Ecobiogeography, spatial and temporal variations of microzooplankton along the east coast of India

Thesis submitted to the
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by

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Certificate

I hereby certify that the thesis titled as "**Ecobiogeography, spatial and temporal variations of microzooplankton along the east coast of India**" submitted by Jyothibabu. R., Research Scholar (Reg.No.2203), National Institute of Oceanography, Regional Centre, Kochi-18, is an authentic record of the research carried out by him under my supervision, in partial fulfillment of the requirement for the Ph.D degree of Cochin University of Science and Technology in Marine Science and that no part thereof has previously formed the basis for the award of any degree, diploma or associateship in any university.

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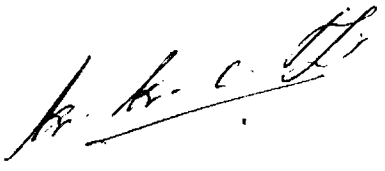

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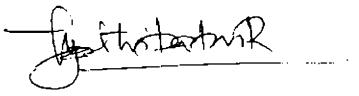
DECLARATION

I hereby declare that the thesis titled as **"Ecobiogeography, spatial and temporal variations of microzooplankton along the east coast of India"** submitted by me is an authentic record of the research carried out me, under the supervision of Dr. K.K.C. Nair, Scientist - in - Charge, Regional Centre of National Institute of Oceanography, Kochi-18, in partial fulfillment of the requirement for Ph.D degree of the Cochin University of Science and Technology in Marine Science and that no part of this has been presented before for any other degree, diploma or associateship in any university.



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CONTENTS

Chapter 1

Introduction and review of literature

1.1. General Introduction

Planktonic communities comprise a wide variety of organisms that form the basis of marine food webs. They are adapted physiologically and morphologically to live in the waters of the oceans. Many are capable of regulating their position in the water column by means of various types of locomotory appendages and other regulatory mechanisms. It is needless to mention that they all are subjected to passive movement induced by wind and currents.

The plankton has traditionally been divided in to phytoplankton (autotrophic) (Plate 1.1a) and zooplankton (heterotrophic) (Plate 1.1b), but this division requires further expansion in the light of recent plankton research and taxonomic reorganization. While the microcrustacea, rotifers, coelenterates, ctenophores, annelids and molluscs can be called zooplankton, and the diverse range of autotrophic organisms distantly related could be termed as phytoplankton, there are other groups, which do not fall completely under the above categories. The Protozoa consist of diverse group of organisms with a variety of nutritional modes and are no longer regarded as a Phylum in the Animal Kingdom, but as a Sub-Kingdom in the Kingdom Protista (Wittaker, 1969 and Margulis, 1974).

Bacteria are some of the smallest among the plankton community and the role of bacteria within the ecosystem was believed to be only as decomposers. Research during the last 20 years has shown that they, in fact, play a far more vital role in sustaining the food web. Due to their small size and resultant large surface area to volume ratio, bacteria are highly successful exploiters of dissolved minerals and compounds. The protists (ciliates and flagellates), consume bacteria as a nutritional requirement. Meso and macro zooplankton in turn consume Protists. This type of recycling in the food web is known as the **microbial loop** (Azam *et al.*, 1983) (Figure 1.1, Pathway 2).

Among the zooplankton, microzooplankton is understood to play a significant role in plankton community and hence their ecology and dynamics needs attention. Furthermore some of the recent studies in Indian waters have indicated their role in the 'microbial loop', which mediates energy flow in aquatic environment (Mangesh *et al.*, 1996; Madhupratap *et al.*, 1996, 2001; Nair *et al.*, 1999). The ecological role of microzooplankton in marine system has been the subject of extensive investigations world wide (Gast, 1985 and Pierce & Turner, 1992). These studies suggest that microzooplankton play a significant role in determining carbon flow in marine ecosystems.

1.2. Definition,composition and characteristics of microzooplankton

Planktonic organisms have been classified in different ways and one of the most important classifications is based on their body size. Accordingly, Dussart (1965) classified plankton as ultraplankton (<2μm), nanoplankton (2 - 20μm), microplankton (20 - 200μm), mesoplankton (200μm - 2mm) and megaplankton (> 2mm). Sieburth *et al.*, (1978) has categorized plankton as femtoplankton (0.02 - 0.2μm), picoplankton (0.2 - 2μm), nanoplankton (2 - 20μm), microplankton (20 - 200μm), mesozooplankton (200μm - 2mm) and megaplankton (> 2mm). While the above classifications are based on body size, the organisms of the different categories are heterogeneous and consist of diverse group of organisms with many nutritional modes like autotrophy, heterotrophy, mixotrophy (autotrophy combined with heterotrophy), phagotrophy (indiscriminate particle feeding) etc. Microplankton also consists of both autotrophic and heterotrophic forms. Since the modes of nutrition (autotrophy and heterotrophy) is considered as one of the most basic character for categorizing animals and plants, the heterotrophic forms of microplankton (20 - 200μm) are referred as **microzooplankton**, which taxonomically composed of both protozoans and metazoans. Among the organisms constituting the assemblage of marine protist grazers, ciliates and heterotrophic dinoflagellates are the major contributors in the 20 - 200μm size ranges and microzooplankton primarily consists of ciliates and heterotrophic dinoflagellates, with a contribution from crustacean larval stages.

According to the definition by Dussart, (1965) microzooplankton (Plate 1.2) are phagotrophic organisms that are <200μm in length and comprised of both Protozoa and Metazoa. However, since the lower threshold in size is not identified in the above definition, the community may include organisms in the size range of 2 - 20μm, which may have different names depending on the classification scheme (Dussart, 1965 and Sieburth *et al.*, 1978) and hence this definition has left with much ambiguity.

Ciliates are an important component of the protistan plankton in the seas, estuaries and freshwaters (Beers and Stewart, 1967,1969,1971; Rassoulzadegan & Gostan, 1976; Pace & Orcutt, 1981; Smetacek, 1981; Sorokin, 1981; Revelante & Gilmartin, 1983; Sherr *et al.*, 1986a). Reviews by Sorokin *et al.*, (1985); Banse (1982) and Porter *et al.*, (1985) have dealt on the factors influencing ciliate production. They are a major component of planktonic food webs (Porter *et al.*, 1985 and Lynn and Montagnes, 1991). They are also known to comprise an abundant and productive component of neritic environments (Burkill, 1982; Verity, 1987; Sherr & Sherr, 1988; Lynn & Montagnes, 1991; Pierce & Turner, 1992). Fenchel (1988); found that ciliates could graze significant quantities of autotrophic and heterotrophic microbial production in temperate and boreal waters.

Tintinnids are the most common and widespread group of shell-building protozoan ciliates populating the planktonic fauna. They are numerically important as second-trophic level feeders, grazing upon small diatoms, dinoflagellates and other ultra-and nanoplankton. Quantitative information on abundance and distribution of Tintinnina from neritic and coastal environments (Hedin, 1974; Burkovosky, 1976; Hargraves, 1981) as well as from oceanic waters (Beers & Stewart, 1971; Kimor & Golandsky, 1977; Krsinic, 1982; Tumantseva, 1983a& b) are available. Early works of Wright (1907), Gran, (1933), and Gran and Braarud, (1935) provide species list of tintinnids. Johansen (1976) has described seasonal distribution of tintinnids from a coastal inlet of Canada.

Dinoflagellates, which lack chloroplasts, have been known by taxonomists for about a century and the naked forms were earlier recognised as phagotrophs

since they contain food vacuoles (Gaines & Elbrachter, 1987). The feeding mechanism and the prey of colourless thecate dinoflagellates have been studied only recently and it has been revealed that they also are phagotrophic (Gaines & Taylor, 1984; Jacobson & Anderson, 1986; Hansen, 1991b). Although rarely quantified, the heterotrophic dinoflagellates could make up a substantial biomass, which at times can even exceed that of other zooplankton groups (Kimor, 1981; Smetacek, 1981; Dale & Dahl, 1987; Lessard, 1991). Until now zooplankton ecologists and protozoologists have not paid much attention to these organisms because they have been regarded as the representatives of the phytoplankton. The reason for this was the insufficient knowledge on the ecological role this group as grazers in the marine pelagic food web.

Heterotrophic nutrition patterns in dinoflagellates are diverse and the strategies employed include auxotrophy, mixotrophy and osmotrophy (Gaines & Elbrachter, 1987). In the present study, the term heterotrophic dinoflagellate is used to describe those species that are obligate heterotrophs that lack chloroplasts. There is evidence that planktonic dinoflagellates feed on a prey size spectrum from bacteria (Lessard & Swift, 1985) to large diatoms (Hansen, 1992), copepod eggs and even early naupliar stages of copepods (Sekiguchi & Kato, 1976). The ability of dinoflagellates to feed on such a wide size spectrum of prey may reflect the variety of feeding mechanisms that they employ. Three mechanisms of feeding on phytoplankton have been described: ingestion of entire cells (strict phagotrophy); use of a peduncle to pierce the prey cells and to suck out the cell contents (myzocytosis); and deployment of cytoplasmic veil to enclose prey cells with in which digestion of the prey occurs (pallium feeding) (review by Elbrachter, 1991).

Heterotrophic dinoflagellates are often abundant and ubiquitous protists in marine environments (Lessard, 1991; Hansen, 1991a; Strom & Buskey, 1991; Verity *et al.*, 1993a). They play diverse ecological roles like 1) predators on a broad range of prey species including bacteria, phytoplankton, heterotrophic protists, and metazoans; 2) important prey for some metazoans; 3) some are not only prey for copepods, but also predators of the eggs and naupliar stages of the some copepod

species and 4) some are predators of and simultaneously prey for other dinoflagellates (reciprocal predation). In the latter two cases, the predator-prey relationship can be reversed at any time and, as a result, carbon can be quickly recycled between populations of different trophic levels. This reversal of the predator-prey relationship may affect our conventional view of energy flow and carbon cycling in the marine planktonic community.

In recent years, there has been an upsurge of interest in research on microzooplankton in the marine ecosystem, owing to the recognition of their importance in trophic dynamics. They are widespread and comprise a substantial portion of the marine zooplankton community, even though their biomass is usually less than the biomass of meso and macrozooplankton (Beers & Stuart, 1969 & 1971). However, due to small body size, microzooplankton, have higher weight specific physiological rates such as feeding, respiration, excretion and growth (Fenchel, 1987 & Verity, 1985) than large metazoans, and they are capable of exploiting pico and nanoplankton, which are inefficiently utilized by large metazoans such as copepods (Nival & Nival, 1976). They also act as a significant food source for a variety of invertebrate and vertebrate predators (Robertson, 1983; Stoecker & Egloff, 1987; Stoecker & Capuzzo, 1990; Fukami *et al.*, 1999). According to Stoecker & Capuzzo (1990), protozoan microzooplankton form a potential food for the early larval stages of marine fishes, hence they have a lucrative value in mariculture. Thus microzooplankton are an important link in transferring pico and nannoplankton production to higher trophic levels. In addition to their impact on phytoplankton production, microzooplankton grazing can significantly, effect bacterioplankton and suggest as an important mechanism controlling communities of bacteria (Azam *et al.*, 1983; Albright *et al.*, 1987; Bernad & Rassoulzadegen, 1993). Beyond their trophic role, protozooplankton has also been implicated as important agents of nutrient regeneration (Probyn, 1987) and are thought to act as trophic intermediate between the bacterioplankton and larger mesozooplankton grazers (Haas & Webb, 1979 and Gifford & Dagg, 1991).

1.3. Role of microzooplankton in the food web

Natural zooplankton communities consist of a great variety of species. Although quantitative studies on microzooplankton were pioneered many years ago (Lohmann, 1908), only recently a renewed interest has been generated for this group, a major component in planktonic food webs. They are thought to play a significant role in determining carbon flow in marine ecosystems (Gast, 1985 and Pierce & Turner, 1992). Because of their high metabolic and growth rates, microzooplankton are able to consume a significant proportion of daily primary production. In addition to their impact on phytoplankton production microzooplankton grazing can significantly affect bacterioplankton and has been suggested as an important mechanism controlling bacterial communities (Turley *et al.*, 1986; Albright *et al.*, 1987; Bernard & Rassoulzadegan, 1993). Microzooplankton have also been implicated as important agents of nutrient regeneration (Probyn, 1987) and are thought to act as trophic intermediates between the bacterioplankton and larger mesozooplankton grazers (Hass and Webb, 1979 and Gifford & Dagg, 1991).

The realization that phytoplankton biomass and productivity are dominated by nanoplankton (<20μm; Malone, 1980 and references therein) and picoplankton (<2μm; Sieburth *et al.*, 1978; Stoecker & Antia, 1986; Stoecker, 1988 and references therein) raised questions concerning the efficiency of utilization of the majority of phytoplankton by grazers. The assumption that copepods and other zooplankton are unable to crop these algae efficiently (Marshall, 1973) led to the consideration that microzooplankton grazers might be able to do so. Direct microscopic examination on microzooplankton have indicated that they consume phytoplankton, heterotrophic flagellates, cyanobacteria and heterotrophic bacterioplankton (Taylor, 1978; Smetacek, 1981; Johnson *et al.*, 1982; Gifford, 1985; Laval-Peuto *et al.*, 1986; Sherr *et al.*, 1986a; Rassoulzadegan *et al.*, 1988).

In near shore (Heinle *et al.*, 1977) and oceanic (Silver & Alldredge, 1981; Caron *et al.*, 1982; Silver *et al.*, 1984) environment, small flagellates and ciliates may be an important food source for zooplankton. A simulation model given by

Parsons & Kessler (1986) shows that the presence of microzooplankton during introduction of freshwater plumes can enhance zooplankton production by many folds. Madhupratap & Parulekar (1993) found higher zooplankton density in the presence of ciliates. Inclusion of tintinnids in the diet of female *Acartia tonsa* can increase egg production by 25% compared with a pure algal diet (Stoecker & Egloff, 1987). Similarly, inclusion of tintinnids in the diet of larval ctenophores increases their early survival (Stoecker *et al.*, 1987b). Similar laboratory experiments conducted by Klein Bretler (1980) found that a number of marine copepods grew better when their standard algal diet was supplemented with heterotrophic flagellates.

Heterotrophic microflagellates are considered to be the major bacteriovores in pelagic waters (Fenchel, 1982 and Sieburth & Davis, 1982). However, ciliates are also important consumers of bacteria in some planktonic marine environments (Gast, 1985; Rivier *et al.*, 1985; Sherr & Sherr, 1987). The ciliates are a known food source for macrozooplankton, including fish larvae and copepods (Berk *et al.*, 1977 and Robertson, 1983) and may represent a direct trophic link among picoplankton, nanoplankton and metazoans (Porter *et al.*, 1979 and Johnson *et al.*, 1982).

The importance of microzooplankton in different ecosystems is evident from the previous account and has become increasingly evident during the past decade. By virtue of their small body size, microzooplankton can exploit small food particles, which may be unavailable to larger animals, and they may act as significant food source for larger metazoan predators (Stoecker & Egloff, 1987 and Stoecker & Capuzzo, 1990). They thus have a central role in the nutrition of microbial system especially in areas where seasonal stratification occurs in the water column. In the tropical oceans, relatively strong stratification occurs in most of the regions, but seasonally, some areas become mixed due to some physical processes. So it has been thought that intra- annually there may be two possible food chains existing (Cushing, 1989). During the productive season (well mixed water column) zooplankton may follow pathway 1 (Figure 1.1). However, during

oligotrophic condition (strongly stratified water column) zooplankton switch over to pathway 2-the 'microbial loop' (Figure 1.1). Under such stratified conditions dissolved nutrients above the thermocline are generally low and the phytoplankton are dominated by small flagellates. A study by Aksnes & Egge, (1991) pointed out that small cells with high surface to volume ratio have a higher efficiency for utilization of nutrients than large cells. This implies that smaller cells proliferate in these nutrient-low waters. A relatively high percentage of the gross primary production ends up as dissolved organic matter, which is utilised by bacteria. Within the euphotic zone free-living bacteria may account for the major part of the total heterotrophic activity in the sea (Pomeroy, 1974) and cyanobacteria could account for much of the autotrophic production (Johnson and Sieburth 1979; Platt 1983; Li *et al.*, 1983). However, their very small size puts bacteria beyond the reach of many zooplankton. Azam *et al.*, (1983), pointed out how these bacterioplankton may be linked to metazoan food chain *via.*, a microbial loop. They envisaged that water column bacteria utilizes dissolved organic matter, mainly of phytoplankton origin, for growth and that their densities are controlled by predation by heterotrophic flagellates. Flagellates, in turn, are preyed upon by microzooplankton and the so-called herbivorous zooplankters preferentially feeding upon microzooplankton (Wiadnyana & Rassoulzadegan, 1989). There are also evidences of microzooplankton directly ingesting bacteria (Sherr & Sherr, 1987 and Gast, 1985) thereby short-circuiting the microbial loop. It has been recently recognized that microbial and microzooplankton components of aquatic food webs are much more important than previously thought. Due to the close coupling between these two components, relatively little organic carbon may leave the euphotic zone, especially where microzooplankton represents the major route for the uptake of organic carbon thus influencing the biogeochemical cycle.

Studies on grazing impact of microzooplankton in different areas were carried out by Landry and others using dilution technique (see Landry & Hasset, 1982; Landry *et al.*, 1995; Landry *et al.*, 1998). James & Hall (1998) studied the grazing rates of microzooplankton on total phytoplankton, picophytoplankton and

bacteria in Sub Tropical, Sub Tropical Convergence and Sub Antarctic waters in winter and spring of 1993. They found that the grazing impact on total chlorphyll *a* standing stock and phytoplankton production ranged from 10-92% in winter and 4-57% in spring, respectively. The abundance of microzooplankton was generally higher in spring than winter. Grazing by microzooplankton is known to be quantitatively significant (Burkill *et al.*, 1987; 1993 a, b; Verity *et al*, 1990 & 1993b) because of their central role in the microbial system where they graze particles of a large range of sizes. This allows the incorporation of a greater proportion of the primary production into the food chain. Microzooplankton is capable of consuming a significant proportion of primary production (Frost, 1991), which is reported to be of 40-70% of the total primary production (Riley *et al.*, 1965 and Beers & Stewart, 1970). Indeed, field experiments have demonstrated that microzooplankton consumes between 10 and 75% of daily primary production (Garrison, 1991 and Pierce & Turner, 1992). Studies (Capriulo & Carpenter, 1983 and Cosper & Stepien, 1982) have shown that certain components of the microzooplankton community alone would have consumed 20-100% of primary production. Burkill (1982), Capriulo &Carpenter (1983) and Verity (1987) found that the tintinnids are responsible for the consumption of ~30% of the annual primary production, a value of the same order of magnitude as those consumed by copepods. Johnsson (1987) and Stoecker *et al.*, (1987c) pointed out that the autotrophic and mixotrophic ciliates also contribute to primary production in the microplankton size fraction.

Observations of Garrison *et al.*, (1984) suggest that the grazing impact of microzooplankton on phytoplankton in high latitudes might be similar to that observed in the lower latitudes. Recent studies have shown that they dominate among the grazers of tropical oceanic phytoplankton in the Atlantic (Burkill *et al.*, 1993a; Verity *et al.*, 1993 a and b), Indian (Burkill *et al.*, 1993b) and Pacific Oceans (Miller, 1993). Studies speculate that microzooplankton may be important grazers during the spring bloom (Heinbokel, 1978a; Landry & Hasset 1982; Capriulo & Carpenter 1983). Grazing pressure of microzooplankton on

phytoplankton is responsible for not only regulating the phytoplankton species (e.g. Capriulo & Carpenter, 1983 and Paranjape, 1990), or filter/mucus feeding mesozooplankton directly ingesting bacteria (Sorokin, 1981) but also regulating the size compositions (Blackbourn, 1974; Johansen, 1976; Verity, 1986a). In coastal and inshore areas they are known to control the growth of certain species by selective predation (Hewes *et al.*, 1985 and Burkill *et al.*, 1987).

The works of Eppley & Peterson, (1979); Gilbert, (1982); Wheeler & Kirchman, (1986); Caron & Dennet, (1988); Ferrier and Rassouldegan, (1991), have shown that the primary production in the oceans relies mostly on nutrients recycled in the euphotic zone by protozoa rather than bacteria. Also the importance of the microbial communities in recycling processes increases as the system approaches oligotrophy (Harrison, 1980).

1.4. Objectives and the scope of the present study

Our knowledge about microzooplankton is still very fragmentary particularly from the Indian waters. Along the west coast of India, the available literature (Mangesh *et al.*, 1996 and Mangesh, 2000) points out the importance of microzooplankton in the Arabian Sea. In Arabian Sea, microzooplankton contribution to the total biomass of zooplankton was considerable and in some seasons it exceeded that of mesozooplankton thereby contributing much to the productivity.

In the east coast of India, Prasad, (1956); Krishnamurthy & Santhanam, (1975 & 1978); Krishnamurthy & Damodara Naidu, (1977); Damodara Naidu & Krishnamurthy, (1985); Godhantaraman *et al.*, (2001); Godhantaraman & Krishnamurthy, (1997); Sujatha Mishra & Panigrahy, (1999) have contributed to the literature on tintinnids and their studies were concentrated in the estuarine and very coastal regions of east coast of India. Moreover, none of these studies attempted to understand microzooplankton as a heterogeneous group. They did not address heterotrophic dinoflagellates and aloricate ciliates and hence majority of the microzooplanktonic organisms remained unaccounted. There are increasing evidences to consider that heterotrophic dinoflagellates and aloricate ciliates are the

important microzooplanktonic organisms in tropical regions along with tintinnid ciliates (Leakey *et al.*, 1994; Mangesh *et al.*, 1996, Jyothibabu *et al.*, 2003). There is virtually no seasonal data available on microzooplankton from the Bay of Bengal with an extensive and systematic coverage.

In the present study an attempt has been made to understand the microzooplankton community along the east coast of India. Most of the earlier studies projected Bay of Bengal as an oligotrophic system where phytoplankton growth is limited by a number of factors among which nutrients are the foremost (Ryther *et al.*, 1966; Radhakrishna *et al.*, 1978a; Radhakrishna, 1978b; Gomes *et al.*, 2000; Prasanna Kumar *et al.*, 2000; Madhupratap *et al.*, 2003). Hence it is logical to consider that most of the primary production in the Bay of Bengal could be contributed by small sized phytoplankton harnessing the available resources, which in turn can be utilized efficiently by the microzooplankton only (Pathway 2 of Figure 1.1). Hence microzooplankton could play an important role in transferring primary organic carbon to higher trophic levels in this region.

Objectives of the present study can be listed as

- To understand the taxonomic composition of microzooplankton in the Bay of Bengal
- To study the fluxes of biomass of microzooplankton in comparison with mesozooplankton
- To study the temporal and spatial variations of microzooplankton
- To investigate the ecobiogeography of microzooplankton
- To understand the magnitude of microzooplankton herbivory in the Bay of Bengal.

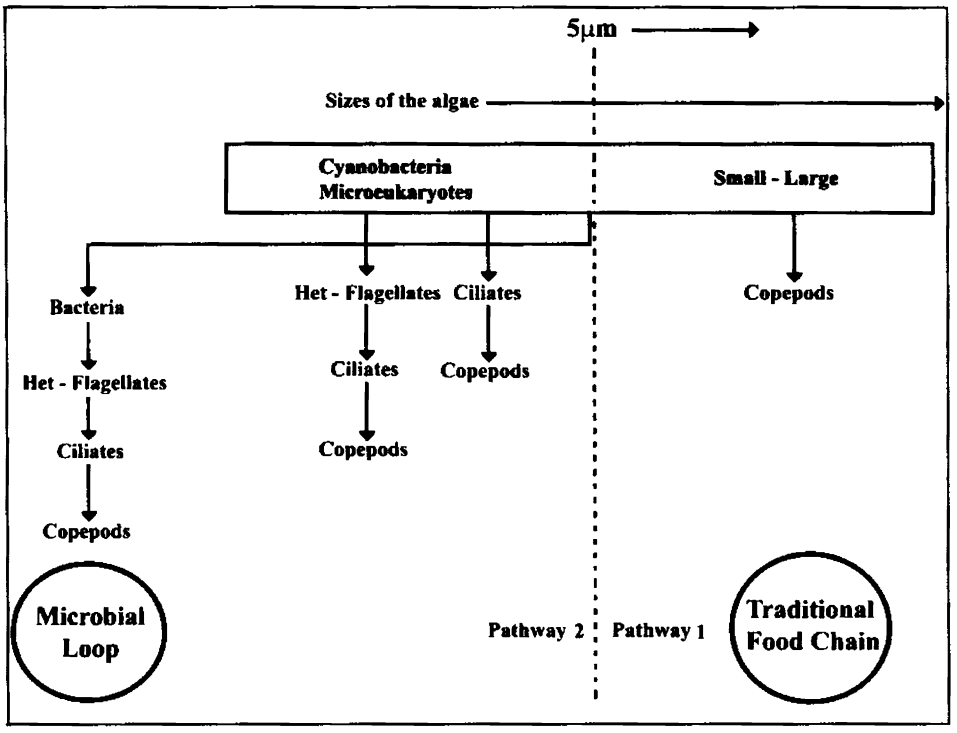
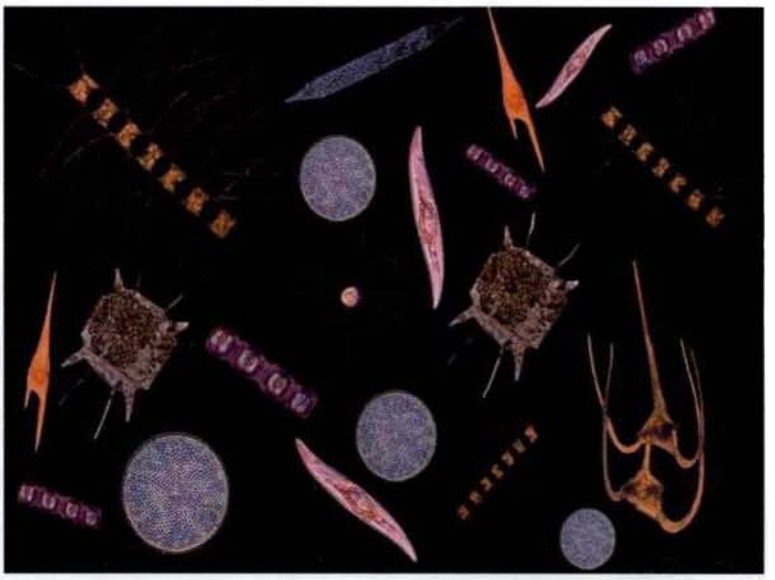


Figure 1.1. The structural difference between the microbial loop and the traditional food chain (Cushing, 1989 – freely adapted from Azam *et al.*,1983)



a) Phytoplankton

b) Zooplankton

Plate 1.1

Plate 1.2. Microzooplankton

Chapter 2

The Environment - Bay of Bengal

2.1. General features of the Bay of Bengal

The Bay of Bengal, extends between latitudes 0° and 23°N and longitudes 80° and 100°E occupying an area of 4.087 x 10^6 km^2. It is surrounded on three sides by landmasses and is a region of positive water balance. The average annual excess of precipitation over evaporation is of the order of 70 cm (Venkateswaran, 1956). The total annual river runoff in the Bay of Bengal has been estimated to be 2000 km^3 (Sen Gupta *et al.*, 1977 and Naqvi & Naik, 1983). All the major rivers of India, Bangladesh and Myanmar drain into the Bay of Bengal. It is a unique ocean with interrelated oceanographic, biological and sedimentary processes driven by the monsoon winds. The semi enclosed nature of the Bay and its proximity to the equator make it different from other ocean. Associated with monsoon is the large volume of freshwater supply and sediment input by Ganges, Brahmaputra and other rivers (Figure 2.1). Thus the prevalent low salinity plays a major role in various exchange processes between the atmosphere, surface and deep waters that affect the biological and biochemical processes.

2.2. Physical aspects

Understanding of the physical oceanography of the Bay of Bengal is largely based on the evaluation of the climatological features of the area and its neighborhood. The hinterland of the Bay of Bengal is defined as the extensive land area that contains the tributaries and distributaries of the major rivers, which flow into the Bay. The hinterland acquires special importance because of the extensive river runoff into the Bay and its effect on water properties. Thus the catchment areas, the plains and the deltas of the big rivers- Brahmaputra, Cauvery, Damodar, Ganges, Godavari, Irrawady, Krishna, Mahanadi, Mahaveli, Pennar and Salween- fall in to the hinterland (Varkey *et al.*, 1996).

The Bay and its hinterland cover a wide range of climatic features. Since the climate of the study area is primarily influenced by the monsoons, a climatic classification based on amounts of precipitation, particularly about the length of dry and wet seasons, is relevant and such a classification for this area is presented by Landsberg *et al.*, (1966). The hinterland of the Ganges, Brahmaputra, Damodar, Mahanadi and Mahaveli experiences tropical rainy climates and tropical humid summer climates with humid winters. The rivers that flow into the bay across the southeast coast of India are associated with landmasses of tropical semi-deserts of dry climates with humid winters.

Rain over the Bay of Bengal shows strong seasonality. The southeast coast of India has a winter rainfall maximum and the rest of the east coast of India, Bangladesh and Myanmar have a summer rainfall maximum (Ramage, 1984). Over the Bay of Bengal storms and depressions are observed mostly from June to November (Rao, 1981). Tropical cyclones in the Bay of Bengal during the post monsoon transition period are associated with very heavy rain and stormy winds especially in the coastal areas (Rao, 1981). The existing literature presents the following hydrographical setting in the Bay of Bengal during different seasons.

During the winter monsoon, surface salinities in the Bay of Bengal ranges between 27.0 and 33.0 practical salinity unit (psu). The 33.0 psu isohaline runs almost parallel to the coast. Lowest salinity (27.0 psu) is observed in the region around 20°N and is a result of river runoff from the Ganges - Brahmaputra system. At 100 m, over most of the shelf, salinity varies between 34.6 psu and 34.9 psu except near the river mouths where the effect of freshwater discharge is still noticeable (Suryanarayana, 1988, Suryanarayana *et al.*, 1991). At 200m, salinity is more uniform with insignificant mixing with top diluted water (<34.5 psu). During this season along 14°N surface salinities vary from 32.0 to 34.4 psu from about 100 to 300 km offshore compared with 27.0 to 32.5 psu along 20°N from 50 - 300 km offshore. At about 17°N, surface salinities vary between 27 psu (near the shore) and 33.5 psu (about 200 km). Less salinity extends up to 200 km and vertically occupies about 60 m of the water column. During the season in the 20°N, surface

salinities vary from 27 psu near the shore to 32.5 psu towards offshore (300m). The low saline water (>34.5 psu) extends up to over 300 km from the shore and up to 50m of depth.

During summer monsoon, the surface salinities range between 22.0 psu and 34.0 psu over the coastal area. The 33.0 psu isohaline forms a boundary across central east coast (at about 16°N) between the southern high salinity belts. The low salinity front in the north is formed as a result of heavy run off from the Mahanadi - Ganges-Brahmaputra system. Off Madras, the diluted water extends up to about 50 m with more or less uniform thickness, whereas in winter the pattern shows wavy structures. Off Visakhapatnam (around 17°N) the diluted water extends up to around 70 - 90 m with a wavy pattern across the shelf. In the northern regions (near 20°N), the diluted water extends up to >110 m with almost uniform thickness (Shetye *et al.*, 1991). Further northwards salinity decreases to 21.0 psu. Gopalakrishna & Sastry (1985) reported a low salinity of 20.0 psu around 20°N.

During the intermonsoon season, sea surface temperature (SST) increases from 27.5°C in the north to 30.5°C in the central Bay. The SST distribution indicates the warming of the surface waters between winter and summer. The lower SSTs in the northwestern Bay show the after effects of strong surface cooling during winter. The higher SSTs in the central Bay represent the seasonal peak during intermonsoon. During the summer monsoon, warm waters (>29.5°N) are noticed in the northwestern Bay. From this region, SST decreases gradually to 28°C toward southwest along Indian coast. In general it can be seen that the surface waters south of 14°N are cooler (<29°C) compared with those north of 14°N. During winter monsoon, the lowest SST is 25.5°C observed in the northern Bay and SSTs around 26°C are seen in the central east coast of India. In the southern and central Bay, Rao & Jayaraman, (1968) reported variations of SST between 26°C and 28.6°C during February-March 1963 and the highest SSTs (>27.5°C) were attributed to the diurnal sea surface temperature maximum. The temperature difference from the head of the Bay to the Southern Bay is 3.0°C (Balaramamurthy, 1958 and Wyrtki, 1971). The southward increase of temperature is partly accounted

for by the latitudinal variation of insolation. In the northwestern Bay, cold (<26.0°C) surface waters and a temperature inversion of 1°C at 50m at the distance of 360km from the Gopalpur coast was reported during 1965 (Sankaranarayana & Reddy, 1968). Rao & Sastry, (1981) reported temperature inversions of 1.5°C at depths of 5 - 50 m in the northern Bay during January 1963. Suryanarayana *et al.*, (1993) and Pankajakshan *et al.*, (2002) have also reported low (<26.5°C) temperature at near surface depths and a temperature inversion of 2°C at subsurface layers in the northwestern Bay during winter period.

Murty & Varadachari (1968) reported strong upwelling of the Waltair coast and weak upwelling along off Madras during summer monsoon of 1964. The difference in the intensity of upwelling during this period was attributed to the relatively strong winds along the coast of Waltair. Naqvi *et al.*, (1979) reported moderate level of upwelling along east coast of India during summer monsoon, even though the runoff from the rivers may partially compensate for the offshore movement of the surface waters (Sen Gupta *et al.*, 1977). Hydrographic data collected (Shetye *et al.*, 1991) during the summer monsoon of 1989 along the east coast of India showed (a) an upwelling band (about 40 km wide) along most of the coastline and (b) a southward moving freshwater plume over the northwestern Bay of Bengal.

The turbidity of the waters of the east coast of India varies greatly from season to season depending on runoff and associated suspended load. Suspended sediment enters the Bay of Bengal through the many rivers mainly during the summer monsoon. The Bay receives about $16x10^8$ tonnes of silt yearly (Suryanarayana, 1988) along with abundant runoff. The suspended load settles down or gets transported away from the river mouths depending upon currents. La Fond & Sastry, (1957) used a hydrophotometer to study the transparency of the coastal waters along the east coast of India. They found that in the summer season, turbid water tends to remain near shore and flows down the coast. As the rainy season recedes the water becomes clearer in near shore areas, remaining, however, more turbid than over the shelf. Sundara Raman & Sreerama Murty, (1968) found

that during the month of March (intermonsoon) the transparency was 100% at >8 km off the Karaikal coast.

2.3. Chemical aspects

The immense river runoff into the Bay of Bengal is expected to influence the biogeochemical cycles to a great extent. In addition to supplying large amounts of dissolved and suspended matter, the runoff may also affect the chemistry through controls on circulation and mixing. The rivers from these regions are known to make excessively large contributions to the global transport of suspended load by rivers to the ocean (Milliman & Maede, 1983) and the lithogenic substances may strongly influence the sedimentation of biogenic matter (Ittekkot *et al.*, 1992). This is expected to significantly alter the water-column regeneration processes, the extent of which remains unknown.

In the Bay of Bengal, dissolved oxygen concentration in the mixed layer is close to the saturation values. As depth increases, the oxygen concentration decreases and like other parts of the northern Indian Ocean, the Bay also experiences depletion of dissolved oxygen at intermediate depths (Wyrtki, 1971). However unlike the Arabian Sea, the redox conditions within the oxygen minimum layer in the Bay of Bengal are just above those required to support denitrification (Rao *et al.*, 1994). The oxygen concentrations at comparable depths below the thermocline are generally lower in the Arabian Sea than in the Bay of Bengal (Wyrtki, 1971). This may be attributed to a high rate of supply and oxidation of organic matter in the former region due to a higher rate of organic production at the surface.

However the sediment trap deployments have shown that organic carbon fluxes to the deep Bay of Bengal are higher than those in the Arabian Sea (Ittekkot *et al.*, 1991). Ittekkot *et al.*, (1991) postulated that a large riverine input of nutrients might support the large export of production in the Bay of Bengal. But the available data on nutrients are not compatible with this interpretation. The chemical data available show that the rivers flowing into the Bay might not contribute much to the inorganic nutrient pool (Sen Gupta & Naqvi, 1984; Prasanna Kumar *et al.*, 2002).

Rao *et al.,* 1994), has given two possible explanations for the observed higher sinking fluxes with the inferred lower respiration rates in the Bay. The first possibility, the export production in the Bay of Bengal may be lower than that in the Arabian Sea, but the extend of water column regeneration from the soft tissue may also be lower as a consequence of incorporation of organic carbon in the fast settling matter due to the large terrigenous inputs. There are other evidences to believe that the organic matter reaches the deep sea floor in relatively undecomposed state in the Bay of Bengal (Broecker *et al.*, 1980). The second possibility is, as a consequence of a reduced advection and strong stratification, the supply of fresh and labile DOC to the subsurface layers of the Bay may also be less. This difference assumes significance in view of the reported insufficiency of the vertical sinking fluxes in fuelling subsurface respiration in the Arabian Sea (Ducklow, 1993 and Naqvi & Shailaja, 1993).

Sankaranarayanan & Reddy, (1968) studied the distribution of nutrients in the northern Bay of Bengal and observed marked regional variations. The maximal values of phosphate and nitrate occurred shallower than in the Arabian Sea, at 600 - 800m and 300-800m respectively. No increase in silicate concentrations is observed in the surface waters of the northern Bay, in spite of massive river runoff, which occurs in the region.

The most recent publication mentioning the nutrient distribution in the Bay of Bengal during summer monsoon (Prasanna Kumar *et al.*, 2002) reports that, in the Bay the upper 30m of the water column has depleted levels of nitrate. They further observed that the nitracline (in general) is situated between 50 and 100m depths. Silicate distribution in the Bay showed similarity to that of nitrate, except for a high concentration of more than 2μM in the upper waters of the north. The higher silicate indicated that it must have originated from the source in the north.

2.4. Biological aspects

The biological productivity of any oceanic region is largely based on the organic production (primary production) of that region. Measurements of primary production in the Bay of Bengal were made for the first time during Galathea

Expedition. Subsequently, during International Indian Ocean Expedition (IIOE) similar measurements were made from many parts of the Bay of Bengal (Kabanova, 1964,1968; Krey, 1973,1976). Later, Radhakrishna *et al.*, 1978a; Radhakrishna, 1978b; Devassy *et al.*, 1983; and Bhattathiri *et al.*, 1980) studied the primary productivity of Bay of Bengal. Most of the studies depict Bay of Bengal as an oligotrophic system. Although, many major world river systems, bring in large quantities of suspended and dissolved substances, the narrow shelf, heavy cloud cover, less light penetration have been attributed as reason for this (Qasim, 1977; Radhakrishna, 1978b, Gomes *et al.*, 2000). More recently, Prasanna Kumar *et al.*, (2002) and Madhupratap *et al.*, (2003) reported Bay as a low productive region. During their study (July - August 2001) surface chlorophyll *a* in the Bay weakly increased from 0.06 mg m^{-3} in the south to 0.28 mg m^{-3} in the north, which is 4 - 5 times less, compared to Arabian Sea (0.32 - 1.12 mg m^{-3}) during the same season. Integrated chlorophyll *a* (up to 120 m) apart from being low varied only nominally from 9 - 11 mg m^{-2} in the Bay of Bengal compared to Arabian Sea values (26 – 60 mg m^{-2}). Integrated primary productivity (up to 120 m) was also less in the Bay of Bengal and varied from 89 - 221 mg Cm^{-2} d^{-1} compared to Arabian Sea (770 – 1782 mgC m^{-2} d^{-1}).

Due to their sheer abundance and intermediary role between phytoplankton and fish, the zooplankton are mainly the index of utilization of aquatic biotope at the secondary trophic level. Zooplankton distribution usually shows patchiness and studies on mesozooplankton up to 1985 suggest an increasing trends in biomass towards the south in the Bay of Bengal. Maximum biomass (0.75 – 1 ml m^{-3}) was observed off the region between Madras and Visakhapatnam while the other regions had much lower biomass (See review by Desai & Kesava Das, 1988). Madhupratap & Parulekar, (1993) reviewed the earlier works in the Bay of Bengal and reported the lack of good coverage for zooplankton in the Bay of Bengal. Despite fairly high production along its western boundary during southwest monsoon, zooplankton standing stock appears to be of the modest ranges. IIOE data have averages ranging from 10 - 18 mg m^{-3} from the northern Bay. Other data

available show 31- 54 mg m^{-3} during August - September between 10 - 13°N (Achuthankutty *et al.*, 1980) and 18 - 31 mg m^{-3} in June between13 - 17°N (Nair *et al.*, 1981). Both of these reports show much poorer values for the rest of the coastal areas (Nair *et al.*, 1977).

During night increase of biomass and abundance of zooplankton species including those of carnivores occur in the upper 200m layer as a result of upward migrations, including those of carnivores, from deeper waters. A large number of epipelagic species however does not migrate to mesopelagic depths probably because they cannot survive in the poorly oxygenated waters of the oxygen minimum layers (Madhupratap & Parulekar, 1993).

The preceding account on Bay of Bengal illustrates the peculiarities of this region as a tropical basin and the available information on hydrography and biological parameters. However, it is also evident that this region is one of the least explored areas in the Indian Ocean especially with regard to many biological aspects. Hence, the present investigation is relevant while it has generated seasonal data on many of the biological parameters (chlorophyll *a*, primary production and mesozooplankton biomass). In addition to this, a fresh data set has been generated for microzooplankton, an important component of the planktonic food web, which has hitherto not been studied in this region.

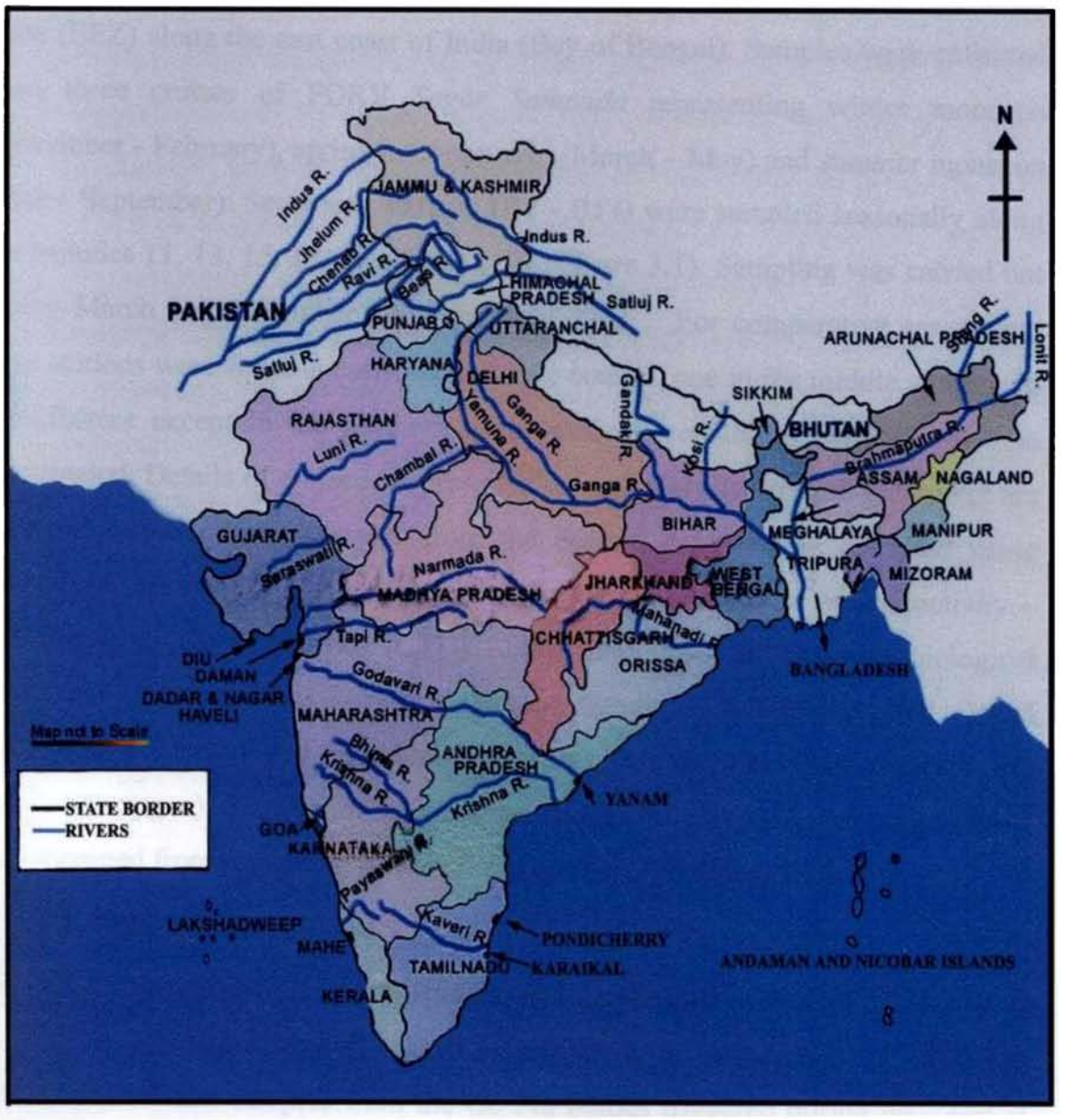


Figure 2.1. Major rivers of India

Chapter 3

Materials and methods

3.1. Sampling

Samples for microzooplankton were collected from the Exclusive Economic Zone (EEZ) along the east coast of India (Bay of Bengal). Samples were collected from three cruises of FORV *Sagar Sampada* representing winter monsoon (November - February), spring intermonsoon (March – May) and summer monsoon (June - September). Seventeen stations (B1 - B17) were sampled seasonally along the latitudes 11, 13, 15, 17, 19 and 20.5 °N (Figure 3.1). Sampling was carried out during March and December 2001 and July 2002 . For comparative assessment three stations were fixed in each transect, one coastal, one in the middle and one in the offshore except in the northern most transect were only two stations were investigated. Details of collection, preservation and analysis for each parameter are described below. Water samples from the desired depths were collected using thoroughly cleaned Go Flo bottles (5 litre capacity) attached to a Conductivity – Temperature - Depth profiler (CTD) rosette and used for studying biological parameters (microzooplankton, phytoplankton standing stock (chlorophyll *a*) and primary productivity) and chemical parameters (nitrate, phosphate, silicate and dissolved oxygen). Profiles of temperature and salinity at each sampling station were obtained from respective sensors fitted on to a CTD (Plate 3.1a).

3.2. Biological parameters

3.2.1. Microzooplankton (Qualitative and quantitative study)

In the present study, all microzooplankton in the size range 20 - 200 μm were studied. Water samples from the Go Flo bottles triggered during up - cast at depths of 150, 120, 100, 75, 50, 20, 10 m and surface were collected for microzooplankton samples at each station. From each depth, 5 - 7 litres of water samples were collected and transferred in to black carboys. Although Joint Global Ocean Flux Studies (JGOFS) protocols (UNESCO, 1994) suggest 250 ml – 2 litres volume as standard for microzooplankton, in the present study more quantity (5 - 7

litres) were processed to get fair representation of microzooplankton while the Bay of Bengal is reported to be oligotrophic. Initially the water samples from each depth were prefiltered gently through a 200 µm bolting silk to remove the mesozooplankton and the filtered samples were collected in black polythene bottles. Subsequently, samples were concentrated by siphoning through a PVC tubing with it's cod end fitted with a 20 µm Nitex screen for retaining all the microzooplankton of ≥20 µm size at the bottom of the carboy. Thus microzooplankton samples were concentrated to 100 ml volume and then preserved in 1 - 3% acid Lugol's solution. These microzooplankton concentrates were then used for enumeration, identification and estimating the biomass.

Organic carbon being the principal component of all organisms and its transfer at various trophic levels draws comparisons and computation at biomass level and bioenergetics. Estimate of carbon biomass of microscopic planktonic organisms are usually made by converting microscopic size measurements to cell volumes, which are then converted to carbon biomass using empirically or theoretically derived carbon to volume ratios.

During the analysis, the initial sample concentrates (ca. 100 ml) were allowed to settle for 3 days. The settled samples were observed in Sedgwick rafter counting chamber under inverted microscope (Plates 3.1b & c) with phase contrast optics at 100 – 400x magnifications. Microzooplankton were identified and categorized in to the following four groups: ciliates, heterotrophic dinoflagellates, other protozoans and micrometazoans. The ciliates and heterotrophic dinoflagellates were identified up to the species level wherever possible and the others were identified up to genus level following available publications (Kofoid & Campbell, 1904; Jorgensen, 1924; Marshall, 1969; Karen, 1970; Subrahmanyan, 1971; Gopinathan, 1975; Taylor, 1976; Corliss, 1979; Small *et al.*, 1985; Maeda,1985 &1986; Lynn *et al.*, 1988). Photomicrographs of the identified species were taken using a Nikon camera and proper scaling was presented on the images. Appropriate body dimensions (µm) of the organisms were measured using a micrometer and the suitable conversion factors were reviewed by Gifford & Caron,

(2000). The lorica volume of tintinnids and cell volume of naked ciliates were determined according to their geometric configurations. From lorica volume (μm^3) the body weight of a tintinnid (pgC) was calculated using the equations described below. The cell volume of tintinnid ciliate in the present study was assumed as 50% of lorica volume, similar to the method by Gilron & Lynn (1989). The carbon content of naked ciliates was converted from cell volume using a factor of 0.19 pg C μm^{-3} (Putt & Stoecker, 1989) and 0.14 pg C μm^{-3} for dinoflagellates (Lessard, 1991). The carbon content of copepod nauplii was calculated by assuming 16 ngC/individual (Uye, 1982).

3.2.2. Microzooplankton herbivory

Microzooplankton herbivory experiments were carried out at four locations along the south east coast of India during winter monsoon. Microzooplankton herbivory were shown in JGOFS and other studies to be a major pathway for the trophic transformation of phytoplankton in surface waters (Burkill *et al.*, 1993a, Verity *et al.*, 1993b). It therefore provides important information about the flux of organic carbon in surface waters. Microzooplankton herbivory is defined as the rate of grazing of phytoplankton organic carbon by microzooplankton per unit volume of seawater. The units of this are mgC $liter^{-1}$ day^{-1}. During the present study, microzooplankton herbivory experiments were carried out at four stations in the southeast coast of India during winter monsoon.

One of the most important methods, which had been used routinely in JGOFS measurements, was the "dilution approach" of Landry & Hassett (1982). The dilution approach protocol is based on the experimental determination of phytoplankton growth in a dilution series. The dilution series is made up by combining the natural microbial community (natural sea water) with seawater that has been filtered free of microbial components. The theoretical and practical considerations of this technique are fully described in Landry & Hassett (1982). Essentially, phytoplankton growth is assumed to be density independent with specific growth rates that are constant for all dilution conditions. Per capita clearance rates of microzooplankton are assumed to be constant among the dilution

treatments, leading to proportionately higher phytoplankton mortality with greater concentrations of microzooplankton. Consequently there is a progressive uncoupling with dilution between phytoplankton growth and mortality due to grazing. It is further assumed that phytoplankton growth and grazing mortality are appropriately represented by exponential rates.

Before starting the experiment, experimental bottles was marked up for appropriate dilution (e.g. 40% concentration should be marked externally with water proof marker) and all experimental polycarbonate bottles were acid cleaned and rinsed in distilled water. Concentrations used in the dilution series were 100%, 75%, 50% and 25% of ambient concentration with triplicate bottles incubated at each concentration. Sufficient water was filtered (approximately half the overall water) free of microbial community using 0.2 μm porosity Millipore filter papers. This 'predator - and - prey' free water then combined with the unfiltered seawater to generate concentrations of 100, 70, 40 and 10% made up to 2 litres in acid washed polycarbonate bottles.

Experimental bottles were mixed gently by inverting them slowly. Sub samples were taken from each bottle for phytoplankton pigments and filtered onto 0.2 μm Millipore filters. Filter papers were stored in deep freezer until required for analysis. Sub-samples were also taken from each bottle for determination of microzooplankton at the beginning and end of the experiment, which was 24 hours. Experimental dilution bottles were incubated under simulated deck incubation with appropriate light attenuation filters.

Phytoplankton biomass was quantified through measurement of chlorophyll *a* soon after sampling, since pigments degrade rapidly with time. Chlorophyll *a* was analysed spectrophotometrically (Strickland & Parsons, 1972).

Turnover rate of phytoplankton by microzooplankton (days $^{-1}$) was calculated from the slope of regression equation (= 1-e $^{-slope}$). Rate of grazing of chlorophyll (mg chl liter $^{-1}$ day $^{-1}$) was calculated from turnover rate by multiplying the ambient chlorophyll concentration (= chlorophyll concentration* turnover rate).

Rate of grazing of phytoplankton carbon by microzooplankton was calculated from chlorophyll rate * carbon to chlorophyll ratio. This ratio varies between 10 and 200 an average of 40 was used for oligotrophic open waters.

3.2.3. Phytoplankton standing stock (Chlorophyll *a*)

By definition, the term chlorophyll (Chl) denotes a group of photosynthetic pigments important for carbon fixation and capable of absorbing blue - violet and red light. Two liters of water from each standard depth was filtered through GF/F filters (nominal pore size 0.7μm) to estimate chlorophyll *a* and estimated spectrophotometrically (Hitachi, Model, U - 2000) using 10 ml 90% acetone for extraction (Strickland & Parsons 1972). The Chl *a* pigments were extracted for 24 hours in 10 ml 90% acetone (Qualigens AR, Mumbai) in a refrigerator overnight. Samples were brought to room temperature and the absorbance was measured using a spectrophotometer. The chlorophyll *a* was calculated by the following equations.

$Chl\ a\ (chlorophyll\ a) = 11.6\ E_{665} - 1.31\ E_{645} - 0.14\ E_{630,}$ Where.,

E stands for the absorbance values, at wavelengths indicated at the subscripts. The absorbance was measured in 10 cm cells and 'cell-to-cell blank' corrections were made as described in Strickland & Parsons, (1972).

3.2.4. Primary production

Primary production is defined as the uptake of inorganic carbon by autotrophic communities for the formation of new cellular component into the eventual production of particulate organic matter. The rate of carbon fixation by autotrophs in seawater was measured by tracing the uptake of radioactive ^{14}C ($Na_2 H^{14}CO_3$). Primary production is expressed as 'mg carbon m^{-3} d^{-1}. A known concentration of radiocarbon was added to the seawater sample and the ratio of the uptake of radiocarbon to the added radiocarbon by the phytoplankton was converted to total carbon uptake by multiplying with the total inorganic carbon in the sample. Vertical profiles of production measurements were integrated to yield a production rate per unit area in units of 'mg carbon m^{-2} d^{-1}.

Polycarbonate bottles (PC, Nalgene, USA) used for primary productivity measurements were soaked for 72 hours in a 5% solution of detergent. These bottles were then rinsed thoroughly with deionized water and subsequently soaked for 72 hours in the acid cleaning solution (0.5N HCl solution prepared with distilled water). Bottles were then rinsed 3 times with Milli-Q water (or distilled water) and allowed to stand there for at least 48 hrs.

For measuring primary productivity, water samples were obtained from 8 predetermined depths (0, 10, 20, 50, 75, 100 and 120 m) from the euphotic zone in the Bay of Bengal. From each depth, samples were collected to five clean bottles. Before addition of radioactive carbonate, none of the samples were exposed to light (as either light can enhance productivity or degrade/reduce the cell capacity to produce due to light shock in samples particularly from deeper depths). To each PC bottle containing seawater sample (~250 - 300 ml) 1 ml of aqueous solution of 5μCi of radioactive carbon (BRIT, Bhabha Atomic Research Centre, Department of Atomic Energy, Mumbai) was added. To determine the initial activity of ^{14}C added at time zero, 0.2 ml of sample from one of the bottle was transferred to a scintillation vial and 0.2 ml of ethanolamine was added to it (ethanolamine prevents the radiolabelled inorganic CO_2 from escapement in to the atmosphere). Similarly, sample in one of the bottle was filtered through 47mm GF/F filter paper for determining the initial adsorption of the ^{14}C by the particles in the bottle. From the remaining four bottles from each depth, one was covered with aluminum foil and transferred to a black bag to determine the dark production. Thus, one dark and three light bottles were used from each depth for *in situ* incubation for 12 hours from sunrise to sunset. The bottles were deployed *in situ* corresponding with their depths of origin by suspending them on a polypropylene line attached to a buoy with a life line (Plates 3.2 a & b). The "mooring" system used to be deployed approximately one hour before sunrise, and was allowed to drift freely for 12 hours during the fair weather. However, during inclement weather, primary productivity mooring used to be tied to the ship with adequate leave way for drifting. The ship

was occasionally maneuvered to keep the PP mooring ~150 - 200 m away from her. The mooring system was invariably retrieved *ca* ~ 30 minutes after sunset.

Upon retrieval, samples in each bottle were filtered on to GF/F filter and the filters were transferred to scintillation glass vials. Drop of 0.5 N HCl was added to each vial and capped overnight. All vials were kept at room temperature until the radioactivity was counted. Before counting, all vials were uncapped and left open overnight. Five ml of liquid scintillation cocktail (SISCO-Bombay) was added and the radioactivity counted in a liquid scintillation system (Wallac, Finland). The counts were converted to daily production rates (mg C m^{-3} d^{-1}), which were obtained from the triplicates samples, which generally agreed within ± 10% of covariance and were averaged to obtain the mean value for a given depth. Production in the dark bottle was subtracted from the mean obtained from the light bottles to correct for adsorption. The daily production rate at given depths was used to calculate the integrated water column production (mg C m^{-2} d^{-1}). The following equation was used for the calculation.

Primary Production (mg C m^{-3} day^{-1}) = 1.05 x S_{DPM} x W / S_A x T, Where, 1.05 - correction for the lower uptake of ^{14}C compared to ^{12}C, S_{DPM} - DPMs in filtered sample, DPM - disintegration per minute, W - dissolved inorganic carbon (DIC) concentration in sample (~25000 mg C m^{-3}), Sample Activity (S_A) - V * T_{DPM} /A_{Vol}, T - time (days), V - volume of filtered sample (liters), T_{DPM} - Total ^{14}C DPMs (in 0.25 ml), A_{Vol} - volume taken to measure sample activity.

3.2.5. Mesozooplankton biomass

Mesozooplankton is a group of heterotrophic organisms that depend on organic matter produced by autotrophic (as well as microheterotrophic) organisms for their nutrition and are an important component in the food web of the oceans. Generally, it has a body size >200μm.

The zooplankton samples were collected with a Multiple Closing and Opening Plankton Net (Hydro - Bios, mouth area 0.25 m^2, mesh width 200 μm) (Plate 3.2c), which has an electronic depth sensor. The net can be operated at desired depths with the help of a deck unit onboard. Zooplankton samples were

collected from the bottom of the thermocline up to the surface so that the representation of zooplankton biomass up to ~ 200m depth could be accounted.

Mesozooplankton biomass was measured as displacement volume, which was converted to dry weight (1 ml displacement volume = 0.075 g dry wt.) and to carbon (34.2% of dry wt.) (Madhupratap *et al.*, 1981 and Madhupratap & Haridas, 1990).

3.3. Environmental data

3.3.1. Temperature and Salinity

Temperature and salinity profiles from the study area were obtained from CTD (Sea Bird Electronics Seacat, SBE 911 Plus, USA) profiler onboard FORV *Sagar Sampada*. Data were collected from 28 stations along 6 latitudinal transects with 1° difference in longitude. The physical environmental data derived were used for interpreting the biological components.

