM all three components of diversity were higher along WB than CB, this was attributed to presence of large numbers of *Trichodesmium* sp.

- From the elaborate and varied experimental analyses, it is possible to substantiate that phytoplankton response to nutrient enrichments is spatially distinct. This result emphasizes on the regional differences within the BoB as far as the growth response of phytoplankton is concerned. From the experiment it was observed that phytoplankton responded rapidly in the northern bay as compared to the open ocean and western Bay stations. Further, the ratio of inorganic nitrate to phosphate compounds in the BoB is usually lower than the Redfield ratio suggesting possible nitrate limitation for phytoplankton growth.

- The nutrient enrichment experiment also elicited varying response from diatoms of different species. Changes in nutrient concentrations seem to affect phytoplankton directly and bacteria indirectly. This would probably be affecting organic matter composition, quantity and its export to the deep in the BoB.

- With phytoplankton in declining growth phase or, when nutrient(s) were limiting, a rapid increase in DOC was observed. DOC utilization by bacteria was ascertained by measuring the changes in their abundance and production. Also, the assimilation efficiency of carbon is much poorer in the BoB (<27%) than the widely assumed 33%.

- Copepods persisted to become the dominant zooplankton in the microcosms set up for assessing the grazing impacts. Ciliates remained the dominant microzooplankton at the end of weeklong grazing experiments. In the open ocean stations, phytoplankton standing stock was sufficient to support the mesozooplankton biomass suggesting a top-down control. A strong coupling was observed between the bacteria and the microzooplankton. This could be attributed to the direct predation of ciliates on bacteria rather than the phytoplankton suggesting the occurrence of a bacterial based food web (bottom up control) in the northern and coastal regions of the BoB. The microbial food web is therefore an important link in the BoB for transfer of organic matter to higher trophic levels. Not withstanding some of the minor deficiencies of running the microcosms with assortments of biological components, the new results from this study are providing clues on grazing impacts, DOM production and utilization rates, the latter ranged widely among ship-board *vis a vis* unialgal culture experiments.

Future Prospects

By and large, this study has accomplished and provided many newer insights into the phytoplankton ecology and diversity from the poorly visited Bay's open waters. Yet, not all is exhausted. There are many new questions that have risen due to this study. Some of them are listed below for further and, immediate follow up.

1. What are the physiological adaptations the phytoplankton in the Bay have mastered to be so highly diverse despite low-light, poor nutrient concentrations and low saline water capping?
2. The concept of microbial loop is gaining familiarity in the ecology of Indian Ocean. Yet, quantitative analyses of energy and carbon transfer from bacteria to micro- to meso- zooplankton aren't forthcoming. Taking cues from this rather founding study, many questions need to be answered. They can be:
    A: What are the micro- and meso- zooplankton grazing rates?
    B: How bacteria and many size groups of phytoplankton respond to such impacts? and,
    C: What fraction of DOM ultimately becomes recalcitrant?

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