3.3.2. Transparency

Water column transparency is generally expressed in terms of attenuation coefficient and is a measure of the physical conditions of the water column in terms of its light penetration capability (Pickard & Emery, 1982). It is important for a variety of reasons. For eg. if the nutrients are not limiting, the biological productivity of a given water column is directly dependent on the amount of sunlight with depth, known as euphotic zone. The classic method of measuring water clarity is by lowering Secchi disc overboard and visually noting the depth at which it disappears from normal visual range. This method is dependent on the intensity of sunlight and its incident angle.

During the present study, Secchi disc was used to measure the water transparency in all the primary productivity stations. A rope was tied to the disc for lowering it from the vessel's deck in to the water. The water depth at which the disc disappeared from view was recorded. Operationally, this was achieved by lowering the disc one meter beyond the depth where it disappeared followed by lifting it up for reappearance. The mean of two readings was taken as the transparency. From the observed transparency value, attenuation coefficient (k) was calculated using

the following formula. Higher attenuation coefficient indicate high turbidity and less light penetration.

Attenuation coefficient (k) = 1.7/D; Where 'D' is the Secchi disc depth.,1.7 is a constant for oceanic (clear) waters and 1.4 is for coastal (turbid) waters.

3.3.4. Dissolved oxygen

Dissolved oxygen (DO) in seawater was measured following Winkler's method as described in Strickland & Parsons (1972). Water samples collected from desired depths in the rosette of Niskin bottles (General Oceanics, USA) were carefully collected in to oxygen glass bottle (50 ml) without trapping air bubbles. Immediately samples were fixed by adding 0.5 ml of Winkler A (manganous chloride) and 0.5 ml of Winkler B (alkaline iodide) solution to each 50 ml of water samples.

The dissolved oxygen analysed by titration method was calculated using the formula

Dissolved Oxygen (ml/litre) = 5.6 * N * (S - b_m) * V/(V - 1) * (1000/A), Where.,

N - Normality of the thiosulphate, S - Titre value for sample

b_m - Mean titre value for blank, V - Volume of the sample bottle

A - Volume of sample titrated (50ml)

3.3.5. Nutrients (nitrate, phosphate and silicate)

Samples for nutrients were collected into clean glass bottles. The analyses were carried out in an autoanalyser SKALAR (Model 51001-1). The principle behind the measurements are as follows.

Nitrate in the sample was first reduced to nitrite by passing through a reducing column filled with copper amalgamated cadmium granules. The reduced nitrate (NO_3) i.e nitrite (NO_2) then reacts with sulphanilamide in an acid solution. The resulting diazonium compound got coupled with N-(1-Naphthyl)-ethylenediamine dihydrochloride to form a colored azo dye, the absorbance is measured spectrophotometrically at 543nm. The concentration of reactive nitrate is given in μmol l^{-1}. Silicate in the sample was acidified and mixed with an ammonium molybdate solution forming molybdosilicic acid. This acid was reduced

with ascorbic acid to a blue dye, which was measured spectrophotometrically at 810nm. Oxalic acid was added to the sample to avoid phosphate interference. Phosphate in the sample was allowed to react with ammonium molybdate and potassium antimony tartarate in acid medium form an antimony - phospho - molybdate complex. This complex was reduced to an intensely blue coloured complex by ascorbic acid, which was measured spectrophotometrically at 880nm.

3.4. Statistical analyses

3.4.1. Diversity indices

The presence / absence or the number of taxa / species in an area may be due to two factors, (1) Evolutionary history of the geographic area, (2) The interactions of the taxa and their relationships to the physical environment (Clifford & Stephenson, 1975). These factors are not mutually exclusive. Evolution affects the pattern of interactions in a community and the pattern of interactions in a community determine to a great extend the course of evolution. In the competition between two taxa / species, one taxon / species are almost always appear to cause extinction of the other in the absence of mitigating factors such as fluctuating environment and spatial heterogeneity. Therefore the number of groups and their relative abundance are the basis of descriptions such as simple, complex or dominated by one or a few groups, each of which refers to the general term diversity. Thus diversity indicates the degree of complexity of a community structure. It is a function of two elements namely number of taxa / species and their abundance or equitability, that is, richness and evenness with which the individuals are distributed among the group. Diversity is a concise expression of how individuals in a community are distributed with in subsets of the groups. Diversity decreases when one or a few groups dominate in a community, when individuals of a more common group replace individuals of rare groups or when one or a few groups rapidly reproduce.

Diversity is often related to certain environmental characteristics of water masses and the degree of complexity of the flow of energy with in the community. The measurements of the temporal variation of diversity provide useful information

on the succession of the community structure. Diversity is generally greater in waters of lower latitudes than in higher latitudes, higher in marine environments than in freshwater and the lowest in brackish waters (Sanders, 1968). Diversity is reported to the higher in the deep sea than in shallow waters and it decreases gradually with depth. Higher diversity tends to be seen in areas of greater environmental stability / predictability especially if associated with higher levels of productivity (Dumpar, 1960; Patten, 1962 and Paine, 1966). To mathematically analyze and compare changes in aquatic communities due to environmental stresses, species diversity (Pielou, 1966 a &b) is one of the tools, which can be made use of. Odum (1971) has defined species diversity indices as ratios between the number of species and important values such as biomass (wet weight), numbers and productivity etc.

Several diversity indices have been proposed and among which the following were used in the present study.

(a) Margalefs index (Margalef, 1951)

$\alpha, = (S-1) / \log_e N$

(b) Simpson's index (Simpson, 1949)

$Sl_a = 1 - \Sigma n_i (n_i - 1) / N (N-1)$

(c) Shannon and weaver

$H = -\Sigma (p_i \log_2 p_i)$ where $p_i = n_i / N$ (Shannon and weaver (1963)

Dominance of the taxonomic group is studied by means of evenness indices. The abundance relationships in a community have been measured in terms of the evenness component of the diversity index where evenness expresses the degree of equality of the abundance of the taxa / species of the community.

Heips evenness index

$h_e = (e^H - 1) / (S-1)$, $S>1$ (Heips, 1974)

3.4.2. Analysis of variance (ANOVA)

Three way ANOVA is applied to compare between stations, between species and between depths and also to see whether there is any station - species, station -

depth and species - depth specificity / interaction based on species abundance for ciliates and dinoflagellates separately for each season (Snedecor & Cochran, 1967).

3.4.3. Cluster analysis

Bray Curtis similarity index (Clifford & Stephenson1975) is applied for the $\log_{10}$ (X+1) converted data of species abundance, to study similarity between species and between depths at each station during different seasons. Similarity index calculated for species is presented as a Dendrogram using group linkage clustering techniques. Similarity between depths is presented as MDS (Non - Metric Multi Dimensional Scaling (MDS) (Clarks & Gorley, 2001).

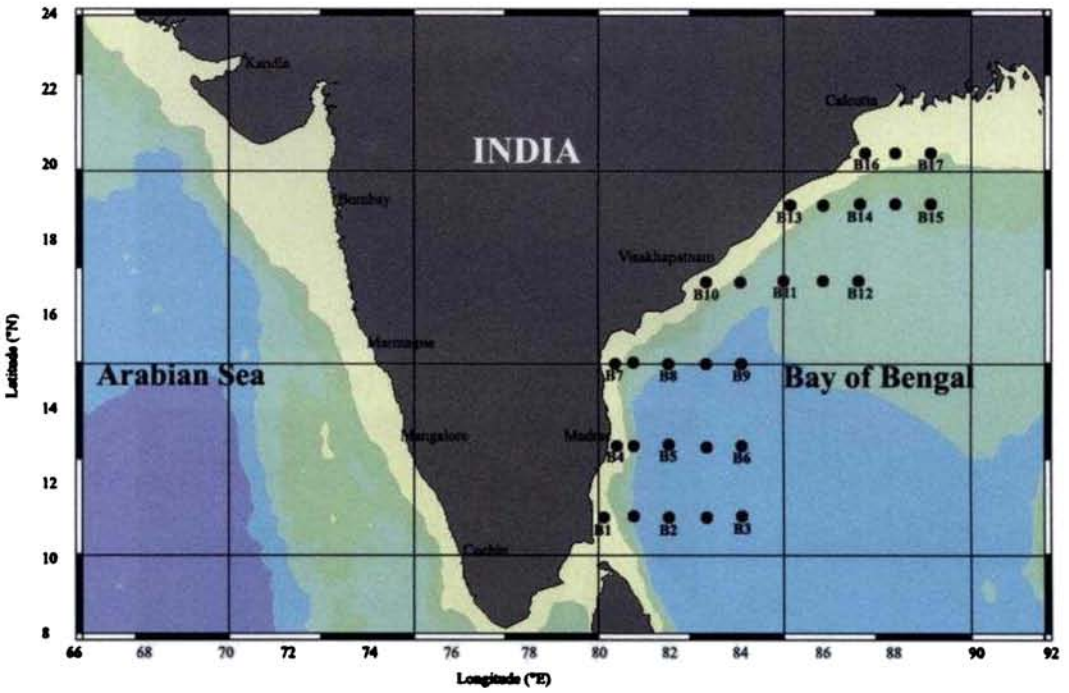
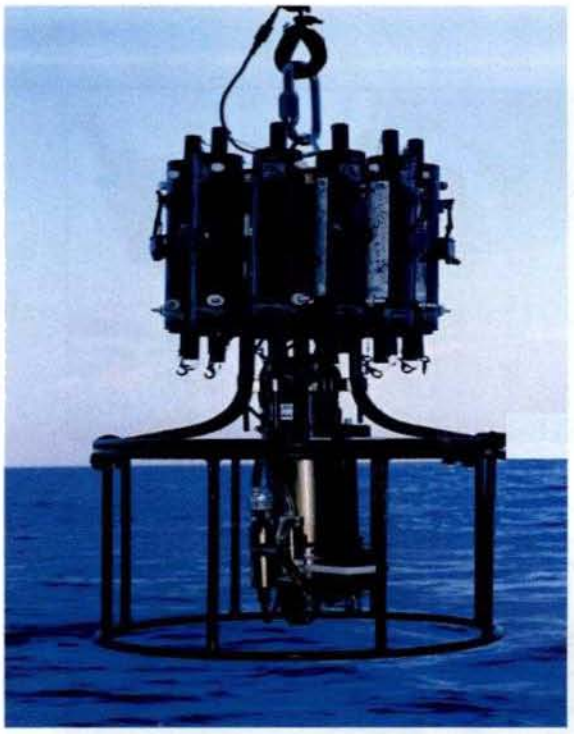
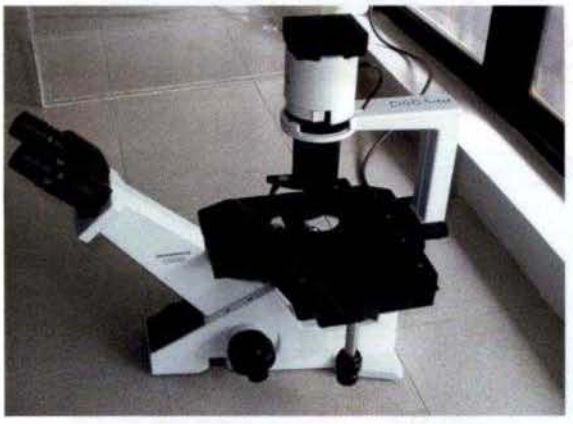


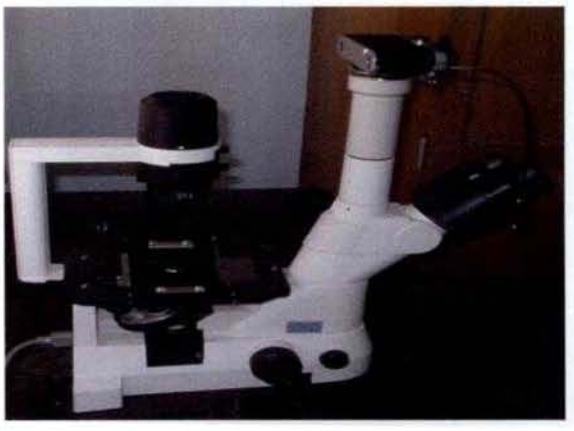
Figure 3.1. Station locations



(a) CTD



(b) Olympus CK 30

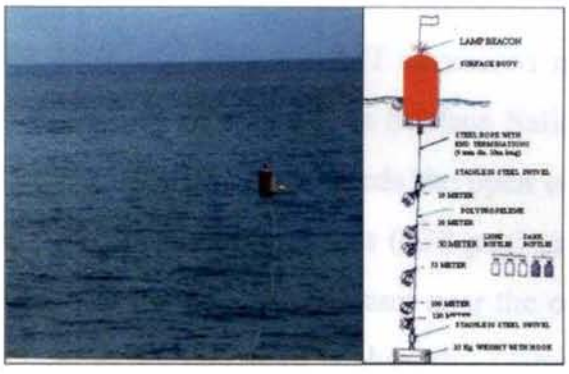


(c) Nikon TS 100

Plate 3.1

(a)

(b)


LAMP BEACON
SURFACE BUOY
STAINLESS STEEL SWIVEL
POLYPROPYLENE
STAINLESS STEEL SWIVEL

(c)

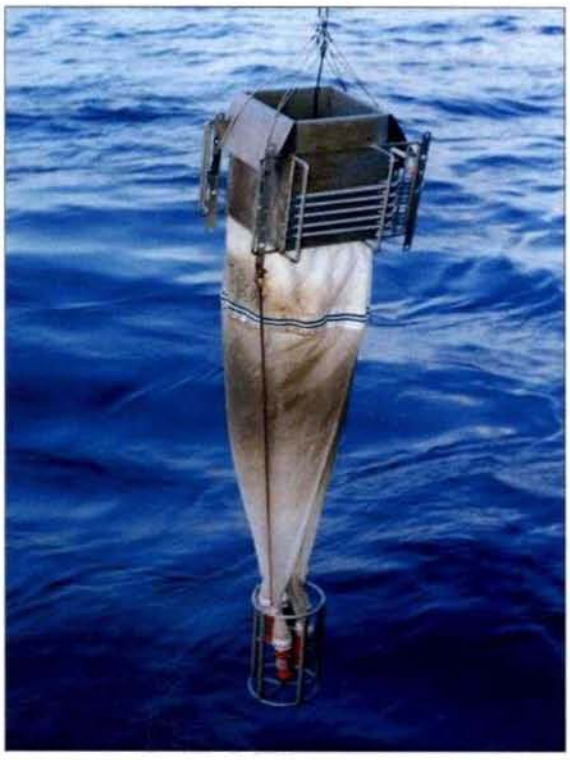


Plate 3.2

Chapter 4

Results - Physicochemical environment

4.1. Physical environment

4.1.1. Winter monsoon

During the season, sea surface temperature (SST) ranged between 25.5 and 29.2°C (Figure 4.1a). SST in general showed a steady decrease towards the coast along 11 and 13°N. Along 15°N, SST was found to vary from 27.7 – 28.4°C with minimum at 83°E. To the north of 15°N, the SST decreased northward and the lowest (25.5°C) was observed along 20.5°N. Sea Surface Salinity (SSS) ranged from 25.3 – 33.8 psu, with high saline waters towards the open ocean region along the southeast coast and relatively low saline waters (<30 psu) prevailed along the entire east coast (Figure 4.1b). Salinity was minimum near the coast along 19 and 20.5°N that could be attributed to the inflow of Mahanadi - Ganges - Brahmaputra river systems. Similarly coastal regions along 15°N showed low salinity due to the Krishna river influx. Mixed layer depth (MLD) ranged between 5 – 50m and was very shallow in the regions where SSS were low (Figure 4.1c). In general, MLD increased towards offshore from 11 – 17°N, except along 15°N, where it shallowed (~10m) towards 83°E. Obviously MLD in the northern transects was shallow (<10m) due to low surface salinity.

Vertical thermal structure along 11°N showed relatively deeper isothermal surface layer in the open ocean region (Figure 4.2a). But near the coastal areas, thermal structure showed an inversion below 30m. Another significant observation was the doming of isotherms (cold core eddy signature), which was clear below 150m, centered around 82°E and was more conspicuous at 200m depth. Salinity structure in the upper 50m showed frontal pattern towards the coast indicating the freshwater influx from the continent (Figure 4.2a). Isopycnals in the upper 50m resembled the isohaline pattern, below which the temperature dominated over salinity in the density field (Figure 4.2a). The vertical profiles along 13°N

resembled the pattern along 11°N but the eddy signals were not so prominent as that of the latter transect (Figure 4.2b). However along 15°N, profiles of temperature, salinity and density showed prominent eddy signatures, which was intense at 75m between 82 and 83°E (Figure 4.2c). Doming of isolines was also evident along 17 and 19°N, but with a weaker gradient.

Salinity structure in the upper 40m along 17°N showed a frontal pattern with low saline waters near the coast, which indicated the freshwater influx from the continent, which had a gradient of almost 2 psu in the upper 50m (Figure 4.3a). But along 19°N, the low salinity pools were observed about 200km from the shore with a gradient of almost 5 psu in the upper 50m (Figure 4.3b). Salinity structure along 20.5°N also showed a frontal pattern due to fresh water influx from the continent with a sharp gradient of 8 psu in the upper 50m (Figure 4.3c). The most conspicuous feature in the thermal structure along the northern transects was the presence of cold surface waters overlying the warmer waters (thermal inversion). The amplitude of the thermal inversions increased northward and the maximum (>3°C) were observed in the northern transects (19°N & 20.5°N), while small scale inversions (<0.5°C) were noticed in the southern regions (Figures 4.4 a & b).

During the season, transparency (attenuation coefficient) of the water column varied from 0.047 – 0.094 (Avg. 0.070) and the minimum was observed at the oceanic station along 15°N and maximum at the coastal station along 20.5°N (Table 4.1). Along the coastal transect, maximum sunlight penetration was found at 15°N. Attenuation coefficient ranged between 0.054 and 0.094 (Avg.0.075) and minimum (0.047) was observed along 13°N. Average euphotic column (considered as 1% of the surface illumination) along the coastal transect (69m) was much lower than the oceanic transect (82m) which indicated the presence of higher suspended matter in the former compared to the latter the mean value for all the stations was 76m.

4.1.2. Spring intermonsoon

SST showed minimum spatial variability, which ranged between 28.6°C and 30.25°C, with minimum near the coast along 15°N and maximum along the open

ocean waters along 13°N (Figure 4.5a). SSS ranged from 32.8 - 34.3 psu and low salinity pockets were observed at the surface layer about 200 – 400 km away from the shore particularly between 13 – 19°N (Figure 4.5b). The warm and low saline waters in the oceanic region provided stratified surface layer which resulted in thin mixed layer (<30m), however along 17°N, between 84 – 86°E, comparatively deeper MLD was observed (~40m) (Figure 4.5c). Isopycnals showed stratification and resembled the pattern of salinity at the surface layer but in the deeper waters they followed the isothermal pattern.

The vertical thermal structure along 11°N and 13°N showed the warm surface layer (>30°C) (Figures 4.6a & b). Along these transects pools of low salinity was found around 200m away from the coast. The near shore values of SST along 15°N were relatively lower (<29°C) than that of the offshore values (~30°C) (Figure 4.6c). In this transect, pools of low salinity were observed much far from the coastal region (~400km from the shore) compared to 13°N and the salinity structure showed sharp gradients in the upper 120m, below which the gradients were minimum. The density stratification at the surface reduced the mixed layer depth, and the denser water (~20.5) was observed near the shore. Isopycnals of the sigma-t structure showed dominance of salinity over the temperature in the upper 50m, below which temperature dominated the density field.

The vertical thermal structure along 17°N exhibited warm surface isothermal layer, below which it showed gentle down curving of isotherms (warm core eddy signature) centered around 85°E (Figure 4.7a) and the feature was more conspicuous at 150m depths. Below the surface layer, isohalines also showed downsloping towards 85°E and the low saline patches at the surface layer were observed about 300km from the shore. The isopycnals at the surface layer followed the same trend as the salinity, below which the density reflected combined effects of temperature and salinity and showed downsloping of isolines towards 85°E. Though the downsloping was not intense as at 17°N, temperature, salinity and sigma-t structure along 19°N also exhibited downsloping of isolines towards 87°E

(Figure 4.7b). However along 20.5°N, temperature, salinity and density profiles did not show any significant feature (Figure 4.7c).

Attenuation coefficient during the season ranged between 0.036 - 0.062 (Avg. 0.048) and minimum value was found at the oceanic station along 13°N and maximum at the coastal station along 20.5°N (Table 4.1). Generally coastal stations showed lower euphotic column depth (Avg. 96m) compared to the oceanic stations (Avg. 117m). Along the coastal stations, attenuation coefficient varied from 0.045 – 0.062 (Avg. 0.053) where as in the oceanic stations it ranged between 0.036 – 0.058 (Avg. 0.044) and euphotic column was maximum at 13°N and minimum along 20.5°N and it varied from 81 – 141m (Average 106m).

4.1.3. Summer monsoon

In general, warm sea surface (>29.2°C) was observed during the period except near the coast along 15°N where SST dropped to 27.9°C (Figure 4.8a). SSS varied from 27.9 – 29.4 psu and showed marked north – south gradients where higher values were found at the northernmost transect (Figure 4.8b). Relatively high saline waters (>33.5 psu) were present along the southeast coast, whereas in the northeast coast the SSS was considerably less and the lowest value of 25 psu was observed near the coast along 20.5°N. Similar to the SSS distribution, MLD showed north – south gradients and along the south east coast it was relatively thick and it ranged from 30 – 60m, but shallowed towards the northern transects (19° and 20.5°N) except near the coast along 15°N where comparatively shallower MLD was noticed (Figure 4.8c).

Vertical thermal structure along 11°N showed a relatively deeper isothermal surface layer (>50m), below which dome shaped isolines (eddy signatures) were distinct and the maximum ascent was observed at 175m depth of 82°E (Figure 4.9a). Comparatively high surface salinity was observed in the coastal region and the sigma-t structure showed relatively deep mixed layer along this transect, except near the coast. In general, the isopycnals of the density structure followed the isotherms indicating the dominance of temperature over salinity in the density field. Vertical structure of temperature, salinity and density along 13°N showed relatively

deeper MLD, which oscillated between 40 – 50m depth (Figure 4.9b). Below 75m, isotherms, isohalines and isopycnals showed upsloping towards the coast indicating subsurface upwelling. Another notable feature was the appearance of a high salinity core (>35.2 psu) between 75 and 150m, centred around 82.5°E, where the thermal structure showed diffused thermocline. The vertical thermal structure along 15°N showed fine upsloping of isotherms towards the coast and relatively cold waters (<28°C) at the surface (Figure 4.9c). The upsloping of isotherms are conspicuous in the upper 100m. The isohalines and isopycnals also showed upsloping towards the coast in the upper 75m, which indicated the upwelling processes. Distribution of temperature, salinity and density along 17°N showed fine upsloping of isolines from the offshore region (Figure 4.10a). Vertical profiles of temperature along 19 and 20.5°N showed an appreciable isothermal surface layer (Figures 4.10 b&c), but the low saline waters were dominant over the temperature resulted in density stratification in the surface layers and a reduced mixed layer.

A gradual increase in the extinction coefficient towards north was a general feature of the season, which indicated relatively high suspended load towards north and the average value was 0.084 (Table 4.1). Along the coastal transect, extinction coefficient varied from 0.060 - 0.130 and maximum was found along 20.5°N. Along this transect, euphotic column was maximum (84m) at 15°N and minimum (39m) was at 20.5°N. Average value of the euphotic column along the coastal transect was 63m. Along the oceanic transect, attenuation coefficient was maximum (0.121) at 20.5°N and minimum (0.054) at 11°N and the average value for the transect was 0.081. Average depth of the euphotic column along the coastal stations was low (63m) compared to oceanic stations (68m) and the average euphotic column during the period was 66m.

4.2. Chemical environment

Distribution of chemical parameters such as dissolved oxygen, nitrate, phosphate and silicate were studied along coastal, middle and offshore stations during different seasons. Vertical distributions of these chemical parameters were plotted up to a depth of 200m.

4.2.1. Winter monsoon

Along the coastal stations northernmost latitudes showed higher dissolved oxygen concentration (200μM) in the surface waters (Figure 4.11a) and the upper 20m water column had >170μM. Nitrate distribution showed its absence in the upper 30m water column and in the surface layers latitudinal variations of nitrate was not well marked (Figure 4.11b). Similar to nitrate distribution, silicate also was low in the upper 30m water column and 1μM contour of silicate was found around 30m depth in the southernmost transect around 20m in the northernmost location (Figure 4.11c). Distribution of phosphate showed downsloping towards north and the upper 30m water column was devoid of any measurable quantities of phosphate (Figure 4.11d).

Similar to the coastal transect, dissolved oxygen concentration in the upper 30m water column along the middle transect was >170μM (Figure 4.12a). In deeper waters relatively low oxygen concentration was found at comparatively shallow depth compared to coastal transect. The oxygen concentration at 60m depth along the middle transect was 40μM while at the same depth along the coastal transect showed 100μM. Upper 100m water column along the middle transect had more than 20μM of oxygen concentration while at the same depth along the coastal transect it was more than 30μM. Relatively low oxygen concentration along subsurface waters is due to the cold core eddy which was centered along the middle stations. Nitrate concentration in the upper 30m water column was less than 1μM and in the subsurface layers it followed the pattern of dissolved oxygen. (Figure 4.12b). The 12μM contour of nitrate which was found below 80m along coastal transect was found around 60m along the middle transect. Silicate concentration was less than 1μM in the upper 30m and a marginal upliftment in the subsurface layers was found resulting in higher concentration of this nutrient in shallower depth compared to coastal stations. These features further support the cold core eddy signatures found at the subsurface layers along the middle stations (Figure 4.12c), which was evident in the physical features. However phosphate distribution did not show any features of eddy formation. However downsloping of phosphate

contours towards north in the subsurface layers was more intense and 1μM contour was at shallower depth along this transect compared to the coastal areas (Figure 4.12d).

Like the coastal and middle stations, dissolved oxygen along the offshore stations showed >170μM concentration in the upper 30m water column below which upsloping towards north was evident (Figure 4.13c). Oxygen distribution in the subsurface layers were similar to those along the coastal transect. Nitrate distribution was also similar to the distribution along the coastal transect, but 1μM contour was found at much deeper depths (50m) (Figure 4.13b) compared to the coastal station (40m). Below 40m, downsloping of isolines towards north was observed. Silicate distribution at the surface along the transect was similar to the middle transect where upper 25m water column had less than 1μM concentration (Figure 4.13c). Phosphate was below measurable concentration and latitudinal variation was not evident. However below 40m, phosphate contours showed a marginal downsloping towards north (Figure 4.13d).

4.2.2. Spring intermonsoon

Along the coastal transect, dissolved oxygen concentration was >190μM in the upper 40m water column (Figure 4.14a). Isolines of dissolved oxygen below 40m showed a downsloping towards north. Distribution of nitrate showed its absence in the upper 50m water column and 1μM contour was at deeper depth (60m, Figure 4.14b). In the surface layers, distribution of silicate was similar to nitrate. Upper 40m water column had undetectable levels of silicate concentration (Figure 4.14c). Upsloping of isolines towards north was evident and 1μM concentration of silicate found below 40m in the southern region could be traced above 40m in the northern region. Phosphate distribution also showed similarity to the nitrate and silicate. 1μM contour of phosphate was below 40m, which showed absence of measurable quantity of this nutrient above 30m depth (Figure 4.14d).

Upper water column (0-50m) along the middle stations was well oxygenated (>180μM) compared to the coastal stations (Figure 4.15a). The upsloping of isolines towards north was evident. In the southern region oxygen concentration

was relatively higher (>200μM) at the surface. Distribution of nitrate was similar to the distribution along coastal transect where it was below measurable concentration in the upper 50m water column. At 100 and 160m depth nitrate distribution showed pockets of low concentration, which was supportive to the warm core eddy signatures found in the physical features. Silicate concentration also was similar to the distribution along the coastal transect where upper 50m water column showed less than 1μM concentration. However the eddy signatures found in the distribution of nitrate was not so prominent in the silicate distribution although tilting of isolines were observed at subsurface layers (Figure 4.15c). Upper 40m of the water column showed less than 1μM concentration of phosphate (Figure 4.15). Similar to nitrate distribution, low concentration pockets of phosphate were seen below 60m depth along 15°N and 17°N that indicated warm core eddy.

Along the oceanic transect, dissolved oxygen concentration in the surface water was relatively higher in the southern transects (Figure 4.16a). Upsloping of isolines towards north was evident indicating higher nitrate concentration in relatively shallower depth in the northern region. Along the transect, upper 50m water column had >1μM nitrate (Figure 4.16b). Like coastal and middle transects, upper 50m water column along the transect had less than 1μM concentration of silicate (Figure 4.16c) and a gradual upsloping of isolines towards north was evident. Phosphate distribution showed undetectable concentration up to 50m depth (Figure 4.16d).

4.2.3. Summer monsoon

Dissolved oxygen concentration along the coastal stations showed >180μM in the upper 30m water column and higher concentration was found in the northern transect (Figure 4.17a). During the period, 1μM nitrate contour was found at 30m depth. Nitrate distribution showed peculiar features, which were typical for upwelling processes (Figure 4.17b). At 15°N, 10m depth had 1μM nitrate concentration and in other stations of the transect 1μM contour of nitrate was around 30m depth. Silicate distribution was similar to the nitrate, with higher concentration (1μm) at 10m depth along 15°N (Figure 4.17c) and in other stations

at 20 – 30m depth. Distribution of phosphate showed less than 1μM concentration in the upper 40m depth in the southern latitudes which shallowed up to 20m depth in the northernmost transect (Figure 4.17d).

Along the middle transect, upper 30m had >170μM concentrations of dissolved oxygen (Figure 4.18a) and northern regions had generally higher concentration. Nitrate concentration in the upper 20m water column was undetectable and 1μM contour was found around 30m depth in the south and shallowed up to around 20m depth in the northern transects. Downsloping of isolines in the deep waters towards north was also observed (Figure 4.18b). Silicate distribution showed <1μM concentration in the upper 30m water column (Figure 4.18c). The 1μM contour of silicate which was present at 30m depth at the southern region shallowed up towards north. Higher concentration of silicate at relatively shallower depth in the north could be due to the immense river discharge in that area. Phosphate distribution showed downslopping of 1μM contour towards north and the upper 40m water column had <1μM concentration (Figure 4.18d).

Along the oceanic region, upper 20m water column was almost uniformly saturated with >180μM of dissolved oxygen and the latitudinal variations was less (Figure 4.19a). Below 40m depth gradual upslopping of isolines towards north was visible. Nitrate showed its absence in the upper 20m water column and 1μM contour was noticed at 30m depth (Figure 4.19b). Distribution of silicate was similar to nitrate in the upper layers and 1μM silicate was found around 30m (Figure 4.19b). Phosphate was below 1μM concentration in the upper 30m water column (Figure 19d). In the deeper waters downsloping of isolines towards north was observed.

4.3. Summary

During winter monsoon, sea surface temperature (SST) showed marked north - south variability and generally decreased towards north and a minimum value of 25.5 was observed along 20.5°N (Figure 4.1a). Sea surface salinity ranged from 25.3 – 33.8 psu and relatively low saline waters (<30psu) prevailed along the entire east coast (Figure 4.1b). Minimum salinity (<28 psu) was found at the coastal

station along 15, 19 and 20.5°N due to the freshwater influx from Krishna River in the former and Mahanadi – Ganges – Brahmaputra river influx in the latter regions. Generally, mixed layer depth (MLD) varied from 5 – 50m and increased towards offshore regions in the southern transects due to high salinity and temperature and decreased towards north due to low surface salinity (Figure 4.1c). Vertical structure of temperature, salinity and density showed subsurface cold core eddy features which was generally below 50m along transects 11 – 19°N. However, along 15°N, cold core eddy signatures were evident up to a depth of 25m (Figure 4.2b). The most outstanding feature in the thermal structure along the northern transects was the presence of cold surface waters overlying the warmer waters (thermal inversion). The amplitude of the thermal inversion increased northward and the maximum (>3°C) was observed in the northern transects (19 and 20.5°N), while small-scale inversion (<0.5°C) was noticed in the southern regions (Figure 4.4). Transparency of the water column (attenuation coefficient) varied from 0.047 – 0.094 (Avg. 0.070) (Table 4.1). Average euphotic column along the coastal transect (69m) was much lower than the offshore transect (82m) and the average euphotic column for the entire region was 76m. During the period, upper 40m water column had less than 1μM concentration of nutrients (nitrate, silicate and phosphate). Subsurface layers along the middle transects showed elevated concentration of nitrate and silicate due to the subsurface cold core eddy which was centered along the transect (Figures 4.11 – 4.13).

During spring intermonsoon, SST showed minimum spatial variability and ranged between 28.6 and 30.25°C (Figure 4.5a). SSS also showed minimum spatial variability during the period, which ranged between 32.8 and 34.3 psu and the low saline waters were found 200 – 400 km away from the shore (Figure 4.5b). Warmer and low saline waters in the offshore region provided stratified surface layers which resulted in thin mixed layer (<30m, Figure 4.5c). Vertical structure of temperature, salinity and density showed warm core eddy features below 75m along 15, 17 and 19°N (Figures 4.6 – 4.7). Distribution of nitrate and silicate was below measurable concentration in the upper 50m water column and 1μM contour was present at 60m

depth (Figures 4.14 – 4.16). Along the middle transect vertical distribution of nitrate and phosphate showed warm core eddy features where low pockets of concentration were found at deeper depths along 17 and 19°N (Figure 4.15). During the period transparency value was maximum (Avg. 0.048). Euphotic column was maximum during the season that varied from 81 – 141m with an average of 106m (Table 4.1).

During summer monsoon SST varied from 27 – 30.2°C and higher value (>29.4°C) were found north of 19°N (Figure 4.8a). SSS showed relatively high saline waters along the southern transects (Figure 4.8b). Northern transects showed low salinity with a minimum (25psu) along 20.5°N. MLD showed similarity to the SSS distribution and varied from 30 – 60m which shallowed towards northern transects (Figure 4.8c). Vertical structure of temperature, salinity and density showed fine upsloping of isolines towards the coast along 15 and 17°N, which indicated the upwelling process (Figures 4.9 & 4.10). Profiles of temperature along 19 and 20.5°N showed a deep isothermal layer, but the low saline waters were dominant over temperature resulted in density stratification in the surface layers and hence reduced mixed layer. Mean attenuation coefficient was maximum (0.084) during the period and the euphotic column was minimum (Avg. 66m) (Table 4.1). Vertical distribution of nitrate and silicate showed peculiar features, which indicate the upwelling process operating along 15 and 17°N (Figure 4.17). Along these transects vertical distribution of nitrate and silicate showed sharp upsloping of isotherms towards the coast (1μM of nitrate and silicate was found at 10m depth). In other stations, 1μM of these nutrients were found at 30m depth (Figures 4.14 – 4.19).

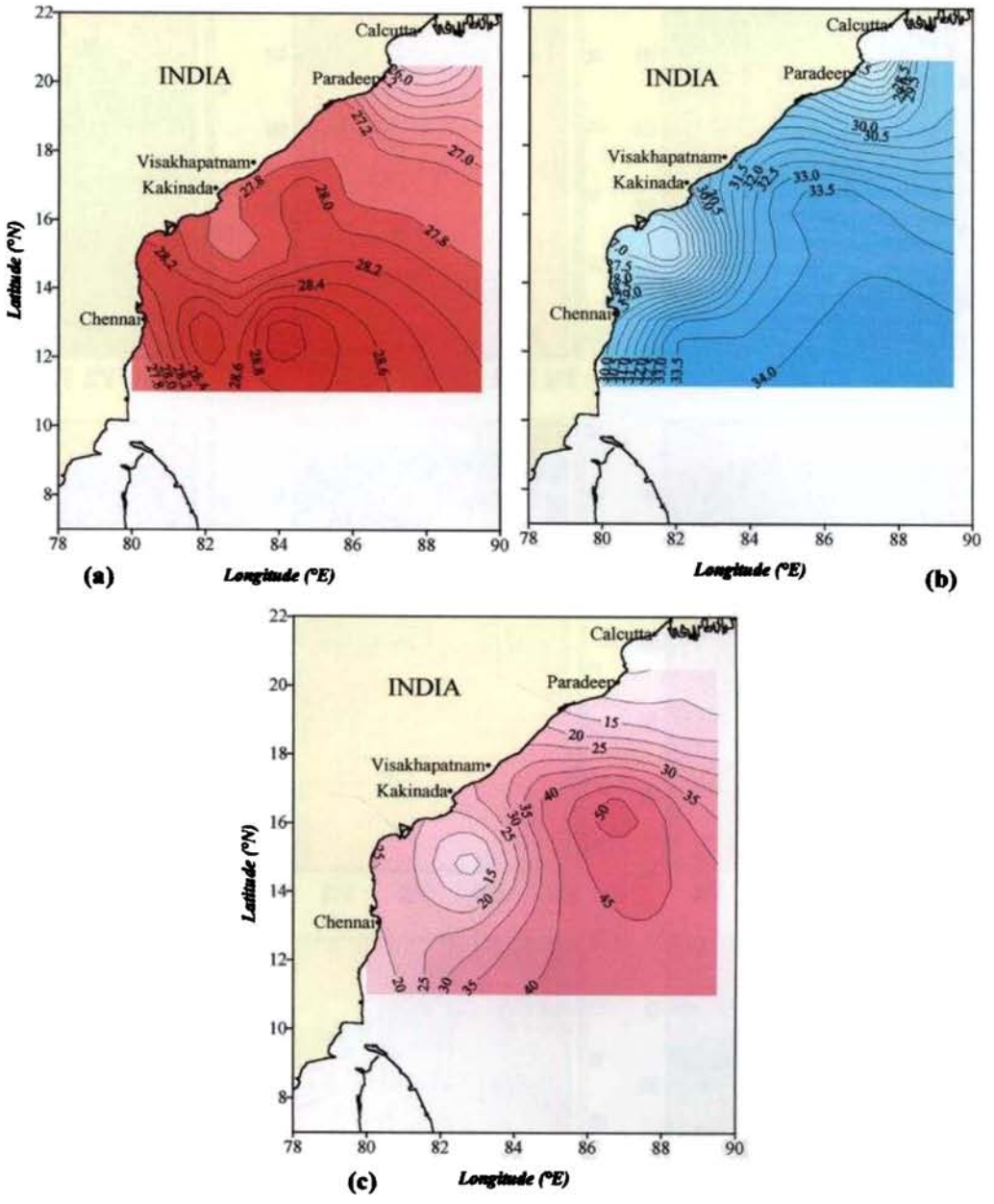


Figure 4.1. Distribution of (a) sea surface temperature (°C), (b) surface salinity (psu) and (d) mixed layer depth (m) during winter monsoon in the western Bay of Bengal

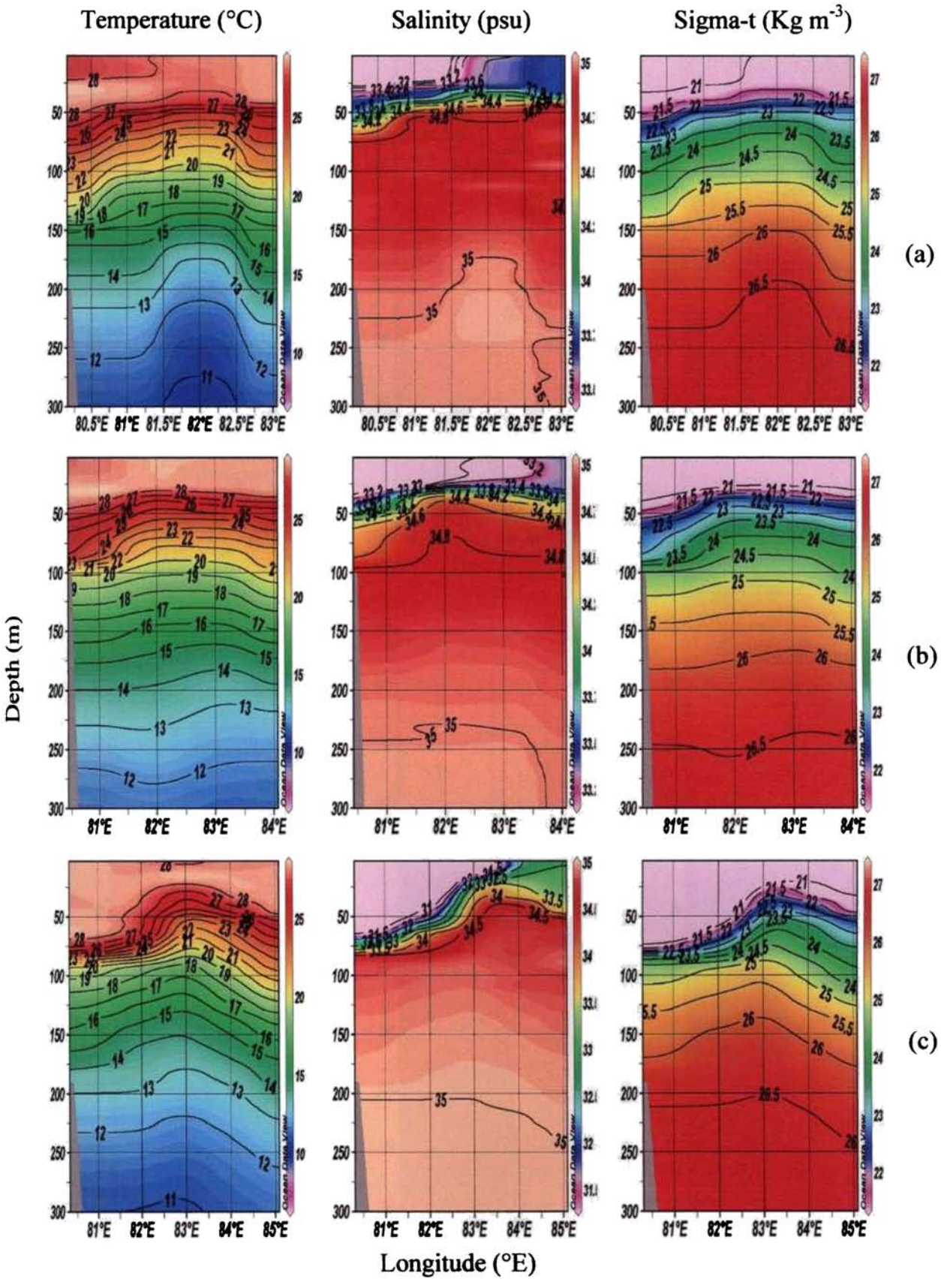


Figure 4.2. Vertical distribution of temperature, salinity and sigma-t along (a) 11°N (b) 13°N and (c) 15°N during winter monsoon in the western Bay of Bengal

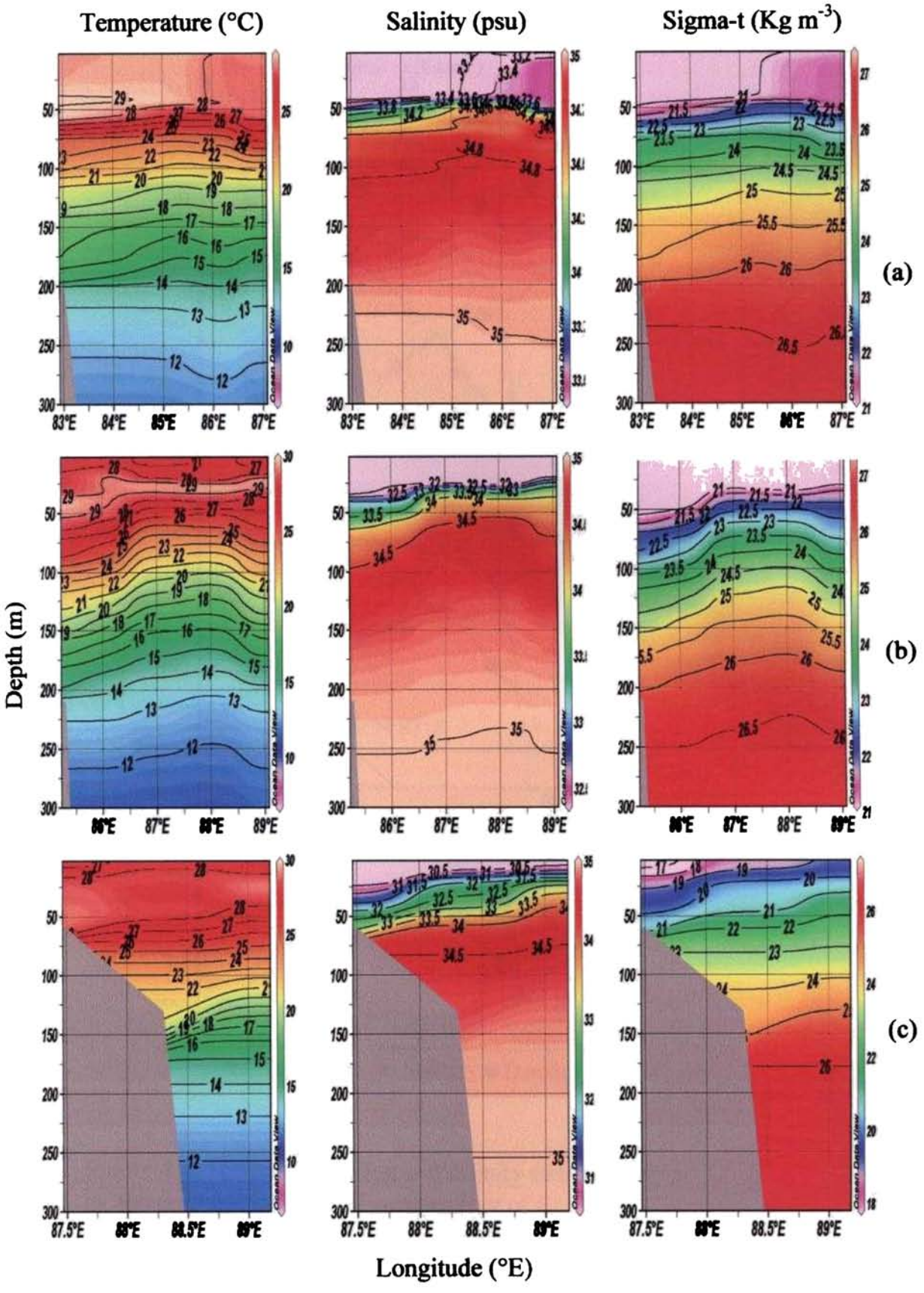


Figure 4.3. Vertical distribution of temperature, salinity and sigma - t along (a) 17°N, (b) 19°N and (c) 20.5°N during winter monsoon in the western Bay of Bengal

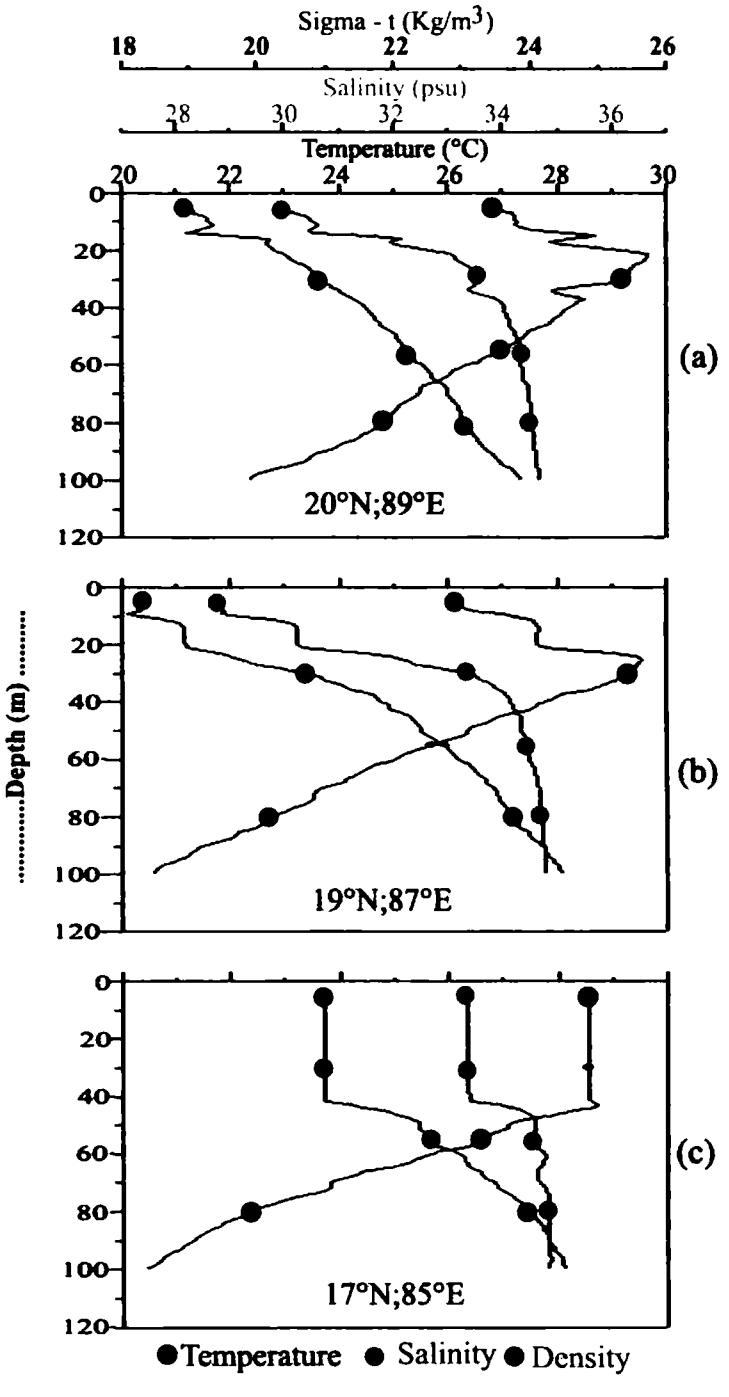


Figure 4.4. Thermal inversion and salinity stratification in the northern latitudes of western Bay of Bengal

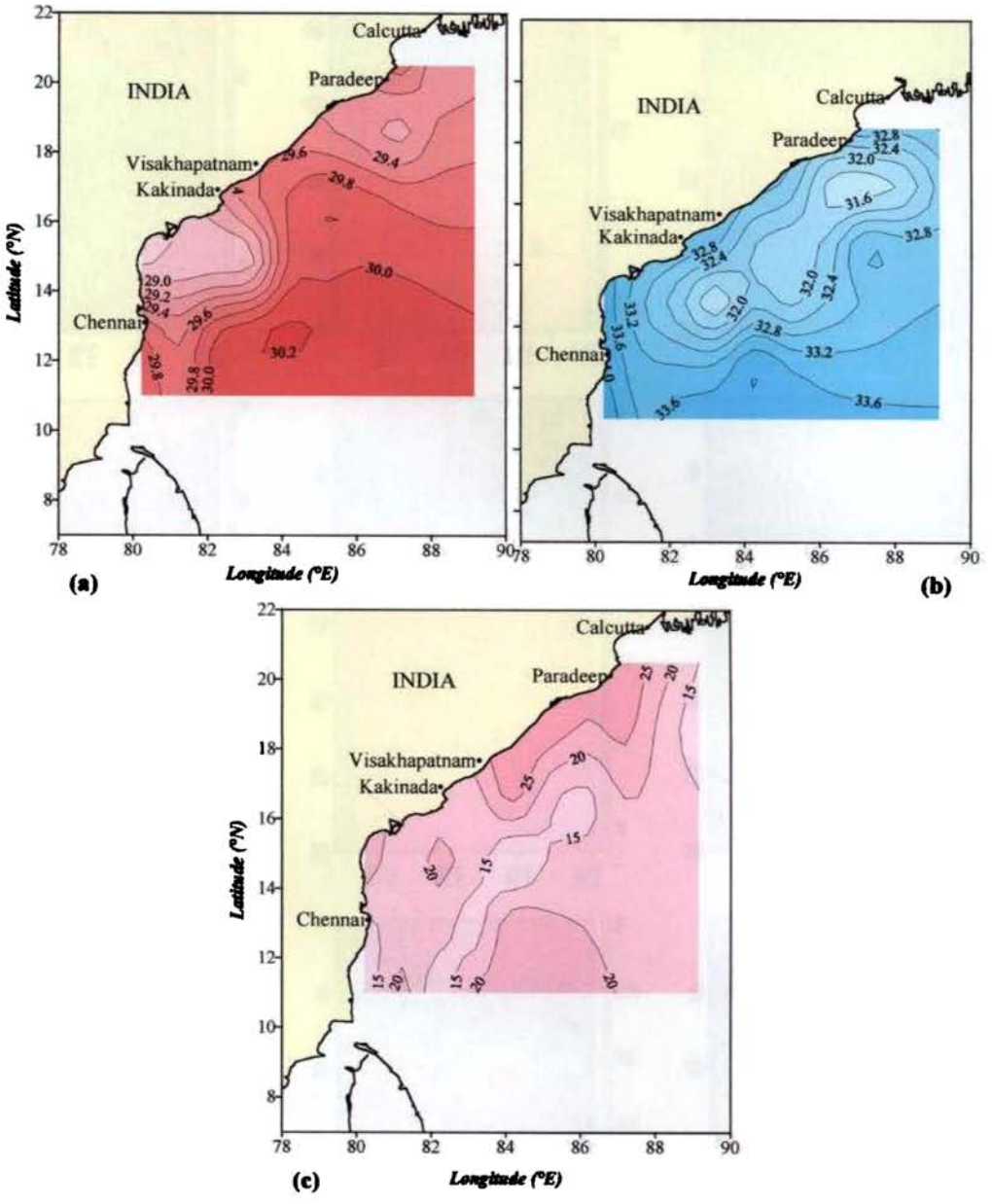


Figure 4.5. Distribution of (a) sea surface temperature (°C), (b) sea surface salinity (psu) and (c) mixed layer depth (m) during spring intermonsoon in the western Bay of Bengal

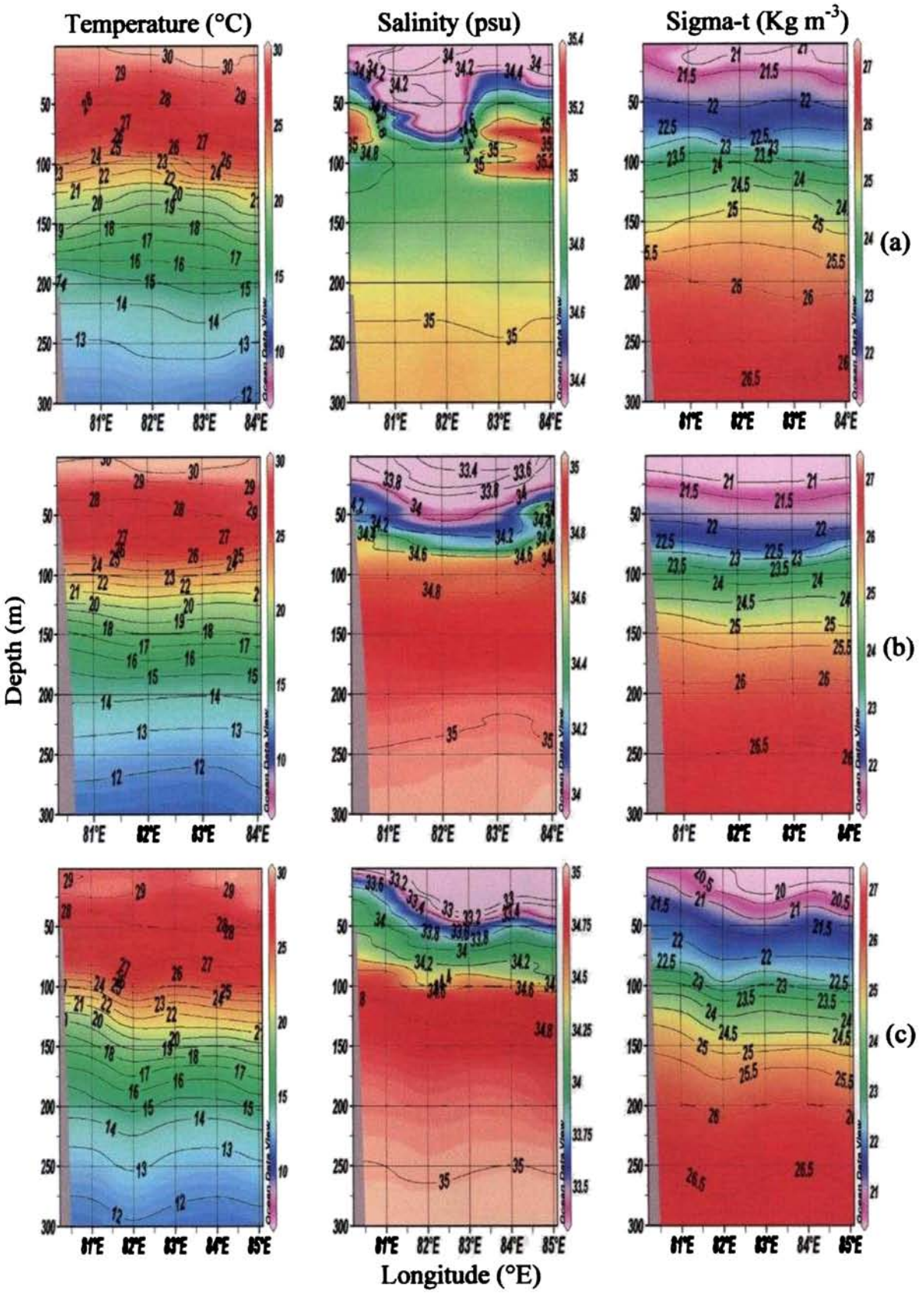


Figure 4.6. Vertical distribution of temperature, salinity and sigma-t along (a)11°N, (b) 13°N and (c) 15°N during spring intermonsoon in the western Bay of Bengal

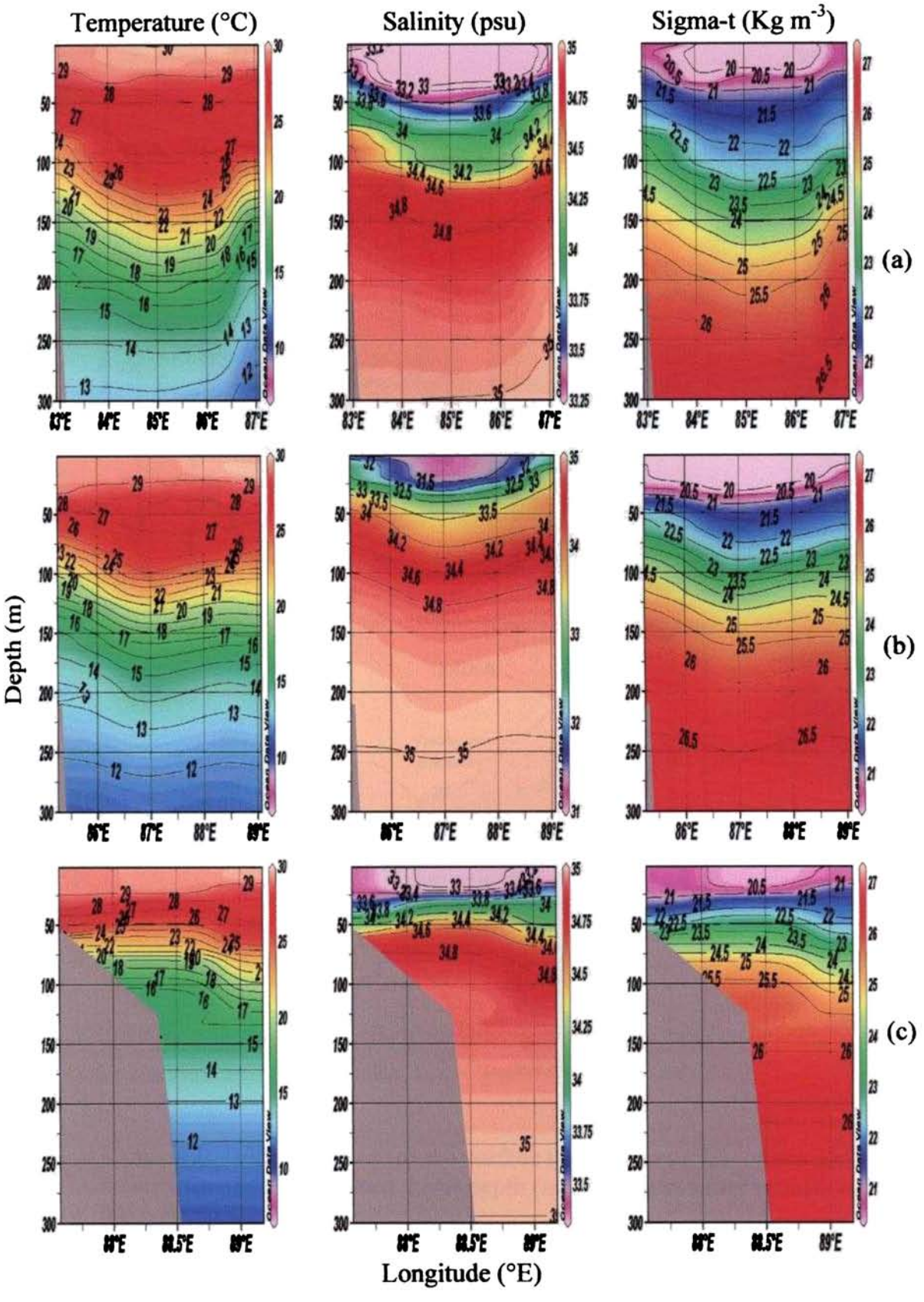


Figure 4.7.Vertical distribution of temperature, salinity and sigma-t along (a) 17°N, (b) 19°N and (c) 20.5°N during spring intermonsoon in the western Bay of Bengal

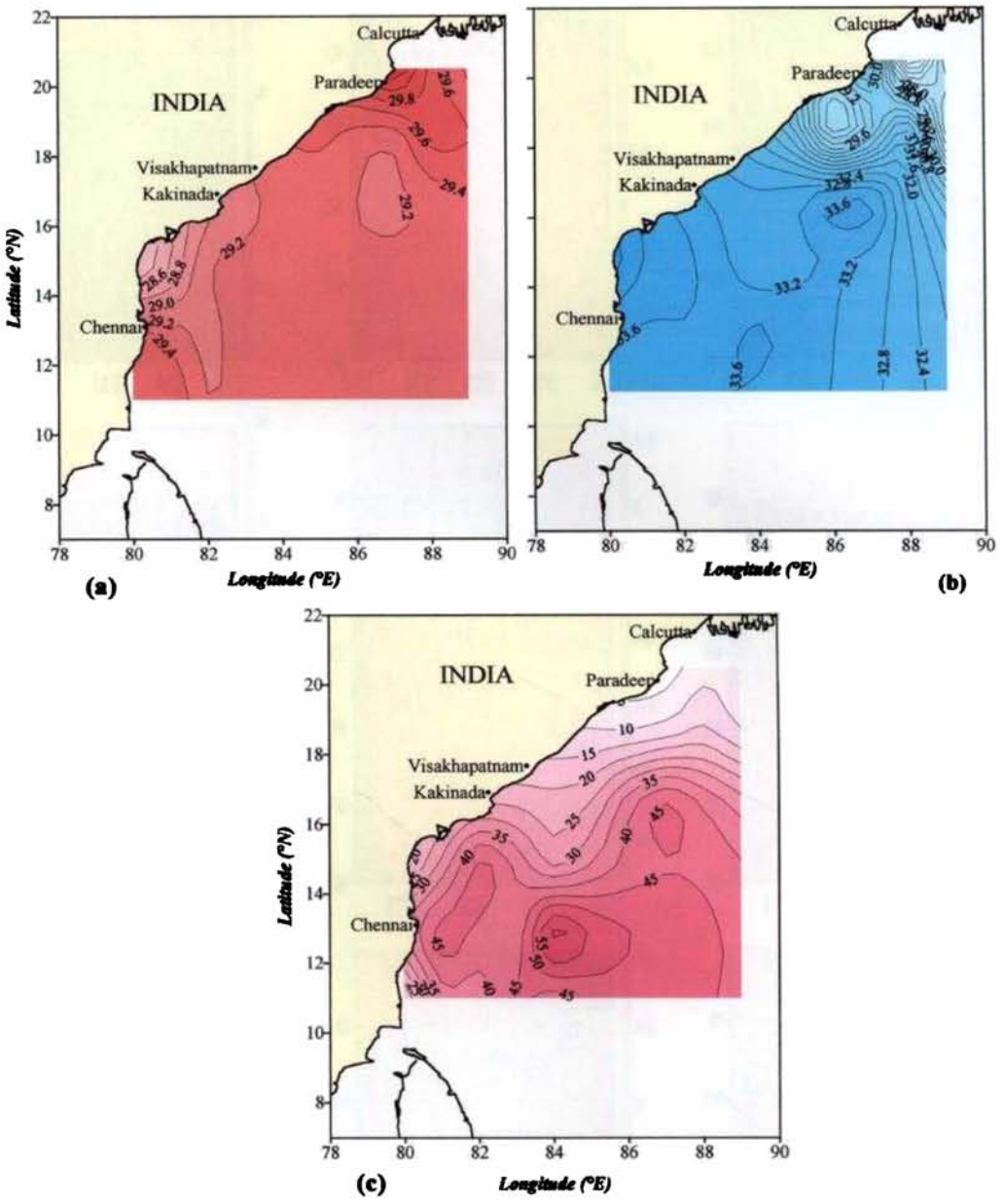


Figure 4.8. Distribution of (a) sea surface temperature (°C),(b) sea surface salinity (psu) and (c) mixed layer depth (m) during summer monsoon in the western Bay of Bengal

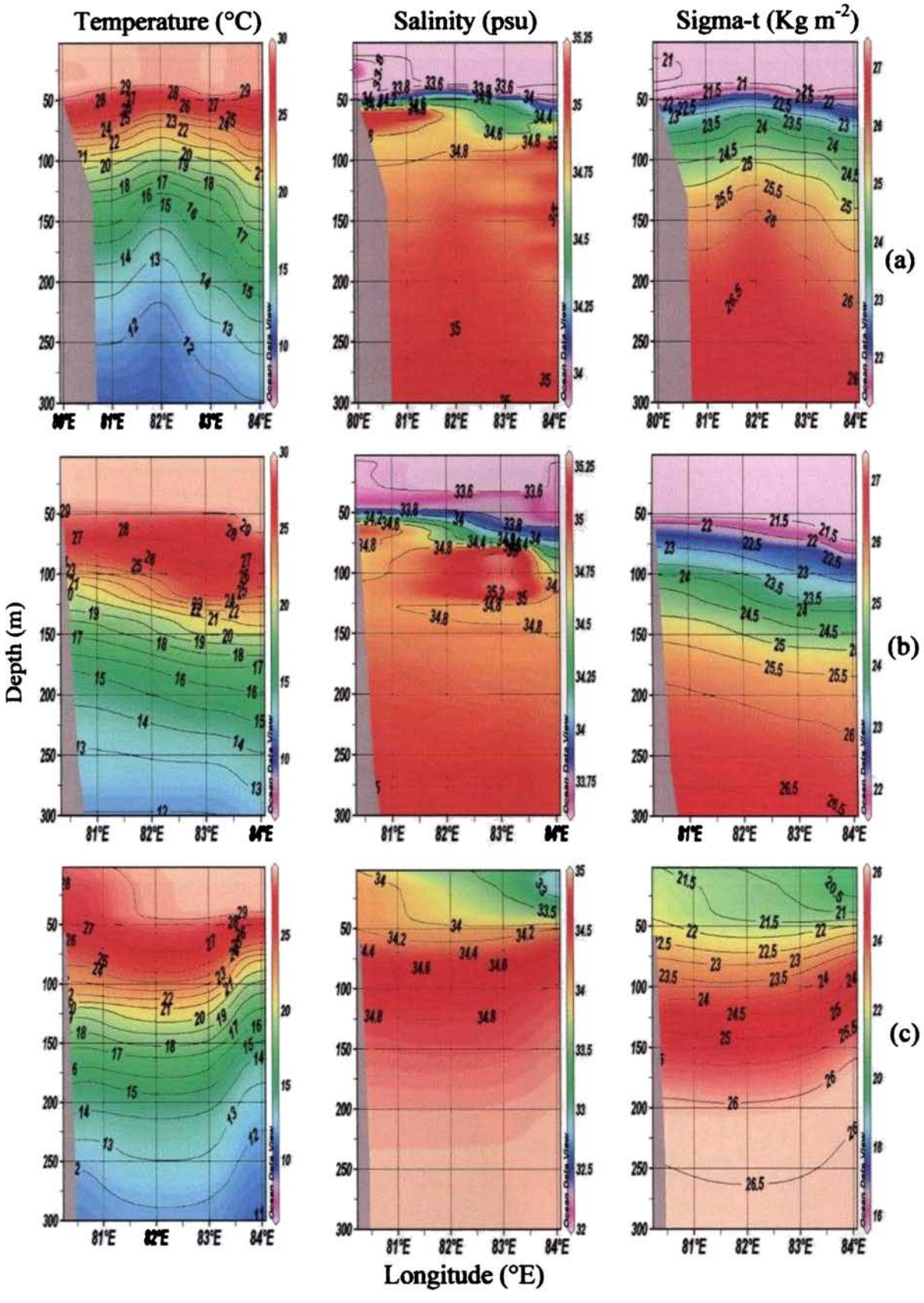


Figure 4.9. Vertical distribution of temperature, salinity and sigma-t along (a) 11°N, (b) 13°N and (c) 15°N during summer monsoon in the western Bay of Bengal

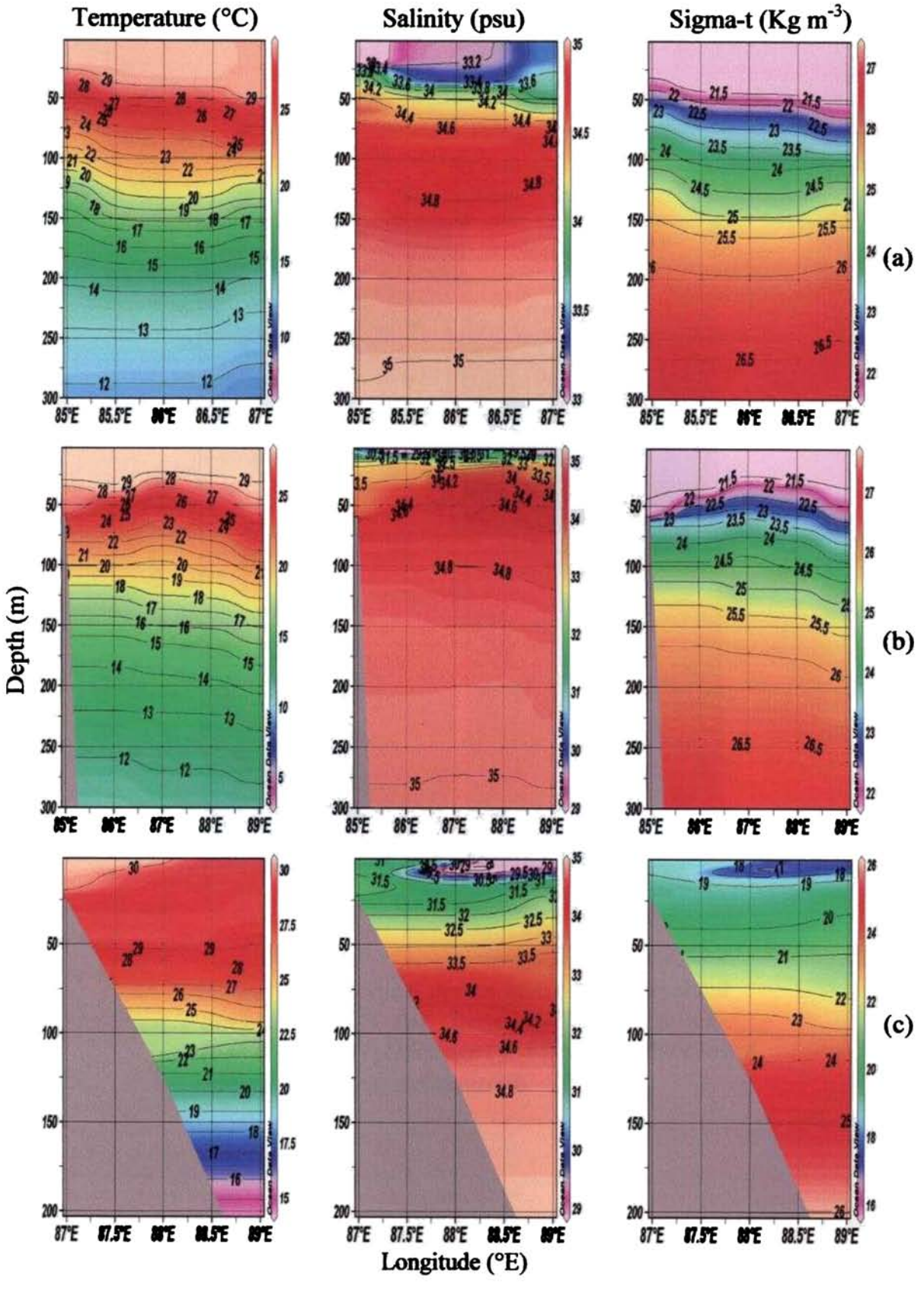


Figure 4.10. Vertical distribution of temperature, salinity and sigma-t along (a) 17°N, (b) 19°N and (c) 20.5°N during summer monsoon in the western Bay of Bengal

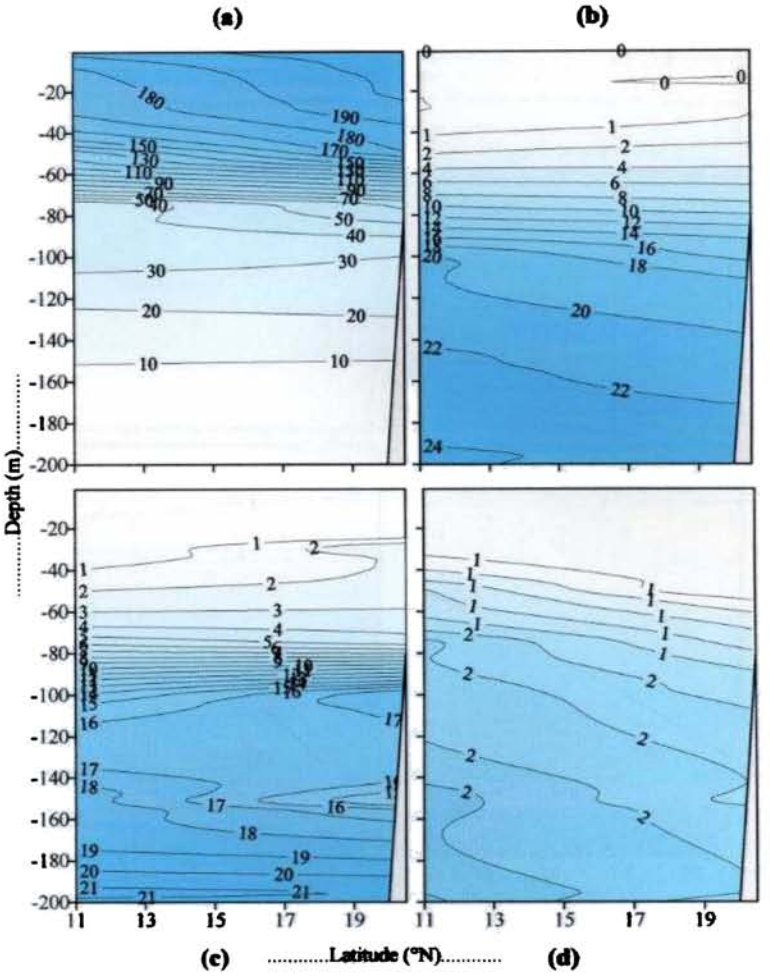


Figure 4.11. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the coastal stations during wintermonsoon

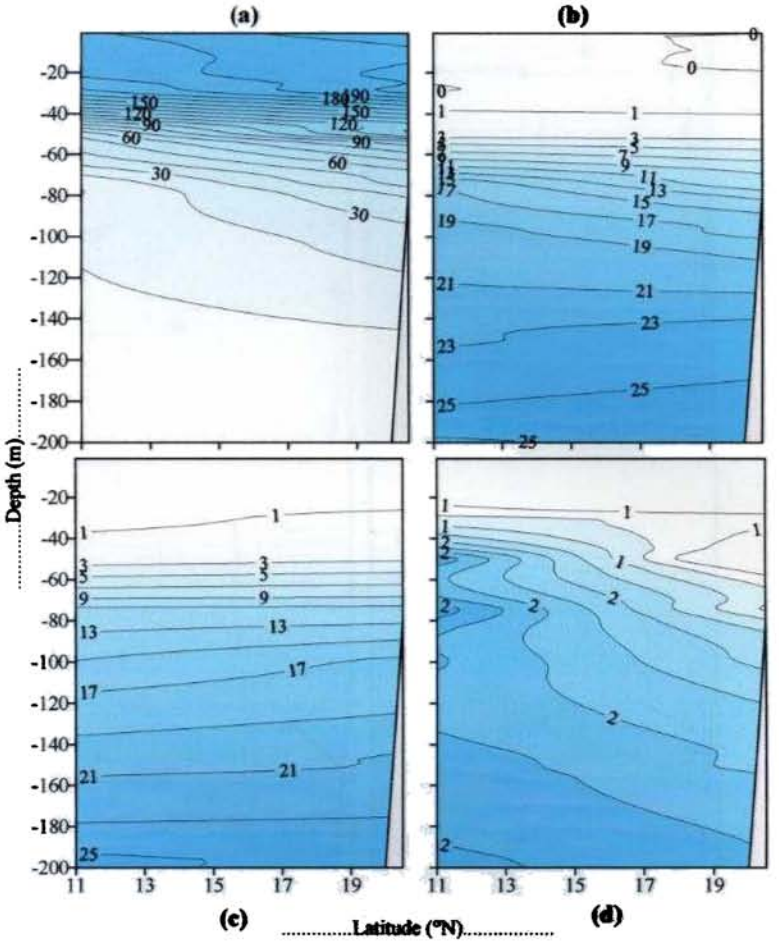


Figure 4.12. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the middle stations during wintermonsoon

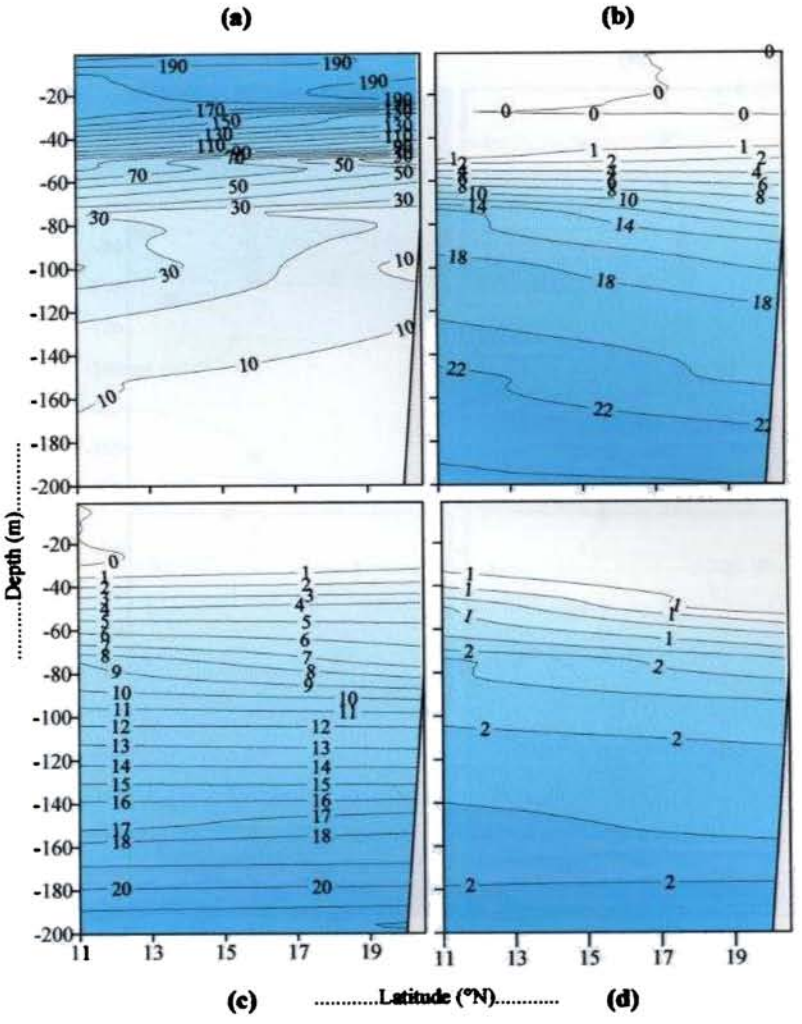


Figure 4.13. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the oceanic stations during wintermonsoon

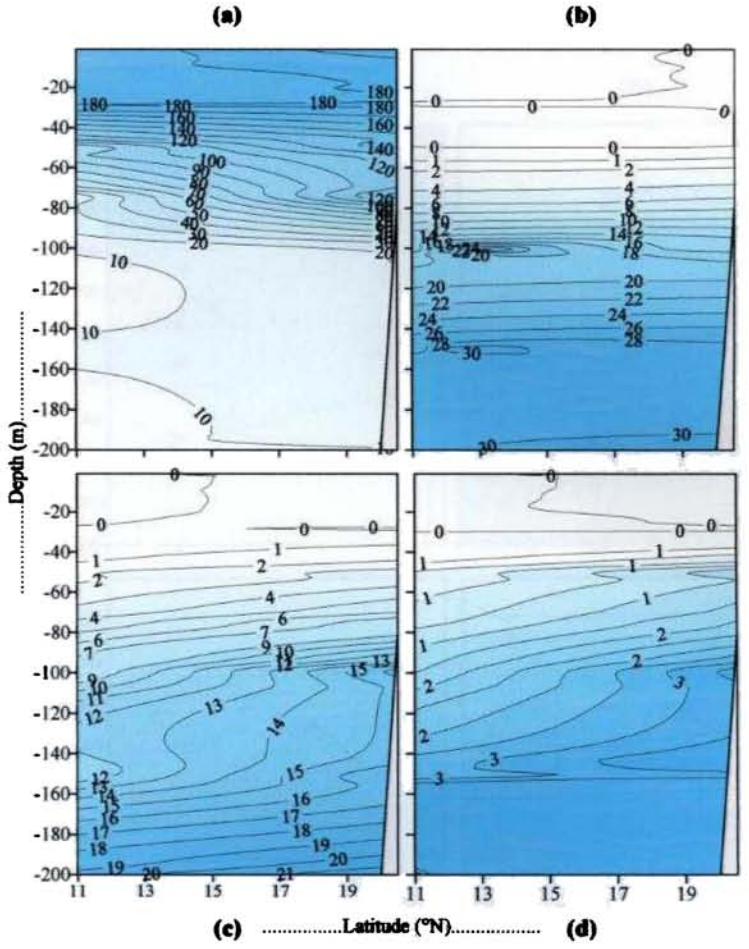


Figure 4.14. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the coastal stations during spring intermonsoon

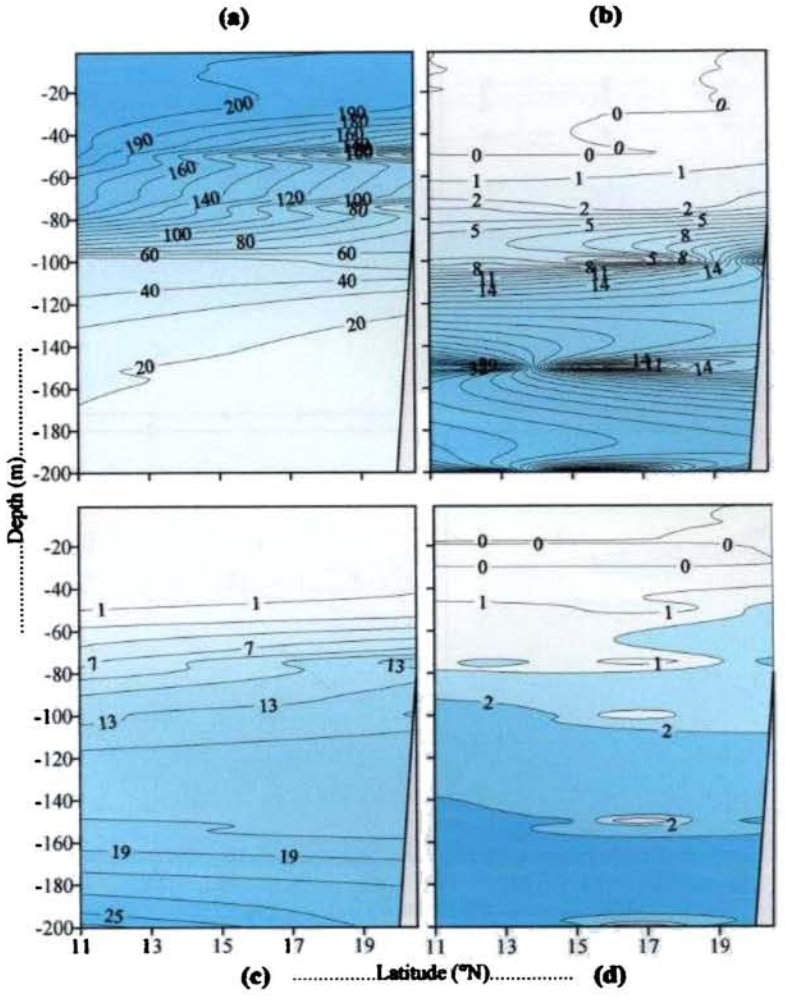


Figure 4.15. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the middle stations during spring intermonsoon

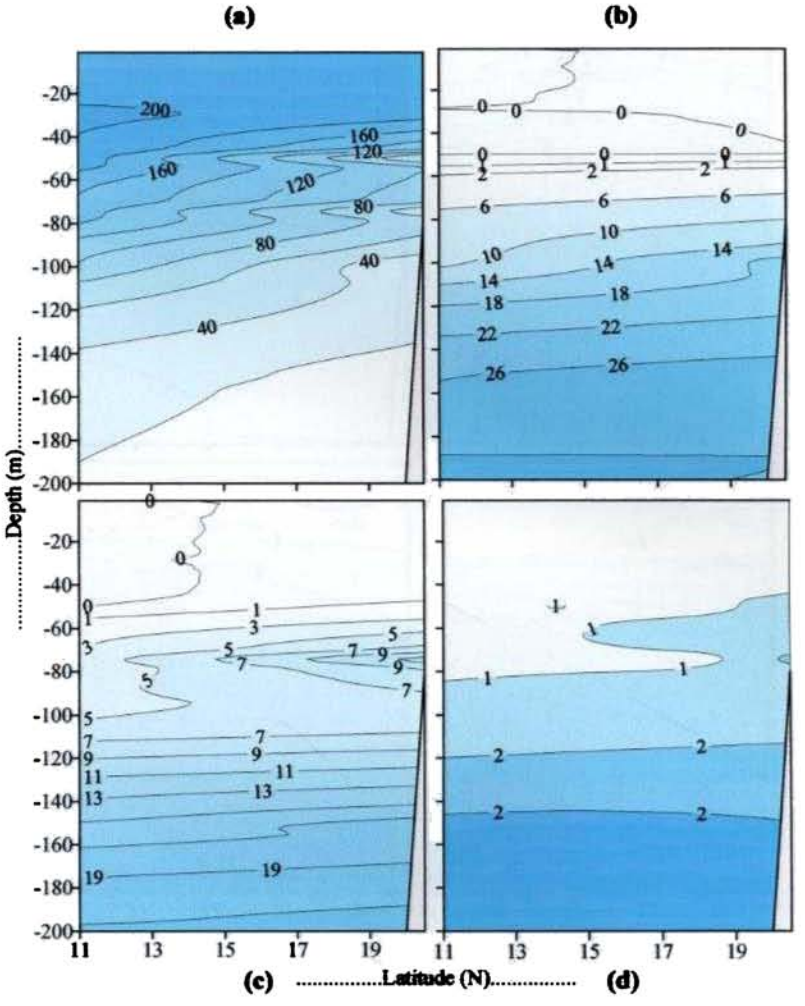


Figure 4.16. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the oceanic stations during spring intermonsoon

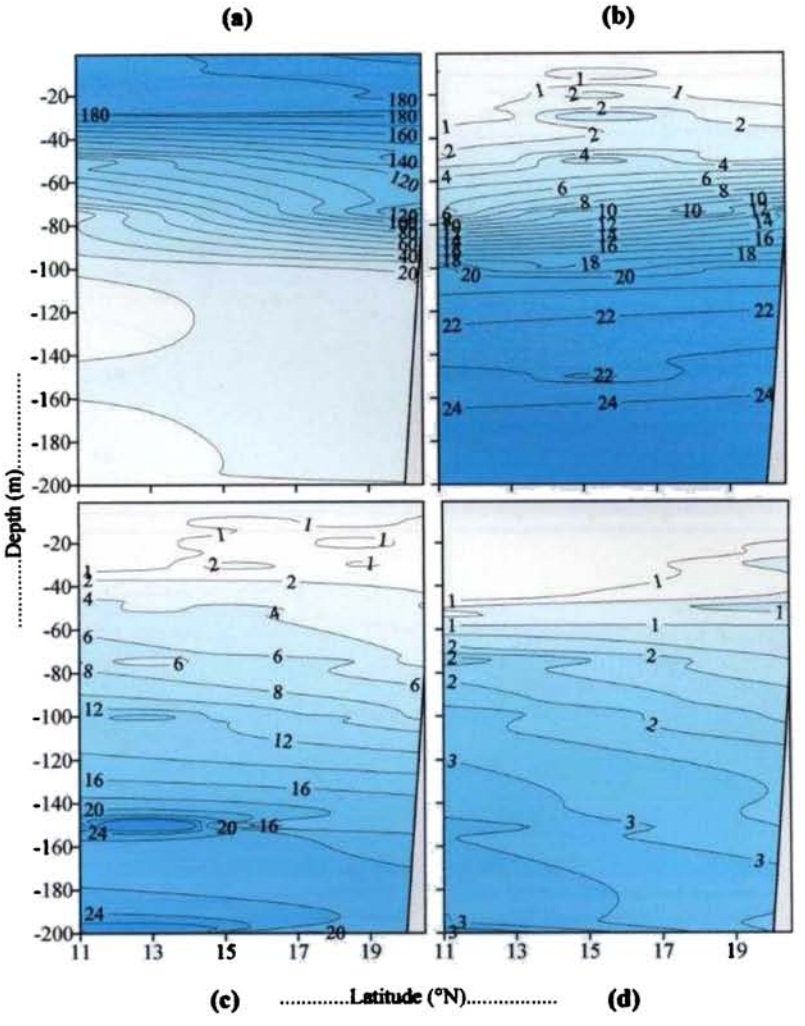


Figure 4.17. Vertical distribution of (a) dissolved oxygen ($\mu M\ l^{-1}$), (b) nitrate ($\mu M\ l^{-1}$), (c) silicate ($\mu M\ l^{-1}$) and (d) phosphate ($\mu M\ l^{-1}$) along the coastal stations during summer monsoon

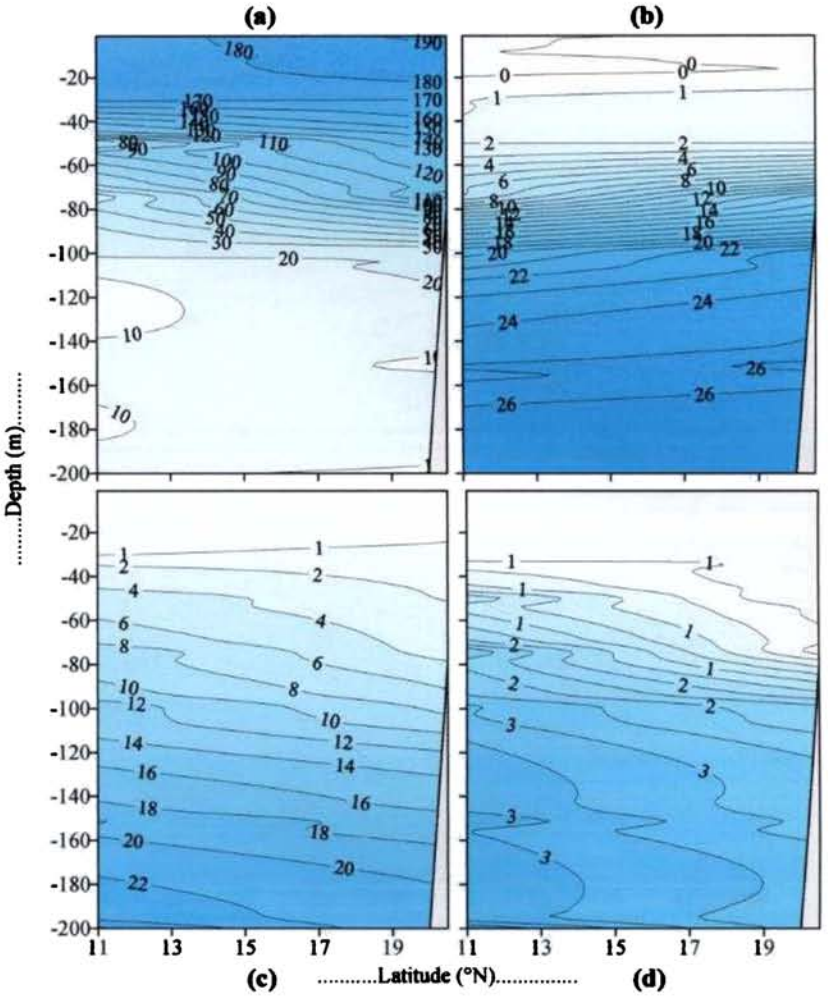


Figure 4.18. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μM l^{-1}) and (d) phosphate (μM l^{-1}) along the middle stations during summer monsoon

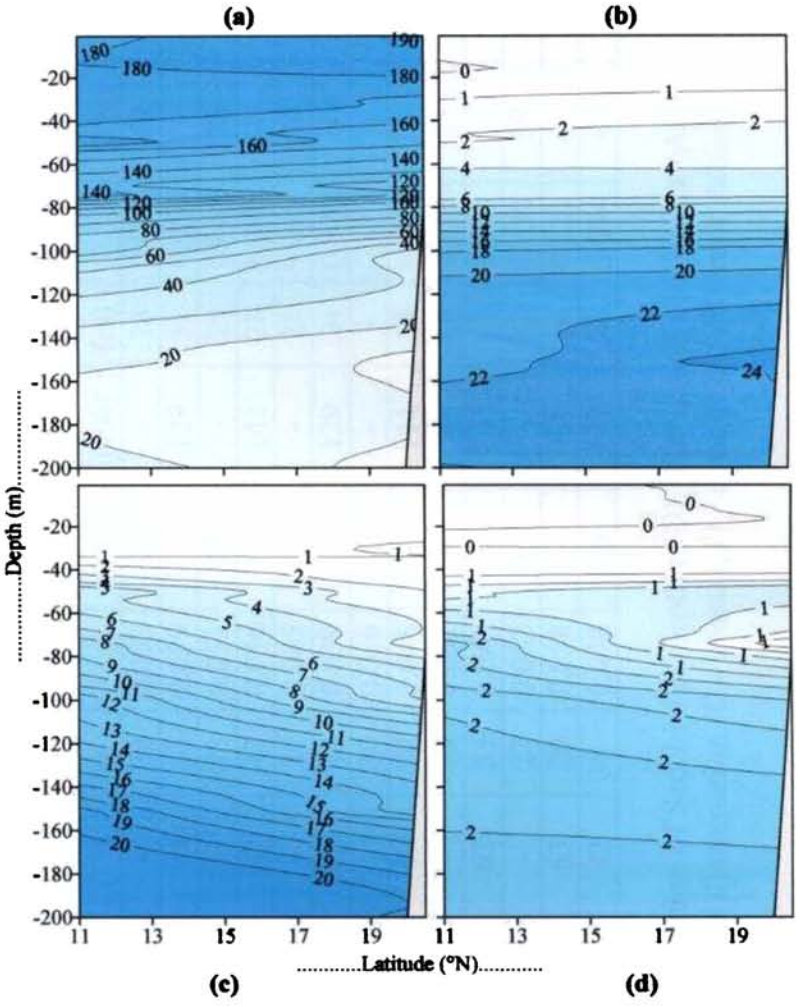


Figure 4.19. Vertical distribution of (a) dissolved oxygen (μM l^{-1}), (b) nitrate (μM l^{-1}), (c) silicate (μ Ml^{-1}) and (d) phosphate (μM l^{-1}) along the oceanic stations during summer monsoon

Position		Winter monsoon				Inter monsoon				Summer monsoon			
Lat. (°N)	Lon. (°E)	SD (m)	AC	C (1%)	O (1%)	SD (m)	AC	C (1%)	O (1%)	SD (m)	AC	C (1%)	O (1%)
11	80	21	0.080	63	-	32	0.053	96	-	23	0.073	69	-
11	84	33	0.051	-	99	43	0.039	-	129	31	0.054	-	93
13	80.5	25	0.068	75	-	33	0.051	99	-	26	0.065	78	-
13	84	29	0.058	-	87	47	0.036	-	141	28	0.060	-	84
15	81.5	31	0.054	92	-	37	0.045	111	-	28	0.060	84	-
15	85.5	36	0.047	-	108	43	0.039	-	129	24	0.070	-	72
17	83	23	0.073	70	-	30	0.056	90	-	-	-	-	-
17	87	23	0.073	-	69	37	0.045	-	111	24	0.070	-	72
19	85	20	0.085	60	-	33	0.051	99	-	15	0.113	45	-
19	89	21	0.080	-	63	35	0.048	-	105	15	0.113	-	45
20.5	87	18	0.094	54	-	27	0.062	81	-	13	0.130	39	-
20.5	89	21	0.080	-	63	29	0.058	-	87	14	0.121	-	42
Averages		25	0.070	69	82	36	0.048	96	117	22	0.084	63	68

Table 4.1. Seasonal fluctuation of Secchi disc depth (SD), attenuation coefficient (AC) and depth of 1% of surface illumination (C - coastal, O - oceanic) at different stations.

Chapter 5

Results - Biological environment

5.1. Phytoplankton standing stock (chlorophyll *a*)

5.1.1. Winter monsoon

During winter monsoon, chlorophyll *a* at the surface waters varied from 0.01 - 0.2 mg m^{-3} (Avg. 0.16 mg m^{-3}) (Table 5.1) and maximum was found at the oceanic station along 11°N (B3). Column chlorophyll *a* varied from 6 – 16 mg m^{-2} (Avg. 11.5 mg m^{-2}) (Table 5.1) and maximum (16 mg m^{-2}) was found at the middle station along 15°N (B8) where cold core eddy signatures were prominent. Latitudes 11 – 15°N (hereafter referred as southern transects) showed higher average surface and column chlorophyll *a* (0.12 mg m^{-3} and 13.4 mg m^{-2} respectively) compared to 17 – 20.5°N (hereafter referred as northern transects) (Table 5.2). Vertical distribution of chlorophyll *a* during the season showed a uniform pattern (Figure 5.1 – 5.3). In most of the stations, upper 50m water column sustained maximum concentration chlorophyll *a* and below which it decreased with increasing depth.

5.1.2. Spring intermonsoon

During intermonsoon, chlorophyll *a* at the surface varied from 0.01 - 0.22 mg m^{-3} (Avg. 0.089 mg m^{-3}) (Table 5.1) and the maximum was found at the coastal stations along 20.5°N. Maximum column chlorophyll *a* (20.3 mg m^{-2}) was found at the oceanic station along 11°N (B3) and the minimum (8.5 mg m^{-2}) at the coastal station along 15°N (B7) with an average of 13.8 mg m^{-2}. During the period average column chlorophyll *a* was higher (Avg. 13.4 mg m^{-2}) in the southern transects (Table 5.2). During the period column primary production was slightly higher in the northern transects compared to the south (250 mgC m^{-2} d^{-1} vs. 236 mgC m^{-2} d^{-1}). Vertical distribution of chlorophyll *a* showed peculiar features (Figures 5.1 - 5.3). Except along 20.5°N, chlorophyll *a* concentrations in the surface waters were relatively less and the maxima were found in deeper depths (from 50 – 75m) (Figures 5.1 – 5.3). But along 20.5°N, higher chlorophyll *a* concentration was

found in the upper 20m water column and the chlorophyll maxima were invariably found above 20m.

5.1.3. Summer monsoon

During summer monsoon, chlorophyll *a* at the surface varied from 0.09 - 0.8 mg m^{-3} (Avg. 0.246 mg m^{-3}) (Table 5.1) and maximum was found at the coastal station along 15°N (B7). Maximum column chlorophyll *a* (42.8 mg m^{-2}) also was found at the coastal station along 15°N (B7) and minimum (5.3 mg m^{-2}) at the coastal stations along 11°N. Maximum average surface and column chlorophyll *a* (0.27 mg m^{-3} and 22 mg m^{-2} respectively) was found at the southern transects (Table 5.2). Vertical distribution of chlorophyll *a* showed a different pattern compared to spring intermonsoon. During the season, higher chlorophyll *a* concentration was present in the surface layers and below 20m there was a decrease with increasing depth (Figures 5.1 - 5.3).

5.2. Primary production

5.2.1. Winter monsoon

During winter monsoon, primary production at the surface waters varied from 2.2 - 10.5 mgC m^{-3} d^{-1} (Table 5.1) and maximum was found at the station along 15°N (Table 5.1). Column primary production varied from 87 – 401 mgC m^{-2} d^{-1} (Table 5.1) and the maximum (401 mgC m^{-2} d^{-1}) was along 15°N where the cold core eddy signatures were evident. Surface and column primary production was higher in the southern transects (5.71 mgC m^{-3} d^{-1} and 275 mgC m^{-2} d^{-1} respectively)(Table 5.2). Vertical distribution of primary production during the season showed a general pattern. In all the stations, upper 20m water column sustained maximum primary productivity and below which it decreased with increasing depth (Figures 5.1 – 5.3). Primary productivity maxima were found at 10m depth in most of the stations except in the oceanic stations along 19°N and 20.5°N where maxima were at the surface.

5.2.2. Spring intermonsoon

During spring intermonsoon, primary production at the surface varied from 1 – 15 mgC m^{-3} d^{-1} and the maximum value (15 mgC m^{-3} d^{-1}) was found at the

oceanic station along 15°N (Table 5.1). Maximum column primary production (385 mgC m^{-2} d^{-1}) was found at the coastal station along 13°N and the minimum (149.4 mgC m^{-2} d^{-1}) was at the coastal station along 17°N. Higher surface primary production (Avg.7.55 mgC m^{-2} d^{-1}) was found in the southern transects. However the average column primary production in the southern and northern transects was comparable (236 mgC m^{-2} d^{-1} vs 250 mgC m^{-2} d^{-1}) (Table 5.2). Vertical distribution of primary production showed features similar to winter monsoon, where higher primary production was in the surface waters and the maxima were found in shallower depths (in the upper 20m)(Figures 5.1 – 5.3).

5.2.3. Summer monsoon

During summer monsoon, primary production at the surface varied from 1 – 45.8 mgC m^{-3} d^{-1} and the maximum (45.8 mgC m^{-3} d^{-1}) was found at the coastal station along 19°N (Table 5.1). Maximum column primary production (556 mgC m^{-2} d^{-1}) was found at the coastal station along 19°N followed by the coastal station along 15°N (470 mgC m^{-2} d^{-1}). Higher surface primary production was found in the southern transects but the column values showed relatively higher primary production (297 mgC m^{-2} d^{-1}) in the northern region compared to the south (238 mgC m^{-2} d^{-1}) (Table 5.2). During the period, vertical distribution of primary production was similar to winter and spring intermonsoon and higher values were relatively at shallower depths (mostly in the upper 20m) (Figures 5.1 – 5.3).

5.3. *Trichodesmium* bloom

Trichodesmium or 'sea saw-dust', is a marine cyanobacterium or 'blue-green algae', belonging to the family Oscillatoriacea, closely related to many freshwater species. These filamentous cyanobacteria is the most important known nitrogen-fixer in the sea, contribute considerably to the 'new production'.

During spring intermonsoon, two oceanic blooms of *Trichodesmium erythraeum* (Plates 5.1a & b), first one stretched around 10 km off Karaikkal (Lat.10°58' N, Lon.81°50' E) and the second one off south of Calcutta (Lat.19° 44' N, Lon. 89° 04' E) (Figure 5.4). The second bloom was comparatively less stretched. The blooms were so intense and appeared as a thick layer of saw dust on

the surface waters. Samples were collected with a plastic bucket and the adhering nature of the algae made it difficult to handle the sample. One small trichome was taken on a glass slide, pressed gently after placing a cover slip and observed under a compound microscope (Plate 5.1c). Average column values of different chemical parameters in the upper 30m water columns were below measurable concentration (<0.1μM), which indicated the oligotrophic nature of the water column. The weather was calm and the transparency was high (Secchi disc depth >30m). The surface seawater temperature was warm (>29°).

5.4. Mesozooplankton biomass

During winter monsoon, biomass of zooplankton varied from 230 – 1539 mgC m^{-2} (Avg. 776 mgC m^{-2}) (Table 5.3). Maximum biomass (1539 mgC m^{-2}) was found at the coastal station along 15°N. Zooplankton biomass was mostly contributed by copepods (>80%). In the southern region, biomass varied from 410 – 1539 mgC m^{-2} (Avg.883 mgC m^{-2}) and in the northern region it varied from 230 – 1231 mgC m^{-2} (Avg. 750 mgC m^{-2}). Average biomass in the southern region (883 mgC m^{-2}) was higher than the northern region (756 mgC m^{-2}).

During inter monsoon, zooplankton biomass varied from 174 – 1410 mgC m^{-2} (Avg. 406 mgC m^{-2}). Maximum biomass (1410 mgC m^{-2}) was found at the coastal station along 15°N. Excluding the coastal station along 15°N, variation of biomass between stations were minimum during the season. In the southern region, biomass varied from 205 - 1410 mgC m^{-2} and in the northern region from 174 - 974 mgC m^{-2}. Average biomasses of northern (410 mgC m^{-2}) and southern regions (418 mgC m^{-2}) were comparable (Table 5.3).

During summer monsoon, zooplankton biomass varied from 229 – 1949 mgC m^2 (676 mgC m^{-2}). Maximum biomass (1949 mgC m^{-2}) was found at the oceanic location 19°N. In the southern region biomass varied from 229 – 872 mgC m^{-2} and in the southern region from 308-1949 mgC m^{-2}. During the season average biomass in the northern region was considerably higher (928 mgC m^{-2}) compared to the south (480 mgC m^{-2}) (Table 5.3).

In general, during intermonsoon spring zooplankton biomass was considerably less in the entire study area. But during winter and summer monsoon biomass distribution showed noticeable geographical variations. Southern regions had higher zooplankton biomass during winter monsoon (883 mgC m^{-2}) followed by summer monsoon (480 mgC m^{-2}). Contrasting to this, the northern region showed higher average biomass during summer (928 mgC m^{-2}) followed by winter (656 mgC m^{-2}) (Table 5.3).

5.5. Summary

Maximum average surface chlorophyll *a* (0.246 mg m^{-3}) and primary production (11 mgC m^{-3} d^{-1}) was during summer monsoon followed by winter and spring intermonsoon (Table 5.1). Average column chlorophyll *a* and primary production was also maximum (18.4 mg m^{-2} and 556 mgC m^{-2} d^{-1} respectively) during summer monsoon and minimum during winter monsoon. Average column primary production varied marginally from 242 – 265 mgC m^{-2} d^{-1} during different seasons. During winter monsoon cold core eddy centered around the middle of the transect along 15°N, which resulted in enhanced phytoplankton biomass (16 mg m^{-2}) and primary production (401 mgC m^{-2} d^{-1}). During summer monsoon upwelling along 15°N resulted in appreciably high standing stock of phytoplankton biomass (42.8 mg m^{-2}) at the coastal station. Vertical distribution of chlorophyll *a* showed higher concentration above 50 m depth during summer and winter monsoon, but during spring intermonsoon higher concentration was found at relatively deeper depths (50 - 75m) (Figures 5.1 - 5.3). However, vertical distribution of primary production showed maximum values above 20m depth in all seasons (Figures 5.1 - 5.3). During spring intermonsoon, two oceanic blooms of *Trichodesmium erythraeum* were observed (Plate 5.1), first one stretched around 10 km off Karaikkal (Lat.10°58' N, Lon.81°50' E) and the second one off south of Calcutta (Lat.19° 44' N, Lon. 89° 04' E). Concentration of nutrients (nitrate, phosphate and silicate) in the upper 30m water column at these stations were below detectable level which showed the oligotrophy of the water column.

During spring intermonsoon zooplankton biomass was considerably less in the entire study area compared to other seasons. During winter and summer monsoon biomass distribution showed noticeable geographical variations. Southern regions had maximum zooplankton biomass during winter monsoon season (883 mgC m^{-2}) followed by summer monsoon (480 mgC m^{-2}). Contrasting to this, the northern region showed higher average biomass during summer (928 mgC m^{-2}) followed by winter (656 mgC m^{-2}) (Table 5.3).

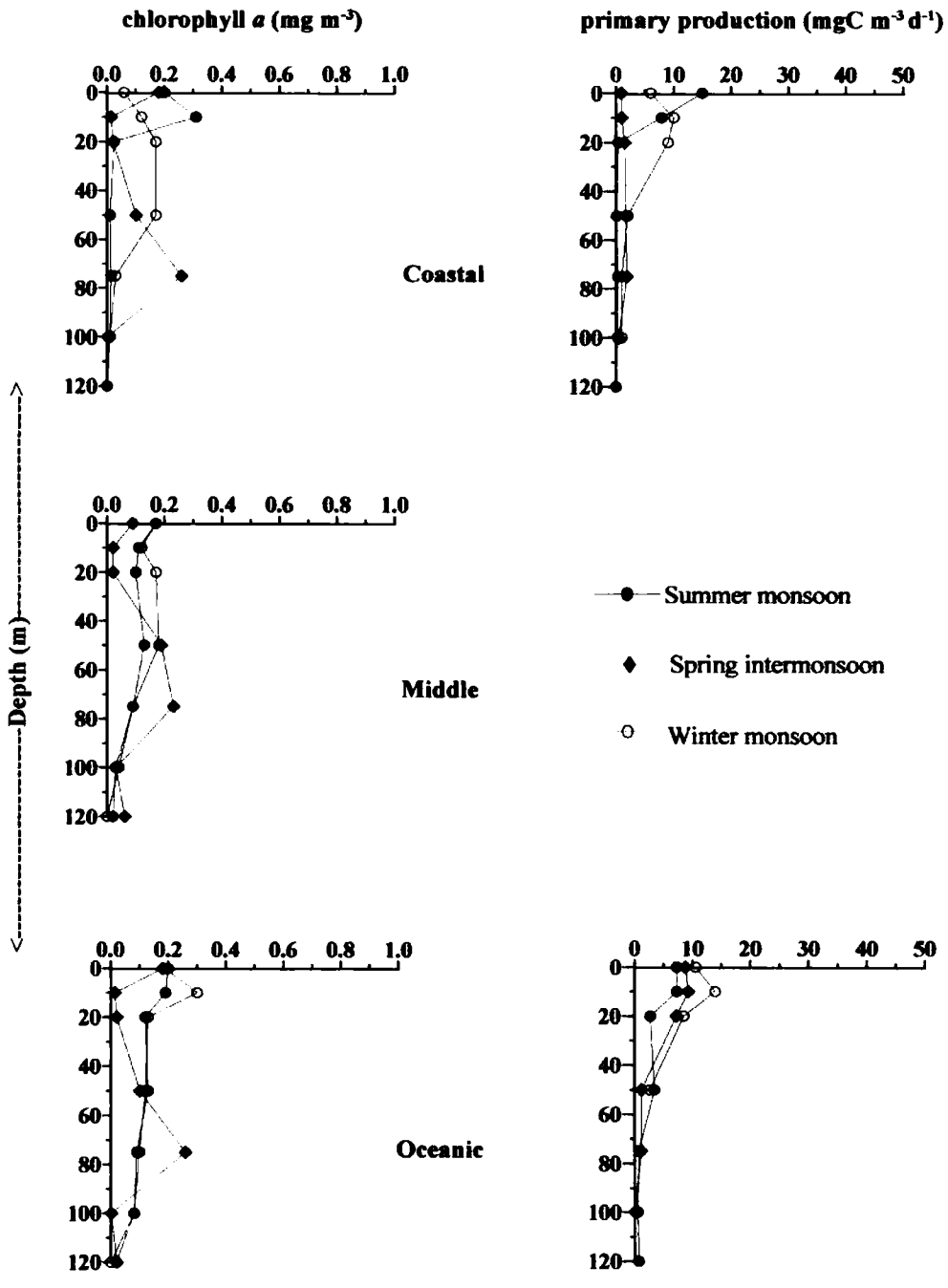


Figure 5.1. Vertical distribution of chlorophyll *a* and primary production along 11°N in the Bay of Bengal

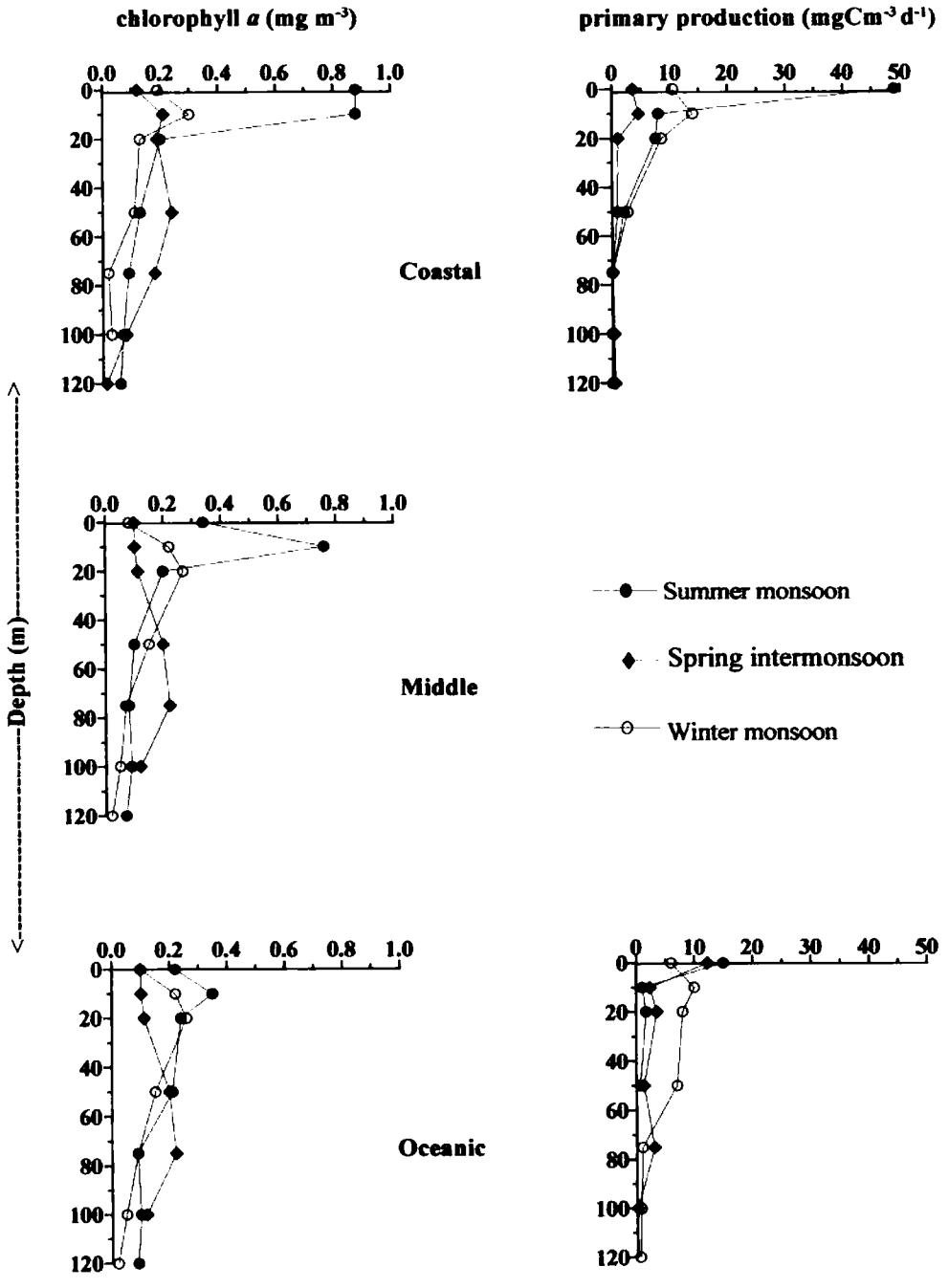


Figure 5.2. Vertical distribution of chlorophyll *a* and primary production along 15°N in the Bay of Bengal

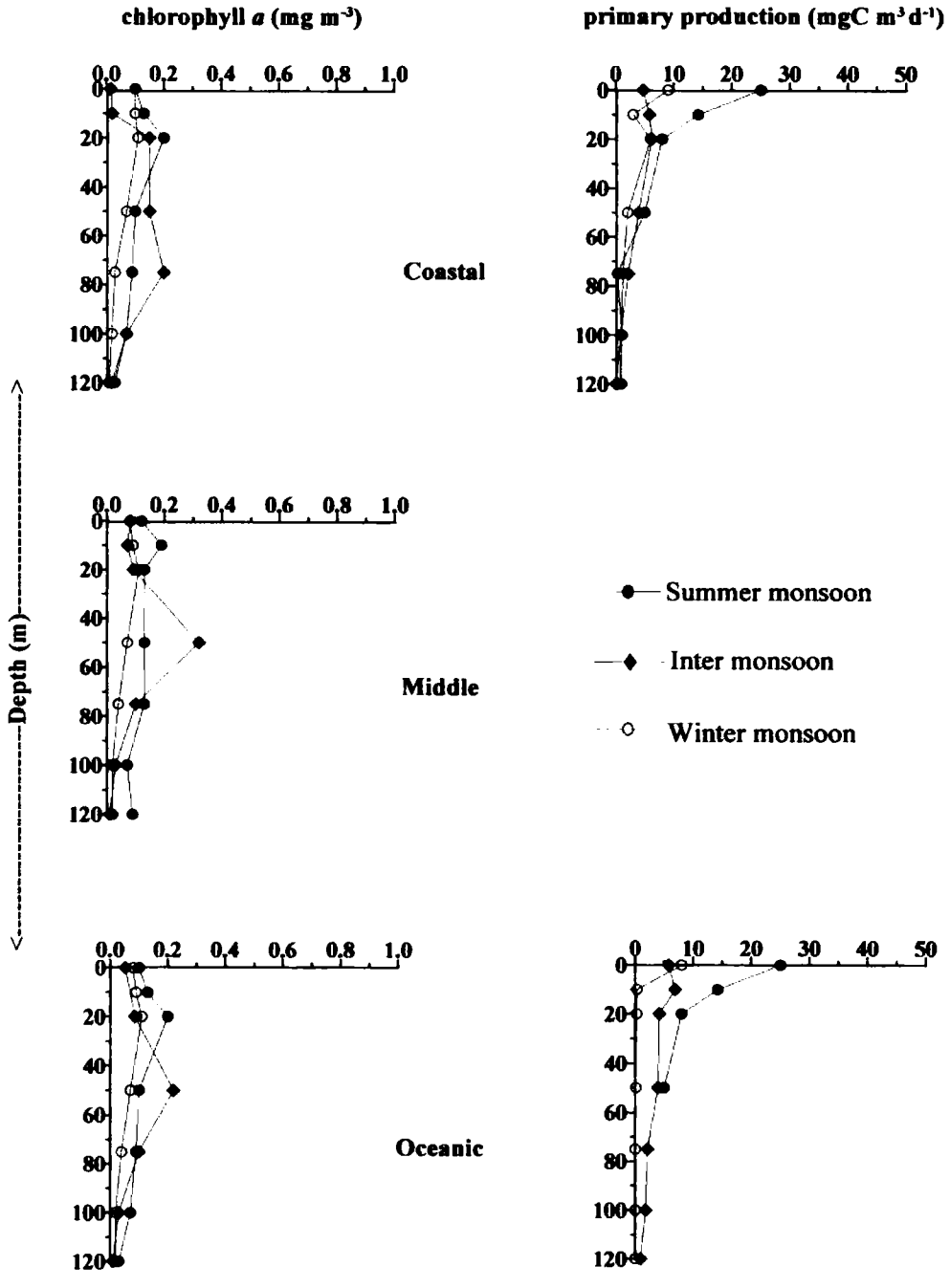


Figure 5.3. Vertical distribution of chlorophyll *a* and primary production along 19°N in the Bay of Bengal

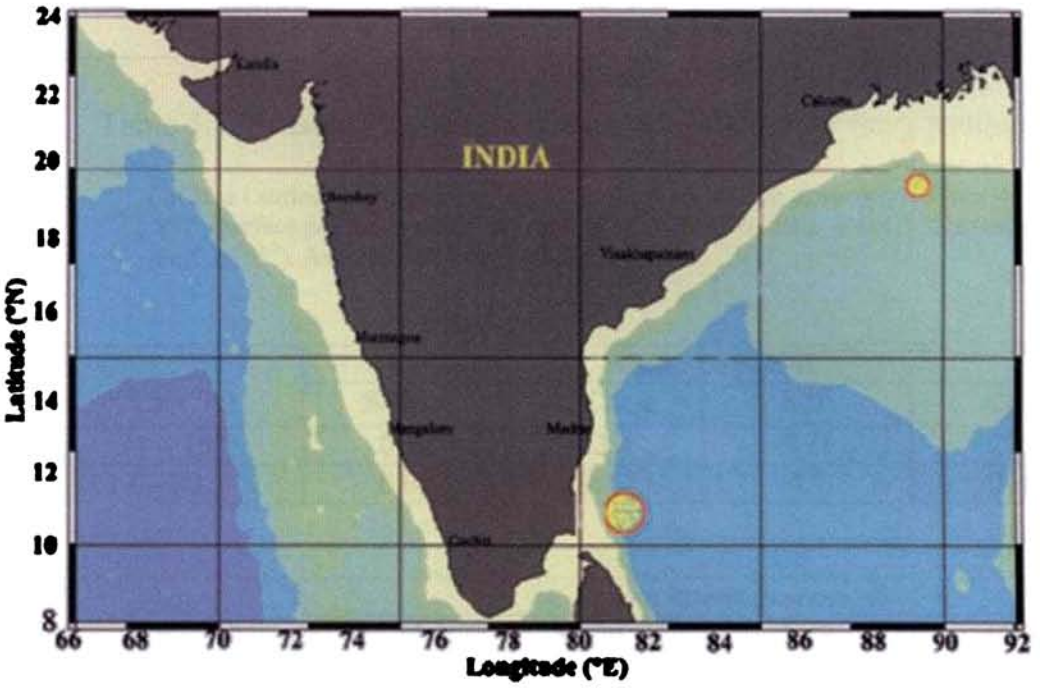


Figure 5.4. ◯ **Locations of blooms of** ***Trichodesmium erythraeum***

Seasons	S Chl.*a*	C Chl.*a*	S PP	C PP
Winter monsoon	0.01 - 0.2 (0.16)	5.6 - 16.3 (11.5)	2.2 - 10.5 (6)	87 - 401 (245)
Spring intermonsoon	0.01 - 0.22 (0.089)	8.5 - 20.3 (13.8)	1 - 15 (5)	131 - 385 (242)
Summer monsoon	(0.09 - 0.8) 0.246	5.3 - 42.8 18.14	1 - 45.8 (11)	60 - 426 (265)

Table 5.1. Seasonal variations of chlorophyll *a* and primary production

(SChl *a* - surface chlorophyll *a* (mg m^{-3}), CChl *a* - column chlorophyll *a* (mg m^{-2}), SPP - surface primary production (mgC m^{-3} d^{-1}), CPP - column primary production (mgC m^{-2} d^{-1}). Averages are in brackets)

Lat (°N)	Winter monsoon			
	SChl.*a*	CChl.*a*	SPP	CPP
11 – 15°N	0.12	13.4	5.71	275
17 – 20.5°N	0.09	9.42	4.7	210

Lat (°N)	Spring intermonsoon			
	SChl. *a*	CChl. *a*	SPP	CPP
11 – 15 °N	0.04	15	7.5	236
17 – 20.5 °N	0.10	12	10.6	250

Lat (°N)	Summer monsoon			
	SChl. *a*	CChl. *a*	SPP	CPP
11 – 15 °N	0.27	22	12	238
17 – 20.5 °N	0.2	13	14	297

Table 5.2. Seasonal averages of chlorophyll *a* and primary production

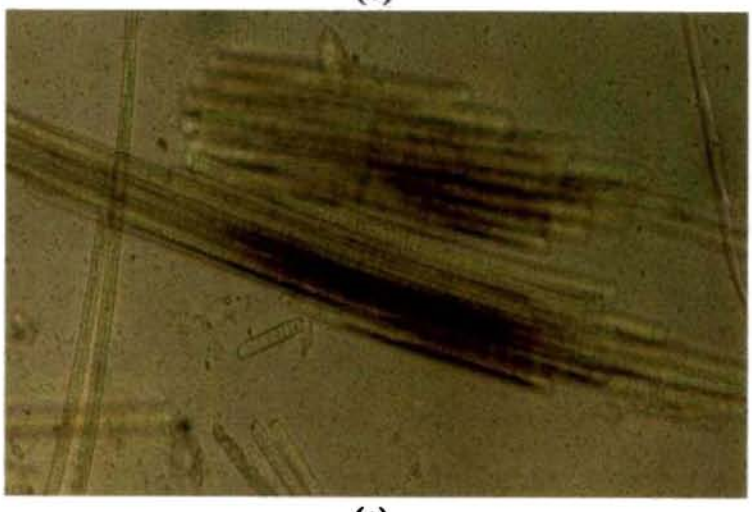
(SChl *a* - surface chlorophyll *a* (mg m^{-3}), CChl *a* - column chlorophyll *a* (mg m^{-2}), SPP - surface primary production (mgC m^{-3} d^{-1}), CPP - column primary production (mgC m^{-2} d^{-1})

Area	Lat. (°N)	Lon. (°E)	Zooplankton biomass (mgC/m^2)		
			Winter	Inter	Summer
Southern region	11	80.5	410	205	615
	11	82	1026	277	872
	11	84	513	225	229
	13	80	718	308	512
	13	83	1539	462	255
	13	84	1179	338	409
	15	81	1539	1410	307
	15	83	410	308	258
	15	85	615	226	871
	Average		883	418	480
Northern region	17	83	923	441	-
	17	85	461	174	871
	17	87	1179	333	860
	19	85	564	974	974
	19	87	410	257	820
	19	89	1231	200	1949
	20.5	88	256	431	308
	20.5	89	230	-	718
	Average		750	401	928
Total Average			776	406	628

Table 5.3. Temporal variations of mesozooplankton biomass from the base of the thermocline to surface during different seasons

(a)

(b)



(c)

Plate 5.1. Trichodesmium erythraeum bloom observed
(a) off Karaikkal and (b) off south of Culcutta and
(c) photomicrograph of two trichome.

Chapter 6

Results – Microzooplankton

6.1. Biocomposition

During the study, microzooplankton community composed of both protozoans and larval stages of invertebrate metazoans. Protozoans were the most dominant group in terms of abundance and biomass. Ciliates, heterotrophic dinoflagellates, radiolarians and foraminifers were the protozoans present in the samples. Among these protozoans, heterotrophic dinoflagellates and ciliates contributed substantially and the individual contributions of sarcordines (radiolarians, and foraminifers) were minor and referred hereafter as 'others'.

6.1.1. Protozoans

Heterotrophic dinoflagellates were the most abundant group of organisms, which contributed maximum of the microzooplankton community irrespective of seasons. Its percentage contribution to the total abundance of microzooplankton ranged between 62 and 77%, 48 and 75% and 57 and 73% during winter, inter and summer monsoon respectively (Figures 6.1 – 6.3). Maximum average contribution of dinoflagellates was during winter (69%) followed by summer (65%) and the least (60%) during inter monsoon season. Maximum percentage contribution of dinoflagellates to the total microzooplankton community was found at the middle station along 17°N (B11).

Altogether 12 genera and 57 species of heterotrophic dinoflagellates were identified during the study. Complete list and photomicrographs of the species identified during the study is presented (Table 6.1 and Plates 6.1 – 6.5 respectively). The most common genera present in the samples were *Protoperidinium, Ornithocercus, Dinophysis, Phalacroma and Podolamphus*. Most common species of dinoflagellates observed during the study were *Peridinium oceanicum, P. conicum, P. divergens, P. grandae, P. claudicans, P. breve, Ornitohocercus thumii, O. magnificus, Podolamphus elegans, P. bipes, Phalacroma doryphorum, P. rotundatum and Dinophysis hastate. Protoperidinium*

was the most abundant genus among dinoflagellates and represented by maximum number of species. Genus *Protoperidinium* represented 21 species during winter, 22 species during inter and 24 species during summer monsoon. During the study, 7 species were present from the genus *Phalacroma* followed by *Ornithocercus* (6 species) and *Podolamphus* (5 species).

Ciliates were the second abundant group of organisms in the samples. Its percentage contribution varied from 4 – 17%, 14 - 33% and 13 – 26% during winter, inter and summer monsoon respectively (Figures 6.1 – 6.3). Maximum average density of ciliates was during intermonsoon (23%) followed by summer (20%) and winter monsoon (14%). During the present study they represented from 35 genera with 78 species (Table 6.2, Plates 6.6 – 6.12). Basically ciliates in the microzooplankton community belong to two distinct categories called loricate ciliates (tintinnids) and aloricate ciliates (oligotrichs). Among ciliates, maximum number of species (8) was present from the genus *Tintinnopsis* followed by *Codonellopsis* (7 species). Genus *Tintinnopsis* was represented by 5 species during winter, 8 species during inter and 7 species during summer monsoon season. Genus *Codonellopsis* had three species during winter, 7 species during inter and 4 species during summer monsoon.

During the study, tintinnids (loricates) were the most dominant group among ciliates followed by aloricates. Tintinnid ciliates had representation from 31 genera with 72 species. Common genera of tintinnids found in the samples were *Tintinnopsis, Amphorella, Undella, Rhabdonella, Eutintinnus, Salpingella, Salpingacantha, Dictyocysta, Codonella* and *Codonellopsis.* Common species of tintinnids found in the study area were *Tintinnopsis cylindrica, T. uruguayensis, T. beroidea, Amphorella quadrilineata, A. aculeate, A. pyramidata, Proplectella claparedi, Undella hyalina, Rhabdonella spiralis, R. amour, Eutintinnus fraknoi, Salpingella acuminata, Salpingacantha ampla, Dictyocysta lepida, D. elegans, Codonellopsis orthoceros* and *Codonella nationalis.* Aloricate ciliates were numerically less compared to tintinnid ciliates and represented by 4 genera and 6 species. The genera of aloricate ciliates present were *Halteria, Lohmaniella,*

Strombidium, Strombilidim, etc. The different species of aloricate ciliates present were *Halteria chlorelligera, Lohmaniella oviformes, L. spiralis, Strombidium bilobum, S. conicum* and *Strobilidium minimum.*

Other protozoans (others) present in the samples belong to two different groups namely radiolarians and foraminifers. They were identified only up to the group level. Collectively their average numerical abundance was 9% during winter monsoon, 8% during inter monsoon and 7% during summer monsoon (Figures 6.1 – 6.3, Plate 6.13).

During winter monsoon 90 species of protozoans were identified from the study area in which 46 species belong to dinoflagellates and 44 to ciliates. Similarly, during intermonsoon 126 species of protozoans were identified among which 48 belong to dinoflagellates and 78 belong to ciliates. During summer monsoon, 109 species of protozoans were found, 50 belong to dinoflagellates and 59 belong to ciliates (Tables 1&2). Apart from these, in all the stations a few representatives of radiolarians and foraminifers were also present, but they were identified only up to the group level and hence could not be included while referring the species composition.

In general, maximum number of species of microzooplankton was found during spring intermonsoon (126) followed by summer monsoon (109) and least during winter monsoon (90). Maximum species of ciliates (78) was during spring intermonsoon followed by summer monsoon (59) and winter monsoon (44). Similarly dinoflagellates had maximum representation of species during summer monsoon (50) followed by spring intermonsoon (48) and least during winter monsoon (46).

6.1.2. Metazoans

Eggs and larval forms of crustaceans formed the metazoan component of the microzooplankton community (Plate 6.13). They formed 8 – 11% in abundance during winter, 6 – 10% during spring intermonsoon and 6 – 10% during summer monsoon (Figures 6.1 - 6.3). These larval forms and eggs were categorized only up

to the group level and hence could not be accounted while detailing about the species composition of microzooplankton community.

6.2. Distribution

6.2.1. Geographical distribution

6.2.1.1. Winter monsoon

Density of microzooplankton integrated up to 10m depth from the surface (hereafter referred as surface density) varied from 27 – 70 x 10^4 m^{-2} (Avg. 49 x 10^4 m^{-2}) and maximum (70 x 10^4 m^{-2}) was found at the middle station along 15°N (B8) (Table 6.3). Southern region (considered as the area from and south of 15°N) showed higher density (Avg. 55 x 10^4 m^{-2}) compared to the northern region (Avg. 43 x 10^4 m^{-2}) (considered as the area north of 15°N) (Figure 6.4a, Table 6.3). During the period, abundance in the coastal (Avg. 49 x 10^4 m^{-2}) and oceanic (48 x 10^4 m^{-2}) stations did not show much variation (Table 6.4). Microzooplankton biomass integrated up to 10m from the surface (hereafter referred as surface biomass) was similar to the density distribution with higher abundance in the southern transects (Avg. 16 x 10^3 mgC m^{-2}) compared the north (Avg. 11 x 10^3 mgC m^{-2}) (Table 6.3). Biomass values varied from 8 – 19 x 10^3 mgC m^{-2} (Avg. 13.5 x 10^3 mgC m^{-2}) and maximum (19 x 10^3 mgC m^{-2}) was at the middle station along 15°N (B8) where maximum abundance was recorded (Table 6.3). Alike the density distribution, coastal and oceanic stations had equal biomass (Avg. 14 x 10^3 mgC m^{-2} and 14 x 10^3 mgC m^{-2} respectively) (Table 6.4).

During the season microzooplankton density integrated up to 150m depth from the surface (hereafter referred as column density) ranged between 205 - 515 x 10^4 m^{-2} (Avg. 350 x 10^4 m^{-2}) (Figure 6.6a, Table 6.5). It was higher (Avg. 410 x 10^4 m^{-2}) in the southern region with highest value (515 x 10^4 m^{-2}) at the coastal station along 15 °N (B7) (Table 6.5). In the northern region, abundance ranged between 205 and 367 x 10^4 m^{-2} (Avg. 283 x 10^4 m^{-2}) (Table 6.5). Coastal stations in the southern region showed higher abundance (Avg. 490 x 10^4 m^{-2}) compared to the oceanic stations (Avg. 369 x 10^4 m^{-2}) (Table 6.6). Density varied from 205 – 515 x 10^4 m^{-2} in the coastal stations and 306 – 457 x 10^4 m^{-2} in the oceanic locations

(Table 6.6). But in the northern region, coastal (296 x 10^4 m^{-2}) as well as oceanic (Avg. 276 x 10^4 m^{-2}) stations did not show much variation in abundance (Table 6.6).

Microzooplankton biomass integrated up to 150m depth from the surface (hereafter referred as column biomass) ranged between 56 – 159 x 10^3 mgC m^{-2} and showed similar trend as that of density distribution with higher biomass (Avg. 119 x 10^3 mgC m^{-2}) in the southern region (Figure 6.7, Table 6.5). In the southern transects the biomass ranged between 86 and 159 x 10^3 mgC m^{-2} and the maximum (159 x 10^3 mgC m^{-2}) was found at the oceanic stations along 13°N (B6). Coastal stations of the southern region showed higher biomass (Avg. 138 x 10^3 mgC m^{-2}) compared to the oceanic stations (Avg. 110 x 10^3 mgC m^{-2}) (Table 6.6). But along the northern transects the average biomass in the coastal stations (84 x 10^3 mgC m^{-2}) was comparable with the open ocean values (86 x 10^3 mgC m^{-2}) (Table 6.6).

6.2.1.2. Spring intermonsoon

Surface density of microzooplankton varied from 23 – 72 x 10^4 m^{-2} (Avg. 51 x 10^4 m^{-2}) and maximum value (72 x 10^4 m^{-2}) was found at the middle station along 17°N (B8) (Table 6.3). Unlike winter monsoon, surface waters of northern region showed higher density (Avg. 57 x 10^4 m^{-2}) compared to the southern transects (Avg. 47 x 10^4 m^{-2}) (Figure 6.4b, Table 6.3). Abundance in the coastal stations (Avg. 46 x 10^4 m^{-2}) was lesser than oceanic station (54 x 10^4 m^{-2})(Table 6.4). Distribution of surface biomass was similar to the density distribution with higher concentrations in the northern transects (Avg. 17x 10^3 mgC m^{-2}) compared the south (Avg. 14 x 10^3 mgC m^{-2}) (Figure 6.5b, Table 6.3). During the season, biomass values varied from 10 – 23 x 10^3 mgC m^{-2} (Avg. 15 x 10^3 mgC m^{-2}) and maximum (23 x 10^3 mgC m^{-2}) was at the middle of the transect along 17 °N (B11) (Table 6.3). Unlike the density distribution, coastal and oceanic stations showed comparable biomass (Avg. 16 x 10^3 mgC m^{-2} and 15 x 10^3 mgC m^{-2} respectively) (Table 6.4).

During the season column density ranged between 211 - 912 x 10^4 m^{-2} (Avg. 702 x 10^4 m^{-2}) (Table 6.5). It was higher (Avg. 724 x 10^4 m^{-2}) in the southern

region with maximum value (912 x 10^4 m^{-2}) at the coastal station along 11 °N (B1) (Table 6.5). In the northern region, abundance ranged between 211 and 858 x 10^4 m^{-2} (Avg. 676 x 10^4 m^{-2}) (Figure 6.6b, Table 6.5). Coastal stations in the southern region showed higher abundance (Avg. 792 x 10^4 m^{-2}) compared to the oceanic stations (Avg. 690 x 10^4 m^{-2}) (Table 6.6). In the southern region abundance varied from 763 – 912 x 10^4 m^{-2} (Avg. 792 x 10^4 m^{-2}) in the coastal stations and 633 – 804 x 10^4 m^{-2} (Avg. 639 x 10^4 m^{-2}) in the oceanic areas sampled (Table 6.6). But in the northern region, average value in the coastal region (639 x 10^4 m^{-2}) was relatively less than the oceanic areas (698 x 10^4 m^{-2}) (Table 6.6).

Microzooplankton column biomass ranged between 110 – 424 x 10^3 mgC m^{-2} and showed similar trend as that of density distribution with higher value (Avg. 247 x 10^3 mgC m^{-2}) in the southern region (Figure 6.7b, Table 6.5). In the southern transects the biomass ranged between 195 and 424 x 10^3 mgC m^{-2} and the maximum was found at the coastal station along the 11°N (B1)(Table 6.5). Coastal stations of the southern region showed higher biomass (Avg. 303 x 10^3 mgC m^{-2}) compared to the oceanic stations (Avg. 220 x 10^3 mgC m^{-2}) (Table 6.6). But along the northern transects the average biomass in the coastal stations (177 x 10^3 mgC m^{-2}) was lesser than the open ocean values (224 x 10^3 mgC m^{-2}) (Table 6.6).

6.2.1.3 Summer monsoon

Surface density of microzooplankton varied from 128 – 275 x 10^4 m^{-2} (Avg. 175 x 10^4 m^{-2}) and the maximum value (275 x 10^4 m^{-2}) was found at the middle station along 19°N (B14) (Table 6.3). Northern region showed higher density (Avg. 185 x 10^4 m^{-2}) compared to the southern transects (Avg. 168 x 10^4 m^{-2}) (Figure 6.4c, Table 6.3). Abundance in the oceanic stations showed higher values (179 x 10^4 m^{-2}) compared to the coastal station (166 x 10^4 m^{-2}) (Table 6.4). Distribution of surface biomass was similar to the density distribution with relatively higher concentrations in the southern transects (Avg. 50 x 10^3 mgC m^{-2}) compared the north (Avg. 46 x 10^3 mgC m^{-2}) (Figure 6.5c, Table 6.3). During the period, biomass varied from 27 – 79 x 10^3 mgC m^{-2} (Avg. 48 x 10^3 mgC m^{-2}) and maximum (79 x 10^3 mgC m^{-2}) was at the coastal station along 20.5°N (A17) (Table 6.3). Unlike the

density distribution, coastal stations showed higher surface biomass (50 x 10^3 mgC m^{-2}) compared to the oceanic stations (47 x 10^3 mgC m^{-2}) (Table 6.4). Distribution of average surface biomass in the northern region (46 x 10^3 mgC m^{-2}) was comparable with the southern region (50x 10^3 mgC m^{-2}) with a marginal increase in the latter (Table 6.3).

During the season microzooplankton column density ranged between 323 - 710 x 10^4 m^{-2} (Avg. 575 x 10^4 m^{-2}) (Table 6.5). It was higher (Avg. 630 x 10^4 m^{-2}) in the southern region with maximum value (710 x 10^4 m^{-2}) at the offshore station (B9) along 15 °N (Figure 6.6c, Table 6.5). In the northern region, abundance ranged between 323 and 593 x 10^4 m^{-2} (Avg. 505 x 10^4 m^{-2}) (Table 6.5). Coastal stations in the southern region showed higher abundance (Avg. 646 x 10^4 m^{-2}) compared to the oceanic stations (Avg. 621 x 10^4 m^{-2}) (Table 6.6). During the season, column density varied from 612 - 704 x 10^4 m^{-2} in the coastal stations and 552 – 710 x 10^4 m^{-2} in the oceanic locations (Table 6.6). Coastal stations along the northern region also showed relatively lesser densities (Avg. 446 x 10^4 m^{-2}) compared to the oceanic stations (Avg. 529 x 10^4 m^{-2}) (Table 6.6).

Microzooplankton column biomass ranged between 86 – 210 x 10^3 mgC m^{-2} and showed similar trend as that of density distribution with higher values (Avg. 166 x 10^3 mgC m^{-2}) in the southern region (Figure 6.6c, Table 6.5). In the southern transects the biomass ranged between 131 and 210 x 10^3 mgC m^{-2} and the maximum was found at the middle station along the 11°N (B2)(Table 6.5). Coastal stations of the southern region showed higher biomass (Avg. 174 x 10^3 mgC m^{-2}) compared to the oceanic stations (Avg. 162 x 10^3 mgC m^{-2}). But along the northern transects the average biomass in the coastal stations (Avg. 133x 10^3 mgC m^{-2}) was comparable with the open ocean values (Avg. 132 x 10^3 mgC m^{-2}) (Table 6.6).

6.2.1.4. Temporal variations

Summer monsoon showed higher surface density of microzooplankton (Avg. 175 x 10^4 m^{-2}) compared to the inter monsoon (Avg. 51 x 10^4 m^{-2}) and winter monsoon (Avg. 49 x 10^4 m^{-2}) (Table 6.3). During summer and spring intermonsoon, northern region showed higher surface abundance (Avg.185 x 10^4 m^{-}

^{2} and 57 x 10^{4} m^{-2}) compared to the south (Figure 6.3, Table 6.3). Surface biomass also showed similar trends with higher concentration during summer (46 mgC m^{-2}) followed by spring (17 mgC m^{-2}) and winter monsoon (13 mgC m^{-2}) (Table 6.3). During summer and spring intermonsoon season higher average surface abundance (179 and 54 x 10^{4} m^{-2}) was at the oceanic region but during winter relatively higher density (49 x 104 m^{-2}) was in the coastal region (Table 6.4).

Distribution of column density showed a different pattern compared to surface density. Maximum average density was observed during inter monsoon (702 x 10^{4} m^{-2}) followed by summer (575 x 10^{4} m^{-2}) and winter monsoon (350 x 10^{4} m^{-2}) (Figure 6.6, Table 6.5). During all the three seasons, southern region showed higher average column density compared to the north. Coastal regions showed maximum average column density (705, 546 and 393 x 10^{4} m^{-2} during inter, summer and winter respectively) irrespective of seasons (Table 6.6). Column biomass showed similar distribution with maximum average biomass (228 mgC m^{-2}) during inter monsoon followed by summer (152 mgC m^{-2}) and winter monsoon (103 mgC m^{-2}). Like column density, biomass also was higher in the southern region irrespective of seasons (Table 6.5).

6.2.2. Spatial (vertical) distribution

6.2.2.1. Winter monsoon

During winter monsoon, numerical abundance of microzooplankton varied from 5 – 83 x 10^{3} m^{-3} and the maximum value was found at 10m depth of the middle station (B8) along 15°N (Figure 6.8). Biomass of microzooplankton ranged between 0.2 and 2.3 x 10^{3}mgCm^{-3} and the maximum value coincided with maximum numerical abundance (Figure 6.9).

During winter monsoon, vertical distribution of microzooplankton at different stations showed uniform pattern. In all stations, maximum abundance of microzooplankton was above 20m depth (20m - surface) below, which it decreased with increasing depth (Figure 6.8). Along 11°N higher abundance was observed at 10m depths in the middle (50 x $10^{3}m^{-3}$) and oceanic (48 x $10^{3}m^{-3}$) stations (B_2 and B_3) but in the coastal station (B1), 20m had maximum density (55 x 10^{3} m^{-3}).

Along13°N, in the middle and oceanic stations (B_5 and B_6), maximum abundance (75 and 73 x 10^3 m^{-3}) were at 20m depth but in the coastal station (B_4) maximum abundance (60 x $10^3 m^{-3}$) was at 10m depth. Along 15°N middle and oceanic stations (B8 and B9) showed maximum abundance (83 and 75 x $10^3 m^{-3}$) at 10m depth and in the coastal station maximum abundance (60 x $10^3 m^{-3}$) was at 20m. Along 17°N, peak was evident at the surface in the oceanic station (B12), but in the coastal and middle station maximum density was observed at 10m depth. Along 19°N, coastal and oceanic stations (B13 and B15) showed surface peaks (45 and 58 x 10^3 m^{-3}) and in the middle station (B14) maximum density (40 x 10^3 m^{-3}) was at 20 m depth. Along 20.5, the oceanic station (B17) had maximum density (48 x 10^3 m^{-3}) at 10m depth and in the coastal station maximum abundance was at the surface (55 x 10^3 m^{-3}).

Like density distribution, microzooplankton biomass was higher above 20m depth (20m – surface) (Figure 6.9). In most of the location higher biomass corresponded to higher numerical abundance. Along 11°N, maximum biomass was observed at 20m depth of the coastal station (B1). Middle and oceanic stations (B2 and B3) in this transect showed maximum abundance at 10m depth. Along 13°N, higher biomass (1.5 mgC m^{-3}) was at surface while at the middle and oceanic station higher biomass was at 20m depth. Along 15°N, middle and oceanic stations (B8 and B9) had higher biomass at 10m depth but in the coastal station, 20m had higher concentration. Along 17°N, coastal and oceanic stations had higher values (1.5 and 1.6 mgC m^{-3}) at surface but the middle station had maximum (1.1 mgC m^{-3}) at 10m depth. Along 19°N and 20.5°N all the stations showed higher biomass at the surface layer. Along 19 °N, coastal and oceanic stations (B13 and B15) had maximum biomass (1.3 & 1.6 mgC m^{-3}) at the surface but in the middle station (B14) maximum biomass was at the surface. Along 20.5°N, coastal stations had maximum biomass at the surface but the oceanic station had maximum at 10m depth. Maximum biomass in the coastal and oceanic stations was 1.5 and 1.2 respectively.

6.2.2.2. Spring intermonsoon

During spring intermonsoon, numerical abundance of microzooplankton varied from 5 – 93 x 10^3 m^{-3} and the maximum value was found at 75m depth of the coastal station along 11°N (Figure 6.10). Biomass of microzooplankton ranged between 0.1 and 3.9 x 10^3 m^{-3} and the maximum value coincided with maximum numerical abundance (Figure 6.11).

Higher concentration of microzooplankton in the subsurface layers was the general feature of the season (Figure 6.10). Subsurface peaks at different stations varied from 10 - 75m depths. Along 11°N, maximum microzooplankton density (74x 10^3m^{-3}) was observed at 50m in the coastal stations (93 x 10^3m^{-3}). In the middle and oceanic stations (B2 & B3), maximum density was found at 50m depth. At the coastal station along 13°N, subsurface maximum (68 x 10^3m^{-3}) was found at 75m depth, but in the middle and oceanic stations (B_5 and B_6), maximum density was observed at 50m depth. Along 15°N, maximum density in all stations (B_7, B_8 and B_9) was observed at 50m. Along 17°N, coastal and middle station had maximum abundance (85 and 88 x 10^3 m^{-3}) at 50m, but the oceanic station (A_{12}) showed maximum density (88 x 10^3 m^{-3}) at 75m depths. Along 19°N, all the three stations showed maximum density at 50m depth. Along 20.5°N, coastal station had maximum density (75 x 10^3 m^{-3}) at 10m depths and at the oceanic station, maximum density (53 x 10^3 m^{-3}) was observed at the surface.

Biomass of microzooplankton varied from 0.1 to 3.9 mgC m^{-3} and the maximum value coincided with maximum numerical abundance (Figure 6.11). Like numerical abundance, biomass distribution also showed subsurface peaks. Along 11°N maximum biomass was observed at 75m depth at the middle and oceanic stations but at the coastal station maximum was at 50m depth. Along 13 °N coastal stations had maximum biomass at 75m depth but at the middle and oceanic stations maximum was at 75m depth. Along 15 °N higher biomass at all the station were at 50m. Along 17°N, coastal and middle station had higher biomass (2.3 and 3.4 mgC m^{-3}) at 50m depth, but in the oceanic station maximum biomass (2.2 mgC m^{-3}) was at 75m. Along 19 °N, coastal and middle station had maximum biomass at 50m

depth but in the oceanic station maximum density was 50m. Along 20.5 °N, coastal station had maximum at 10m depth and in the oceanic station maximum was at the surface.

6.2.2.3. Summer monsoon

During summer monsoon, numerical abundance of microzooplankton varied from 5 – 353 x 10^3 m^{-3} and the maximum value was found at the surface of the oceanic station along 19°N (B17) (Figure 6.12). Vertical distribution pattern of microzooplankton during the season was similar to that of the winter monsoon, but the peaks were found at much shallower depths compared to winter monsoon. Peaks of microzooplankton abundance were mostly confined to the upper 10m water column except at a few locations were it found at 20m depth (Figure 6.12). Coastal and oceanic stations along 11 and 13 °N showed higher density (88 x $10^3 m^{-3}$) at the surface. The middle stations along 11and 13°N had higher density (83 and 93 x 10^3 m^{-3}) at 10m depth. Along 15°N, in the middle and oceanic stations, maximum abundance (70 &148 x 10^3 m^{-3}) was at the surface. But in the coastal station, peak was at 20m. Along 17°N, middle and oceanic stations (B11& B12) showed decreasing trend from the surface. Along 19°N, coastal and oceanic stations (B13 and B15), had maximum abundance at 10m depth and the middle station (B14) showed decreasing trends from the surface. Along 20.5°N, both the stations showed (B16 and B17) similar pattern of decreasing density from surface. The oceanic station along 20.5 showed maximum density (353 x 10^3 m^{-3}).

Biomass of microzooplankton ranged between 0.1 and 3.9 mgC x 10^3 m^{-3} and the maximum value (4.35 x 10^3 mgC m^{-2}) coincided with maximum numerical abundance. Like density distribution, biomass also had peaks mostly confined to the upper 10m water column in most of the stations (Figure 6.13). Coastal and oceanic stations along 11°N had maximum biomass at the surface (2.5 and 2.6 mgC x 10^3 m^{-3}), but at the middle station, maximum abundance was at 10m depth. Along 13 °N all the three stations showed maximum biomass at the surface. Along 15 °N, middle and oceanic stations had higher biomass at the surface but in the coastal station higher biomass was at 20m. Middle and oceanic station along 17 °N also

had higher biomass (2.1 and 3.1 mgC m^{-3}) at the surface. Along 19 °N, middle and oceanic stations had maximum biomass (3.9 and 1.3 mgC x 10^3 m^{-3}) at surface while in the coastal station maximum biomass (1.8 mgC x 10^3 m^{-3}) was at 10m depth. Along the northernmost transect (20.5 °N) both the coastal and oceanic stations showed maximum biomass (2.4 and 7.5 mgC x 10^3 m^{-3}) at the surface.

6.2.2.4. Temporal variations

Generally, vertical distribution of microzooplankton during different seasons showed high concentrations in the upper layers (75m - surface). Distribution of microzooplankton during different seasons clearly showed seasonal fluctuations (Figures 6.8 – 6.13). During summer and winter monsoon maximum density was found at the upper 20m water column below which it decreased with increasing depth. This pattern was particularly prominent during summer monsoon where almost all stations showed maximum abundance above 10m depth. On the contrary, higher density was found at relatively deeper depth (50 - 75m) during inter monsoon.

Vertical distribution of different groups of microzooplankton showed variations during different seasons. During winter and summer monsoon dinoflagellates showed a decreasing trend from the surface (Figures 6.14 – 6.16), except in a few stations where they were maximum at 20m depth.. During winter, ciliates showed more or less uniform distributional pattern except at the middle station along 11°N (B2) where they had higher density in the upper water column. Abundance of ciliates during the season was very low and comparable with the densities of other protozoans and micrometazoans. But the vertical distribution of ciliates during inter monsoon spring was peculiar where higher densities of organisms were at deeper depths. Distribution of dinoflagellates also showed increased densities in the subsurface layers compared to the other two seasons. But the change in the distribution of ciliate abundance was more prominent during the season and concentration in the 50 - 75m water column increased considerably compared to other seasons (Figures 6.14 – 6.16). At many stations other protozoans and micrometazoans also showed higher abundance at subsurface depths. During

summer monsoon ciliates and dinoflagellates showed a decreasing trend in abundance from surface to bottom in almost all the stations. Other protozoans and micrometazoans had a uniform distribution pattern similar to winter monsoon.

6.3. Microzooplankton herbivory

During winter monsoon, microzooplankton herbivory experiments were carried out at four locations (B1, B3, B7 & B9) along the south east coast of India. At each stations at two depths (5m and 40m), grazing experiments were carried out for microzooplankton herbivory. The details of the procedures are discussed in chapter 3.

In the coastal stations along 11°N (B1), magnitude of herbivory was higher (4.8μgC l^{-1} d^{-1}) at 50m depth compared to the surface (1.77μgC l^{-1} d^{-1}). But in the open ocean station (B3) higher grazing rate was at the surface (7.9μgC $l^{-1}d^{-1}$) (Table 6.7). Similarly along 15°N, coastal station showed higher grazing (6.5μgC$l^{-1}d^{-1}$) at the surface layers where as in the oceanic station, higher grazing activity (4.3μgC $l^{-1}d^{-1}$) was observed in deeper waters (40m).

In the surface waters (5m) herbivory ranged between 1.8 – 7.9 μgC $l^{-1}d^{-1}$ (Avg.5μgC l^{-1} d^{-1}) (Figure 4.39a). In deeper depths, herbivory ranged between 3.3 – 4.8 μgC $l^{-1}d^{-1}$ (Avg. 4μgC $l^{-1}d^{-1}$) (Figure 6.17a). In the surface waters 72% of the phytoplankton standing stock was grazed by microzooplankton but at 50m depth 63% of the phytoplankton standing stock was grazed daily. At the surface waters of the oceanic station along 15°N, microzooplankton consumed 76% (maximum) of the phytoplankton standing stock.

The magnitude of grazing at different locations did not show any specific pattern. Both at the surface and 50m depths, the intensity of herbivory fluctuated considerably with respect to locations. Relatively lesser fluctuations with respect to locations were at 50m depth (Figure 6.17a). Surface waters along 11°N showed maximum fluctuations where coastal station had the least value (1.77μgC $l^{-1}d^{-1}$) and the oceanic waters had the maximum (7.9μgC $l^{-1}d^{-1}$).

Relationship between ambient chlorophyll *a* concentration and herbivorous activity showed a significant linear relationship ($r = 0.921$, $n = 8$, $p < 0.05$), which

indicates the dependency of microzooplankton on phytoplankton biomass (Figure 6.17b). But correlation between herbivory and temperature showed absence of a significant linear relationship ($r = 0.244$, $n = 8$, $p > 0.05$) (Figure 6.17c).

6.4 Some ecological aspects of microzooplankton

6.4.1. Relationship with phytoplankton standing stock (chlorophyll *a*)

Relationships between microzooplankton biomass and chlorophyll *a* during different seasons were analysed. It showed that linear relationship was maximum during intermonsoon spring ($r = 0.415$, $n = 108$, $p<0.05$) followed by summer monsoon ($r = 0.279$, $n = 98$) and winter monsoon ($r = 0.122$, $n = 133$, $p <0.05$) (Figure 6.18). Similarly relationships between major groups of microzooplankton (dinoflagellates and ciliates) during different seasons were studied. During all the seasons dinoflagellates and ciliates had significant linear relationship ($p < 0.05$) to the phytoplankton biomass and the magnitude changed during different seasons. During winter and summer monsoon when higher concentration of chlorophyll *a* was available in relatively shallower depth dinoflagellates showed more relationship to phytoplankton biomass compared to the ciliates (Figure 6.19). But during spring intermonsoon when higher phytoplankton standing stock was available in deeper waters ciliates had strong relationship to phytoplankton standing stock (Figure 6.19).

6.4.2. Symbiotic associations of dinoflagellates and cyanobacteria

Symbiotic associations were found in three genera of heterotrophic dinoflagellates namely *Ornithocercus, Histioneis* and *Parahistioneis*. These genera include 8 species among which 5 belonging to *Ornithocercus*, 2 belonging to *Histioenis* and 1 belonging to *Parahistioneis*. These dinoflagellates hosted clusters of cyanobacteria, rod ovoid or spherical shaped (possibly *Syneccococcus* and *Synechocystis*, Noris 1967) located between the upper and lower lists of the horizontal groove of the cells. *Ornithocercus magnificus, O. heteroporus, O. quadratus, O. steinii, O. thumii, Histioneis hyaline, H. striata and Parahistioneis para* showed symbiotic association with cyanobacteria (Plate 6.14). Among these

species, *Ornithocercus thumii* and *O. magnificus* were the most common species, which showed symbiotic associations.

The frequency of occurrence of symbiotic association varied in magnitude during different seasons. During winter monsoon, total occurrence of symbiotic species in the samples analysed were 1230, among which 156 (13%) had symbiotic associations (Table 6.8). During spring intermonsoon total number of symbiotic species were 2856, among which 2772 (97%) showed symbiotic associations. During summer monsoon, total number of symbiotic species was 1860 out of which 210 (11%) were symbiotic. In general, during spring intermonsoon, symbiotic associations were maximum followed by summer monsoon and least during winter monsoon.

6.4. Summary

Microzooplankton community was composed of both protozoans and metazoans among which the former was most abundant in terms of numerical abundance and biomass. Protozoans present in the samples were heterotrophic dinoflagellates, ciliates, radiolarians and foraminifers in which the first two groups were dominant over others and contributed bulk of the microzooplankton community.

Heterotrophic dinoflagellates were the most abundant group of organisms, which contributed substantially to the total abundance and their percentage contribution varied from 48 – 77% during different seasons (Figures 6.1 – 6.3). Altogether 12 genera and 57 species of heterotrophic dinoflagellates were identified. Complete list and photomicrographs of species identified during the study are presented (Table 6.1, Plates 6.1 – 6.5). Genus *Protoperidinium* was the most abundant genus represented by maximum number of species and they were represented by 21 species during winter, 22 species during spring intermonsoon and 24 species during summer monsoon (Table 6.1). *Phalacroma* was the second abundant genus represented by 7 species followed by *Ornithocercus* represented by 6 species.

Ciliates were the second abundant group, which contributed 4 – 33% of the total abundance during different seasons (Figures 6.1 – 6.3). During the study they represented maximum number of species (35 genera and 75 species) (Table 62, Plate 6.6 – 6.12). Loricates (tintinnids) were dominant over aloricates in abundance, which were represented by 31 genera and 72 species among which the genus *Tintinnopsis* represented by 8 species followed by *Codonellopsis*. Aloricate ciliates represented by 4 genera and 6 species. Other protozoans present in the samples belonging to two different groups namely radiolarians and foraminifers and collectively their numerical abundance was 7 - 9% during different seasons (Figures 6.1 – 6.3, Plate 6.13). Metazoan component of microzooplankton was composed of eggs and larval forms of crustaceans, which formed 6 – 11% of the total abundance (Figures 6.1 – 6.3, Plate 6.13).

During winter monsoon, surface density of microzooplankton varied from 27 – 70 x 10^4 m^{-2} (Avg. 49 x10^4 m^{-2}) and maximum (70 x 10^4 m^{-2}) was found at the middle station (B8) along 15°N (Table 6.3). Surface density of microzooplankton in the southern region showed higher surface density compared to north (Figure 6.6a, Table 6.3). Microzooplankton column density varied from 205 – 515 x 10^4 m^{-2} and relatively higher abundance was observed in the coastal stations of the southern transects (Figure 6.6a, Table 6.5). Column biomass of microzooplankton during the period ranged between 56 – 159 x 10^3 mgC m^{-2} and showed similar trend as that of density distribution (Figures 6.1 – 6.3, Plate 6.13).

During spring intermonsoon, surface density of microzooplankton varied from 23 – 72 x 10^4 m^{-2} (Avg. 51 x 10^4 m^{-2}) and maximum (72 x 10^4 m^{-2}) was found at the oceanic station along 15°N (B8). Unlike wintermonsoon, northern regions showed higher microzooplankton density (Avg. 57 x 10^4 m^{-2}) compared to the southern region (47 x 10^4 m^{-2}) (Figure 6.4b). Distribution of surface biomass is similar to the density distribution with higher concentration in the northern region (Avg.17 x10^3 mgC m^{-3}) compared to the south (Avg. 14 x 10^3 mgC m^{-2}) (Figure 6.5b, Table 6.3). During the season, the column density of microzooplankton ranged between 211 – 912 x 10^4 m^{-2} (Avg. 702 x $10^4 m^{-2}$). Similar to winter

monsoon higher abundance was found in the (Avg. 724 x $10^4 m^{-2}$) southern region with maximum value at coastal station (B1) along 11°N (Table 6.5). Coastal stations of the southern area showed higher biomass compared to the oceanic regions but in the north both regions showed comparable biomass (Figure 6.7b, Table 6.6).

During summer monsoon, surface density of microzooplankton varied from 128 – 275 x $10^4 m^{-2}$ (Avg. 175 x 10^4 m^{-2}) and the maximum value (275 x $10^4 m^{-2}$) was found at the middle station along 19°N (B14) (Table 6.3). Northern region showed higher density (Avg. 185 x 10^4 m^{-2}) compared to the southern region (Avg. 168 x 10^4 m^{-2}) (Figure. 6.4c, Table 6.3). Abundance in the oceanic stations showed higher surface abundance compared to the coastal stations (Table 6.4). Distribution of surface biomass was similar to the surface density with relatively higher average concentration in the southern transects (Avg. 50 x 10^3 mgC m^{-2}) compared to the north (Avg. 46 x 10^3 mgC m^{-2}) (Figure 6.5c, Table 4.6). Column density of microzooplankton ranged between 323 – 710 x 10^4 m^{-2} (Avg. 575 x $10^4 m^{-2}$) and was higher in the southern region (Avg. 630 x 10^4 m^{-2}) compared to the northern region (Avg. 505 x 10^4 m^{-2}) (Figure 6.6c, Table 6.5). Like surface density, oceanic stations showed higher abundance during the season (Table 6.6). Microzooplankton column biomass ranged between 86 – 210 x 10^3 mgC m^{-2}, which showed similar trends as that of density distribution with higher values (Avg. 166 x 10^3 mgC m^{-2}) in the southern region (Figure 6.6c, Table 6.5).

In general, maximum surface density and biomass was during summer monsoon (Avg. 175 x 10^4 m^{-2} and 46 mgC m^{-2}) followed by spring intermonsoon (Avg. 43 x 10^4 m^{-2}, 17 mgC m^{-2}) (Table 6.3). However, distribution of column density showed a different pattern compared to surface density and biomass. Average column density and biomass was maximum during spring intermonsoon (Avg. 702 x 10^4 m^{-2}, 228 mgC m^{-2}) followed by summer monsoon (575 x 10^4 m^{-2}, 152 mgC m^{-2}) and minimum during winter monsoon (350 x 10^4 m^{-2}, 103 mgC m^{-2}) (Figure 6.6, Table 6.5).

During winter monsoon, vertical distribution of microzooplankton at different stations showed uniformity. In all stations, higher abundance and biomass of microzooplankton was above 20 m depth (20m – surface) below, which it decreased with increasing depth (Figures 6.8 & 6.9). During intermonsoon higher numerical abundance and biomass of microzooplankton was in the subsurface layers and peaks at different station varied from 10 - 75m (Figures 6.10 & 6.11). Vertical distribution microzooplankton during summer monsoon was similar to the winter monsoon but the peaks of abundance and biomass were found at relatively shallower depths (10m – surface) (Figures 6.11 & 6.13).

Vertical distribution of microzooplankton during different seasons showed clear seasonal fluctuations. During summer and winter monsoon, maximum density was found at the upper 50m water column below which it decreased with increasing depth (Figures 6.14 – 6.16). This pattern was particularly significant during summer monsoon where almost all the station showed maximum abundance above 10m depth. On the contrary, during spring intermonsoon, higher density was found at relatively deeper depths (50 – 75m).

Vertical distribution of different groups of microzooplankton showed variations during different seasons. During winter and summer monsoon, dinoflagellates showed decreasing trend from the surface. During winter, ciliates showed almost uniform distributional pattern except at the middle station along 11°N (B2) where they had higher density in the upper water column (Figures 6.14 – 6.16). Abundance of ciliates during the season was very low and comparable with the densities of other protozoans and metazoans. Vertical distribution of dinoflagellates during spring intermonsoon showed increased abundance in the subsurface layers compared to other two seasons. But the change in the distribution of ciliates was more prominent during the season and ciliate concentration in the 50 - 75m water column increased considerably compared to the other two seasons (Figures 6.14 – 6.16). During summer monsoon ciliates had decreasing trend of abundance from the surface. However dinoflagellates did not show any specific pattern of distribution during summer monsoon.

Grazing experiments showed that microzooplankton herbivory ranged between 1.8 – 7.9 μgC l^{-1} d^{-1} (Avg. 5μgC l^{-1} d^{-1}) at the surface and in the deeper waters (40m) it ranged between 3.3 – 4.8μgC$l^{-1}d^{-1}$ (Avg. 4μgC l^{-1} d^{-1}) (Table 6.17). In the surface waters 72% of the phytoplankton standing stock was grazed by microzooplankton but at 40m depth only 63% of the phytoplankton stock was grazed daily.

Microzooplankton biomass and phytoplankton standing stock during different seasons showed significant linear relationship ($p < 0.05$) (Figure 6.18). Relationship between phytoplankton standing stock and abundance of dinoflagellates and ciliates also showed positive relationship during all the seasons although the magnitude changed seasonally. During summer and winter monsoon (when higher concentration of phytoplankton standing stock was available at relatively shallower depths) dinoflagellates was more related to the phytoplankton biomass (Figure 6.19). But during spring intermonsoon when higher phytoplankton standing stock was available in deeper waters, ciliates had stronger relationship with phytoplankton biomass (Figure 6.19).

Symbiotic associations were found in three genera of dinoflagellates namely *Ornithocercs, Histioneis* and *Parahistioneis* . The species, which showed symbiotic relationship with cyanobacteria, were *Ornithocercus magnificus, O.quadratus, O. steinii, O. thumii, O. heteroporus, Histioneis hyaline, H. striata* and *Parahistioneis para* (Plate 6.14). The frequency of occurrence of symbiotic associations varied in magnitude during different seasons. During spring intermonsoon 97 % of the total occurrence were symbiotic followed by wintermonsoon (13%) and least during summer monsoon (11%).

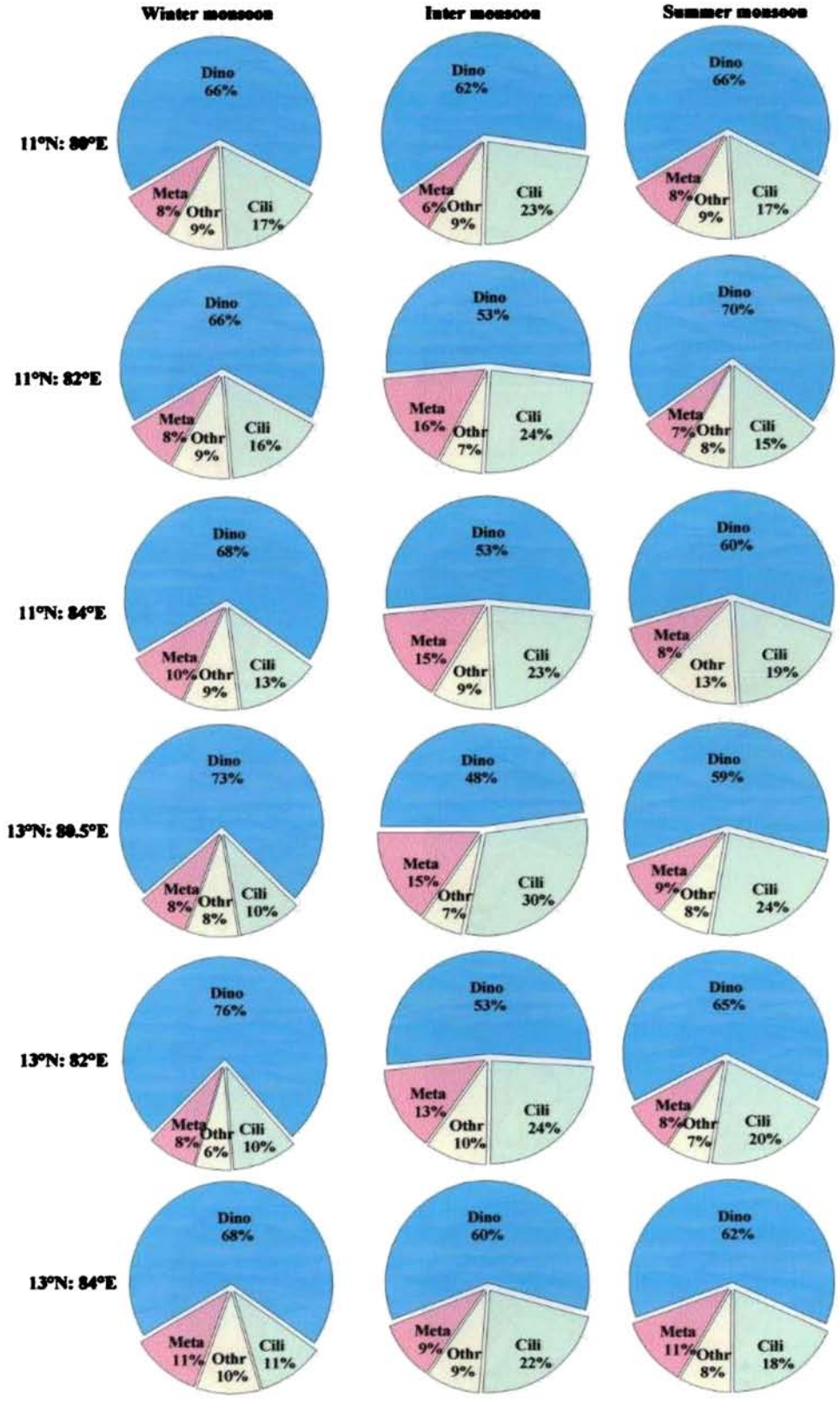


Figure 6.1. Seasonal variation of microzooplankton composition at different stations along 11 and 13°N

(Dino-dinoflagellates, Cili-ciliates, Meta-metazoans,Othr-others)

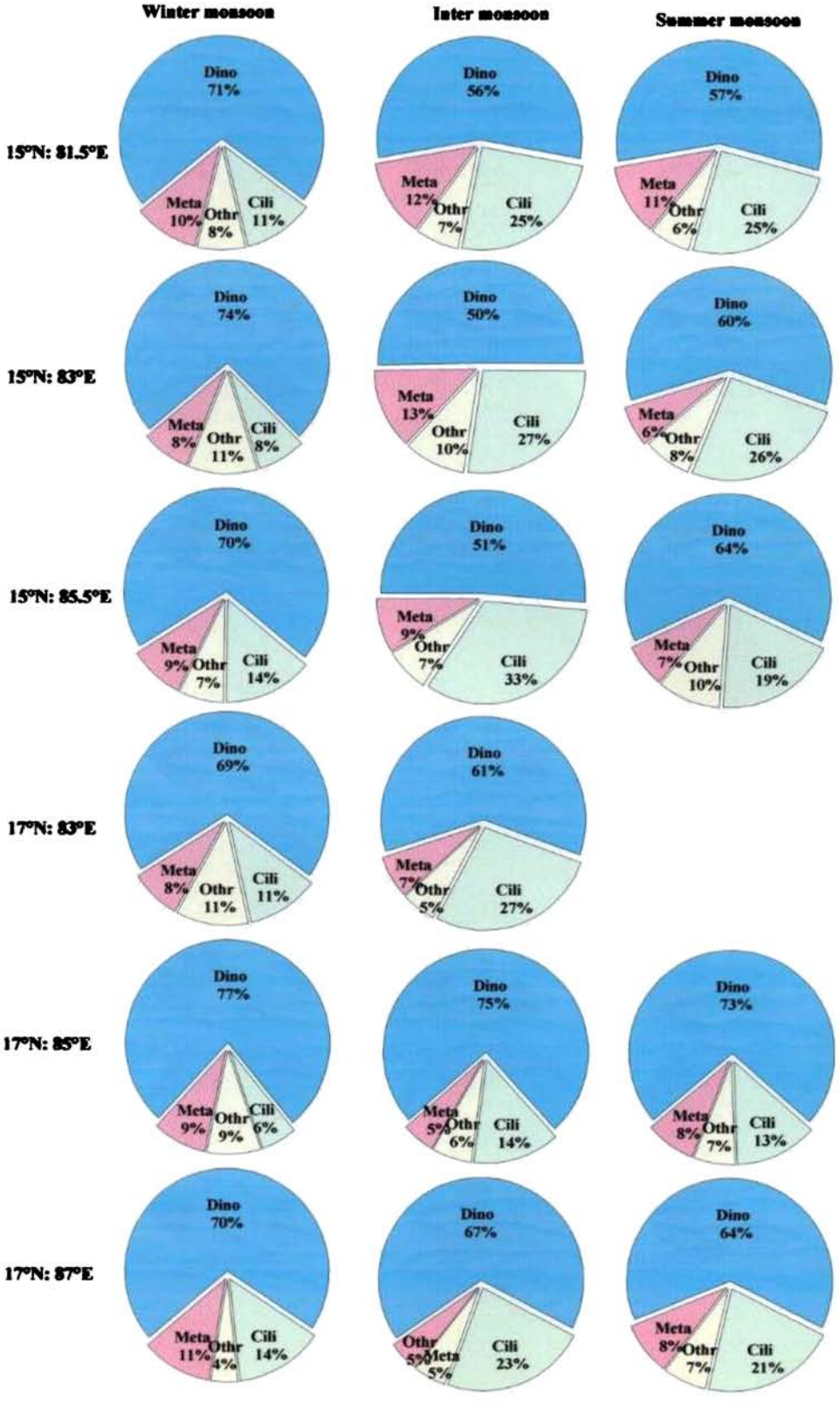


Figure 6.2. Seasonal variation of microzooplankton composition at different stations along 15 and 17°N

(Dino-dinoflagellates, Cili-ciliates, Meta-metazoans,Othr-others)

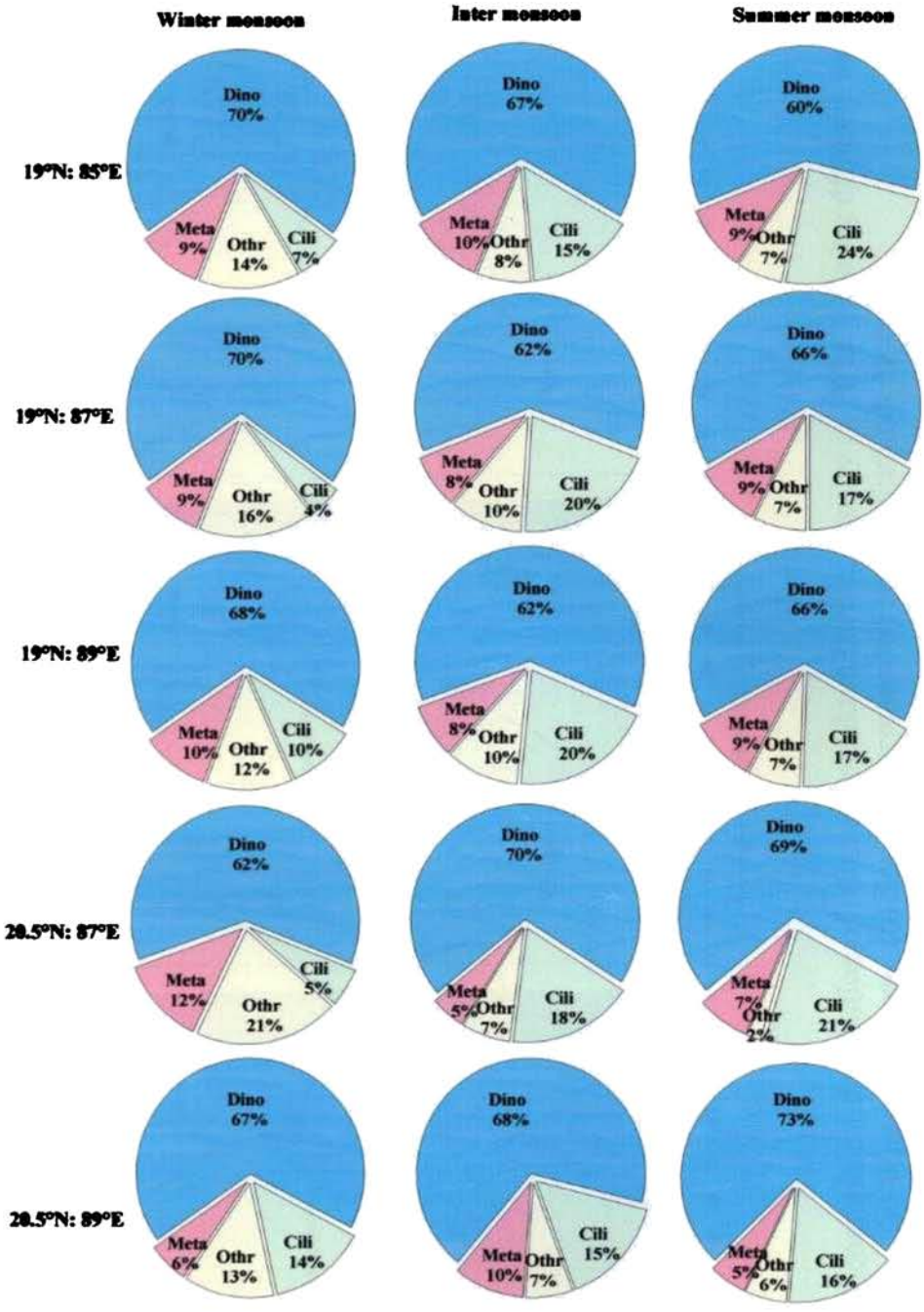


Figure 6.3. Seasonal variation of microzooplankton composition at different stations along 19 and 20.5°N

(Dino-dinoflagellates, Cili-ciliates, Meta-metazoans,Othr-others)

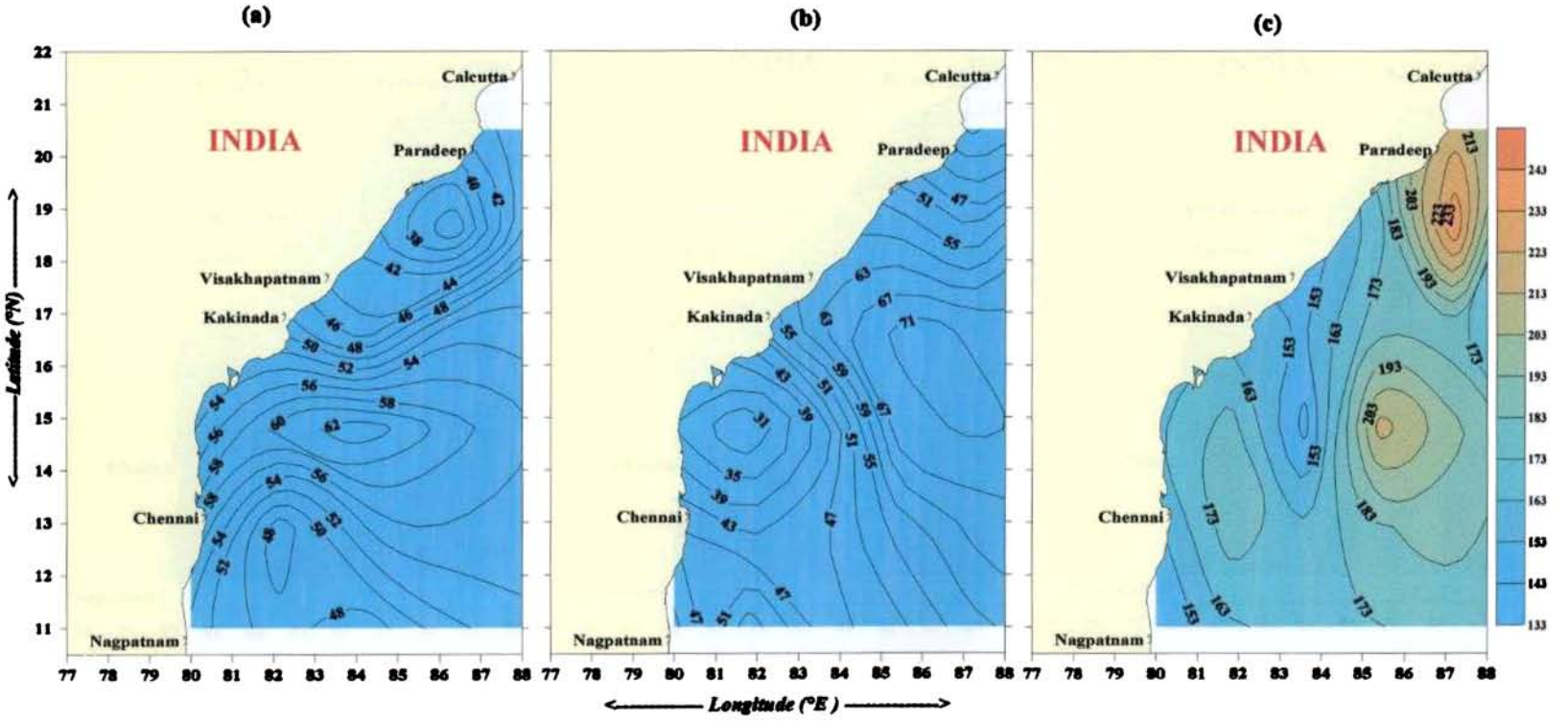


Figure 6.4. Geographical distribution of microzooplankton surface density (x $10^4 m^{-2}$) during different seasons (a) Winter monsoon, (b) Spring intermonsoon and (c) Summer monsoon

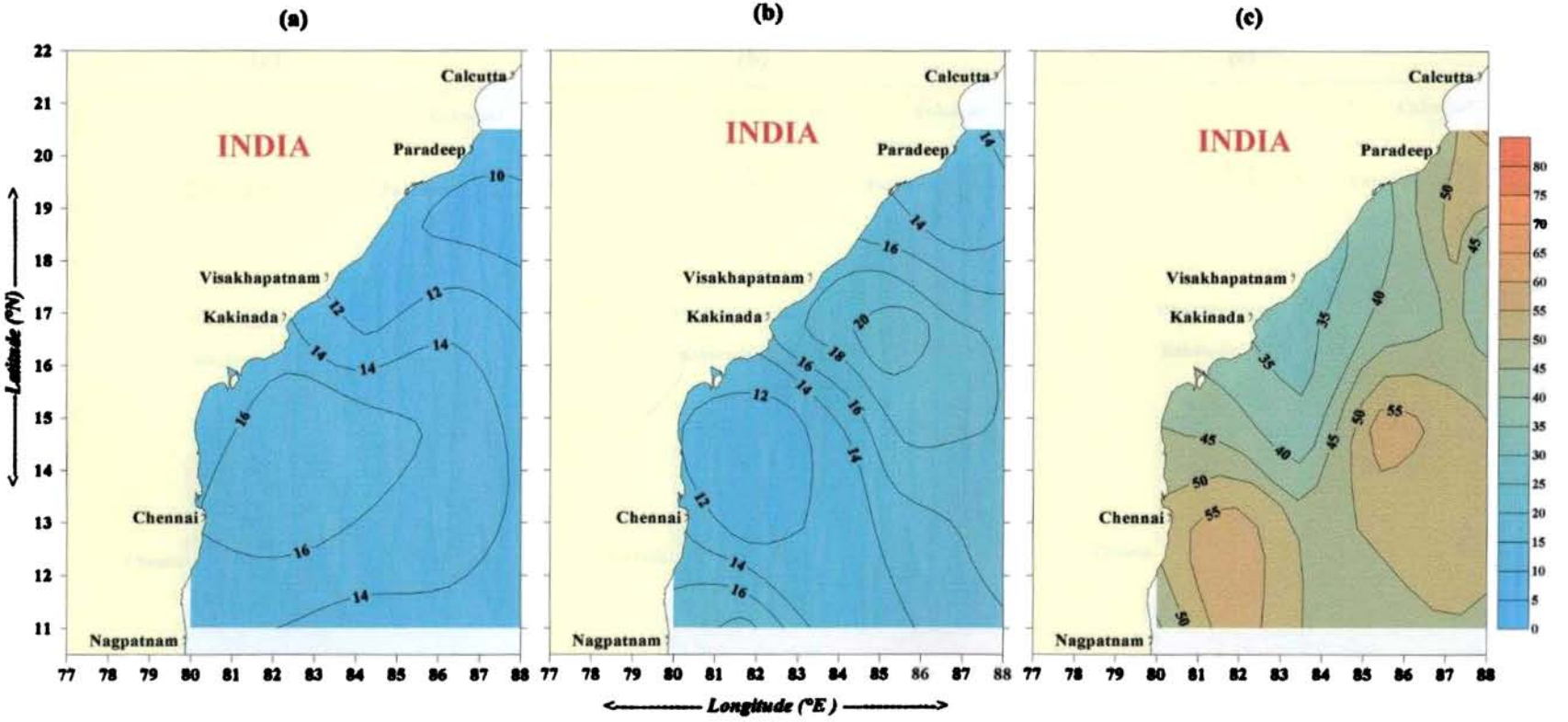


Figure 6.5. Geographical distribution of microzooplankton surface biomass (mgC x $10^3 m^{-2}$) during different seasons (a) Winter monsoon, (b) Spring intermonsoon and (c) Summer monsoon

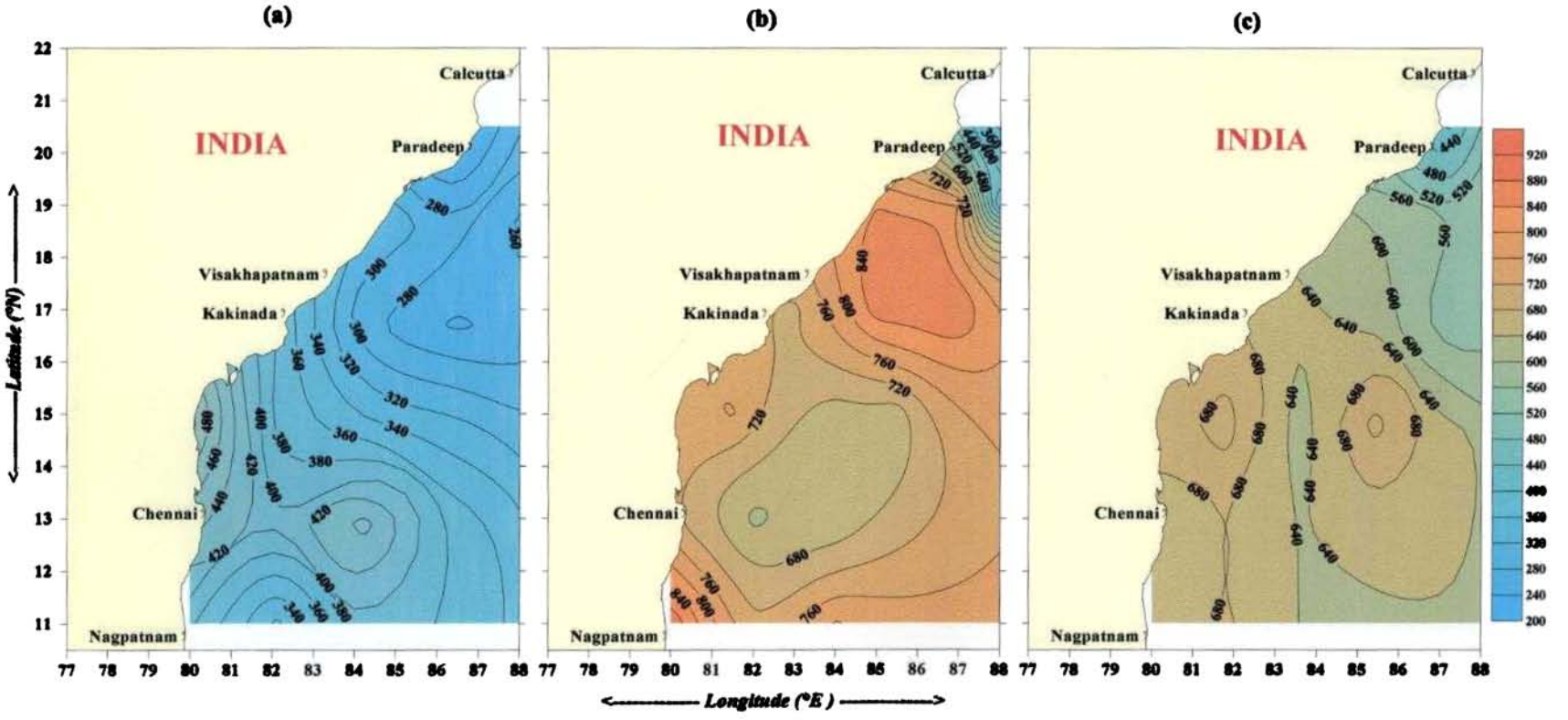


Figure 6.6. Geographical distribution of microzooplankton column density (x $10^4 m^{-2}$) during different seasons (a) Winter monsoon, (b) Spring intermonsoon and (c) Summer monsoon

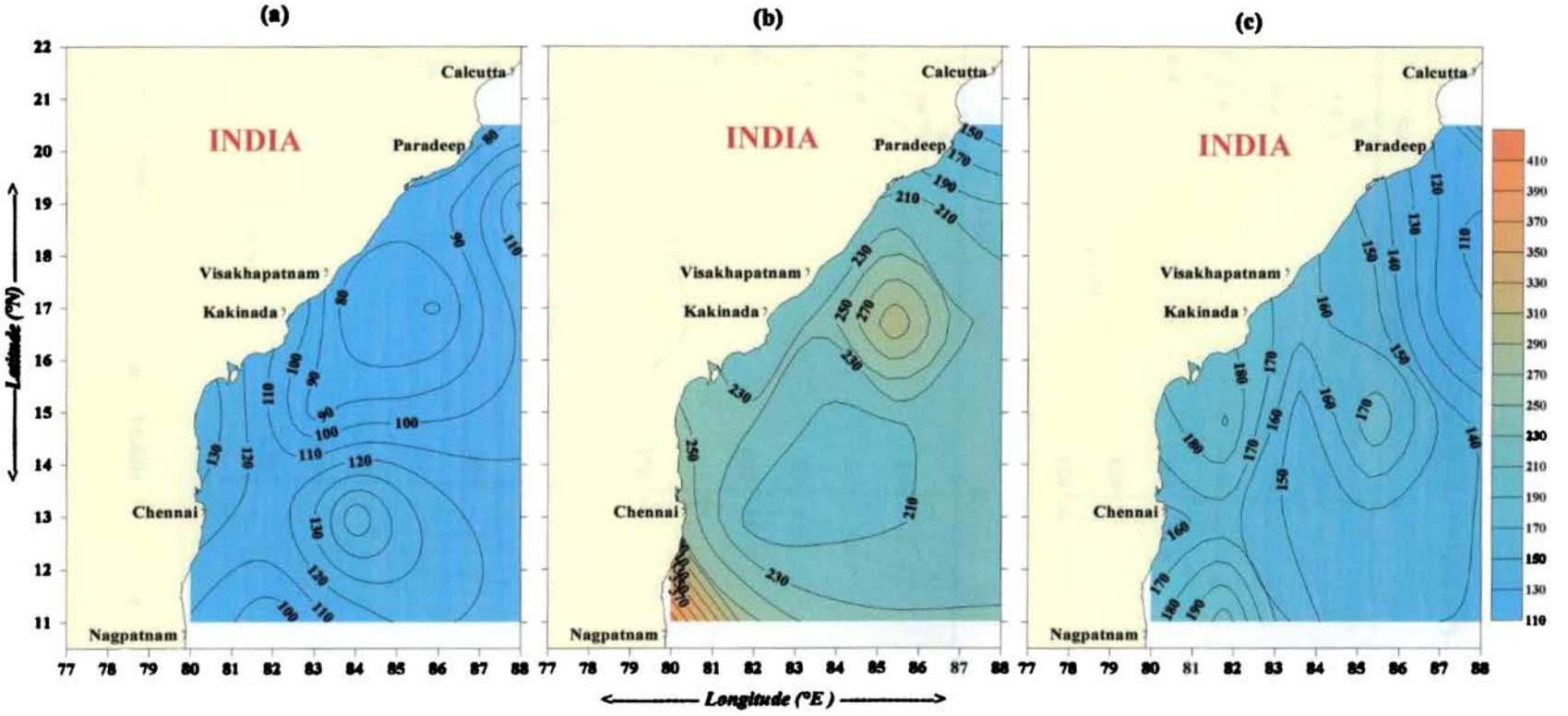


Figure 6.7. Geographical distribution of microzooplankton column biomass (mgCx $10^3 m^{-2}$) during different seasons (a) Winter monsoon, (b) Spring intermonsoon and (c) Summer monsoon

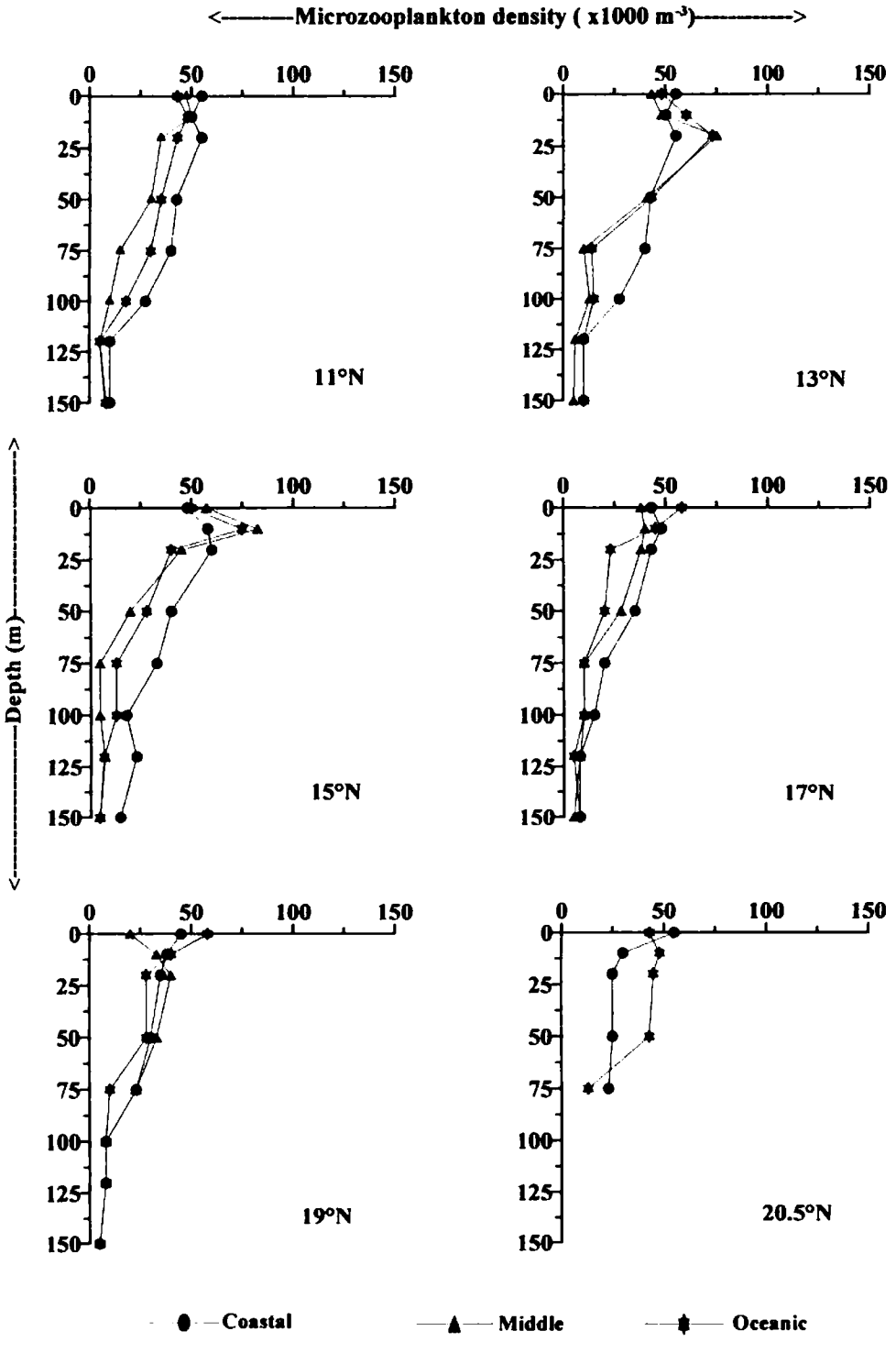


Figure 6.8. Vertical distribution of microzooplankton abundance at different stations during winter monsoon

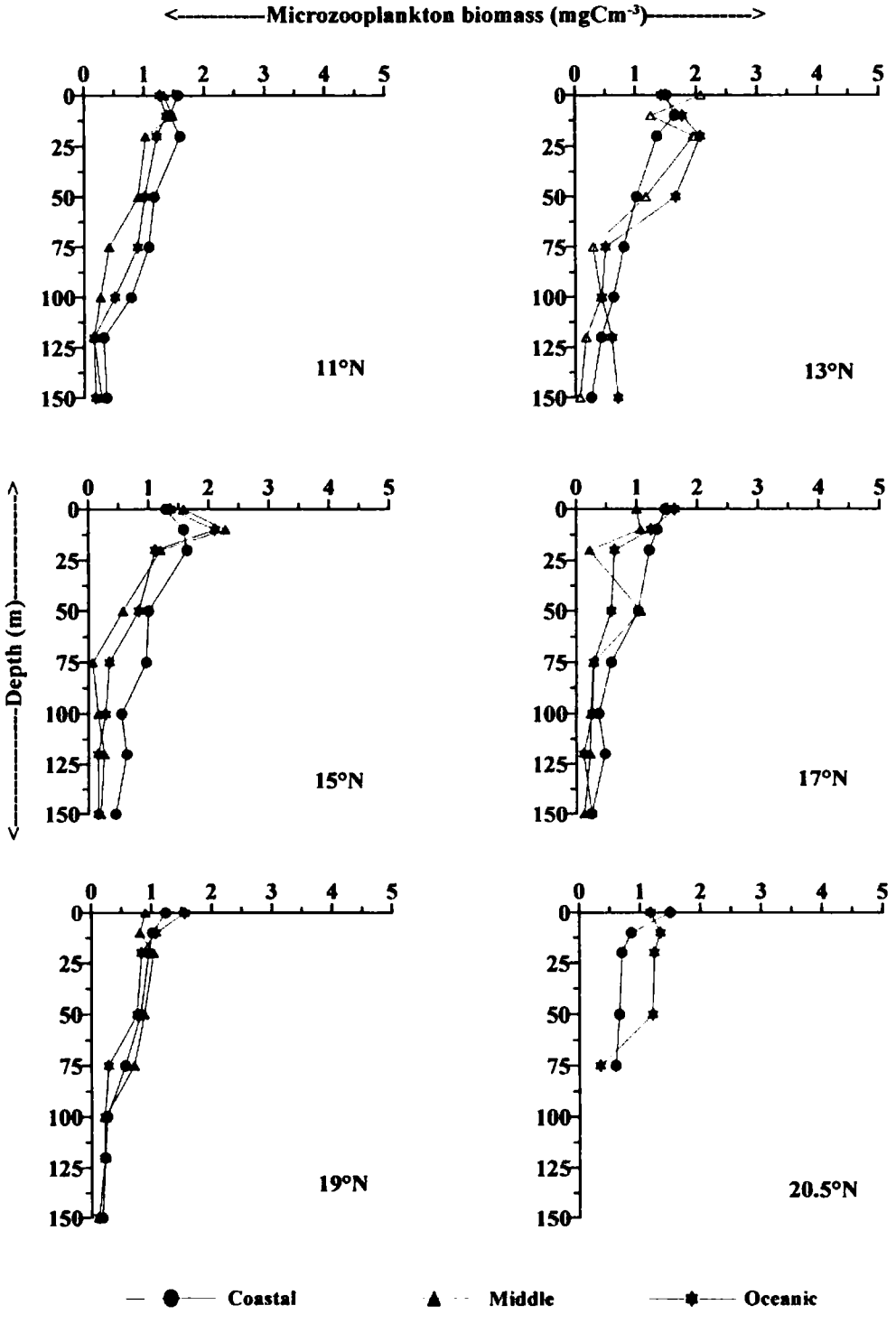


Figure 6.9. Vertical distribution of microzooplankton biomass at different stations during winter monsoon

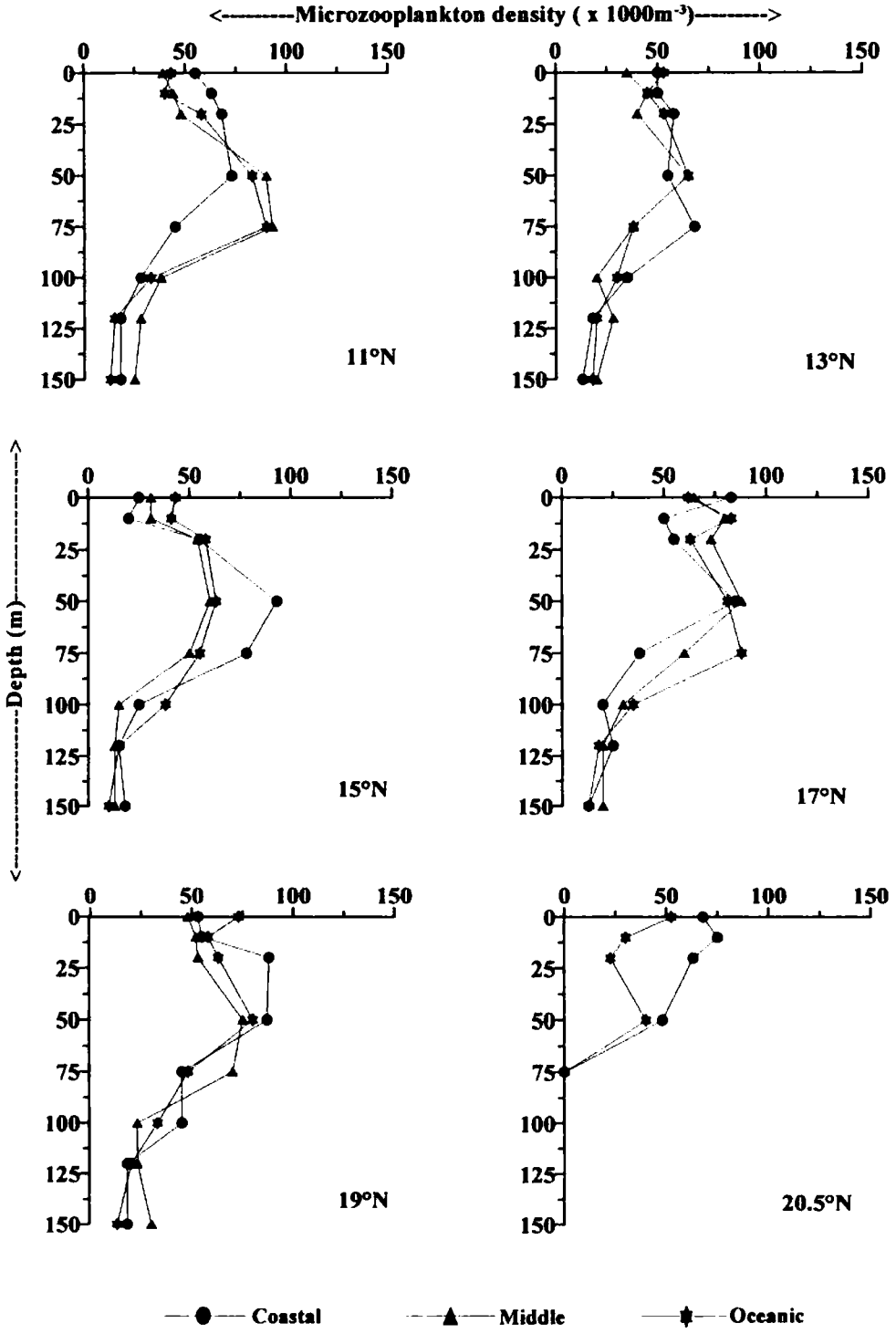


Figure 6.10. Vertical distribution of microzooplankton abundance at different stations during spring intermonsoon

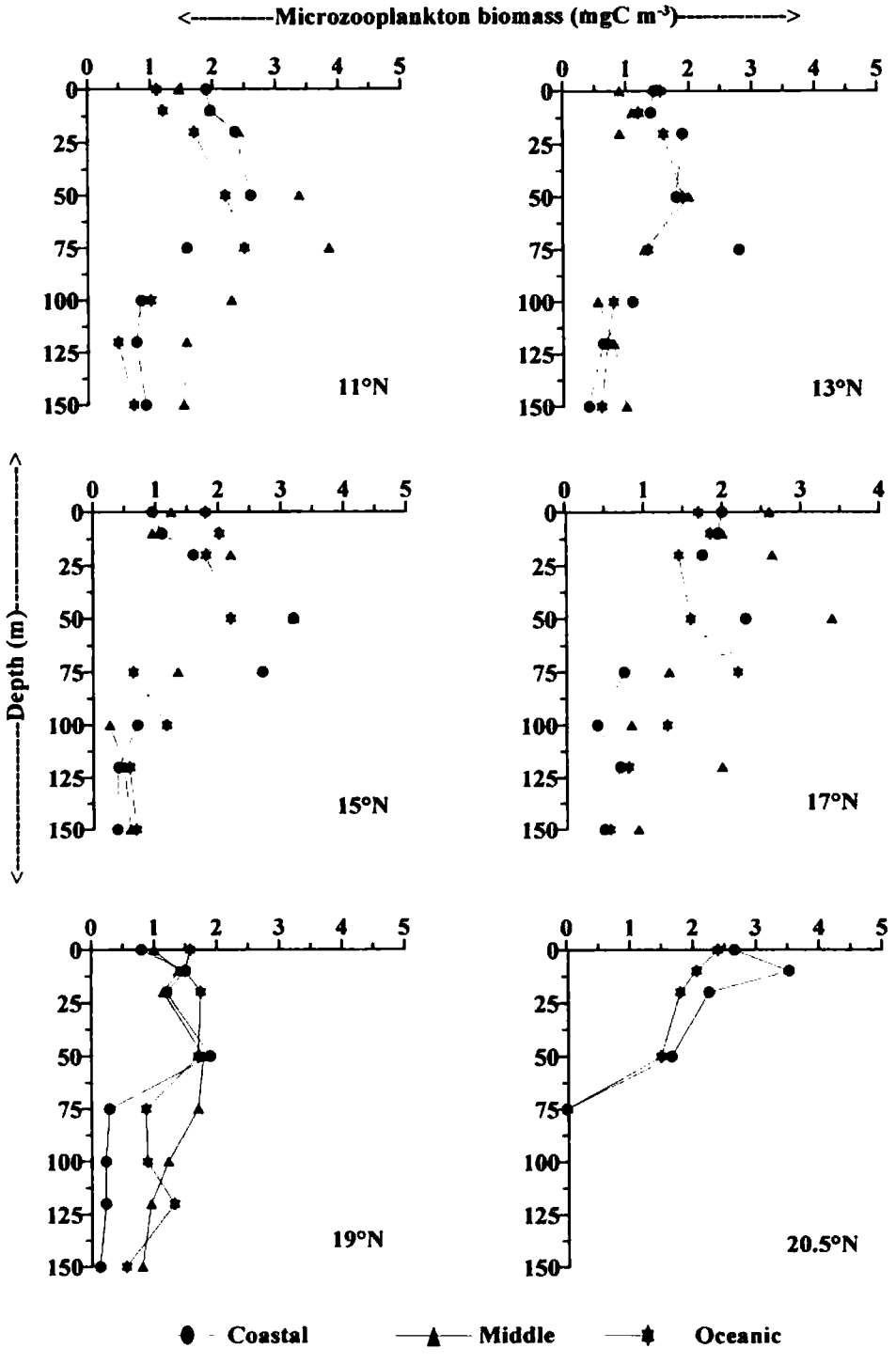


Figure 6.11. Vertical distribution of microzooplankton biomass at different stations during spring intermonsoon

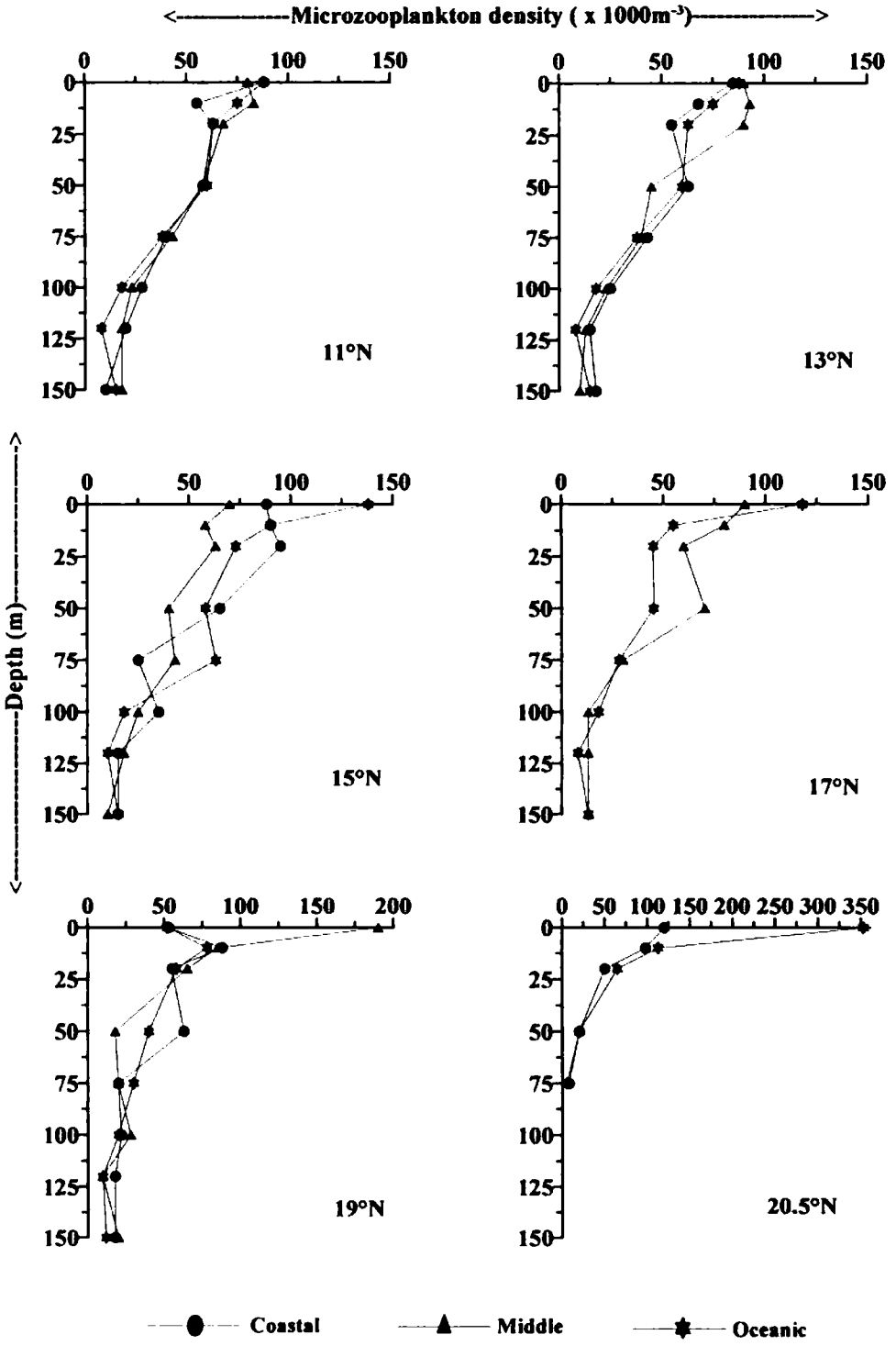


Figure 6.12. Vertical distribution of microzooplankton abundance at different stations during summer monsoon

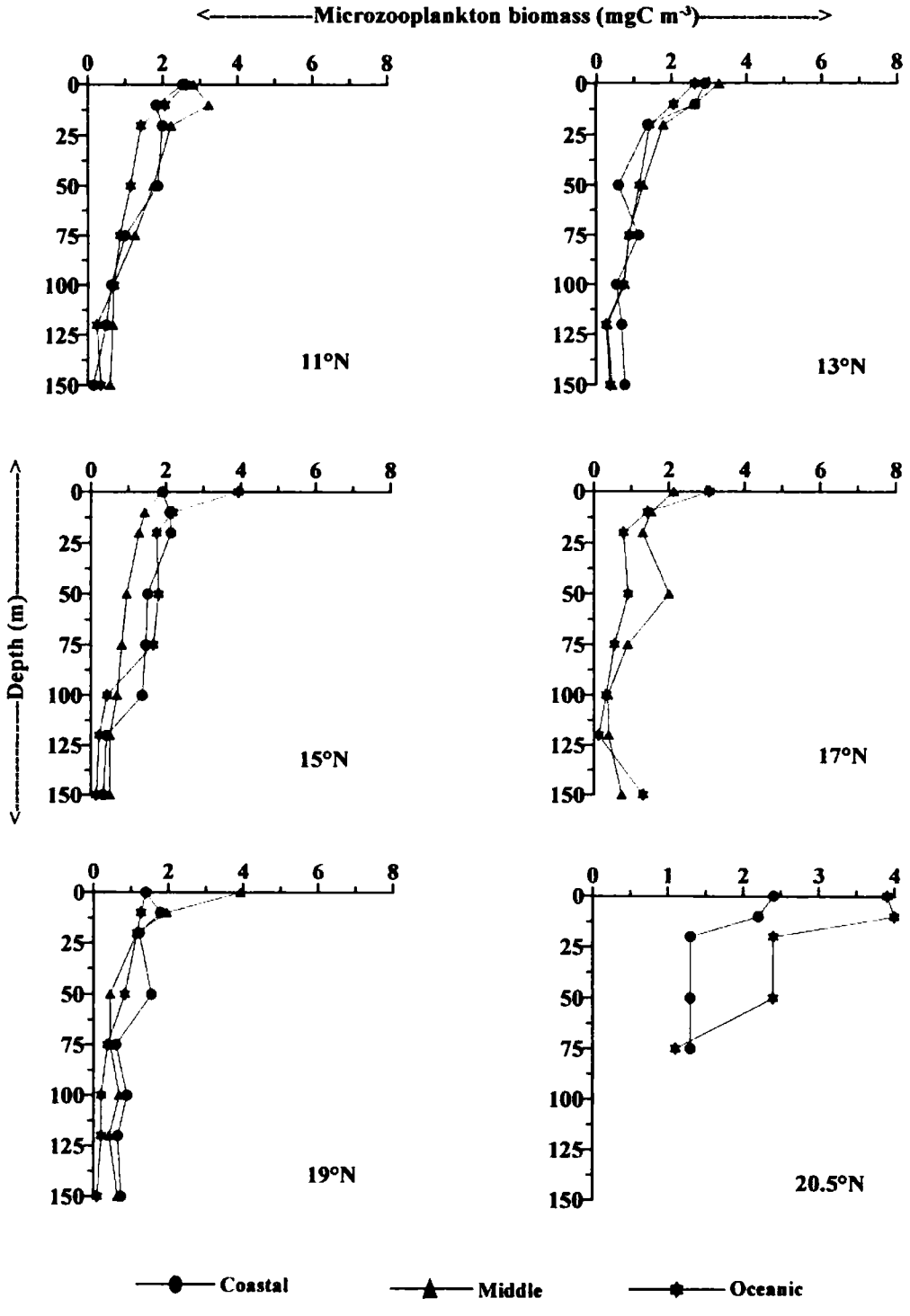


Figure 6.13. Vertical distribution of microzooplankton biomass at different stations during summer monsoon

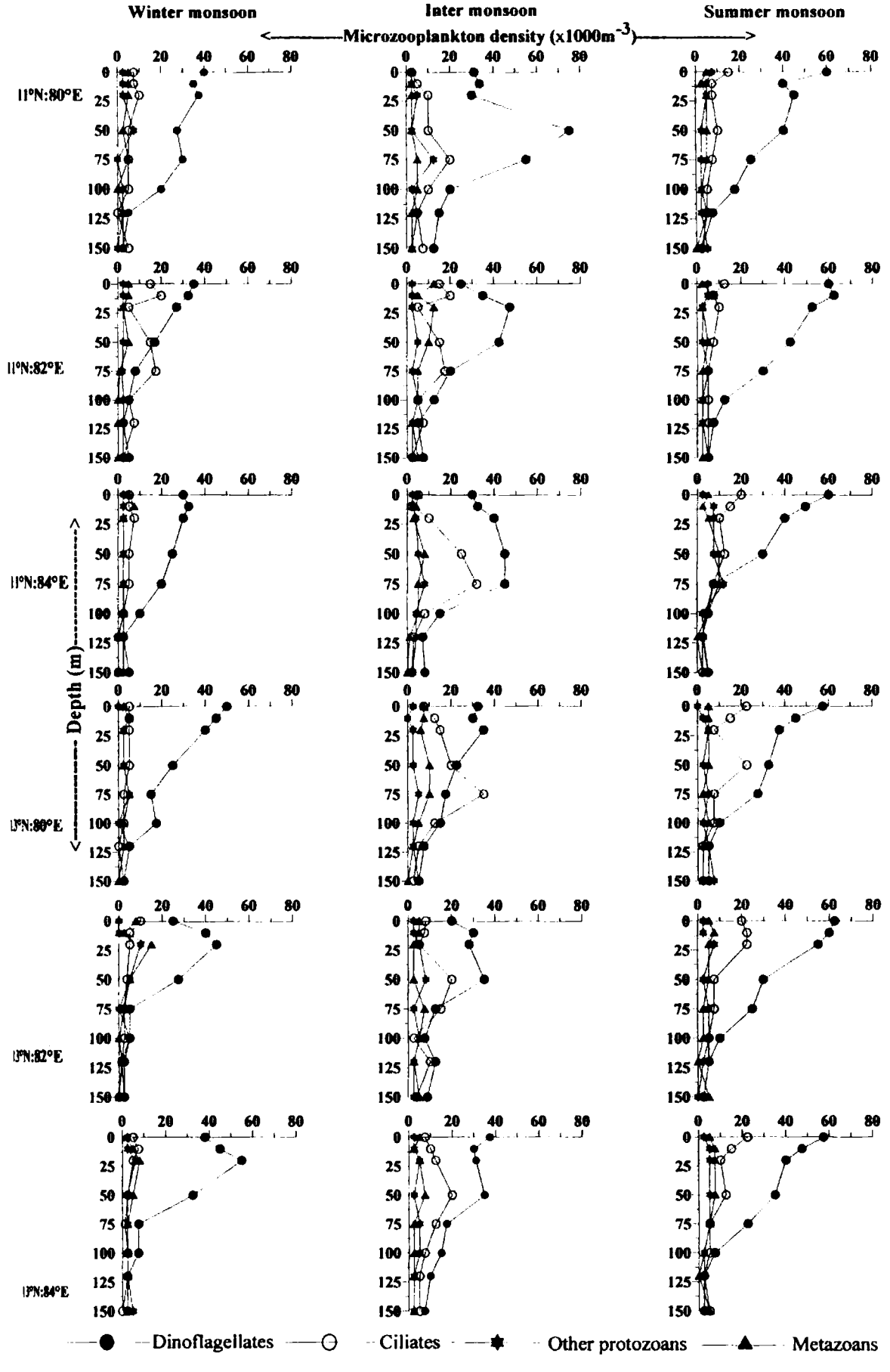


Figure 6.14. Vertical distribution of major microzooplankton groups at different stations along 11 and 13°N during diferent seasons

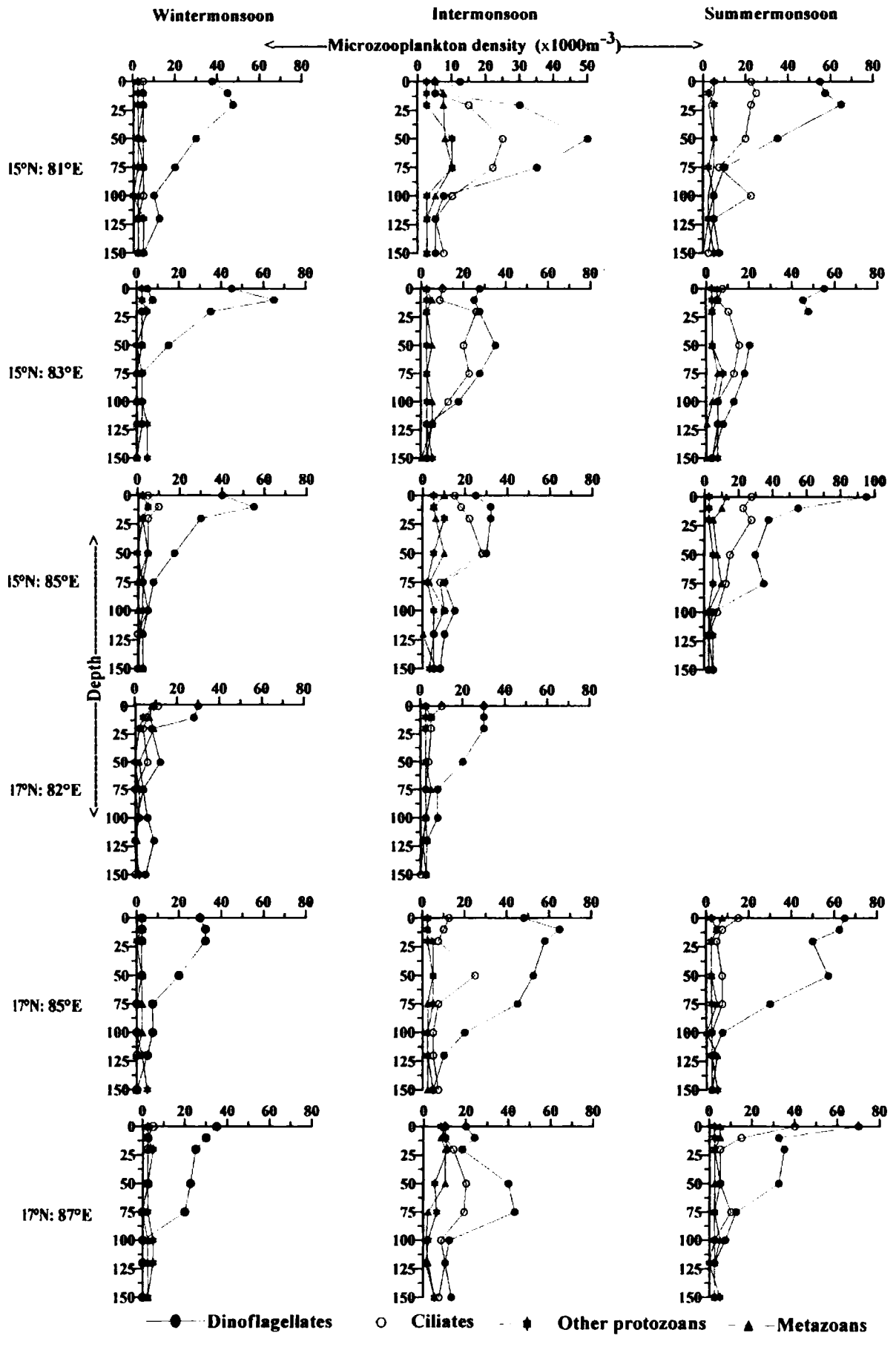


Figure 6.15. Vertical distribution of major microzooplankton groups at different stations along 15 and 17°N during diferent seasons

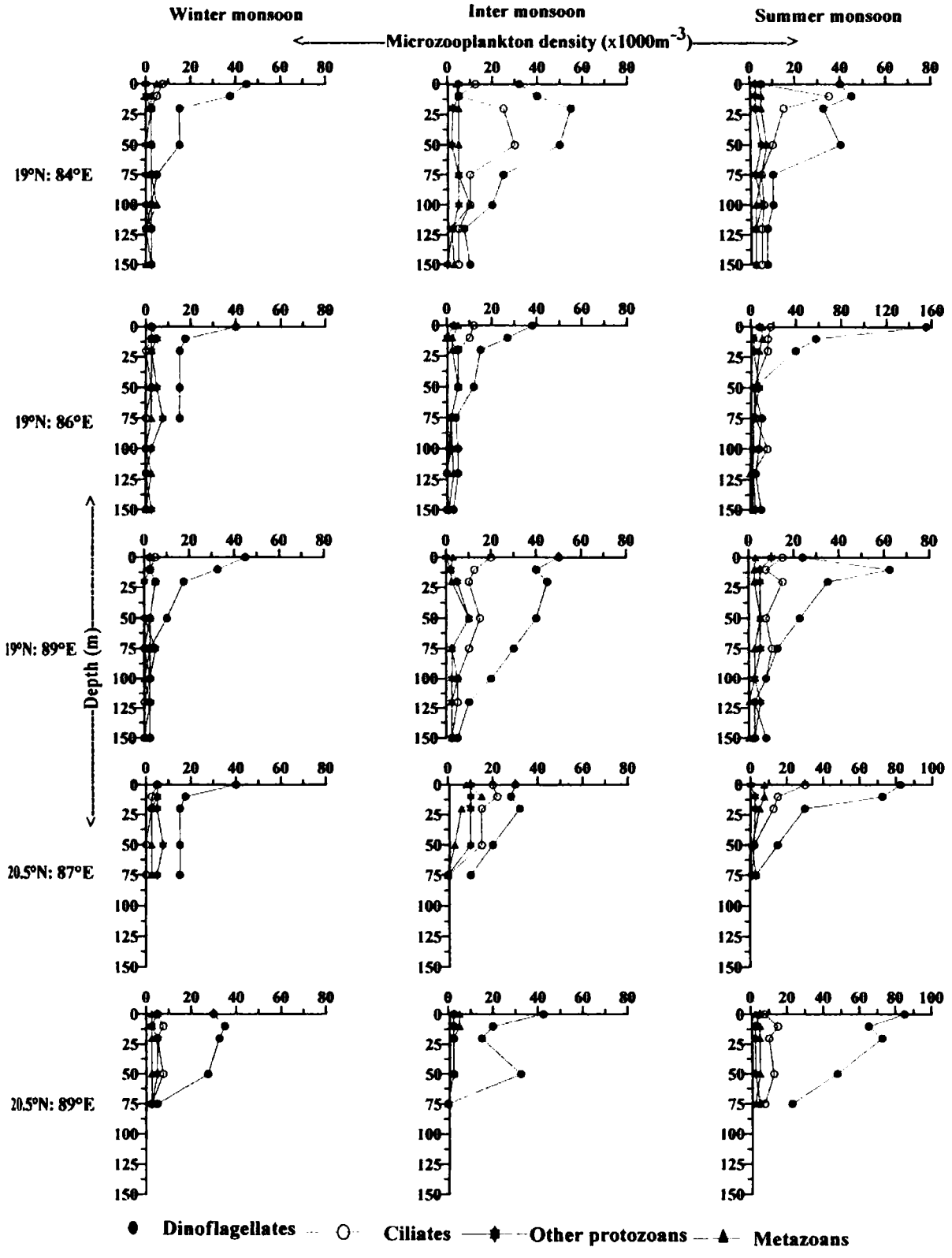


Figure 6.16. Vertical distribution of major microzooplankton groups at different stations along 19 and 20.5°N during diferent seasons

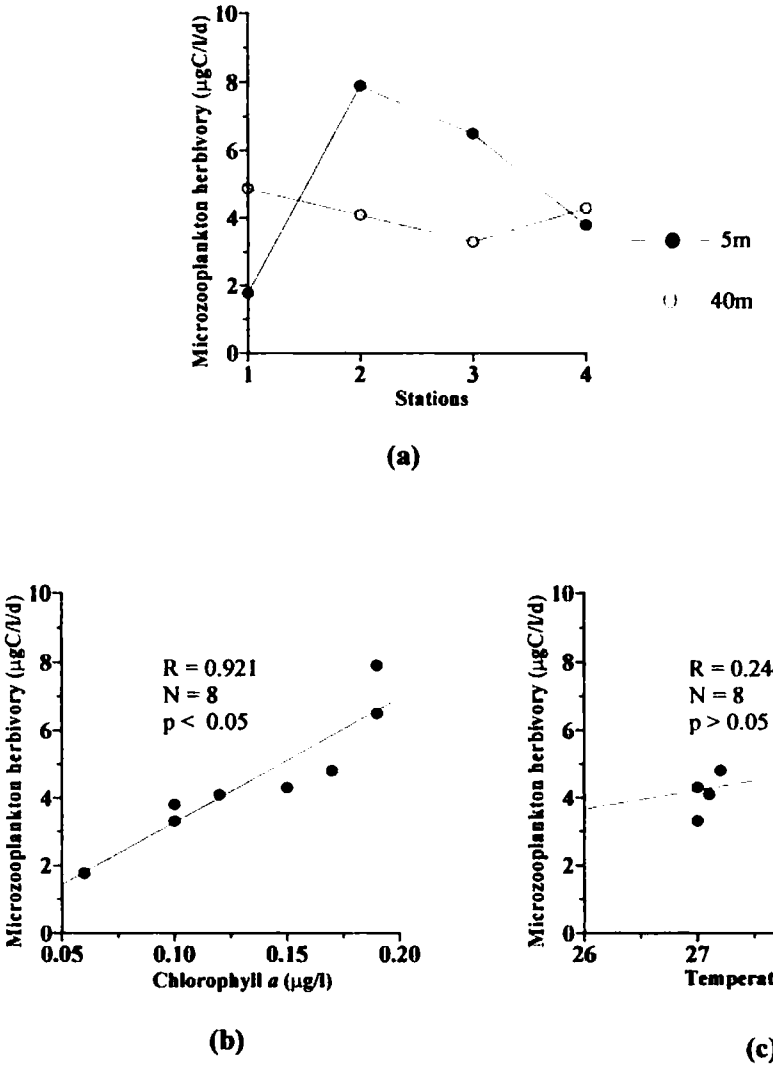


Figure 6.17. (a) shows the magnitude of microzooplankton herbivory at different stations (1, 2,3 and 4 represent stations at 11°N;80°E, 11°N;84°E, 15°N;80°E and 15°N;84°E respectively), (b) and (c) show the relationship between microzooplankton grazing with chlorophyll *a* and temperature

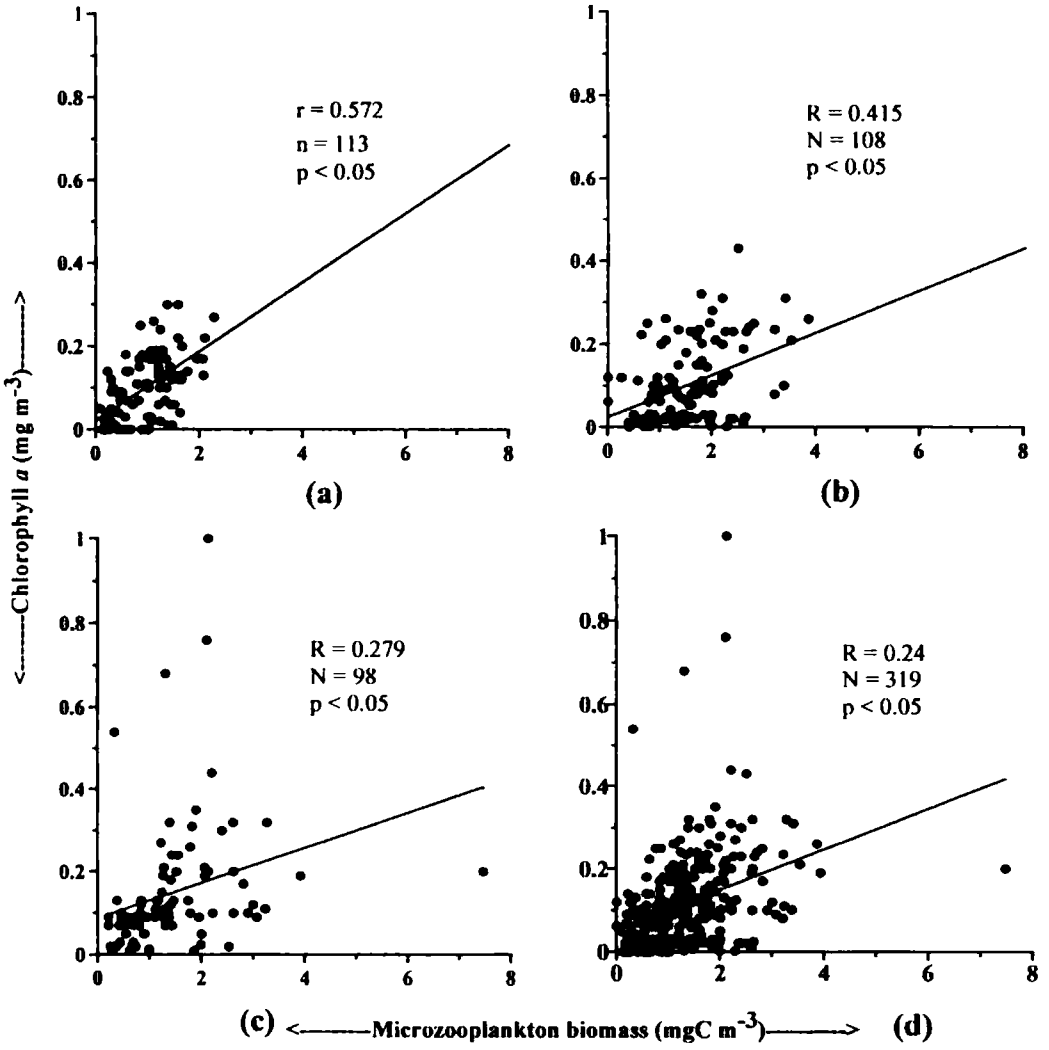


Figure 6.18. Relationship between microzooplankton biomass and chlorophyll *a* during (a) winter monsoon (b) spring intermonsoon (c) summer monsoon and (d) all the seasons combined

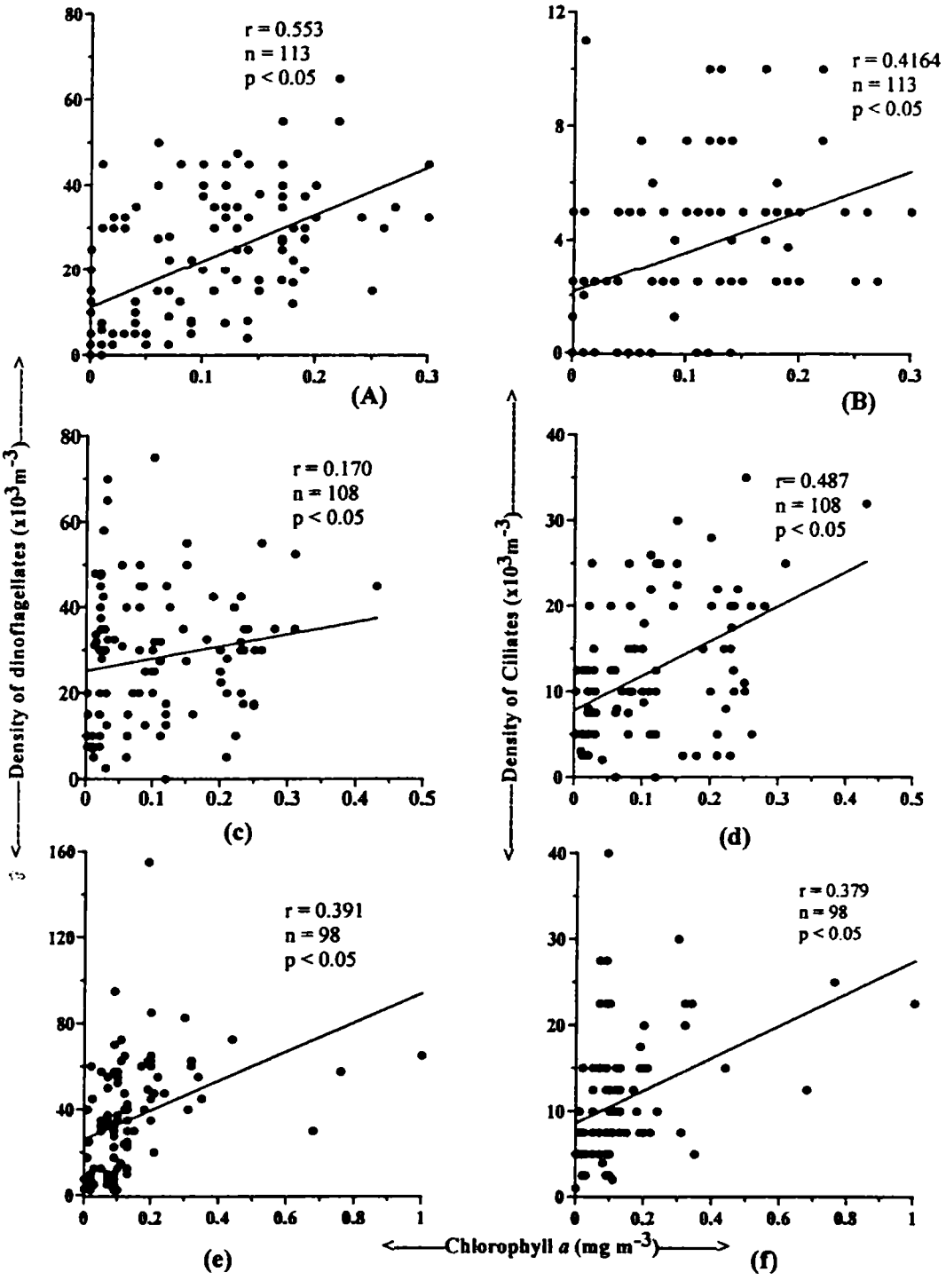


Figure 6.19. Relationship between chlorophyll *a*, density of dinoflagellates and ciliates during (a & b) winter monsoon (c & d) inter monsoon and (e & f) summer monsoon

SN.	Species name	Winter monsoon	Inter monsoon	Summer monsoon
1	*Dinophysis acuta*	+	+	+
2	*D. apicata*	+	+	+
3	*D. hastate*	+	+	+
4	*Diplopsalis lenticula*	+	+	+
5	*Gymnodinium abbreviatum*	+	+	+
6	*Gyrodinium sp.*	+	+	+
7	*Heterodinium blackmanii*	+	+	+
8	*Histioneis hyalina*	+	+	+
9	*H. striata*	+	+	+
10	*Noctiluca scintillans*	+	+	+
11	*Ornithocercus heteroporus*	+	+	-
12	*O. magnificus*	+	+	+
13	*O. quadratus*	+	+	+
14	*O. skogsbergii*	-	-	+
15	*O.steinii*	+	+	+
16	*O. thumii*	+	+	+
17	*Parahistioneis para*	+	+	-
18	*Phalacroma doryphorum*	+	+	+
19	*P. purvula*	+	+	+
20	*P. sp.*	-	-	+
21	*P. cuneus*	+	+	-
22	*P. favus*	+	+	+
23	*P. mitra*	-	+	+
24	*P. rapa*	+	+	+
25	*Podolamphus bipes*	+	+	+
26	*P. elegans*	+	+	+
27	*P. palmipes*	-	+	+
28	*P. reticulata*	+	-	+
29	*P. spinifera*	+	+	+
30	*Protoperidinium breve*	+	-	+
31	*P. brevipes*	-	-	+
32	*P. conicum*	+	+	-
33	*P. crassipes*	+	+	+
34	*P. curtips*	+	+	+
35	*P. depressum*	+	-	+
36	*P. divergens*	+	+	+
37	*P. elegans*	+	+	+
38	*P. fatulipes*	+	+	+
39	*P. globulus*	+	+	+
40	*P. grandae*	+	+	-
41	*P. granii*	+	+	-
42	*P. heteracanthum*	+	+	+
43	*P. latistriatum*	+	-	+
44	*P. leonis*	+	+	+

Continued in the next page

45	*P. longicollum*	-	-	+
46	*P. longipes*	+	+	+
47	*P. nipponicum*	-	+	+
48	*P. oblongum*	-	+	-
49	*P. oceanicum*	+	+	+
50	*P. ovatum*	-	-	+
51	*P. ovum*	-	+	+
52	*P. pellucidum*	+	+	+
53	*P.quarnerese*	+	+	+
54	*P. steinii*	+	+	+
55	*P. tuba*	+	+	+
56	*P. pentagonum*	+	+	+
57	*P. claudicans*	-	+	+
Total		46	48	50

+ *indicate presence*

Table **6.1** - Temporal variations of species composition of heterotrophic dinoflagellates

SN.	Species name	Winter monsoon	Inter monsoon	Summer monsoon
1	*Amphorella gracilis*	+	+	+
2	*A. intumescens*	+	+	+
3	*A. pachytoecus*	+	+	+
4	*A. quadrilineata*	+	+	+
5	*A. tetragona*	-	+	+
6	*Amphorellopsis acuta*	-	+	+
7	*Amphorides minor*	-	+	-
8	*Amplectella sp.*	+	+	+
9	*Ascambelliella armila*	-	+	-
10	*A. retrusa*	+	+	+
11	*Brandtiella palliada*	+	+	+
12	*Canthariella pyramidata*	+	+	+
13	*Codonella acera*	+	+	+
14	*C. amphorella*	+	+	+
15	*C. nationalis*	+	+	+
16	*Codonellopsis ecaudata*	+	+	-
17	*C. minor*	+	+	-
18	*C. morchella*	-	+	+
19	*C. nipponica*	-	+	+
20	*C. orthoceras*	-	+	+
21	*C. ostenfeldi*	+	+	-
22	*C. tessellata*	-	+	+
23	*Cyttarocylis acutiformes*	-	+	+
24	*Dadayiella ganymedes*	-	+	+
25	*D. pachytoecus*	-	+	-
26	*Dictyocysta duplex*	+	+	+
27	*D. elegans*	+	+	+
28	*D. lepida*	-	+	+
29	*Epiplocycloids reticulata*	-	+	-
30	*Epiplocylis undella*	+	+	+
31	*Eutintinnus elongates*	+	+	+
32	*E. fraknoi*	+	+	+
33	*E. lusus undae*	+	+	+
34	*E.tineus*	+	+	+
35	*Favella brevis*	-	+	-
36	*Halteria chlorelligera*	-	+	-
37	*Helicostomella subulata*	-	+	-
38	*Leprotintinnus nordquisti*	+	+	+
39	*Lohmaniella oviformis*	-	+	+
40	*L. spiralis*	-	+	-
41	*Metacylis jorgenseni*	-	+	-
42	*Parundella caudata*	-	+	-
43	*P. lohmani*	+	+	+
44	*Petalotricha ampulla*	+	+	+

Continued in the next page

45	*P. serrata*	-	+	-
46	*Proplectella claparedi*	+	+	+
47	*Protorhabdonella simplex*	-	+	+
48	*Rhabdonella henseni*	+	+	-
49	*R. spiralis*	+	+	+
50	*R. amor*	+	+	+
51	*R.elegans*	+	+	+
52	*R. longicaulis*	-	+	-
53	*R. poculum*	-	+	-
54	*Salpingacantha ampla*	+	+	+
55	*S.sp.1*	+	+	+
56	*Salpingella acuminata*	+	+	+
57	*Salpingella attenuata*	+	+	+
58	*S. decurtata*	-	+	+
59	*S. gracilis*	-	+	+
60	*S. stenostoma*	-	+	+
61	*Steenstrupiella pozzi*	-	+	+
62	*S. steenstrupii*	-	+	+
63	*Stenosemella ventricosa*	-	+	-
64	*Strombidium bilobum*	+	+	+
65	*S. conicum*	-	+	+
66	*Strobilidium minimum*	+	+	+
67	*Tintinnopsis beroidea*	-	+	+
68	*T. butschli*	-	+	-
69	*T. cylindrica*	+	+	+
70	*T. directa*	+	+	+
71	*T. incertum*	-	+	+
72	*T. mortenseni*	+	+	+
73	*T. radix*	+	+	+
74	*T. tocantinensis*	+	+	+
75	*Undella dialata*	+	+	+
76	*U. globosa*	+	+	+
77	*U. hyalina*	+	+	+
78	*Xystonella treforti*	+	+	+
Total		44	78	59

+ indicate presence

Table 6.2 - Temporal variations of species composition of ciliates

	Station location		Winter monsoon		Inter monsoon		Summer monsoon	
	Lat.(°N)	Lon.(°E)	Density	Biomass	Density	Biomass	Density	Biomass
Southern region	11	80	53	15	42	17	143	44
	11	82	49	14	59	19	163	60
	11	84	46	13	42	12	168	47
	13	80.5	59	16	50	14	153	55
	13	82	46	17	40	10	183	59
	13	84	54	16	49	13	163	47
	15	81.5	53	14	23	10	179	40
	15	84	70	19	42	13	128	33
	15	85.5	63	17	73	19	228	61
Average			***55***	***16***	***47***	***14***	***168***	***50***
Northern region	17	83	46	14	67	19	-	-
	17	85	39	10	72	23	170	37
	17	87	52	14	70	18	173	45
	19	85	42	11	54	13	141	32
	19	87	27	9	50	12	275	59
	19	89	48	8	65	15	130	27
	20.5	87	43	11	41	22	218	46
	20.5	89	46	12	34	12	188	79
Average			***43***	***11***	***57***	***17***	***185***	***46***
Total Average			***49***	***14***	***51***	***15***	***175***	***48***

Table 6.3 - Temporal variation of microzooplankton density (x 10^4 m^{-2}) and biomass (x 103 mgC x 10^3 m^{-2}) in the surface layer (10m – surface)

Area	Lat (°N)	Winter monsoon			Spring intermonsoon			Summer monsoon		
			Oceanic			Oceanic			Oceanic	
		Coastal	Middle	Offshore	Coastal	Middle	Offshore	Coastal	Middle	Offshore
Southern region	11	53 (15)	49 (14)	46 (13)	42 (17)	59 (19)	42 (12)	143 (44)	163 (60)	168 (47)
	13	59 (16)	46 (17)	54 (16)	50 (14)	40 (10)	49 (13)	153 (55)	183 (59)	163 (47)
	15	53 (14)	70 (19)	63 (17)	23 (10)	42 (13)	73 (19)	179 (40)	128 (33)	228 (61)
Average		**55 (15)**	**55 (16)**		**38 (14)**	**51 (14)**		**158 (46)**	**172 (51)**	
Northern region	17	46 (14)	39 (10)	42 (14)	67 (19)	72 (23)	70 (18)	-	170 (67)	173 (45)
	19	42 (11)	27 (9)	48 (8)	54 (13)	50 (12)	65 (15)	141 (32)	275 (59)	130 (27)
	20.5	43 (11)	-	46 (12)	41 (22)	-	34 (12)	218 (79)	-	188 (46)
Average		**44 12**	**40 (11)**		**54 (18)**	**58 (16)**		**179 (56)**	**187 (43)**	
Total average		**49 (14)**	**48 (14)**		**46 (16)**	**54 (15)**		**166 (50)**	**179 (47)**	

Table 6.4. Temporal variation of microzooplankton surface density (x 10^4 m^{-2}) and biomass (mgC x $10^3 m^{-2}$) (latter in brackets) along the coastal and oceanic locations

	Station location		Winter monsoon		Inter monsoon		Summer monsoon	
	Lat.(°N)	Lon.(°E)	Density	Biomass	Density	Biomass	Density	Biomass
Southern region	11	80	506	144	912	424	612	175
	11	82	310	91	728	265	649	210
	11	84	391	113	804	238	588	141
	13	80.5	451	128	702	240	622	150
	13	82	409	116	633	195	641	162
	13	84	457	159	652	201	588	141
	15	81.5	515	142	763	246	704	197
	15	84	306	86	664	207	552	131
	15	85.5	343	95	661	211	710	185
Average			***410***	***119***	***724***	***247***	***630***	***166***
Northern region	17	83	367	111	714	199		
	17	85	287	70	858	339	593	158
	17	87	247	69	872	234	477	113
	19	85	316	86	837	195	569	154
	19	87	316	88	797	223	528	122
	19	89	235	122	753	215	493	86
	20.5	87	205	56	367	139	323	112
	20.5	89	294	82	211	110	552	187
Average			***283***	***86***	***676***	***207***	***505***	***133***
Total average			***350***	***103***	***701***	***228***	***575***	***152***

Table 6.5 - Temporal variation of microzooplankton density (x 10^4 m^{-2}) and biomass (x10^3 mgC m^{-2}) in the water column (150m – surface)

Area	Lat (°N)	Winter monsoon			Spring intermonsoon			Summer monsoon		
			Oceanic			Oceanic			Oceanic	
		Coastal	Middle	Offshore	Coastal	Middle	Offshore	Coastal	Middle	Offshore
Southern region	11	506 (144)	310 (91)	391 (113)	912 (424)	728 (265)	804 (238)	612 (175)	649 (210)	588 (141)
	13	451 (128)	409 (116)	457 (159)	702 (240)	633 (195)	652 (201)	622 (150)	641 (162)	588 (141)
	15	515 (142)	306 (86)	343 (95)	763 (246)	664 (207)	661 (211)	704 (197)	552 (131)	710 (185)
Average		**490 (138)**	**369 (110)**		**792 (303)**	**690 (220)**		**646 (174)**	**621 (162)**	
Northern region	17	367 (111)	287 (70)	247 (69)	714 (199)	858 (339)	872 (234)	-	593 (158)	477 (113)
	19	316 (86)	316 (88)	235 (122)	837 (195)	797 (223)	753 (215)	569 (154)	528 (122)	493 (86)
	20.5	205 (56)	-	294 (82)	367 (139)	-	211 (110)	323 (112)	-	552 (187)
Average		**296 84**	**276 (86)**		**639 (177)**	**698 (224)**		**446 (132)**	**529 (133)**	
Total average		**393 (125)**	**327 (99)**		**716 (241)**	**693 (222)**		**566 (158)**	**579 (149)**	

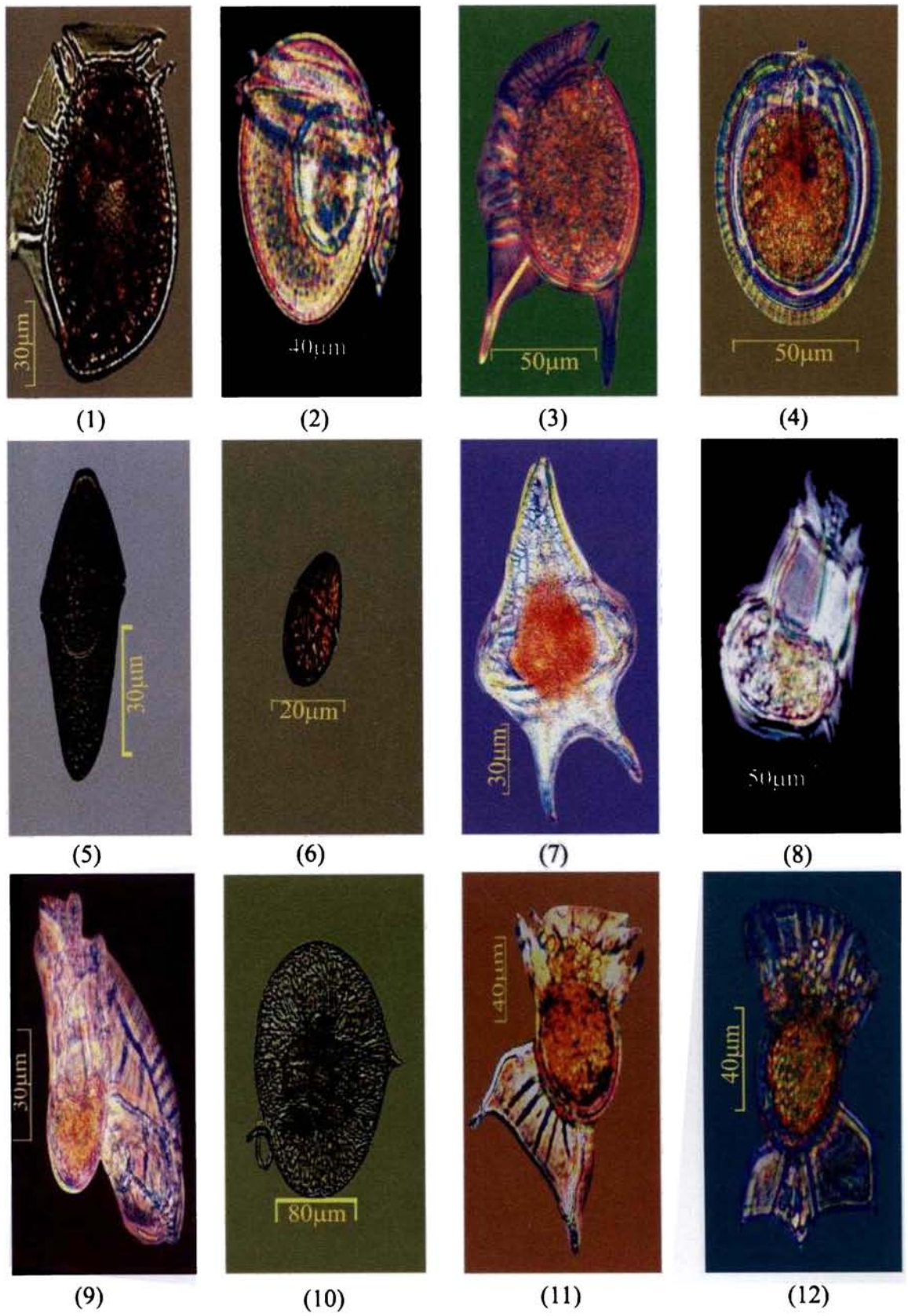
Table 6.6. Temporal variation of microzooplankton column density (x 10^4 m^{-2}) and biomass (mgC x $10^3 m^{-2}$) (latter in brackets) along the coastal and oceanic locations

Station location		Microzooplankton herbivory ($\mu gC\ l^{-1}\ d^{-1}$)	
Lat (°N)	Lon (°E)	5m	40m
11	80	1.77 (59)	4.8 (57)
11	84	7.9 (83)	4.1 (69)
15	80	6.5 (68)	3.3 (67)
15	84	3.8 (76)	4.3 (58)

Table 6.7- Magnitude of microzooplankton herbivory and grazing of phytoplankton standing stock (%) at different locations

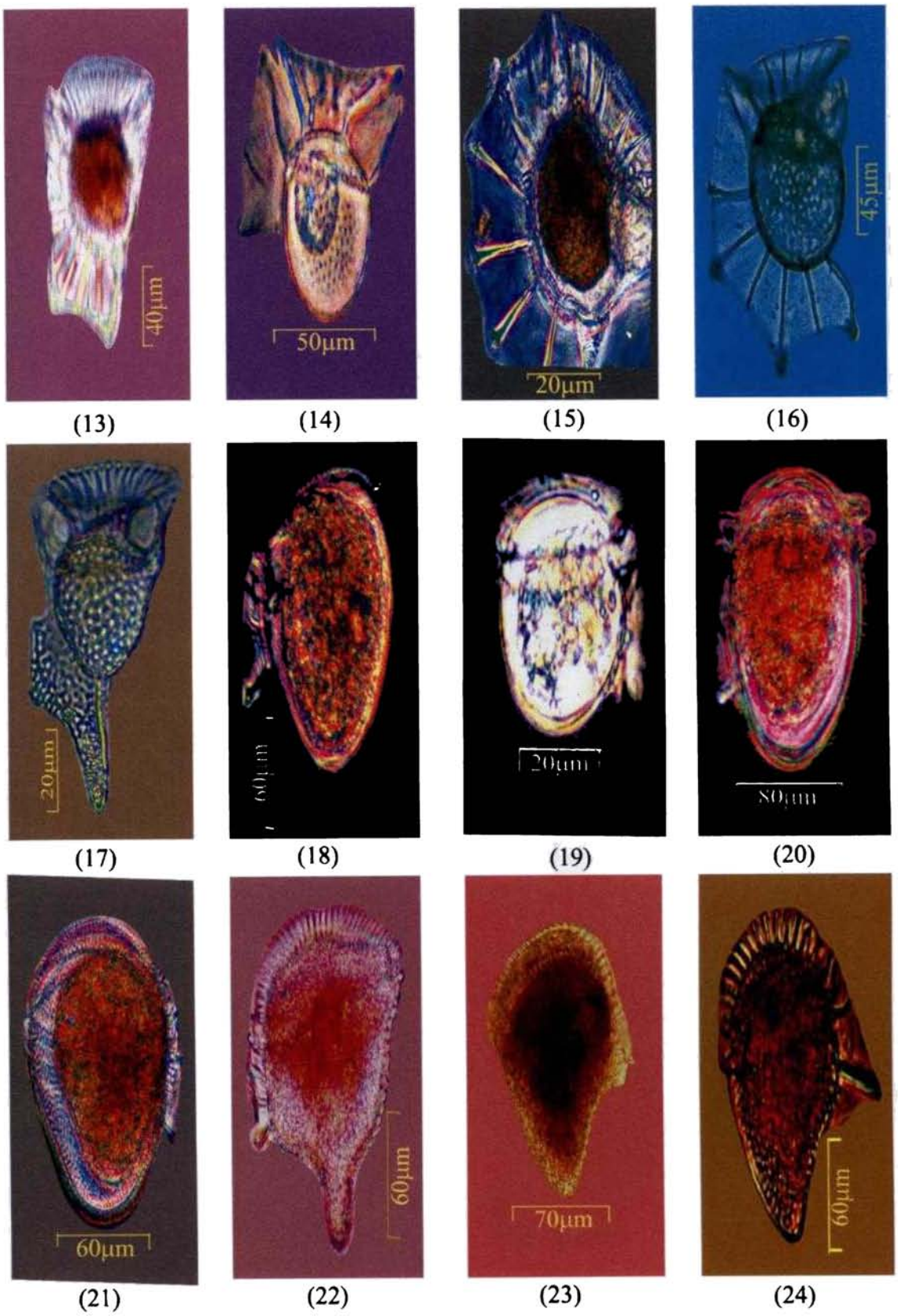
Season	Occurrence of symbiotic dinoflagellates
Winter monsoon	1230 (156)
Spring intermonsoon	2856 (2772)
Summer monsoon	1860 (210)

Table 6.8 – Temporal variation of the occurrence of symbiotic species number of dinoflagellates which showed symbiotic association are given in brackets



(1) *Dinophysis acuta* (2) *D. apicata* (3) *D. hastata* (4) *Diplopsalis lenticula* (5) *Gymnodinium abbreviatum* (6) *Gyrodinium sp.* (7) *Heterodinium blackmanii* (8) *Histioneis hyalina* (9) *H. striata* (10) *Noctiluca scintillans* (11) *Ornithocercus heteroporus* (12) *O. magnificus*

Plate 6.1. Species composition of heterotrophic dinoflagellates

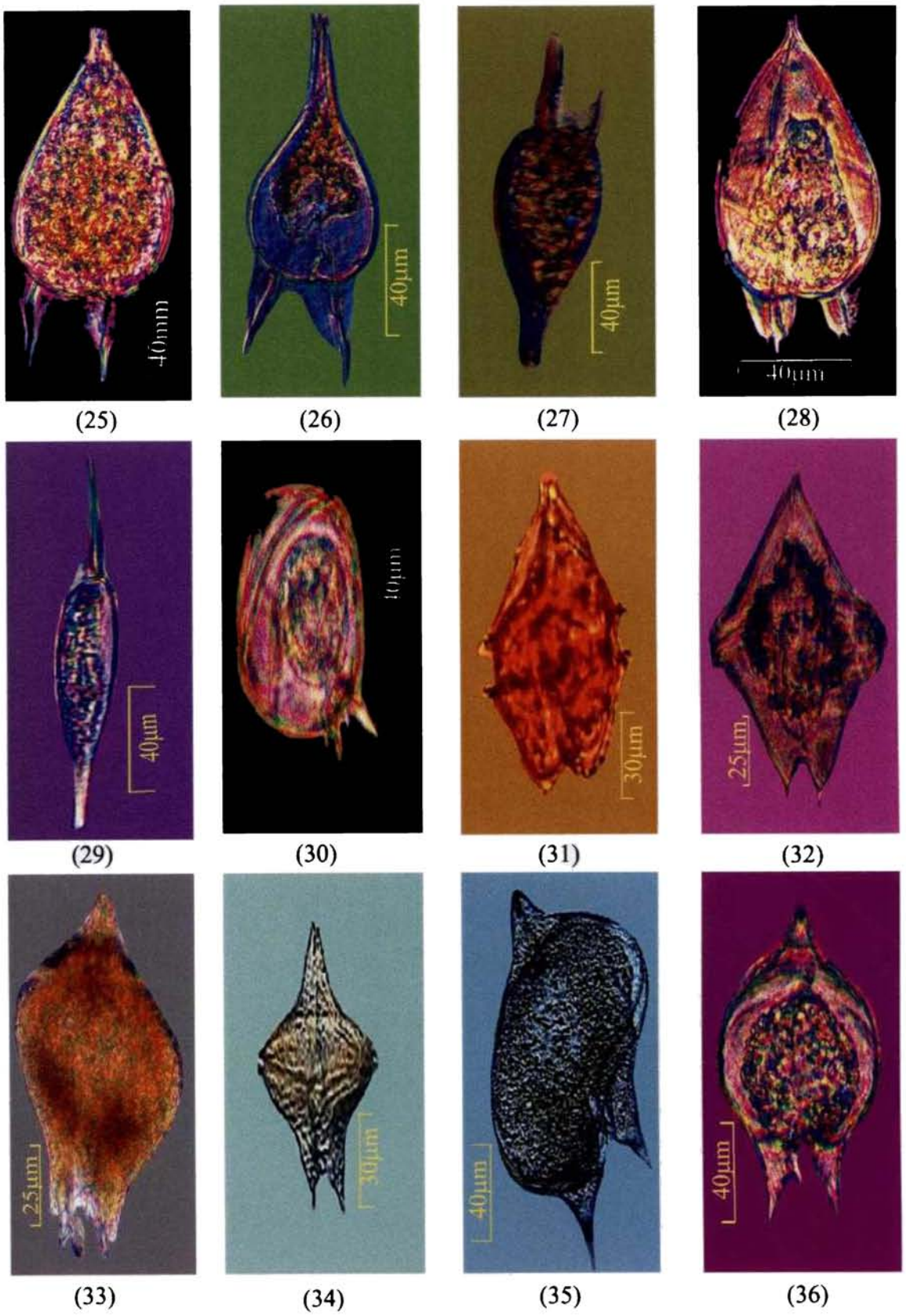


(13) *Ornithocercus quadratus* (14) *O. skogsbergii* (15) *O. steinii* (16) *O. thumii*

(17) *Parahistioneis para* (18) *Phalacroma doryphorum* (19) *P. purvula* (20) *P. sp.*

(21) *P. cuneus* (22) *P. favus* (23) *P. mitra* (24) *P. rapa*

Plate 6.2. Species composition of heterotrophic dinoflagellates (continued)



(25) (26) (27) (28)

(29) (30) (31) (32)

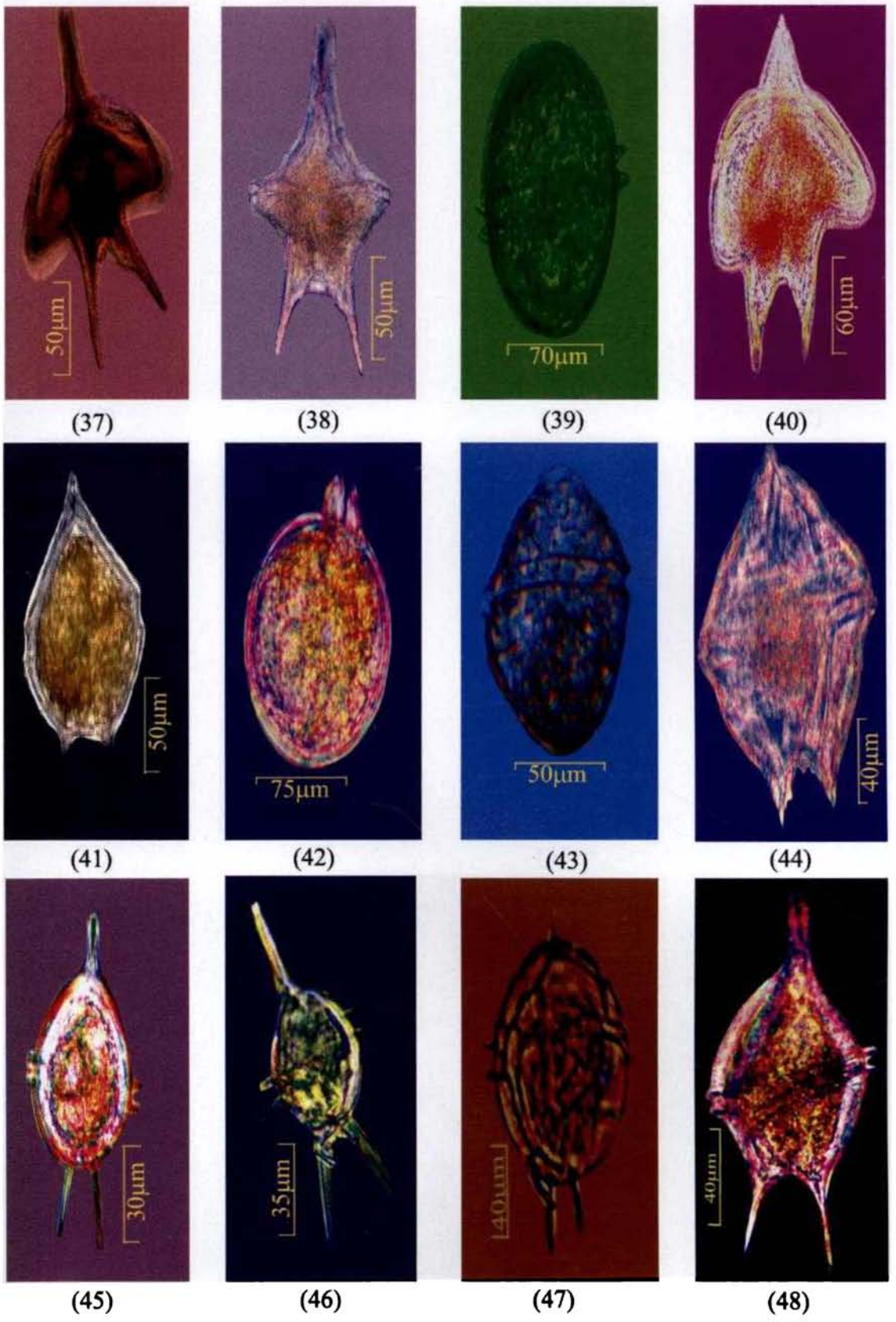
(33) (34) (35) (36)

(25) *Podolamphus bipes* (26) *P. elegans* (27) *P. palmipes* (28) *P. reticulata*

(29) *P. spinifera* (30) *Protoperidinium breve* (31) *P. brevipes* (32) *P. conicum*

(33) *P. crassipes* (34) *P. curtips* (35) *P. depressum* (36) *P. divergens*

Plate 6.3. Species composition of heterotrophic dinoflagellates (continued)

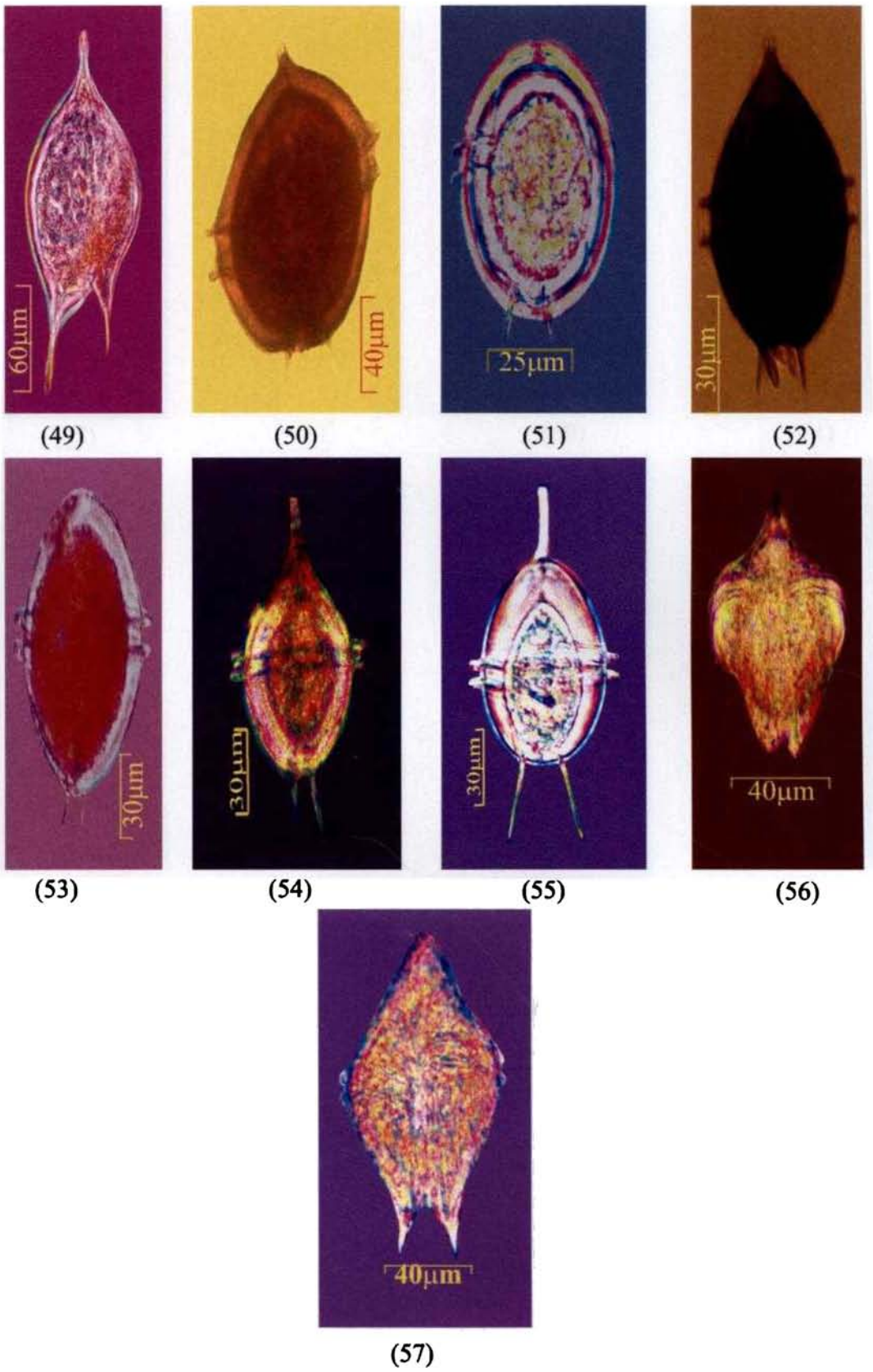


(37) *Protoperidinium elegans* (38) *P. fatulips* (39) *P. globulus* (40) *P. grandae*

(41) *P. granii* (42) *P. heteracanthum* (43) *P. latistriatum* (44) *P. leonis*

(45) *P. longicollum* (46) *P. longipes* (47) *P. nipponicum* (48) *P. oblongum*

Plate 6.4. Species composition of heterotrophic dinoflagellates (continued)



(49) (50) (51) (52)

(53) (54) (55) (56)

(57)

(49) *Protoperidinium oceanicum* (50) *P. ovatum* (51) *P. ovum*

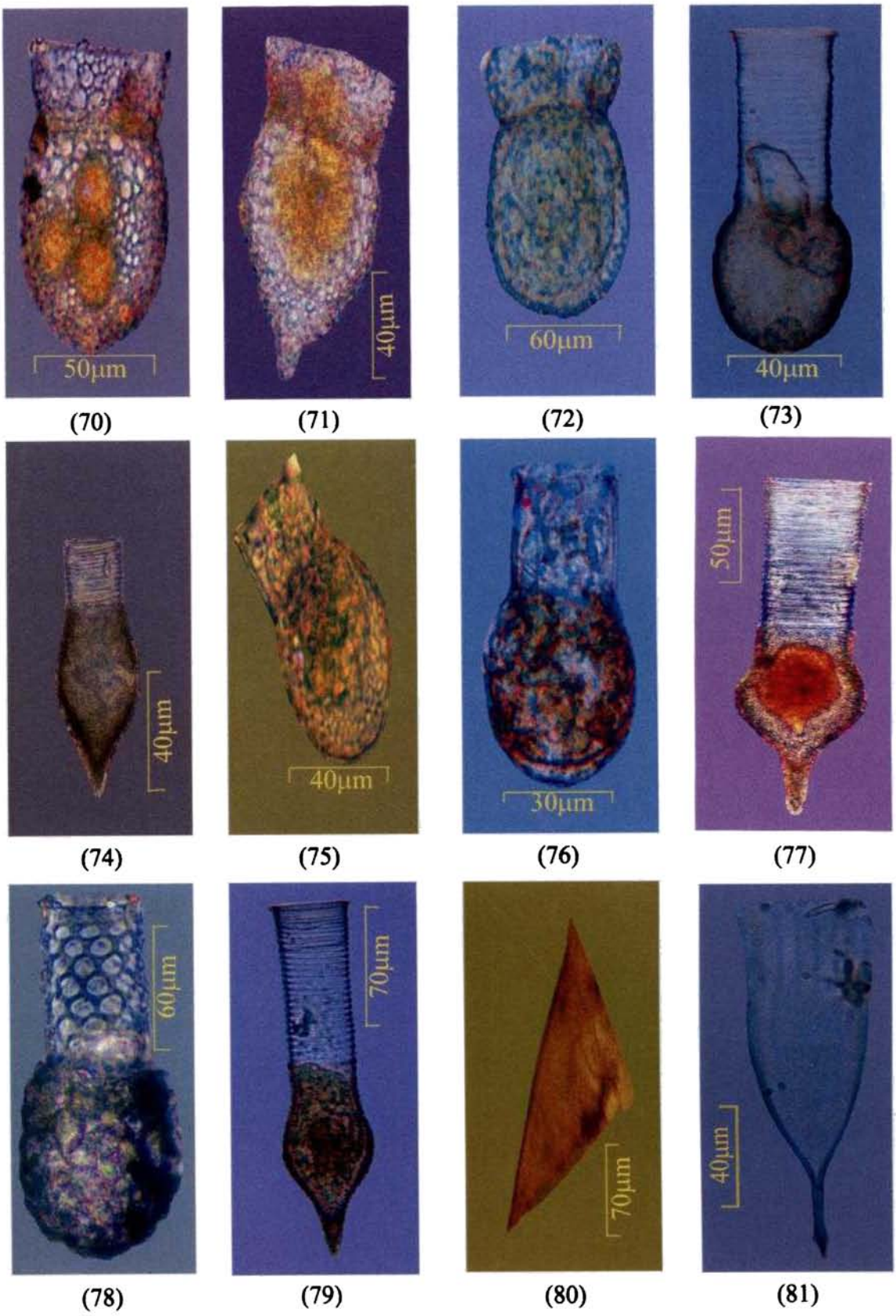
(52) *P. pellucidum* (53) *P. quarnerese* (54) *P. stenii* (55) *P. tuba*

(56) *P. pentagonum* (57) *P. claudicans*

Plate 6.5. Species composition of heterotrophic dinoflagellates (continued)

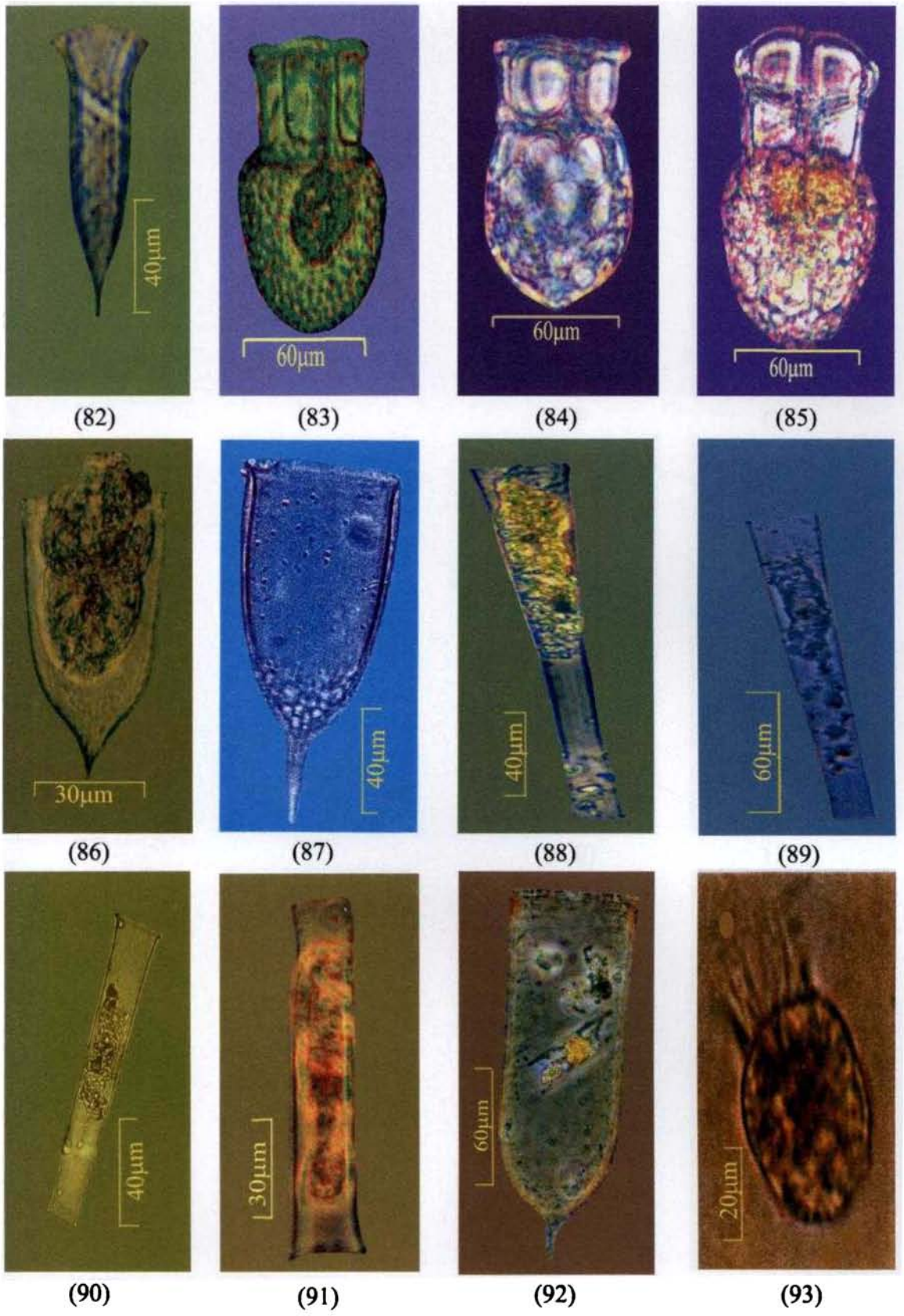
(58) *Amphorella gracilis* (59) *A. intumescens* (60) *A. pachytoecus* (61) *A. quadrilineata* (62) *A. tetragona* (63) *Amphorellopsis acuta* (64) *Amphorides minor* (65) *Amplectella sp.* (66) *Ascambelliella armila* (67) *A. retrusa* (68) *Brandtiella pallida* (69) *Canthariella piramidata*

Plate 6.6. Species composition of ciliates



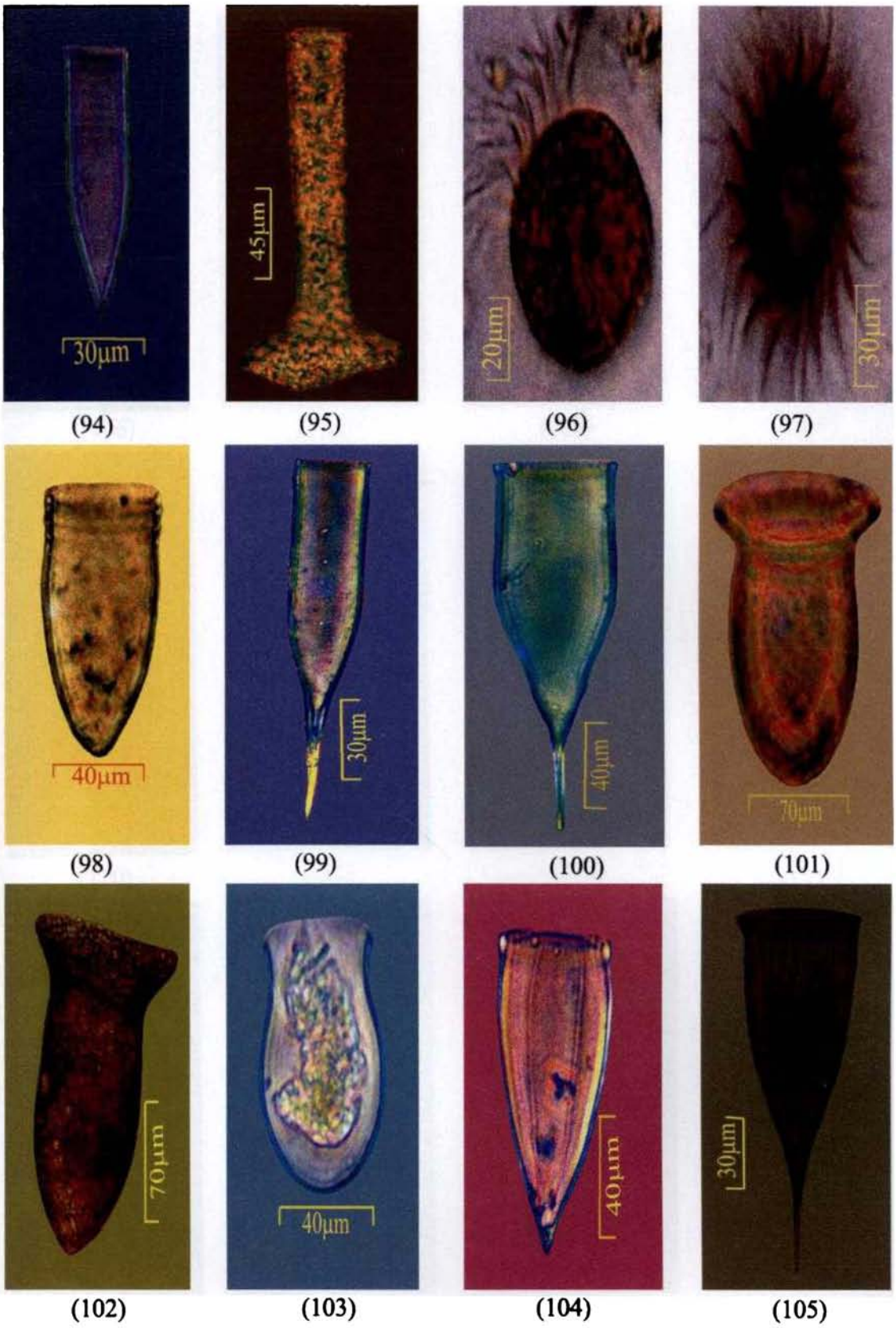
(70) *Codonella acera* (71) *C. amphorella* (72) *C. nationalis* (73) *Codonellopsis ecaudata* (74) *C. minor* (75) *C. morchella* (76) *C. nipponica* (77) *C. orthoceras* (78) *C. ostenfeldi* (79) *C. tesselata* (80) *Cyttarocylis acutiformes* (81) *Dadiella ganymedes*

Plate 6.7. Species composition of ciliates (continued)



(82) *Dadayiella ganymedes* (83) *Dictyocysta duplex* (84) *D. elegans* (85) *D. lepida* (86) *Epiplocycloides reticulata* (87) *Epiplocylis undella* (88) *Eutintinnus elongatus* (89) *E. fraknoi* (90) *E. lusus undae* (91) *E. tineus* (92) *Favella brevis* (93) *Halteria chorelligera*

Plate 6.8. Species composition of ciliates (continued)



(94) (95) (96) (97)

(98) (99) (100) (101)

(102) (103) (104) (105)

(94) *Helicostomella subulata* (95) *Leprotintinnus nordquisti* (96) *Lohmaniella oviformes* (97) *L. spiralis* (98) *Metacylis jorgenseni* (99) *Parundella caudata* (100) *P. lohmanii* (101) *Petalotricha ampulla* (102) *P. serrata* (103) *Proplectella claparedi* (104) *Protorhabdonella simplex* (105) *Rhabdonella henseni*

Plate 6.9. Species composition of ciliates (continued)

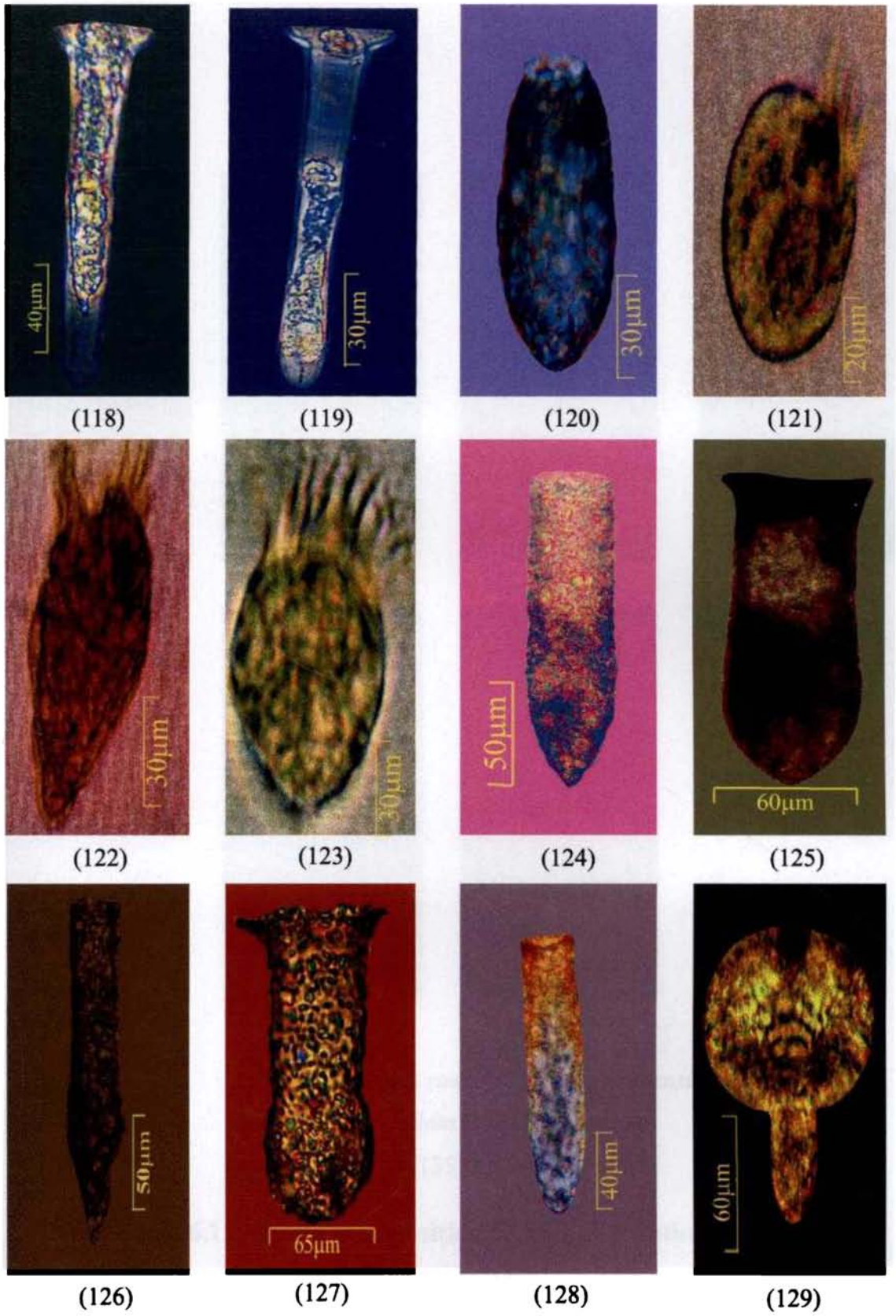
(106) (107) (108) (109)

(110) (111) (112) (113)

(114) (115) (116) (117)

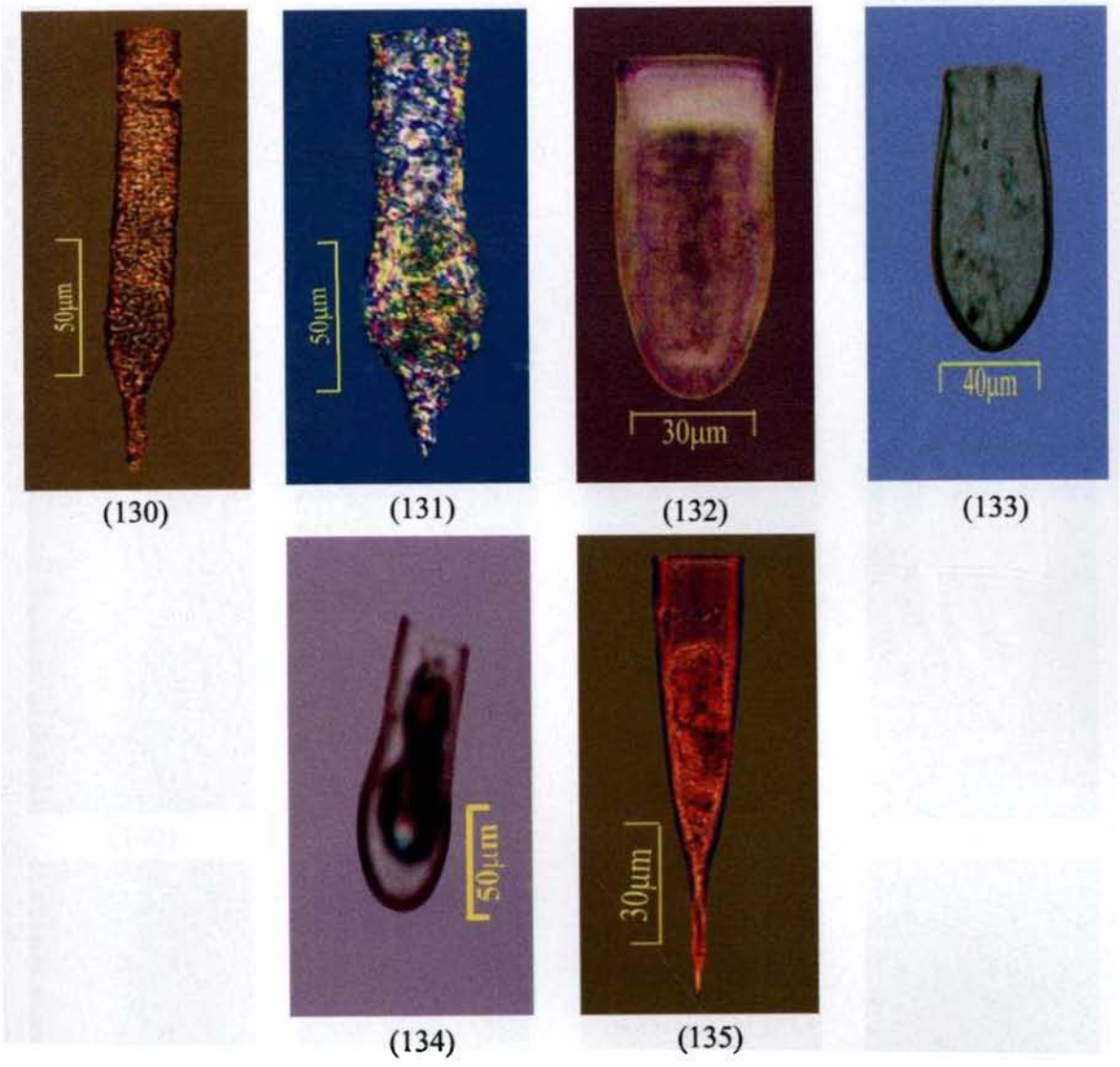
(106) *Rhabdonella spiralis* (107) *R. amor* (108) *R. elegans* (109) *R. longicaulis* (110) *R. poculum* (111) *Salpingacantha ampla* (112) *S. sp. 1* (113) *Salpingella acuminata* (114) *S. attenuata* (115) *S. decurtata* (116) *S. gracilis* (117) *S. stenostoma*

Plate 6.10. Species composition of ciliates (continued)



(118) *Steenstrupiella pozzi* (119) *S. steenstrupii* (120) *Steenosemella ventricosa* (121) *Strombidium bilobum* (122) *S. conicum* (123) *Strobilidium minimum* (124) *Tintinnopsis beroidea* (125) *T. butschli* (126) *T. cylindrica* (127) *T. directa* (128) *T. incertum* (129) *T. mortenseni*

Plate 6.11. Species composition of ciliates (continued)

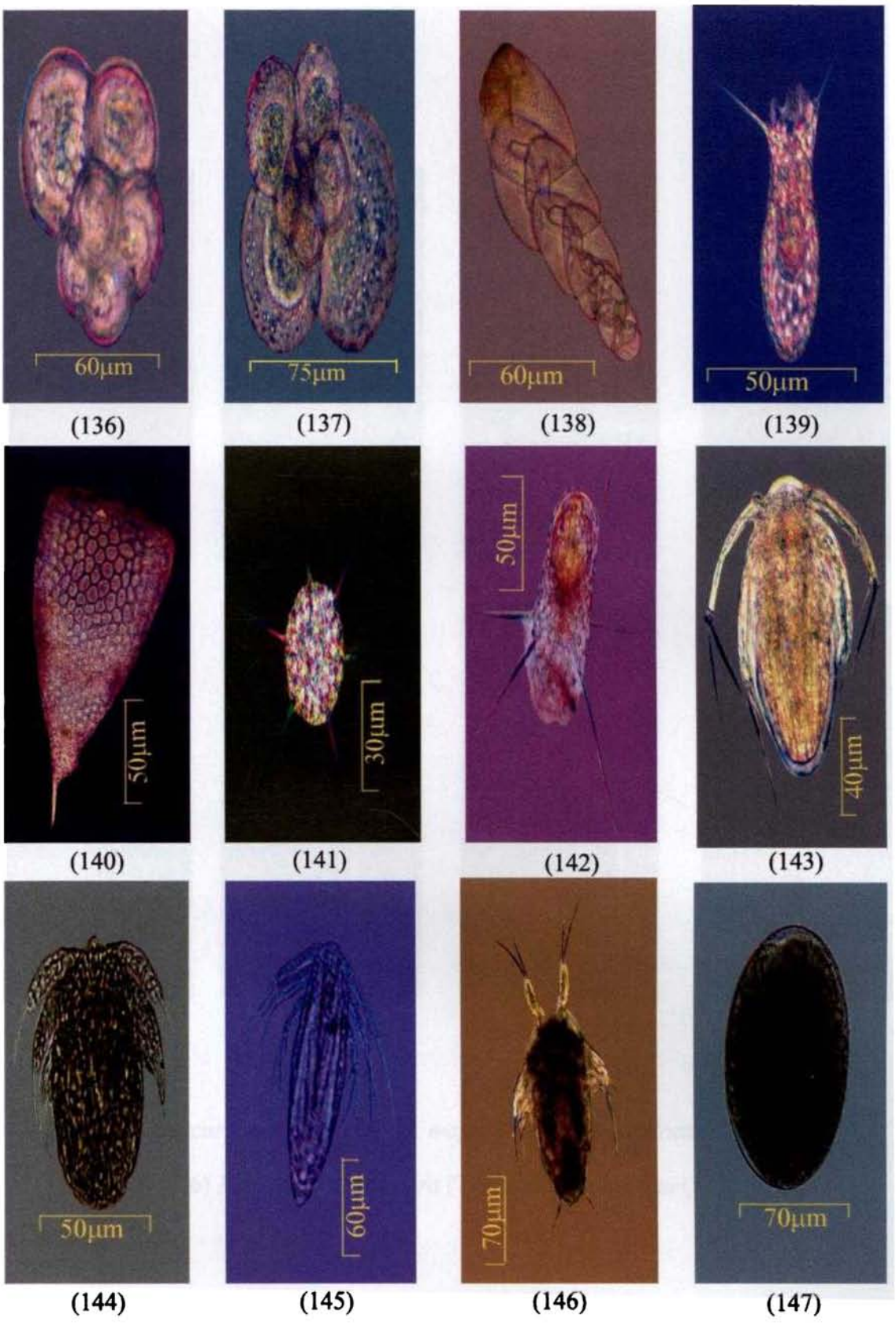


(130) *Tintinnopsis radix* (131) *T. tocantinensis*

(132) *Undella dialata* (133) *U. globosa*

(134) *U. hyalina* (135) *Xystonella trefortii*

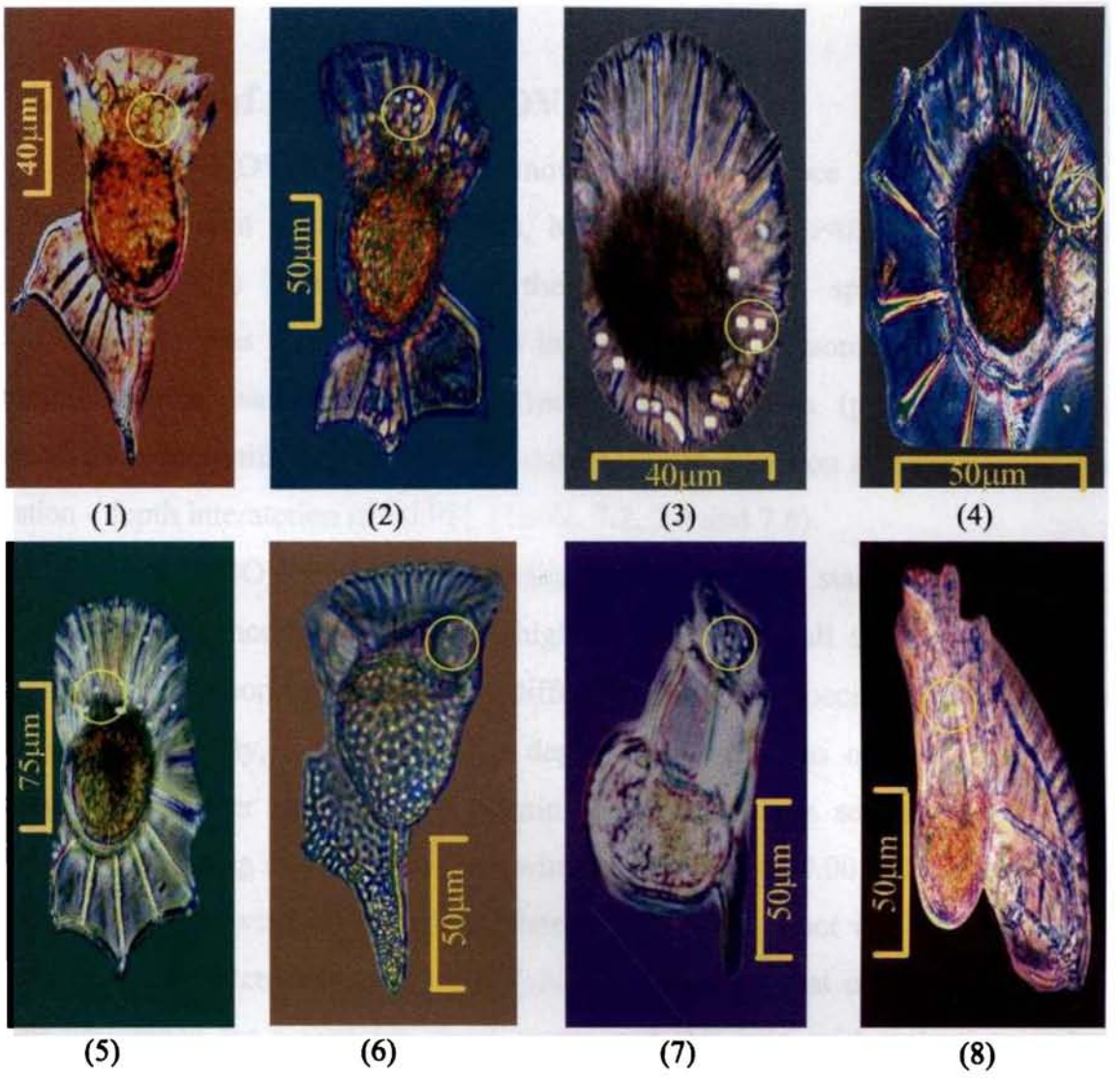
Plate 6.12. Species composition of ciliates (continued)



(136 - 138) *Foraminifers* (139 - 142) *Radiolarians* (143 - 146) *Crustacean(Metazoa) larv*

(147) *Crustacean(Metazoa) egg*

Plate 6.13. 'Others' and metazoans of the microzooplankton community



(1) *Ornithocercus heteroporus* (2) *O. magnificus* (3) *O. quadratus* (4) *O. stenii*

(5) *O. thumii* (6) *Parhaheistioneis para* (7) *Heistioneis hyalina* (8) *H. striata*

Plate 6.14. Species of dinoflagellates of symbiotic association with cyanobacteria

Chapter 7

Statistical analysis

7.1. Analysis of variance (ANOVA)

3 way ANOVA applied for dinoflagalltes abundance showed significant difference between stations ($p<0.005$), between species ($p<0.005$) and between depths ($p<0.005$) irrespective of the seasons. High spatial specificityof dinoflagellates was observed ($p<0.05$) in all the three seasons. Association with specific depths was higher during spring intermonsoon ($p<0.005$) and this specificity were uniform in all stations during winter monsoon as indicated by low station - depth interatction ($p> 0.05$). (Table. 7.2, 7.4 and 7.6).

3 way ANOVA applied for ciliates showed that stations, species and depthwise difference were generally high ($p<0.005$) in all the seasons except during summer monsoon where the difference between species were minimum ($p>0.05$). Generally, higher species - depth interaction was observed in all the seasons and higher specificity of certain species for some selected depth were found during spring intermonsoon and winter monsoon ($p< 0.005$). During summer monsoon, species wise difference of ciliate community was not very prominent, but species - depth interaction was very high. This indicates that most of the species have preference for a common depth zones and this was evident in the vertical distrution of ciliates where higher abundabce was at the surface layers. (Table. 7.1, 7.3 and 7.5).

During spring inter monsoon and winter monsoon, interaction between station and species was small and may be due to the sampling fluctuation ($p>0.05$) while during summer monsoon, certain locations were preferred by the ciliates irrespective of the difference species because, between species, the difference was not high compared to station - species interaction ($p<0.05$). However station depth interaction was noticeble during spring intermonsoon ($p<0.005$).

7.2. Community indices

7.2.1. Ciliates - Spring inter monsoon

Species richness increases from the transect T1 to T6 with minimum richness at T2. Species concentration also follows the same trend as richness factor. A well defined south north gradient was observed for diversity also. The distribution was even at T6 at T4 and non-uniformity or dominance was increasing towards south. Number of species was nearly 3 times at T6, compared to T2, thus showing a direct positive linear relation between the indices (Table 7.7& 7.13).

7.2.2. Dinoflagellates - Spring intermonsoon

Number of species of dinoflagellates during this season was less than 50% of that of ciliates. Species richness showed an increasing trend towards northern latitudes similar to that of ciliates, but with less intensity. Species concentration was higher than that of ciliates at almost all the transects. Species diversity was more uniform among the transects showing a south north increasing gradients with least diversity at T3 while it was high at T2. Species equitability in the distribution of total abundance was more in the case of ciliates than dinoflagellates (Table 7.8 & 7.14).

7.2.3. Ciliates - Summer monsoon

The transects T1 to T6 show an environmental condition, which was uniformly favourable as indicated by the least variation in the number of species even though a small increasing gradients towards north was observed. All the transects presented almost similar richness with least richness at T4 and maximum at T5. T4 to T6 showed less richness compared to spring while in T1 to T3 not much difference could be observed in richness in summer compared to spring. Species concentration for ciliates was more regular in T1 to T4 during summer compared to spring while, T5 to T6 did not show much differences between summer and spring with respect to concentration factor. Species diversity during the period was lower than that of spring at all transects except at T2 where higher

diversity could be observed during summer season. Higher uniformity could be observed at all transects during spring compared to summer (Table 7.9 & 7.15).

7.2.4. Dinoflagellates - Summer monsoon

In this case comparatively less number of species could be obtained at all the transects compared to ciliates during the same season, but seasonal difference was not reflected in the number of species between spring and summer. However reversal could be observed in the species richness during the period compared to spring intermonsoon where increasing gradient towards north was observed. Species concentration, diversity and evenness during summer monsoon showed a marginal reversal trend of that of spring intermonsoon with a decreasing gradient towards north. (Table 7.10 & 7.16).

7.2.5. Ciliate - Winter monsoon -

Number of species observed during this season was less than 50 % of that during spring intermonsoon at T1, T4, T5 and T6 while it was only 68% at T2 and T3. Number of species was between 40% to 80% of that observed during summer, the least being at T5 and highest at T1 and T6. Species richness was less than that observed during spring at all transects while only at T2, T3, T5 and T6 during summer. Species concentration was consistently high at all transects during winter compared to spring and summer. A similar trend in the seasonal variation could be observed with respect to species diversity and uniformity in the distribution of total abundance among the ciliates species (Table 7.11 & 7.17).

7.2.6. Dinoflagellates - Winter monsoon

A steady decrease in the no of species as well as in other indices could be observed during this season. Compared to the other two seasons with a north south decreasing gradient which was just reverse of that observed during summer and spring (Table 7.12 & 7.18).

On comparing between the three seasons, it could be observe that number of species of ciliates decreases steadily from spring intermonsoon to winter through summer reducing to nearly 50 % of the species, with 62 % richness, 67 %

concentration, and species diversity and 78% uniformity during winter compared to spring.

In contrast a homogenised decrease could be observed in the number of species of dinoflagellates during winter (84%), richness being marginally higher (102.5%), concentration being 89%, diversity 95% and uniformity being almost same during winter, compared to spring (Table 7.19 & 7.20).

3 way ANOVA has depicted significant difference between stations and between depth during all the three stations for both ciliates and dinoflagellates the difference between depths was clearly observed in line MDS analysis carried out.

7.3. Cluster analysis

During spring intermonsoon, at station B1 the highly different depth zones were surface (0) and 20 m, while 50 to 150m depths form a good cluster in the case of ciliates. 10, 20 and 50m depth zones present highly similar clusters in the case of dinoflagellates. (Figure 7.1).

At B17, in the case of ciliates, surface and 150m are highly different where as depth zones (10-100 m) form a good cluster, which indicates that, these depths were occupied by similar species. In the case of dinoflagellates the depth zones 0 to 75m represent widely different types of species. 20 and 50 m are more closely associated compared to other depths (Figure 7.1).

During summer monsoon B1 and B17 showed marked variations in ciliates between depths with maximum dissimilarity between 50 and 150 m in the former and between 0 and 150 m in the latter. In contrast to this, well-defined cluster of depths was obtained for dinoflagellates between 0,10,20, and 50 at B1 and 10, 20, 50, 75, 100 and 120 and B17. Dinoflagellates distribution at 10m and 100m depths were widely dissimilar at B1 whereas distribution at 150 m was widely different from the major cluster obtained at B17 (Figure 7.2).

During winter monsoon, for both groups length dispersion was observed with less similarity between depths. In the case of ciliates 120 and 150 m were highly different depth zones while 0, 20, 50 m were similar with 75 m and 100m depicting some pattern of ciliates community structures at B1. In case of

dinoflagellates 0 and 50 m show similarity whereas 50m and 100m depth zones showed widely different relation at B1. At station B17, Surface and 10m depth did not have any abundance of ciliates and the depth zones 20m - 120m was were not much closer. Dinoflagellates species occurring at 10m and 20m are more similar than that occupying the surface of the water column (Figure 7.3).

During spring intermonsoon, dendrogram drawn for grouping of ciliates species delineated 8 different clusters with respective numbers of species as 6, 5, 6, 6, 2, 6, 3 and 12 in the clusters 1 to 8 with more than 60% similarity in the distribution of the species. Highly similar ciliate species were occupied 1- 4, and 7-8 at station B1 (Figure 7.4).

During spring intermonsoon, at station B1, dendrogram grouped 18 dinoflagellates species in to 7 clusters containing two species each in clusters 1 to 6 and 3 species in cluster 7, with more 75% similarity between species (Figure 7.5).

During spring intermonsoon, 66 ciliate species of station B17 were grouped in to 9 distinct clusters containing 4, 11, 2, 6, 2,7, 11, 7 and 4 species respectively. About 14% of the ciliate species in this season were not grouped in any of these clusters. These 9 species which were not present in the grouping requres a condition which was different from the species of the 9 clusters (Figure 7.6).

During spring intermonsoon 20 dinoflagellates species obtained at station B17 were classified in to 5 distinct clusters by Bray curtis similarity analysis. These 5 clusters contain 4, 3, 3, 4, and 6 species respectively, in which the species of the same cluster were linked by group averaging method at more than 60% similarity level (Figure 7.7).

During summer monsoon at station B1, 20 ciliates species were linked at more than 75% similarity level, into 4 clusters, containing 4,2,5,and 3 species. In this season number of species not grouped in any cluster were more than during spring intermonsoon (Figure 7.8).

During summer monsoon at station B1, 20 species of dinoflagellates where grouped into 4 clusters containing 4,2,5 and 3 species with at least 75% similarity between species of the same cluster (Figure 7.9).

During summer monsoon at station B17, 26 Ciliate species were grouped in to 9 desecrete clusters containing 2, 2, 3, 2, 2, 3, 3, 2, and 2 species respectively. These clusters have more thaan 75% similarity in their occurrence. Nearly 20% of the species are ungrouped showing their dissimilarity with these 9 clusters (Figure 7.10).

During summer monsoon at B17, 17 dinoflagellates species were grouped into 4 distinct clusters in which 6, 2, 2 and 5 species were associated with more than 60% similarity. Compared to ciliates, a few numbers of species were ungrouped in this case (Figure 7.11).

During winter monsoon at station B1, 20 ciliates were grouped in to four discrete clusters having 3,2,3 and 4 species respectively which were associated with at least 75%. Similarity between the ciliate species of the same cluster about 40% of the ciliate species are not grouped with other species. This non association shows that these unclustered ciliate species require an environment which is not similar to the species in the clusters (Figure 7.12).

During winter monsoon at station B1, 19 dinoflagellates were grouped in to five clusters containing 4,2,3,4 and 3 species respectively. The species included in these clusters were linked more than 75% similarity. In this season, nearly 64% of the species of this group did not form any of these clusters (Figure 7.13).

During winter monsoon, at station B17 the dendrogram has grouped as 6 ciliates species in to 2 associated clusters with more than 60% similarity. And the other species did not show associations (Figure 7.14).

During winter monsoon at station B17, 17 species of dinoflagellates were grouped in to 3 clusters with more than 60% similarity. These clusters were contributed by 3,10,3 dinoflagllates species respectively (Figure 7.15).

Higher the number of the species smaller the number of clusters with relatively highter species number shows the preferences of the environmental conditions required for the observed clusters. Smaller the number of species, higher the number of clusters with few number of species shows the large variation in the environment of the study area.

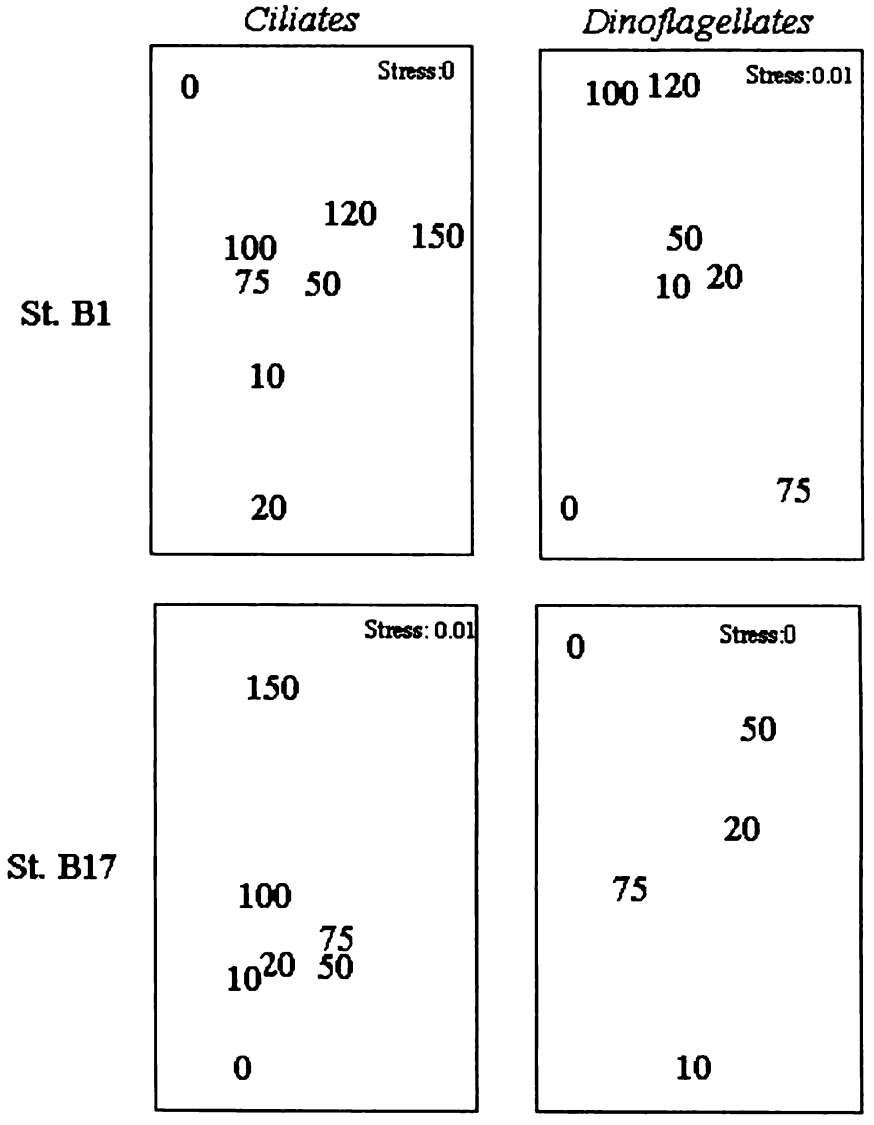


Figure 7.1. MDS analysis during spring intermonsoon

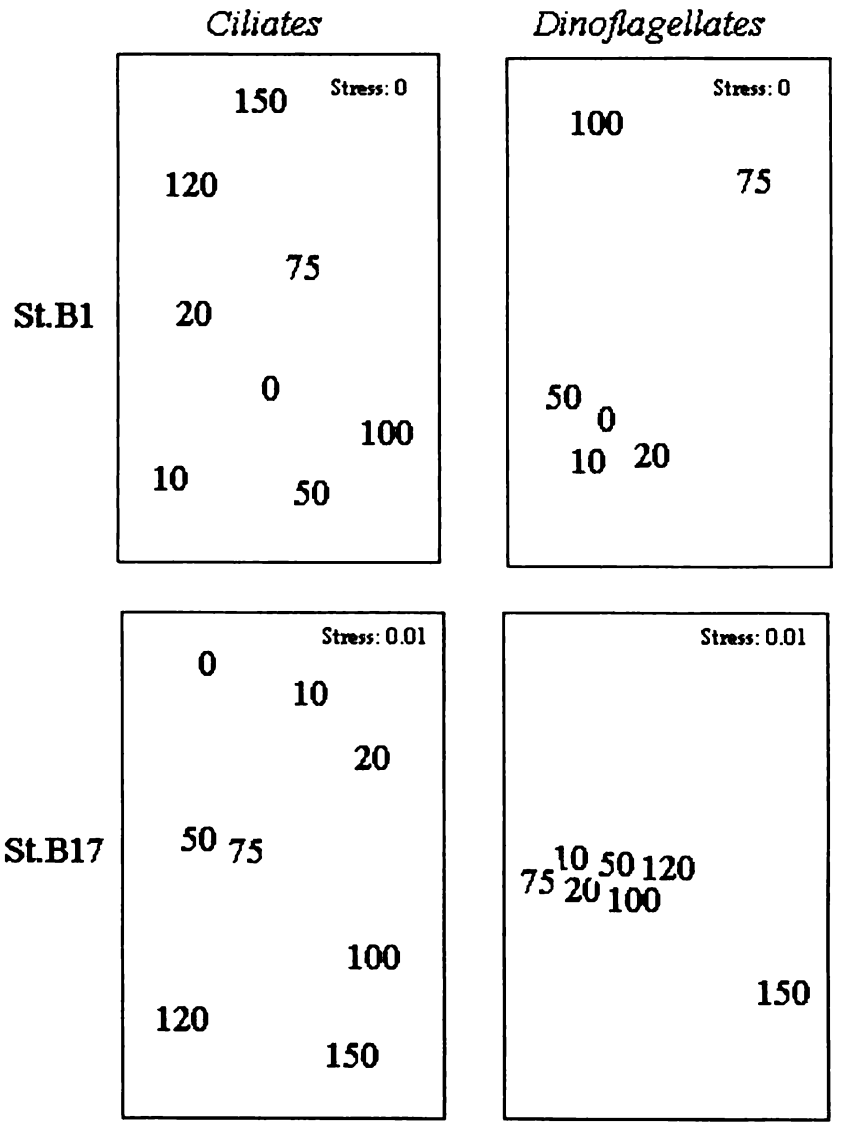


Figure 7.2. MDS analysis during summer monsoon

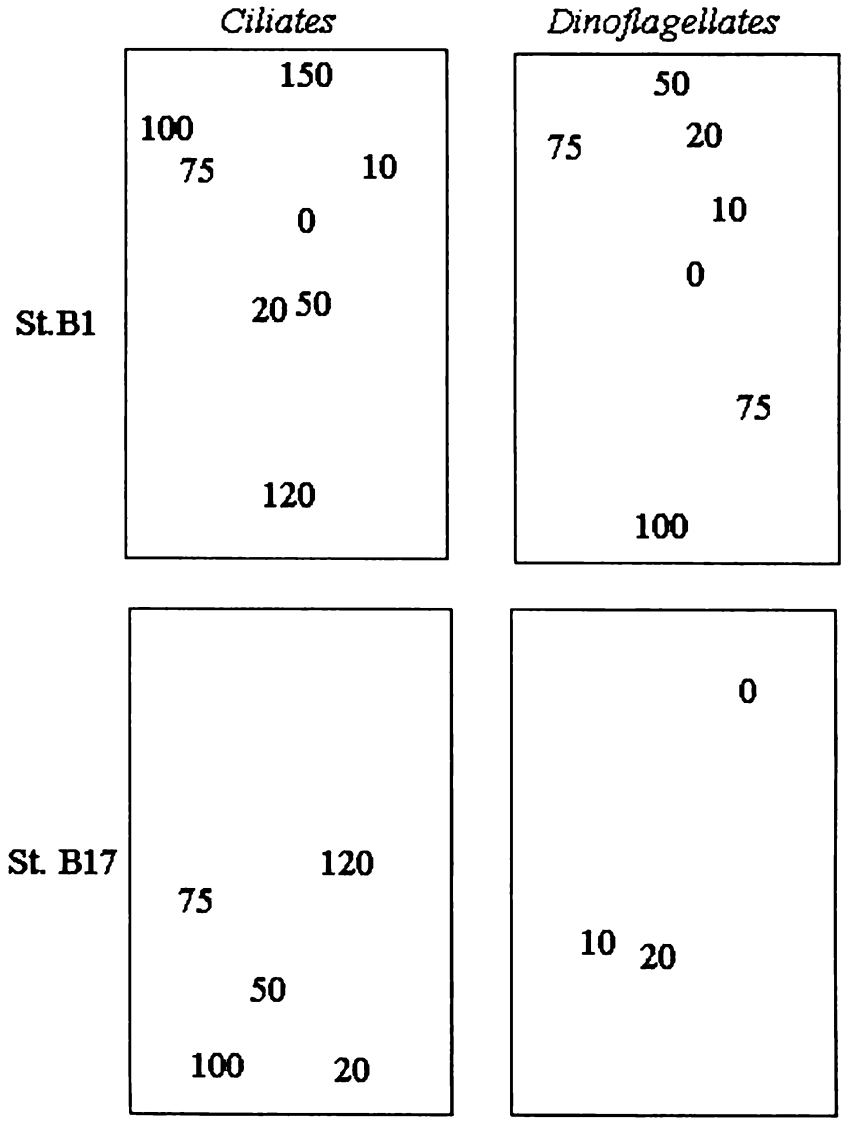


Figure 7.3.MDS analysis during winter monsoon

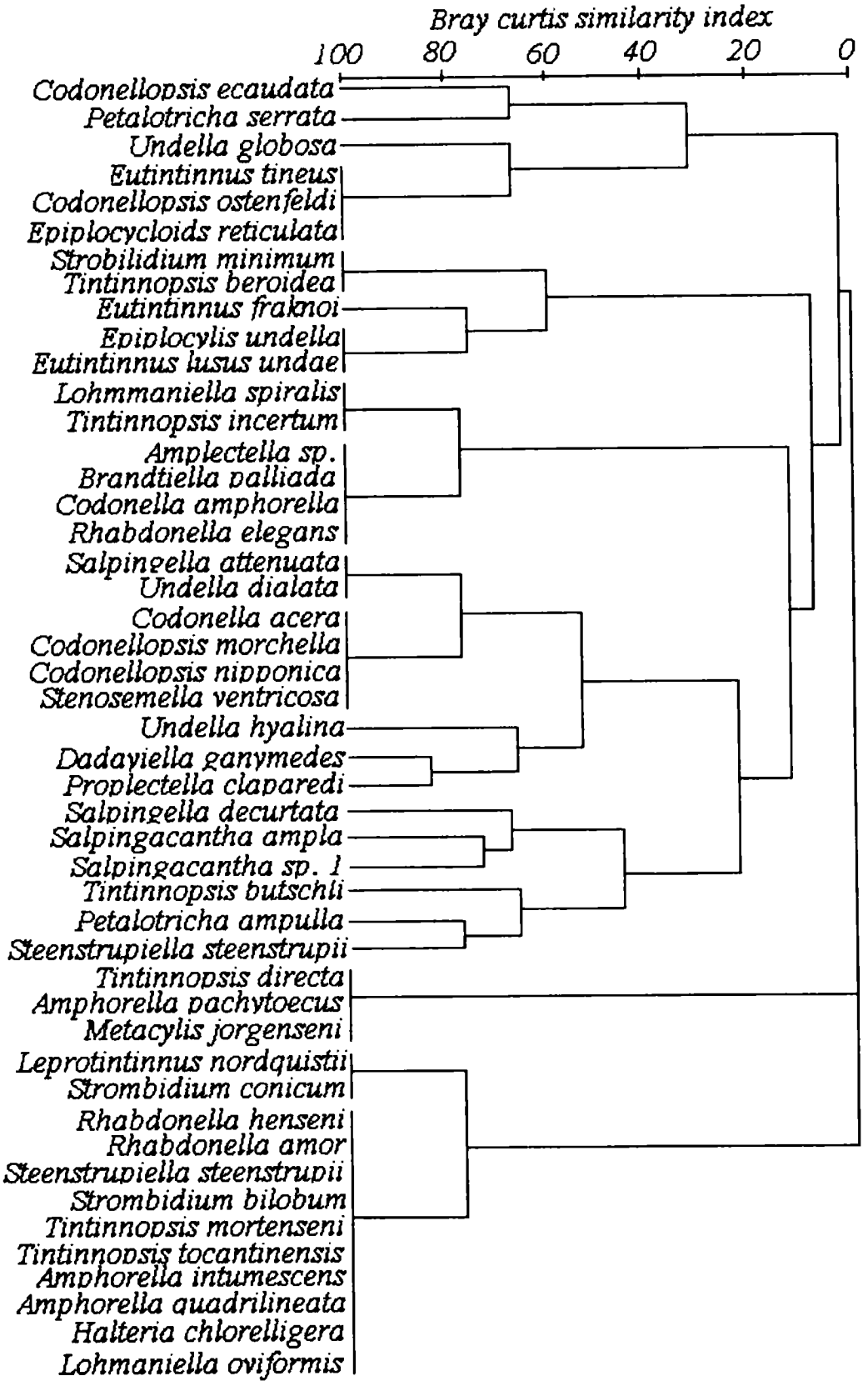


Figure 7.4. Dendrogram for grouping of ciliates based on abundance (No/m^3) at station B1 during spring intermonsoon

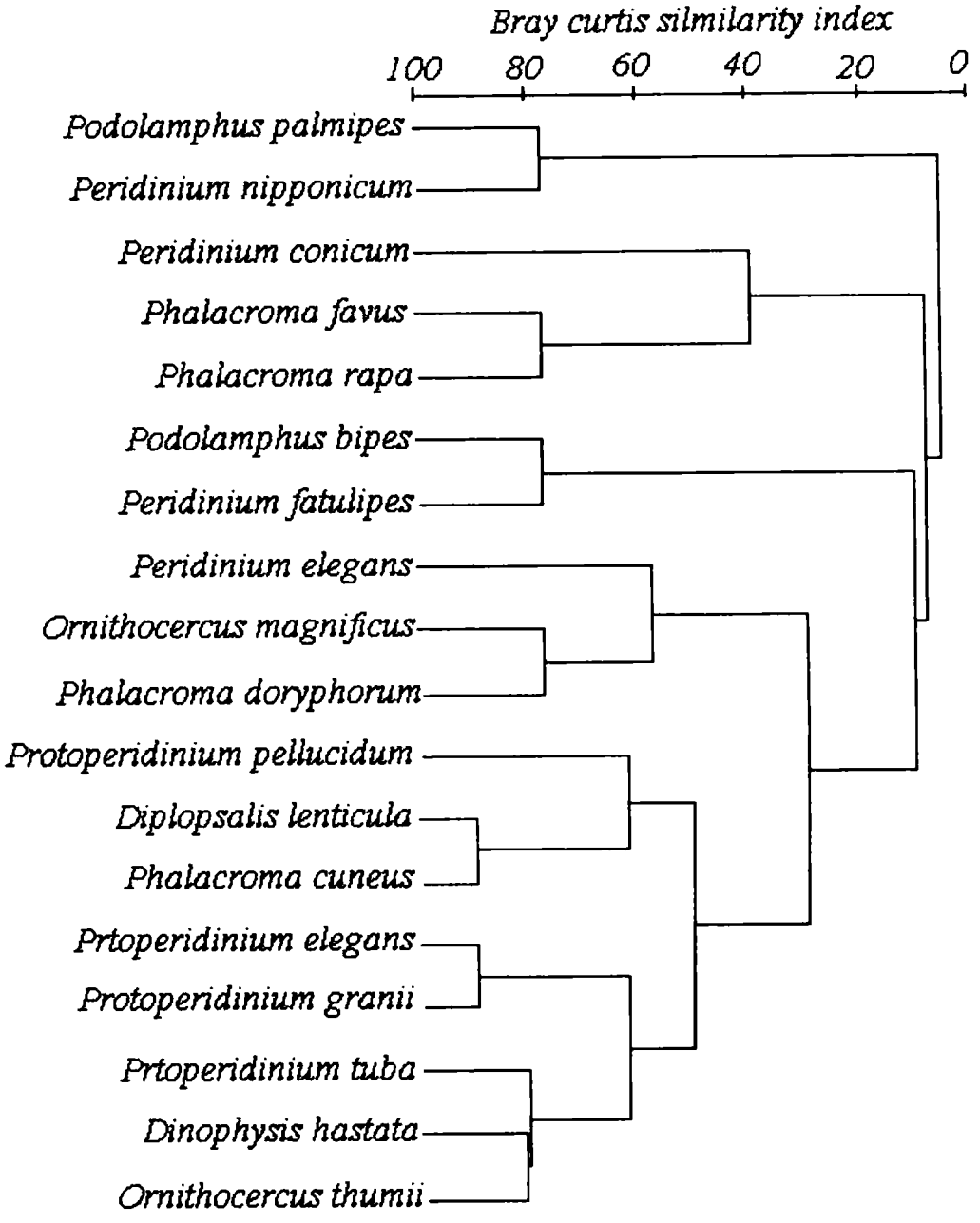


Figure 7.5. Dendrogram for grouping of dinoflagellates based on abundance (No/m^3) at station B1 during spring intermonsoon

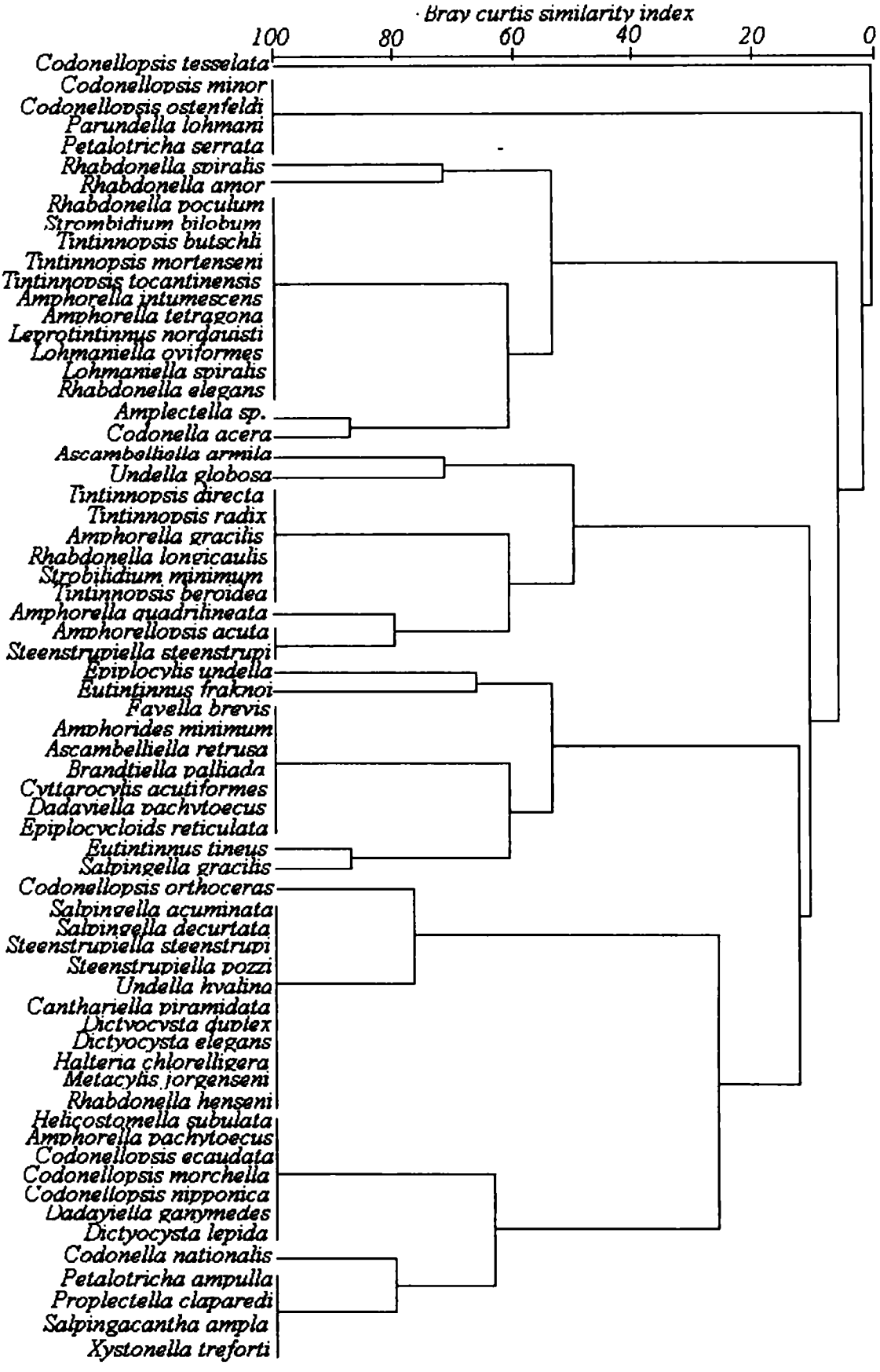


Figure 7.6. Dendrogram for grouping of ciliates based on abundance (No/m^3) at station B17 during winter monsoon

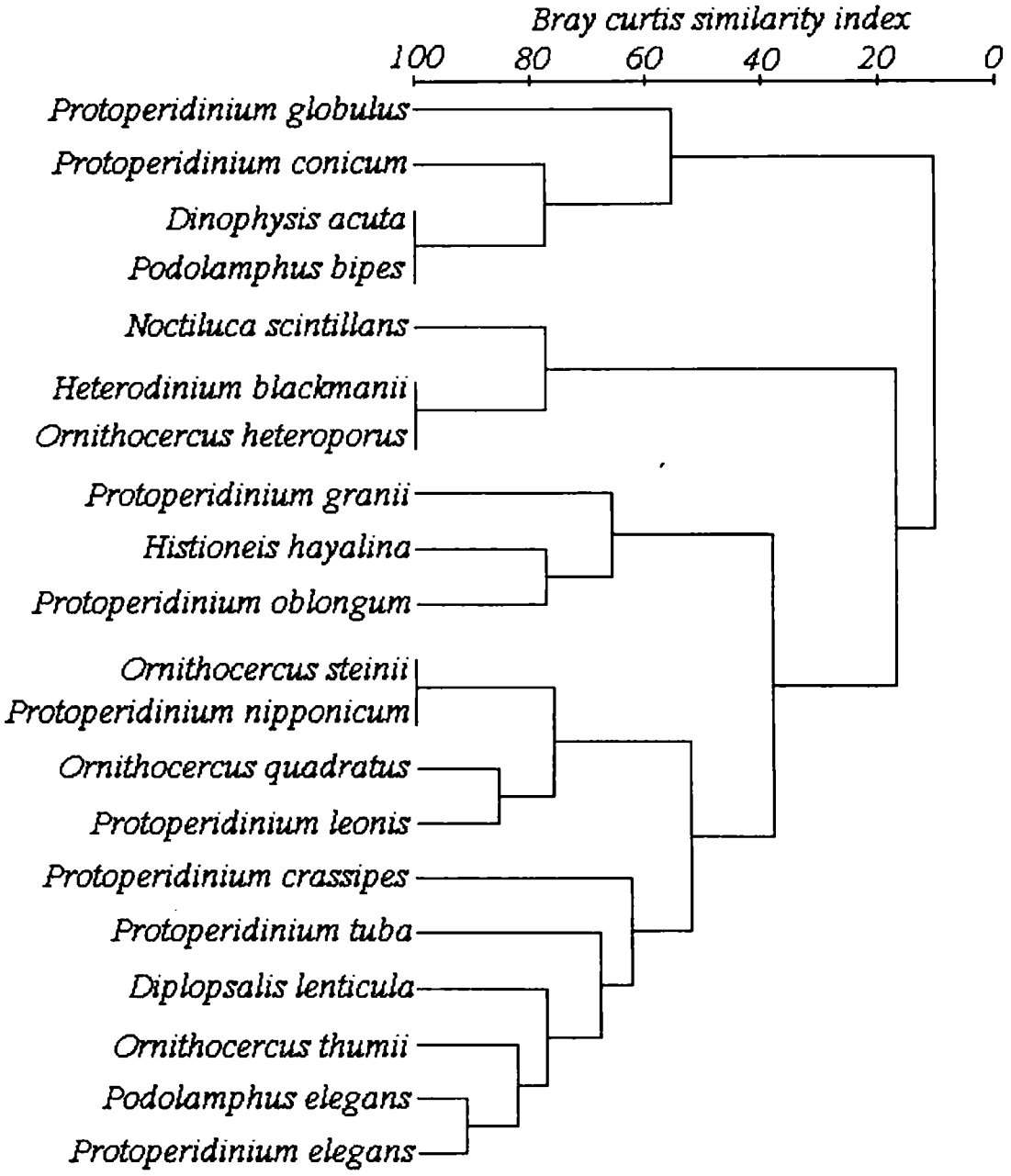


Figure 7.7. Dendrogram for grouping of dinoflagellates based on abundance (No/m^3) at station B17 during spring intermonsoon

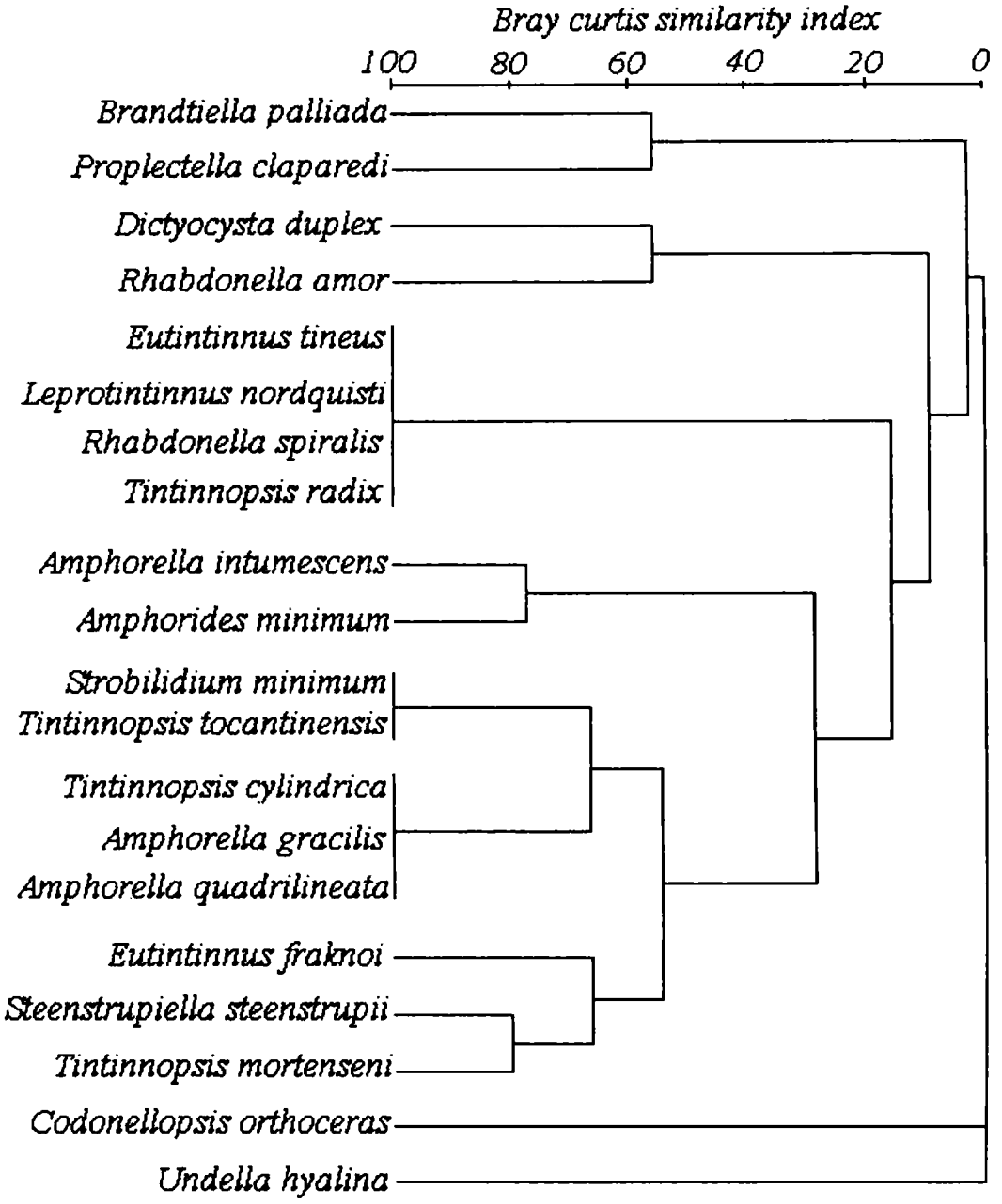


Figure 7.8. Dendrogram for grouping of ciliates based on abundance (No/m^3)at station B1 during summer monsoon

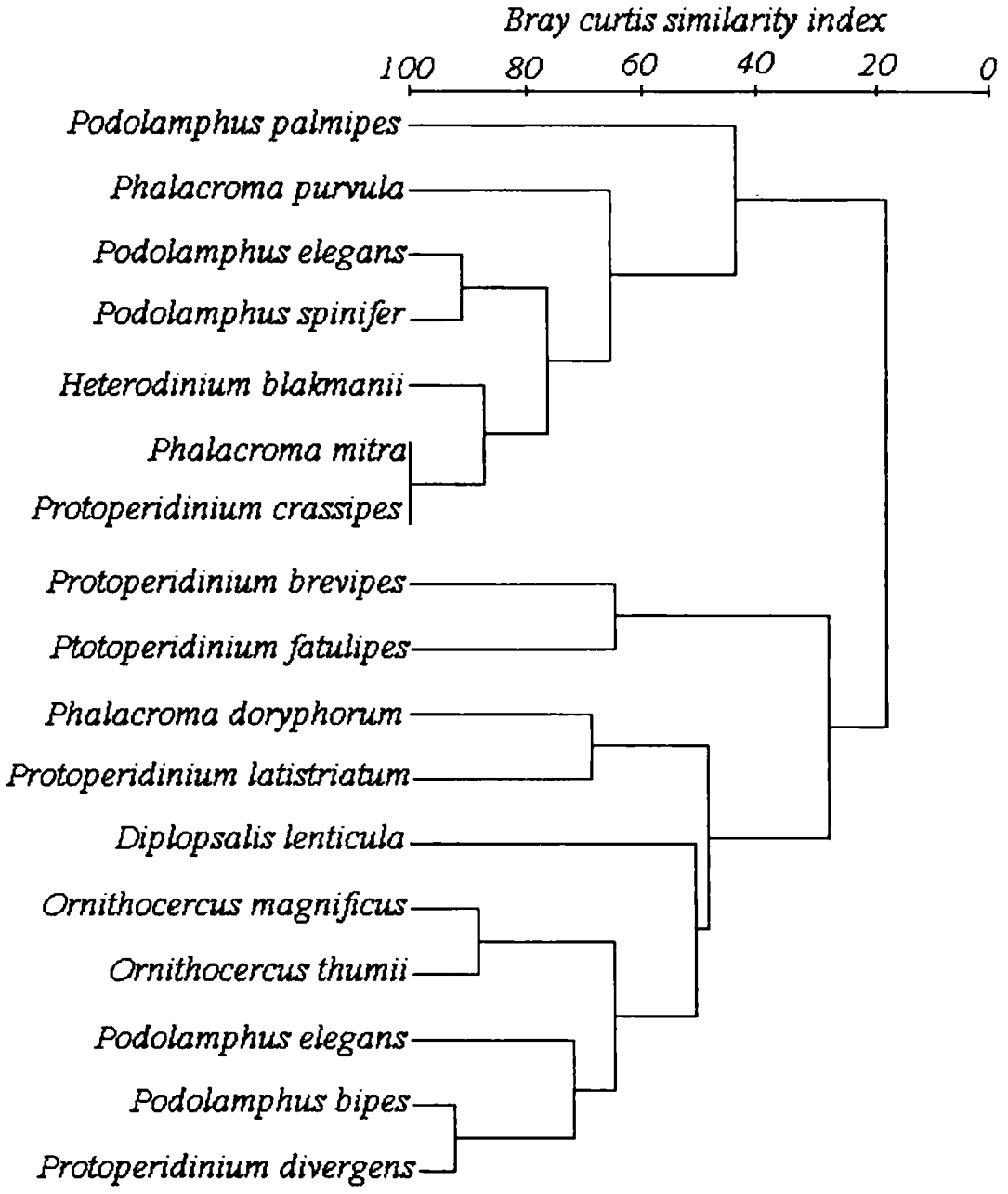


Figure 7.9. Dendrogram for grouping of dinoflagellates based on abundance (No/m^3) at station B1 during summer monsoon

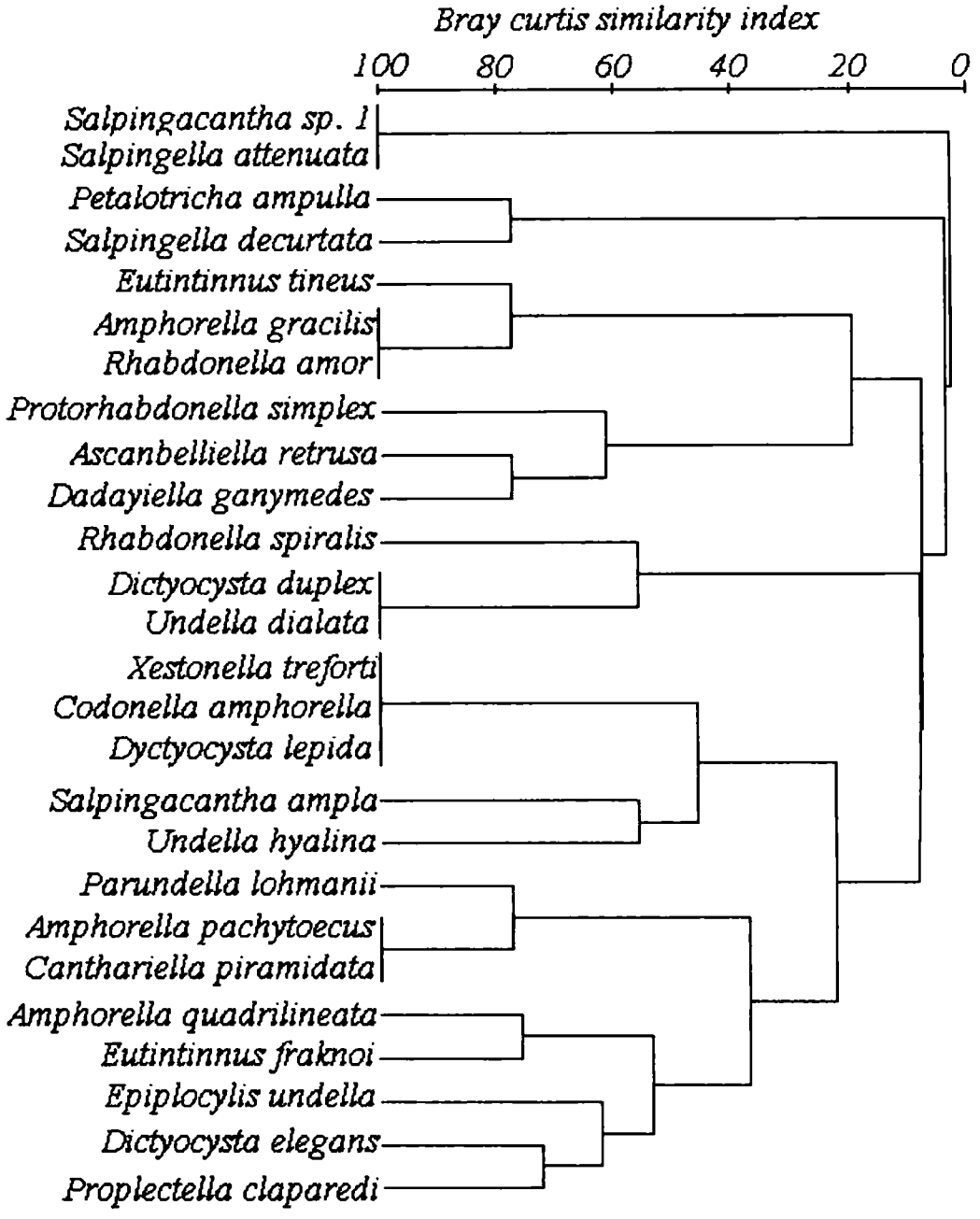


Figure 7.10. Dendrogram for grouping of ciliates based on abundance (No/m^{-3}) at station B17 during summer monsoon

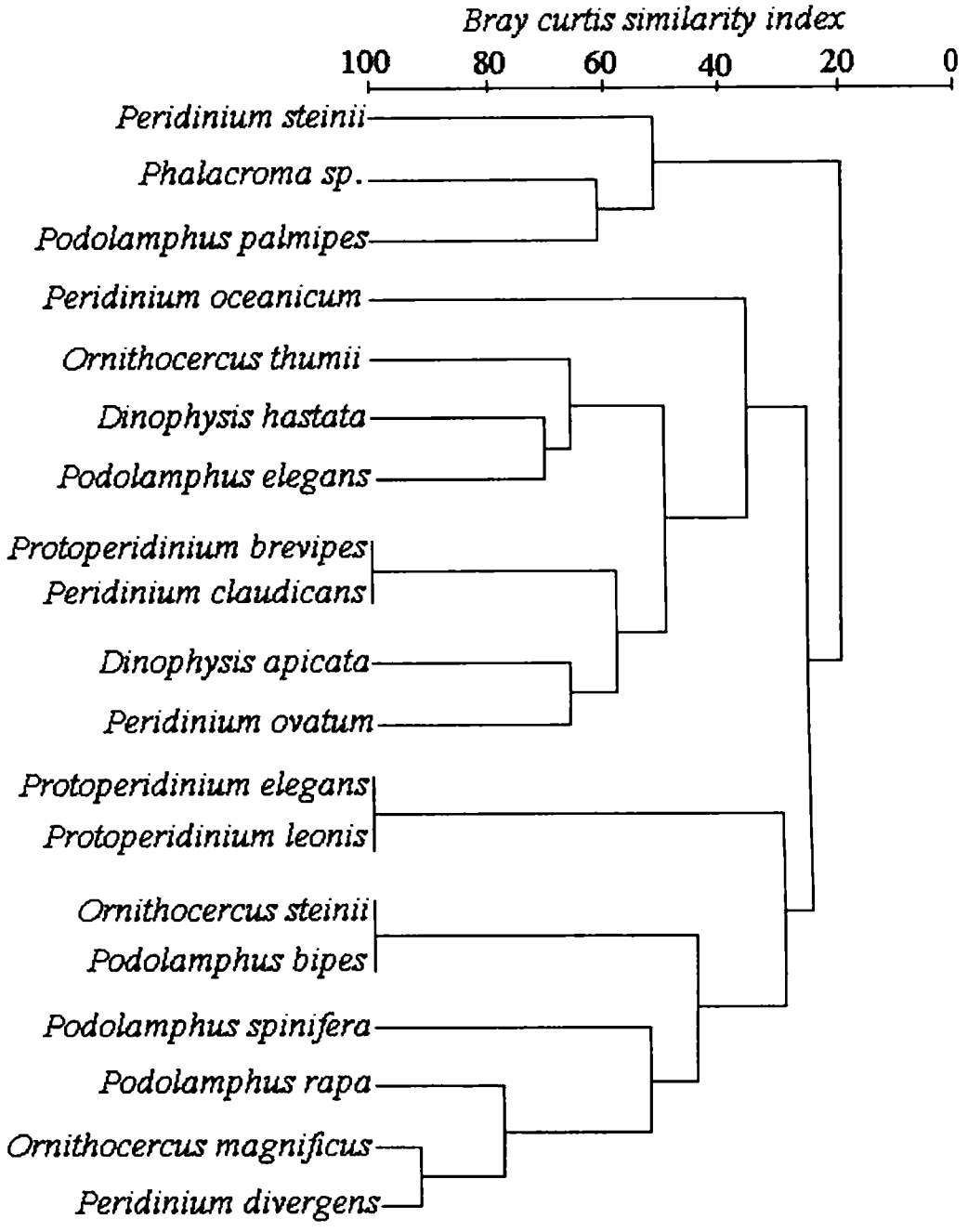


Figure 7.11.Dendrogram for grouping of dinoflagellates based on abundance (No/m^3) at station B17 during summer monsoon

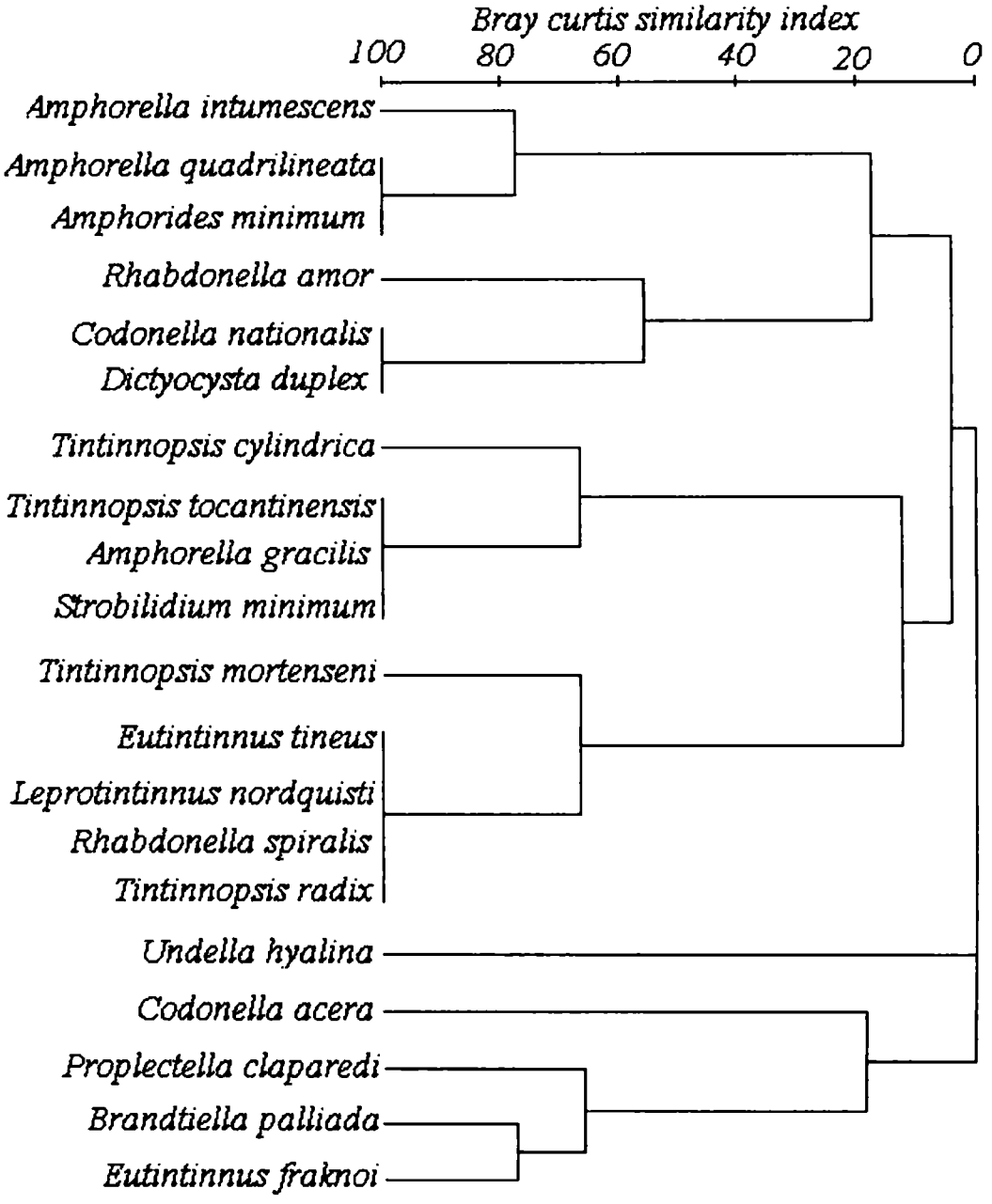


Figure 7.12.Dendrogram for grouping of ciliates based on abundance (No/m^3) at station B1 during winter monsoon

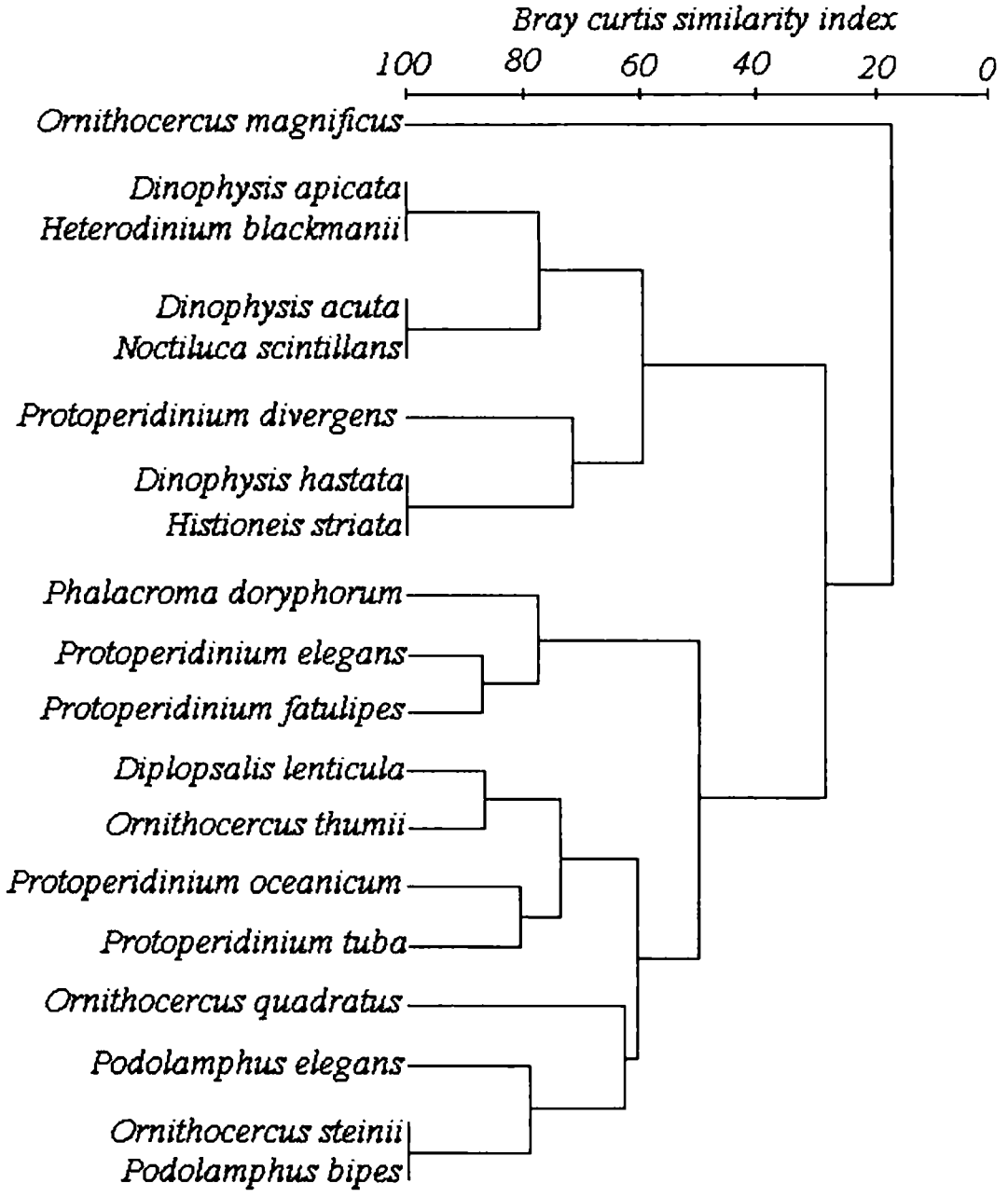


Figure7.13.Dendrogram for grouping of dinoflagellates based on abundance (No/m^3) at station B1 during winter monsoon

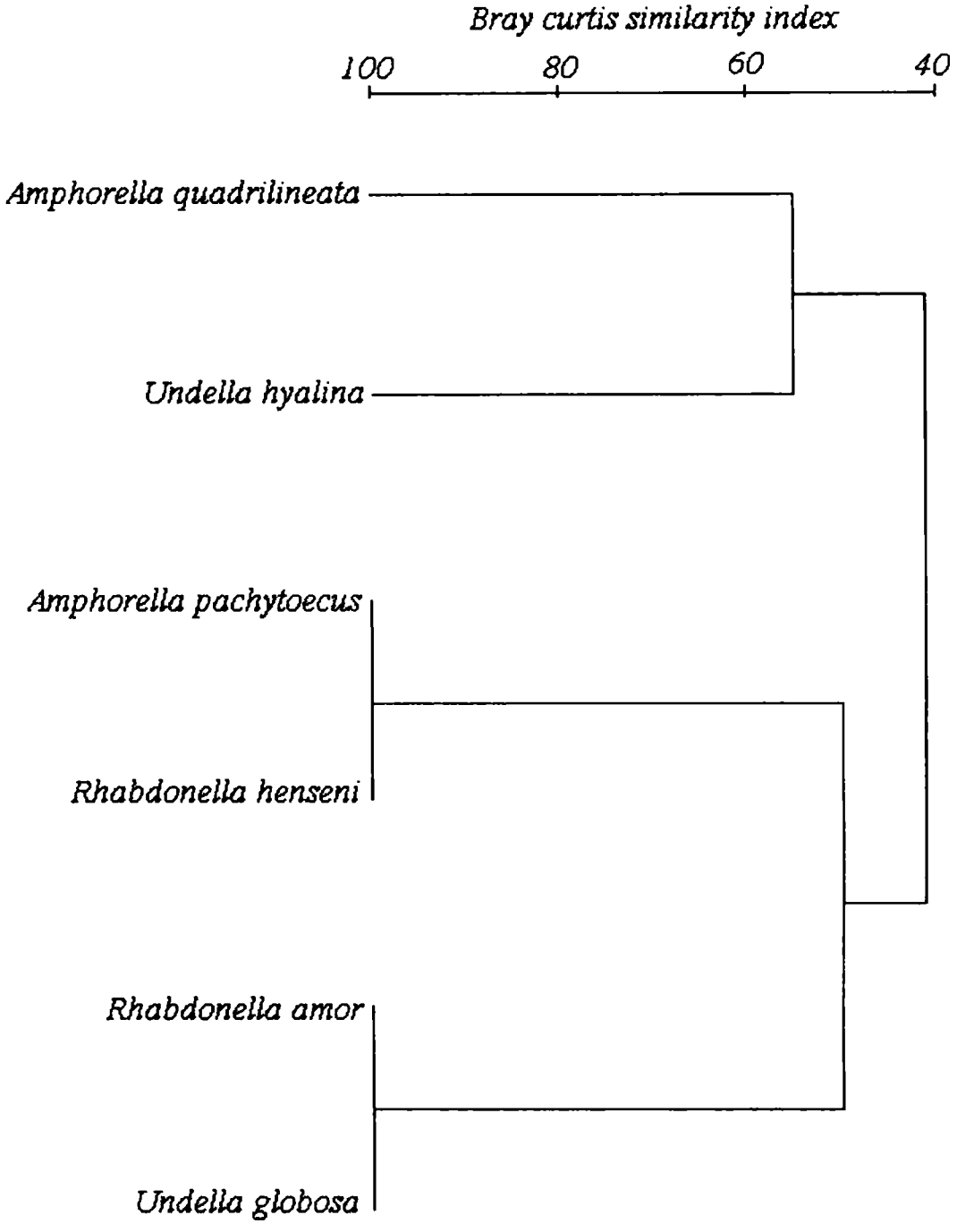


Figure 7.14 Dendrogram for grouping of ciliates based on abundance (No/m3) at station B17 during winter monsoon

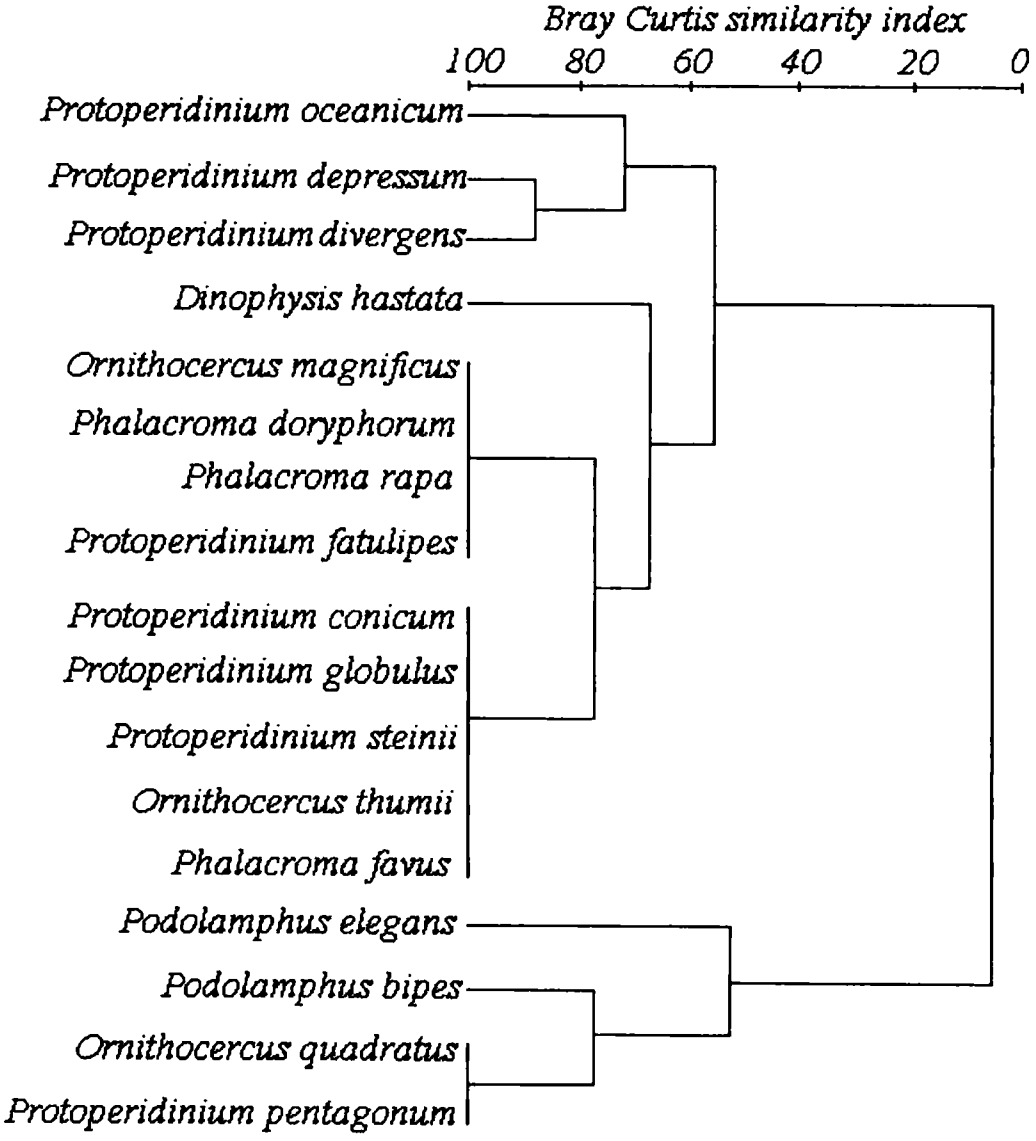


Figure 7.15. Dendrogram for grouping of dinoflagellates based on abundance at station B17 during winter monsoon

Source	D o f	M S S	F Ratio
Stations (A)	16	0.1910	3.8230 ***
Species (B)	43	0.6665	13.3333 ***
Depth (C)	7	1.9189	38.3895 ***
AB interaction	688	0.06780	1.3565
BC interaction	301	0.3291	6.5835 ***
AC interaction	112	0.05387	1.0778
Error	4816	0.04999	
Total	5236		

Table 7.1 – 3 way ANOVA for ciliates during winter monsoon

Source	D o f	M S S	F Ratio
Stations (A)	16	1.4209	6.3394***
Species (B)	43	6.4934	28.9708***
Depth (C)	7	19.0185	84.852***
AB interaction	688	0.5120	2.2846**
BC interaction	301	0.8790	3.9217***
AC interaction	112	0.3065	1.3076
Error	4816	0.2242	
Total	5983		

Table 7.2 – 3 way ANOVA for dinoflagellates during winter monsoon

*- calculated F ratio is significant at 5% level (P< 0.05)
** - calculated F ratio is significatnt at 1% level (< 0.01)
*** - calculated F ratio is significant at 0.5% level (P< 0.005)
D o f – degree of freedom
M S S – mean sum of squares
F ratio - F statistic used for the test

Source	D o f	M S S	F Ratio
Stations (A)	16	0.7212	7.7082***
Species (B)	77	0.9017	9.6380***
Depth (C)	7	4.3977	47.0052***
AB interaction	1232	0.09153	0.9784
BC interaction	539	0.3955	4.2276***
AC interaction	112	0.2450	2.6184***
Error	8624	0.09356	
Total	10607		

Table 7.3 – 3 way ANOVA for ciliates during spring intermonsoon

Source	D o f	M S S	F Ratio
Stations (A)	16	0.6407	2.3629***
Species (B)	47	7.8487	28.9452***
Depths (C)	6	12.9142	47.6259***
AB interaction	752	0.4568	1.6848*
AC interaction	96	0.4513	1.6643*
BC interaction	282	1.1166	4.1177***
Error	4512	0.2712	
Total	571		

Table 7.4 – 3 way ANOVA for dinoflagellates during spring intermonsoon

*- calculated F ratio is significant at 5% level (P< 0.05)
** - calculated F ratio is significatnt at 1% level (< 0.01)
*** - calculated F ratio is significant at 0.5% level (P< 0.005)
D o f - degree of freedom
M S S - mean sum of squares
F ratio - F statistic used for the test

Source	D o f	M S S	F Ratio
Stations (A)	15	0.2642	2.4509***
Species (B)	56	0.1353	1.2552
Depth (C)	7	3.7227	34.5284***
AB interaction	840	0.1955	1.8129*
BC interaction	392	0.1028	9.5298***
AC interaction	105	0.1341	1.2437
Error	5880	0.1078	
Total	7295		

Table 7.5 – 3 way ANOVA for ciliates during summer monsoon

Source	D o f	M S S.	F Ratio
Stations (A)	15	0.6032	2.4632***
Species (B)	49	4.5922	18.7517***
Depth (C)	7	19.4228	79.3100***
AB interaction	735	0.4074	1.6635*
BC interaction	343	0.9343	3.8149***
AC interaction	105	0.4544	1.8555*
Error	5145	0.2449	
Total	6399		

Table 7.6 – 3 way ANOVA for dinoflagellates during summer monsoon

*- calculated F ratio is significant at 5% level (P< 0.05)
** - calculated F ratio is significatnt at 1% level (< 0.01)
*** - calculated F ratio is significant at 0.5% level (P< 0.005)
D o f - degree of freedom
M S S - mean sum of squares
F ratio - F statistic used for the test

STATION		S	R	I	H(s)	E
B1	T1	47	2.7545	0.6953	2.5777	2.3248
B2		40	2.4176	0.6796	2.4159	2.2199
B3		39	2.8629	0.7481	2.6962	2.4413
B4	T2	22	1.7825	0.4361	1.7276	1.9371
B5		26	2.1979	0.6528	2.0987	2.1113
B6		19	2.4151	0.6588	2.2390	2.2456
B7	T3	39	2.9273	0.7586	2.6098	2.4776
B8		17	1.7693	0.4358	1.6990	1.9088
B9		24	3.0786	0.8091	2.7857	2.5428
B10	T4	50	3.9367	0.8235	3.1645	2.8721
B11		47	3.4749	0.6150	2.6880	2.6745
B12		50	3.8309	0.7449	3.0310	2.8281
B13	T5	36	3.5043	0.8130	2.9411	2.7212
B14		33	2.7355	0.6860	2.4510	2.3788
B15		30	3.0335	0.7801	2.7002	2.5332
B16	T6	55	4.0184	0.7585	3.1336	2.9069
B17		66	4.4438	0.7777	3.3486	3.0925

Table 7.7. Community structure indices for ciliates during) spring intermonsoon (depths averaged). T1 – T6 represent the latitudinal transect which correspond to the stations B1 – B17. S- Number of species, R- Margalef's richness index, I-Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

STATION		S	R	I	H(s)	E
B1	T1	18	1.806	0.7758	2.6070	2.4872
B2		15	1.9393	0.8002	2.5024	2.2428
B3		21	2.0561	0.6670	2.3350	2.2300
B4	T2	21	1.4564	0.7427	2.3572	2.1887
B5		12	1.8719	0.6368	2.2135	2.1125
B6		17	1.2051	0.6586	2.0729	2.1971
B7	T3	19	1.4818	0.6261	2.0788	2.0062
B8		15	1.2253	0.5681	2.0000	1.9414
B9		16	1.6256	0.7755	2.5142	2.1917
B10	T4	14	1.8707	0.6503	2.1319	2.01995
B11		21	2.7192	0.8226	2.8136	2.4111
B12		21	2.6118	0.8187	2.7752	2.3859
B13	T5	19	2.3116	0.8280	2.7551	2.3632
B14		19	2.6444	0.8462	2.9111	2.4363
B15		17	2.4213	0.8230	2.7511	2.3536
B16	T6	21	2.9198	0.8512	2.9928	2.5236
B17		20	3.0425	0.8648	3.1137	2.5311

Table 7.8. Community structure indices for dinoflagellates during spring intermonsoon (depths averaged). T1 – T6 represent the latitudinal transect which correspond to the stations B1 – B17. S- Number of species, R- Margalef's richness index, I- Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

STATION		S	R	I	H(s)	E
B1	T1	19	2.2976	0.6457	2.1995	2.2114
B2		21	2.2343	0.5235	2.0207	2.1222
B3		21	2.1458	0.5204	1.9627	2.1091
B4	T2	15	2.4543	0.6723	2.2635	2.0810
B5		21	2.6336	0.5980	2.3654	2.3032
B6		24	2.9298	0.6177	2.5556	2.4259
B7	T3	30	3.2573	0.7584	2.7905	2.5838
B8		16	1.6362	0.4561	1.5717	1.8630
B9		20	2.1660	0.5793	2.0463	2.1097
B10	T4	27	2.0815	0.4892	1.9033	2.0519
B11		17	2.4371	0.7411	2.4478	2.2152
B12		19	1.8255	0.5034	1.7034	1.9538
B13	T5	28	2.8334	0.6829	2.5239	2.4024
B14		34	3.1370	0.8127	2.8966	2.5647
B15		26	2.5453	0.6920	2.4392	2.3047
B16	T6	26	2.62628	0.7899	2.6064	2.3296

Table 7.9. Community structure indices for ciliates during summer monsoon (depths averaged). T1 – T6 represent the latitudinal transect which correspond to the stations B1 – B17. S- Number of species, R- Margalef's richness index, I- Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

STATION		S	R	I	H(s)	E
B1	T1	17	2.4216	0.7308	2.5770	2.2945
B2		13	1.5577	0.6505	2.2370	2.0063
B3		19	2.2452	0.7436	2.4470	2.2197
B4	T2	17	2.2624	0.8175	2.6757	2.3194
B5		15	2.4336	0.7996	2.6329	2.3128
B6		12	2.2998	0.7742	2.5922	2.2953
B7	T3	18	2.4553	0.7697	2.6299	2.3678
B8		18	2.5017	0.8365	2.8487	2.3886
B9		18	2.1252	0.8206	2.7144	2.4169
B10	T4	15	1.6946	0.8004	2.4597	2.3043
B11		6	1.3751	0.6968	1.9886	2.0068
B12		16	2.0846	0.6267	2.3234	2.2462
B13	T5	14	1.4288	0.6813	2.1548	2.1843
B14		19	1.6616	0.7981	2.6731	2.4549
B15		22	1.8831	0.7580	2.4997	2.3323
B16	T6	20	2.3628	0.7985	2.6753	2.3879

Table 7.10.Community structure indices for dinoflagellates during summer monsoon (depths averaged). T1 – T6 represent the latitudinal transect which correspond to the stations B1 – B17. S- Number of species, R- Margalef's richness index, I- Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

STATION		S	R	I	H(s)	E
B1	T1	20	1.8886	0.5472	1.8196	1.9955
B2		15	1.9070	0.5069	1.7906	2.0043
B3		16	1.6741	0.3903	1.5325	1.8918
B4	T2	11	1.9133	0.5714	1.7979	1.9774
B5		14	1.8078	0.5722	1.7381	1.7669
B6		18	2.2151	0.5485	2.0559	2.1213
B7	T3	21	2.1368	0.5855	2.0150	2.0997
B8		18	1.9845	0.4873	1.8349	2.0118
B9		13	1.4976	0.3571	1.3340	1.5668
B10	T4	10	1.8091	0.3889	1.5283	1.9292
B11		10	1.8091	0.3889	1.5283	1.9292
B12		12	1.9008	0.3708	1.6434	1.9653
B13	T5	11	2.3713	0.5324	2.0899	2.1991
B14		8	1.9442	0.4286	1.7022	1.8982
B15		10	1.9522	0.5071	1.7857	1.9975
B16	T6	6	1.9236	0.3929	1.7500	1.7183
B17		6	1.3225	0.3839	1.7055	1.9930

Table 7.11.Community structure indices for ciliates during winter monsoon (depths averaged). T1 – T6 represent the latitudinal transect which correspond to the stations B1 – B17. S- Number of species, R- Margalef's richness index, I- Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

		S	R	I	H(s)	E
B1	T1	19	3.0882	0.8647	3.1310	2.6215
B2		20	2.1765	0.6480	2.5663	2.4138
B3		13	1.8992	0.6997	2.2715	2.2102
B4	T2	11	1.3214	0.5644	1.7649	2.0481
B5		18	1.8324	0.5948	2.3633	2.3044
B6		17	2.6451	0.8511	2.9371	2.5133
B7	T3	13	2.4046	0.7848	2.6546	2.3317
B8		17	2.3235	0.7666	2.5794	2.3604
B9		13	1.8758	0.7161	2.2044	2.0267
B10	T4	13	2.0764	0.7421	2.3475	2.1363
B11		17	2.2282	0.7582	2.4754	2.2941
B12		17	2.5863	0.8190	2.7342	2.3791
B13	T5	14	1.6052	0.6934	2.1990	2.1122
B14		7	0.9550	0.3767	1.1680	1.7209
B15		15	2.0959	0.6244	2.1420	2.1605
B16	T6	17	2.6060	0.8056	2.7374	2.3394
B17		17	2.3696	0.7753	2.5678	2.2962

Table 7.12. Community structure indices for dinoflagellates during winter monsoon (depths averaged). T1 – T6 represent the latitudinal transect which correspond to the stations B1 – B17. S- Number of species, R- Margalef's richness index, I- Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

Transect	S	R	I	H(s)	E
T1	42	2.6783	0.7077	2.5633	2.3287
T2	22.33	2.1318	0.5826	2.0218	2.0980
T3	26.67	2.5917	0.6678	2.3648	2.3097
T4	49.00	3.7475	0.7278	2.9612	2.7916
T5	33.00	3.0911	0.7597	2.6974	2.5444
T6	60.50	4.2311	0.7681	3.2411	2.9997

Table 7.13. Geographical variations in community structure of ciliates during spring intermonsoon. T1 – T6 show increasing latitudes from 11 – 20.5°N.

Transect	S	R	I	H(s)	E
T1	18	1.9323	0.7477	2.4815	2.3200
T2	16.67	1.5113	0.6794	2.2145	2.1667
T3	16.67	1.4442	0.6566	2.1977	2.0464
T4	18.67	2.4006	0.7639	2.5736	2.2973
T5	18.33	2.4591	0.8324	2.8058	2.3844
T6	20.50	3.0162	0.8580	3.0533	2.5274

Table 7.14. Geographical variations in community structure of dinoflagellates during spring intermonsoon. T1 – T6 show increasing latitudes from 11 – 20.5°N

Transect	S	R	I	H(s)	E
T1	20.33	2.2268	0.5632	2.0610	2.1476
T2	20.00	2.6726	0.6293	2.3948	2.2700
T3	22.00	2.3532	0.5981	2.1362	2.1855
T4	21.00	2.1147	0.5779	2.0182	2.0736
T5	29.33	2.8386	0.7292	2.6199	2.4240
T6	26.00	2.6286	0.7899	2.6064	2.3296

Table 7.15. Geographical variations in community structure of ciliates during summer monsoon. T1 – T6 show increasing latitudes from 11 – 20.5°N

Transect	S	R	I	H(s)	E
T1	16.33	2.0748	0.7083	2.4203	2.1735
T2	14.67	2.3319	0.7971	2.6336	2.3092
T3	18.00	2.3607	0.8089	2.7310	2.3911
T4	12.33	1.7181	0.7090	2.2572	2.1858
T5	18.33	1.6578	0.7058	2.4425	2.3238
T6	20	2.3628	0.7975	2.6753	2.3879

Table 7.16. Geographical variations in community structure of dinoflagellates during summer monsoon. T1 – T6 show increasing latitudes from 11 – 20.5°N

Transect	S	R	I	H(s)	E
T1	17.33	2.3880	0.7375	2.6563	2.4152
T2	15.33	1.9330	0.6701	2.3551	2.2886
T3	14.33	2.2013	0.7558	2.4795	2.2396
T4	15.67	2.2970	0.7731	2.5190	2.2699
T5	12.00	1.5514	0.5648	1.8357	1.9979
T6	17.00	2.4878	0.7906	2.6526	2.3178

Table 7.17. Geographical variations in community structure of ciliates during winter monsoon. T1 – T6 show increasing latitudes from 11 – 20.5°N

Transect	S	R	I	H(s)	E
T1	17.00	1.8232	0.4815	1.7142	1.9639
T2	14.33	1.9787	0.5640	1.8640	1.9552
T3	17.33	1.8730	0.4766	1.7280	1.8929
T4	10.67	1.8397	0.3829	1.5667	1.9412
T5	09.67	2.0892	0.4894	1.8593	2.0597
T6	06.00	1.6231	0.3884	1.7278	1.8587

Table 7.18. Geographical variations in community structure of dinoflagellates during winter monsoon. T1 – T6 show increasing latitudes from 11 – 20.5°N

Season	S	R	I	H(s)	E
Winter	12.88	1.8857	0.4682	1.7442	1.9500
Spring inter	33.76	3.0113	0.6984	2.6063	2.4833
Summer	22.75	2.3903	0.5794	2.2685	2.2270

Table 7.19. Temporal diversity indices (average) for ciliates

Season	S	R	I	H(s)	E
Winter	15.18	2.1228	0.6688	2.4024	2.2511
Spring inter	18	2.0708	2.7503	2.5270	2.2765
Summer	16.19	2.0496	2.07564	2.5081	2.2836

Table 7.20.Temporal diversity indices (average) for Dinoflagellates

S- Number of species, R- Margalef's richness index, I- Simpson's concentration index, H (s) – Shannon weaver's species diversity index, E - Heips evenness index

Chapter 8

Discussion

Bay of Bengal (BOB), the northeastern part of the Indian Ocean is completely separated from the northwestern part, the Arabian Sea (AS) by the Indian peninsula. Between these two basins, Arabian Sea is one of the most productive regions of the world ocean (Ryther *et al.*, 1966) and the physical and chemical forcings, which drive Arabian Sea production, is now fairly understood. The main attributes, which enhance the productivity of the area, are the coastal and open ocean upwelling during summer monsoon and the surface cooling in the northern Arabian Sea during winter (Madhupratap *et al.*, 1996; Bhattathiri *et al.*, 1996; Nair *et al.*, 1999). These bring in higher amount of nutrients in to the upper ocean, which enhance the phytoplankton biomass and productivity of the Arabian Sea. Interestingly during spring intermonsoon mesozooplankton biomass remains unchanged although the phytoplankton biomass and primary production remains low in the AS. This peculiar phenomenon (Arabian Sea Paradox) was explained by understanding the microbial food web (microbial loop) that enhances the productivity during intermonsoon (Madhupratap *et al.*, 1996; Ramaiah *et al.*, 1996; Mangesh *et al.*, 1996).

In contrast to the AS, most of the earlier studies in the Bay of Bengal depict it as a low productive system all through the year. The possible reasons suggested by the earlier researchers for the low phytoplankton biomass and PP in the BOB were the unavailability of nutrients in the upper layers due to stratification, heavier cloud coverage and turbidity arising from sediment fluxes that limit effective penetration of solar radiation in the upper euphotic column (Radhakrishna *et al.*, 1978 a&b; Qasim, 1977; Gomes *et al.*, 2000; Prasanna Kumar *et al.*, 2002; Madhupratap *et al.*, 2003). The field observations where further supported by the chlorophyll *a* distribution in the BOB derived from observations by satellites (Sea WiFS), which showed very low chlorophyll *a* values (Gomes *et al.*, 2000 and Prasanna Kumar *et al.*, 2002). The most recent study, during summer monsoon

(recall that during this season column primary production in the southwest coast increases up to 2000 mgC m $^{-2}$ due to upwelling) in the BOB by the JGOFS - India group observed PP values between 328 - 520 mgC m^{-2} d^{-1}, which was comparable with the primary productivity of the AS during spring intermonsoon which is relatively oligotrophic period (Madhupratap *et al.*, 2003). Compared to AS, literature available on different biological aspects of the BOB are less and a comprehensive approach to explain the oligotrophy of BOB in particular is scanty. The preceding findings that discussed the general understanding on the hydrography and productivity of the twin Seas (AS and BOB), which are supportive to infer the results obtained during the present study from the Bay of Bengal during different seasons.

7.1. Physicochemical environment

7.1.1. Winter monsoon

During winter monsoon, distribution of sea surface temperature (SST) showed marked latitudinal variations with maximum (29.2°C) in the southernmost transect and minimum in the northernmost transect (20.5°N). This was apparently due to the increasing intensity of winter towards north. Atmospheric cooling during winter is a common phenomenon in the northern Indian Ocean and its intensity increases towards north (Hastenrath and Lamb, 1970). Sea surface salinity showed clear coastal – offshore variations where low saline waters (<30 psu) prevailed along the entire coast. This was mainly due to the high freshwater discharge from various rivers in to the bay from Indian peninsula. Minimum values of SSS was observed at the coastal stations along latitudes 15, 19 and 20.5°N. These areas are considerably influenced by the Krishna (near 15°N) and Ganges - Mahanadi (19 and 20.5°N) river discharges. Emptying of the major rivers of India in to the Bay of Bengal and its consequences on the physical characteristics of coastal waters of the Bay of Bengal were well reported. The stratification due to freshwater influx could be noticed even at a depth of 100m over most of the shelf areas of the Bay of Bengal (Suryanarayana, 1988). During the present study, fluctuations of mixed layer depth were mostly corresponding to the intensity of salinity stratification.

Generally higher MLD was observed in the oceanic regions where relatively high saline surface waters were present. On the other hand northern regions (19°N and 20.5°N) apparently had low MLD due to strong salinity gradients in the surface layers along these transects. The vertical salinity structure in the upper layers showed clear frontal structures (2-5 psu gradients in the upper layers) towards the coast especially along the transects which were near to the river mouths and was a clear evidence of the river discharge into the Bay. Higher attenuation coefficient (low transparency) during the season along the coastal transect was due to the high suspended and particulate materials derived from the heavy river discharge. The transparency of the water column along the east coast of India varies greatly from season to season depending on the land runoff and associated suspended load and the Bay of Bengal receives about 16 x 10^8 tonnes of silt annually through river discharges, which considerably increase the turbidity of the water column (Suryanarayana, 1988).

During the winter monsoon season, the cold dry air (humidity <45%) from the continents blown over northwestern BOB and thus the atmospheric conditions were favorable for cooling of surface waters and the resultant winter convection. But the heat loss in the surface waters by the atmospheric cooling does not trigger convective overturning in the Bay. The low saline surface layers attains low temperature due to atmospheric cooling but fails to impart it to the deeper waters due to the lack of sinking. This ultimately results in strong thermal inversion and stratification. The low saline waters compensate the static stability loss by the atmospheric cooling, which ultimately result in the absence of winter convection. In the northwestern BOB, thermal inversions of varying magnitude is a known feature and studied by many oceanographers (Sankaranarayana & Reddy, 1968; Rao & Sastry, 1981; Suryanarayana *et al.*, 1993 and Pankajakshan *et al.*, 2002).

Another significant feature observed along the western Bay was the subsurface cold core eddy with high salinity, nutrient, and low dissolved oxygen waters, which was mostly intense below the surface layers. The eddy signatures were more prominent in the middle stations of the study area and along these

stations 1 μM contour of nutrients (nitrate and silicate) was found at relatively shallower depths (~40m) compared to coastal and oceanic stations. The mechanism, which generates the cyclonic eddy, is thought to be the circulation pattern. In November, by the onset of northeast monsoon the Bay of Bengal has a basin wide cyclonic circulation pattern (Eigenheer *et al.*, 2000) with equator ward East Indian Coastal Current (EICC).

Introduction of fresh water in to the BOB reduces the mixed layer, led to the formation of halocline and a thick barrier layer (Rao *et al*, 1989). The formation of barrier layer in the BOB restricts the ocean – atmosphere interaction leading to the thin mixed layer and thus restricts the upward transport of nutrients. In the present study nutrients were found below 40m, which indicate the influence of stratification on vertical distribution of nutrients. The barrier formation was more pronounced in the northwestern BOB during summer and winter due to the increased fresh water influx during the periods (Rao *et al*, 1989).

7.1.2. Spring intermonsoon

Spatial variability of SST was minimum during the season and that could be directly linked to the maximum solar radiation available during the period. SST distribution during the period is indicative of the warming of the surface waters between winter and summer (Varkey *et al.*, 1996). Contrasting to the other season SSS distribution showed peculiar pattern in the surface layers due to the influence of circulation. During the season relatively high saline waters were present in the coastal regions and pockets of low saline waters were found about 200 – 400km away from the coast. This was due to the strong East Indian Coastal Current (EICC), which flows poleward during the season and pushes the low saline waters away from the coast. Furthermore relatively less volume of freshwater reaches the southeast Bay during the season due to the lean discharge from the adjoining rivers. The anticyclonic circulation pattern with pole ward flowing EICC during spring intermonsoon is a well-known feature in the western Bay (Murty *et al.*, 1968; Shetye *et al*, 1991; Sanil Kumar *et al.*, 1997). Shetye *et al.*, (1993) reported a warm water recirculation zone in the offshore region of the Western Boundary Current

(WBC) and cool water eddy like structure in the coastward direction of this boundary current. These studies projected pole ward flowing western boundary current as the net effect of the local and remote forcing. Warm and low saline waters in the oceanic regions provide stratified surface layers and this was the reason for the shallow MLD observed along most of the oceanic regions. Strong stratification leads to the absence of nutrients in the surface layers and inhibit surfacing from deeper waters. During the present study nutrients (nitrate, phosphate, silicate) were found at relatively deeper depths (below 50m) due to stratification. The vertical thermal structure along 17°N exhibited warm surface isothermal layer, below which it exhibits gentle down curving of isotherms centred around 85°E (Fig. 3d). This feature is peculiar of a subsurface warm core eddy more conspicuous at 150m. Pockets of low silicate and phosphate at 75m depth along 15 – 17°N were confirmative of subsurface warm core eddy.

1.3. Summer monsoon

Warmer sea surface temperature was observed during the season and was comparable to the spring intermonsoon. Sea surface salinity showed marked north south variability. Relatively high saline waters (>33.5psu) was present in the south east coast, where as the north east coast had relatively low salinity and the lowest value of 25psu was observed near the coast along 20.5°N. Similar to SSS distribution MLD generally showed north – south gradients and along the south east coast it was relatively thicker (30 - 60m). The latitudinal difference in salinity during the season was due to the difference in the amount of monsoonal rain and the river water reaching in to the BOB. Northeast coast of India gets maximum rain fall during summer monsoon and the rivers in the region bring enormous quantity of fresh water and sediments that empty in to the Bay of Bengal (Ramage. 1984 and Suryanarayana *et al*, 1991) which reduces the surface salinity and transparency of the water column. The salinity stratification in the surface is the reason for the observed low MLD in the northern region.

Signatures of upwelling such as relatively colder waters at the surface layers, shallow mixed layer and nitracline (upsloping of isolines) near to the coast were

observed along 15°N. The prevailing southwesterly winds during the season give rise to southeastward Ekman transport at the surface and this could be the reason for the observed upwelling processes along 15°N. During the present observation upwelled waters remained as a narrow band, which strongly supports the earlier observation by Shetye *et al.*, (1993). However along the southeast coast of India, the upwelled waters were confined below 75m (subsurface upwelling). In general the most important reason proposed for the lack of intense upwelling along the east coast such is the river discharge in the northwestern BOB that makes equator ward flow along the east coast and overwhelm the upwelling processes (Gopalakrishna & Sastry, 1985 and Shetye *et al.*, 1991).

7.2 Biological environment

7.2.1. Wintermonsoon

Vertical and horizontal distribution of chlorophyll *a* and PP in the BOB during different season showed similarity to the observations by many earlier researchers (Gomes *et al.*, 2000 and Madhu *et al.*, 2001). During winter monsoon, surface chlorophyll *a* varied from 0.01 – 0.2 mg m^{-3} and in most of the stations maximum phytoplankton biomass was in the upper 50m water column. Maximum column chlorophyll *a* (16 mg m^{-2}) was found at the middle station along 15°N. This latitudes were influenced by a subsurface cold core eddy, which was centered around 15°N, 84°E and the signatures were evident up to 40m depth. However in other latitudes (11, 13, 17, and 19°N) the eddy signatures were found at much deeper depths and hence could not influence the biology of the upper euphotic column. Subsurface eddies in the Bay of Bengal were reported earlier by Swallow (1983) and Babu *et al.*, (1991). Normally, eddies lead to an enhancement of biological production through the rectified upwelling of nutrients (McGillicudy & Robinson, 1997 and Oschiles & Garcon, 1998). In addition the eddy transfer heat which results in shallowing of mixed layer which in turn can lead to bloom through biota experiencing more light (Levy *et al.*, 1999). But this is particularly significant when upwelled nutrients are available in the surface layers.

During the season, primary production at the surface waters varied from 1 – 10.5 mgC m^{-2}. Maximum primary production was found at the coastal station along 15°N where the cold core eddy signatures were present and maximum average primary production also was along 15°N. Here the eddy signatures were found at relatively shallower depth and were prominent up to 40m depth along this transect. Maximum average primary production value was present along 15°N where cold core eddy signatures where prominent at relatively shallow depth. But the enhanced biological production observed in the present study at the location of the eddy (16 mg m^{-2}) was moderate compared to the other productive regions of the Indian Ocean like the upwelling regions of the west coast (88 mg m^{-2}) and winter convective regions (34 mg m^{-2}) of the northwest coast of India (Bhattathiri *et al.*, 1996). The moderate level of biological production may due to the fact that the eddy was prominent in the subsurface waters, which could not bring considerable amount of nutrients in to the surface waters (upper euphotic column) where sufficient amount of solar radiation is present. Vertical distribution of PP during the season showed higher values below the surface (10m depth) in most of the stations. This observation overrules the opinion of Qasim (1977) that through out the year maximum primary productivity in the Bay of Bengal is seen at the surface due to the lack of photo inhibition. Average mesozooplankton biomass during the period was maximum (776 mgC m^{-2}) among different seasons. During the study, maximum zooplankton biomass was found in the southern region and that could be due to the relatively higher primary production and chlorophyll *a* biomass existing in the region during the season. Higher average zooplankton biomass observed in the coastal stations along the southern region and that might be due to the river water plumes as suggested by Madhupratap *et al.*, (1993).

7.2.2. Spring intermonsoon

It is interesting to note that during inter monsoon spring, chlorophyll *a* at the surface varied from 0.01 – 0.03 mg m^{-3}, which is relatively lower than the other two seasons and this could be mostly due to the strong and extended stratification in the surface layers during the season. Chlorophyll *a* data derived from satellite

presented by Gomes *et al.*, (2000) clearly indicated very low concentration in the offshore regions of the BOB. Except along 20.5°N, chlorophyll *a* concentration was relatively less and the maxima found were at deeper depths (50 – 75m). Gomes *et al.*, (2000) presented almost similar seasonal vertical distribution pattern of chlorophyll *a* and he found subsurface chlorophyll (SCM) maxima at 60 – 80 m depth during inter monsoon spring especially in the offshore stations and the measurements using radiometer clearly indicated that effective solar radiation during inter monsoon spring was optimum compared to the other two seasons. Murty *et al.*, (2000), also found subsurface chlorophyll maxima at 50 – 100m depth during the period in the offshore regions of the study area. Latitudinal variations of chlorophyll *a* and primary production were minimum during the season, which further indicate the lack of strong physical processes that could alter the stratification of the surface waters. Primary production values at the surface varied from 1-12.3 mgC m^{-3} d^{-1}. Like winter monsoon, upper 20m water column had maximum primary production.

In general, during inter monsoon spring zooplankton biomass was considerably less in the entire study area (Avg. 406 mgC m^{-2}) and this could be explained by the hypothesis by Cushing (1989) and subsequently supported by Yentch and Phinney., (1989 and 1995) based on the observations on the seasonal variations in the cell size of phytoplankton from the tropical regions using Flow cytometry. They proposed that in strongly stratified water column, phytoplankton with smaller cell size contribute majority of the standing stock and is important in tropical regions including northern Arabian Sea (Yentch and Phinney, 1995). This hypothesis has particular significance in Bay of Bengal due to the oligotrophic nature around the year as result of stratification, which is maximum during spring inter monsoon. This was clearly indicated in the vertical distribution of physical and chemical parameters during the present study. Hence majority of phytoplankton in Bay of Bengal during spring intermonsoon could be contributed by smaller sized phytoplankton.

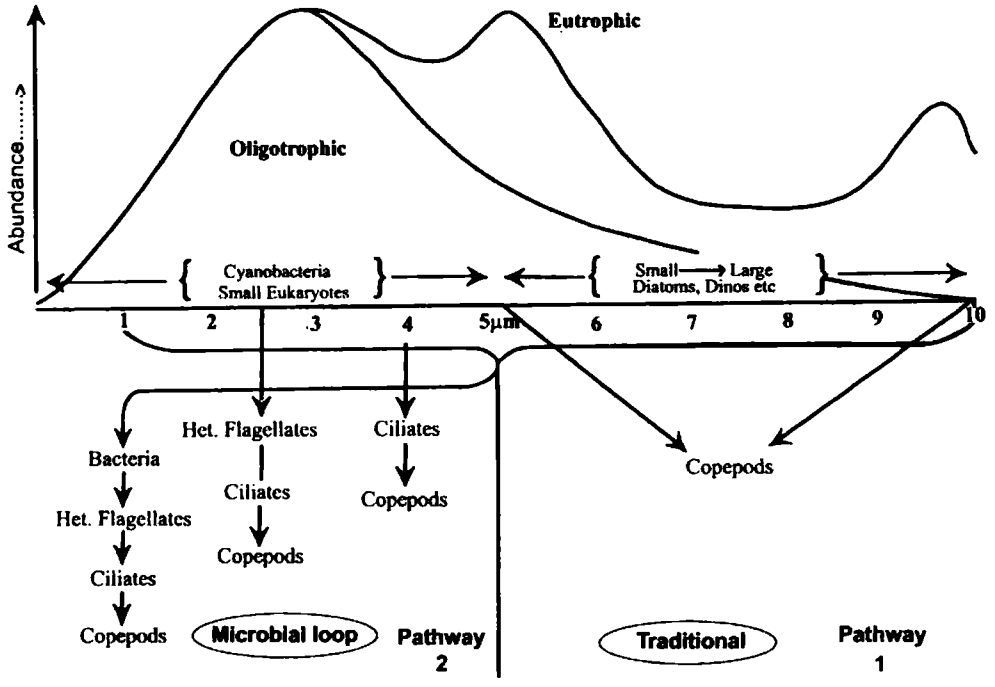


Figure 7.1. Phytoplankton cell size spectra (0.2 - 10µm) for oligotrophic and eutrophic populations. Smaller cells are found in both regions but support a complex food web in oligotrophic (stratified) waters. Large cell sizes occur in eutrophic waters where grazing by copepods is the fate of their production (reproduced from Yentch. C.S and Phinney D.A, 1995). Two curves at the top of the figure were generated from assessing phytoplankton cells using Flow cytometry Yentsch.C.S and Phinney. D.A, 1989)

The observations of Marshall (1973) that copepods and other zooplankton are unable to crop the smaller sized algae efficiently point out the intermediate role played by the microzooplankton in transferring primary biomass to mesozooplankton (Pathway 2). When considering the trophic transfer efficiencies of Cushing (1975), the energy, which transferred from primary level to the mesozooplankton, is less in Pathway 2 compared to Pathway 1. Hence it can be hypothesized that due to strongest stratification during spring intermonsoon, Pathway 2 may be dominant over pathway 1 and hence less amount of primary energy reaches mesozooplankton and this could be the reason for the low mesozooplankton biomass during the period.

7.2.3. Summer monsoon

During summer monsoon, chlorophyll *a* at the surface was relatively higher and varied from 0.09 – 0.8 mg m^{-2} and higher concentration was found in the surface layers and below 20m there was a decrease with increasing depth. Gomes *et al* (2000) found nearly a five-fold increase in offshore chlorophyll *a* value

compared to the intermonsoon spring. During the season, maximum column chlorophyll *a* was found along 15°N where upwelling was found towards the coastal region. During the season, maximum surface production varied from 1 – 45.8 mgC m^{-3} d^{-1} and maximum (45.8 mgC m^3 d^{-1}) was found at the coastal stations along 19°N. Column production also was maximum (556 mgC m^2 d^{-1}) at the coastal station along 19°N followed by the coastal station along 15°N (470 mgC m^2 d^{-1}). It is interesting to note that the column chlorophyll *a* maximum and primary production maximum did not exactly match each other. Gomes *et al.*, (2000) observed similar situations along the upwelling stations of the Bay of Bengal and this anomalous feature could be due to the limitation of light. During the season, higher primary production was found in the surface layers and below 20m there was a marked decrease. In the northern region (from and north of 15°N) all the stations showed maximum PP at the surface.

The phytoplankton standing stock and primary production observed at the location of upwelling during the present study (45.8 mg m^{-3} and 470 mgC m^{-2} d^{-1} respectively) was considerably lower than the upwelling regions of the Arabian Sea during the same period (88 mg m^{-3} and 1760 mgC m^{-2} d^{-1}) (Bhattathiri *et al.*, 1996). This indicates that the intensity of upwelling and its manifestations on biological productivity is considerably less along the east coast of India compared to the Arabian Sea.

The lack of deep subsurface chlorophyll *a* maxima during summer and winter monsoon could be due to the limitation of light on phytoplankton growth and production. Light limitation may partly due to the thick cloud coverage and increased suspended sediments through river discharge during the season. During the present study the mean attenuation coefficient of the water column during summer (0.084) and winter monsoon (0.070) were considerably higher than spring intermonsoon (0.048) when BOB is under optimum illumination by solar radiation illuminated by optimal solar radiation. The effect of light as a limiting factor on phytoplankton growth in the BOB had been the subject of discussion even in the past. Qasim (1977) suggested that intense cloud cover over the BOB might explain

the absence of photo inhibition at the surface. Similar findings were discussed by Radhakrishna *et al* (1978 a & b) and they reported maximum productivity at the surface compared to the other depths sampled in the euphotic zone, which indicated the absence of photo inhibition at the surface waters. They also reported reduced euphotic zone in the inshore areas of BOB that ranged from 6 – 40 m and 40 – 75m in the offshore during summer monsoon, indicating the extend of light limitation during the season. In the present study also euphotic zone showed considerable variations during different seasons. Average coastal and offshore euphotic zone depths were considerably lower during summer monsoon and this was maximum during spring intermonsoon. Gomes *et al.,* (2000) and Madhu *et al.*, (2001) showed the lack of deep subsurface chlorophyll *a* maximum during summer and winter monsoon in the BOB. Similar to the present study, their study showed maximum chlorophyll *a* at much shallower depths during winter and summer monsoon (generally with in the upper 50m water column). Gomes *et al.,* (2000) also calculated the primary production per unit chlorophyll *a* (mgC mg Chl a^{-1} d^{-1}) and found that it was lower during summer and winter compared to spring intermonsoon. The surface irradiation measurements using radiometer clearly indicated that effective solar radiation during summer and winter monsoon is lower than intermonsoon spring Average mesozooplankton biomass during the season was 676 mgC m^{-2} and relatively higher biomass was found in the northern region and this could be due to the influence from river water plumes as suggested by Madhupratap *et al.*, (1993) and Parson & Kessler (1986).

7.3. Microzooplankton

7.3.1. Biocomposition

During the study, microzooplankton community was composed of both protozoans and some larval stages of invertebrate metazoans. Protozoans were the most dominant group in terms of abundance and biomass. Protozoans present in the samples were heterotrophic dinoflagellates, ciliates, acantherians, radiolarians and foraminifers. Among these protozoans, heterotrophic dinoflagellates and ciliates were the most common and the individual contributions of sarcordines

(radiolarians, acantherians and foraminifers) were minor. Mangesh *et al.*,1996 & Mangesh, 2000) found a similar biocomposition for the microzooplankton community in the northern Arabian Sea.

Heterotrophic dinoflagellates were the most abundant group of organisms, which contributed maximum in the microzooplankton community irrespective of the seasons. Its percentage contributions to the total abundance of microzooplankton ranged between 62 and 77%, 48 and 75% and 57 and 73% during winter, inter and summer monsoon respectively. Maximum average contribution of dinoflagellates was during winter (69%) followed by summer (65%) and the least (60%) during inter monsoon season. Earlier Mangesh *et al.*, (1996) and Mangesh (2000) found that the heterotrophic dinoflagellates were the most dominant organisms contributing up to 64% of the community but he did not address the taxonomic composition of this important group. He expressed the need for including this important group in future studies of microzooplankton from these regions. Information is also available on the importance of heterotrophic flagellates as a major component of microzooplankton from the other parts of the world ocean. Earlier work on microzooplankton has shown that heterotrophic dinoflagellates form 40% to 70% of the total standing stock in the coastal regions of northern Atlantic Ocean (Gaines and Elbrachter, 1987; Hansen, 1991a) and subtropical waters (Lessard, 1991). In the review on this group, Lessard (1991) calculated that heterotrophic dinoflagellates accounted for 22 – 67 % of the protozoan biomass in the subtropics and 75 – 97 % in polar waters. The present observations in which heterotrophic dinoflagellates found between 48 and 75% compromises with Lessard's data and slightly higher than the data reported in Arabian Sea (Mangesh, 2000). Similar ranges were also recorded by Burkill *et al.*, (1993a) in northeastern Atlantic Ocean, which varied between 50 and 75%. This in turn suggests that the relative contribution of heterotrophic dinoflagellates to the protozooplankton may become progressively important in higher latitudes and open tropical waters although this may not be the case in estuaries (Mangesh *et al.*, 1996). In the present study, altogether 12 genera and 57 species of heterotrophic dinoflagellates were

identified and the photomicrographs are presented as Plates and are first of its kind from the Indian waters.

During the present study on microzooplankton it was found that the dinoflagellates contributed about 65% of the total numerical abundance. However, no serious attempts have been made to discuss their mode of nutrition and its ecological advantage. Considering the relatively high numerical abundance of the study area, it will be worth discussing on the different modes of nutrition of this group. Bay of Bengal often reported to be a low productive system is considered in this context. Organisms that are able to withstand or overcome the oligotrophic condition may possibly have a better chance of survival in these regions. Most of the oceanic dinoflagellates are colourless heterotrophic forms (Taylor *et al.*, 1987). Recent studies on heterotrophic dinoflagellates showed that they could use numerous specialized mechanisms for heterotrophy (reviews by Kimor, 1981; Gains and Elbrachter, 1987; Hansen, 1991a; 1992; Lessard, 1991). In addition to uptake of dissolved organic substances (Droop, 1959 a & b; Lee, 1977; Morril & Loeblich, 1979) there are at least three types of dinoflagellate phagotrophy (uptake of particulate food). Some dinoflagellates ingest entire cells, resulting in prey organisms (often other dinoflagellates) being visible inside of, and digested with in the predatory dinoflagellate (Norris, 1969; Smetacek, 1981; Uhling and Sahling, 1990; Strom & Busky., 1991; Nakamura *et al.*, 1992). Other dinoflagellates exude an extracellular pseudopodial pallium, which captures diatoms and other prey outside the dinoflagellate cell (Jacobson & Anderson, 1986). Prey is often larger than the dinoflagellate predator, but they are digested extracellularly with prey cell contents transported through the membranous pallium to the dinoflagellate (Gains and Taylor, 1984). A third type of dinoflagellate heterotrophy is where prey cell contents are sucked out through an extruded peduncle (feeding tube), which the dinoflagellates attach to the prey (Spero & Moree, 1981; Spero, 1982; Hansen, 1991b). In the case of two heterotrophic species of the dinoflagellates genus *Dinophysis* (Hansen, 1991b), the dinoflagellate can attach a peduncle to the ciliate *Tiarina fusus* which itself feeds up on autotrophic species of Dinophysis by

engulfing them. In an apparent case of mistaken identity, the ciliate attempts to ingest the heterotrophic *Dinophysis*, which instead attaches a peduncle to the ciliate and kill it by vaccuming out its cell contents. Thus, the initially predatory ciliate becomes the prey of the dinoflagellates it tried to eat. In another example of dinoflagellate predation up on ciliates, Bockstahler and Coats (1993) found that three species of red tide forming dinoflagellates from the Chesapeake Bay are frequent predators of oligotrichs and other ciliates, diatoms and other dinoflagellates. Perhaps, the most interesting example of dinoflagellate heterotrophy yet revealed is that of an undescribed "phantom" dinoflagellate from estuarine waters of North Carolina (Burkholder *et al*, 1992). These dinoflagellates remain encysted in sediments until live fish or fish excreta are present. The dinoflagellates then excyst as motile photosynthetic vegetative cell that kills fish with powerful toxins. While doing so it completes its sexual cycle, with gametes encysting and sinking back to the sediments after fish are no longer present. However, while still in the ephemeral motile stage, the dinoflagellates extrudes a peduncle which it uses to feed on bits of sloughed off tissue from dead or dying fish.

There are other reports of dinoflagellate predation up on metazoans, or at least their reproductive products. Dinoflagellate of the genus *Noctiluca* is well-known phagotrophic predators of phytoplankton and microzooplankton (Anderson & Sorensen, 1986 and Elbrachter, 1991), and they also ingest copepod eggs (Kimor, 1979 and Daan, 1987). In some cases it has been estimated that half to three fourths of the reproductive output of a copepod population was consumed by *Noctiluca* (Sekiguchi & Kato, 1976 and Daan, 1987). Since copepods are among the most frequent predators of dinoflagellates, it is ironic that a dinoflagellate may be a major predator up on the progeny of its most likely predator. From the above discussion it becomes obvious that the dinoflagellate can feed on a variety of organisms including bacteria, phytoplankton, heterotrophic protists and even metazoans and this could enable them to become abundant and ubiquitous protists in marine environments. Furthermore many of the dinoflagellates can live by

establishing symbiotic associations with cyanobacterial cells called 'phaeosomes' (Taylor, 1982 & 1990). This diverse mode of nutrition of dinoflagellates may be the reason for their higher abundance in the study area. It is felt that the role of advantageous modes of nutrition discussed in the present study for the abundance of dinoflagellates in the Bay of Bengal merit more detailed studies targeting its ecological significance.

In the present study, ciliates were the second dominant group of organisms in the samples. Its percentage contribution varied 4 - 33%, which was close to the ranges obtained from off southern California (18 – 32%, Beers and Stewart, 1967; 1970) and lower than Northern Adriatic (12-52%, Revelante and Gilmartine, 1983). However, Mangesh *et al.*, (1996) showed relatively higher contribution of ciliates (24 – 58%) during his studies in the Arabian Sea and that could be due to the higher phytoplankton standing stock in the Arabian Sea. Leaky *et al.*, (1996) found a general relationship between ciliate biomass and phytoplankton biomass in the Arabian Sea and he explained that many ciliates are herbivorous, feeding on both cyanobacteria and algae (Pierce & Turner, 1992; Bernard and Rassoulzadegan, 1993). Indeed, ciliates and phytoplankton biomass have been shown to be positively correlated in marine waters (Lynn & Montagnes, 1991). Although some smaller ciliates may graze picoplankton-sized cells (Rassoulzadegan *et al.*, 1988 and Sheer and Sherr, 1987), ciliates are not considered to be major bacterivores in oceanic waters (Pierce & Turner, 1992). The correspondence between ciliate biomass and bacterial biomass and production is therefore likely to reflect their common utilization of phytoplankton derived food and substrate. However it may also reflect an indirect predator prey relationship between ciliates and bacteria via grazing on bacterivorous nannoflagellates (Verity, 1986a).

During the study, tintinnid ciliates were the most dominant groups among ciliates followed by aloricates. Tintinnid ciliates had representation from 35 genera with 78 species. Literature available on nutritional requirements of tintinnids, shows that they mostly feed on pico and nannoplankton groups[37-40]. Aloricate ciliates were numerically less compared to tintinnid ciliates and represented by 5

genera and 12 species. Dominance of loricate ciliates (tintinnids) over aloricate ciliates were contrary to the results obtained by Leaky *et al.*, (1996) and Mangesh *et al.*, (1996) in the Arabian Sea and they found that the aloricate ciliates represents maximum in the samples followed by tintinnids. Leaky *et al.*, (1996) further observed that the abundance of ciliates were considerably less in low productive areas of the study region and showed clear dependency of microzooplankton on phytoplankton biomass. However Mangesh (2000) found strong positive relationship between bacterial and aloricate abundance suggesting bacterivorous feeding habit to aloricates. But it is a known fact that phytoplankton biomass in the Bay of Bengal is considerably less compared to the Arabian Sea throughout the year. In the present observation the total microzooplankton abundance in the Bay of Bengal was considerably less than that of the Arabian Sea, which may be directly linked to the low productivity of the BOB throughout the year. This information infers that the low concentration of phytoplankton standing stock may be the reason for the observed low aloricate abundance during the study. Another reason for the low densities of aloricates in the Bay of Bengal could be due to the low salinity observed at the surface layers. Low salinity is reported as an important factor, which decrease aloricate ciliates in the estuaries where their abundance is lower than tintinnids (Mangesh, 2000). Bay of Bengal is known for its low saline waters at the surface and the northern part of the Bay of Bengal is particularly is a semi-estuarine system. In addition to this, the regions all along the coast are influenced by the freshwater influx from various rivers.

During the present study Genus *Tintinnopsis* was the most dominant form among the loricate ciliates in the coastal waters, because this genus requires fine sand grains or mineral flakes for constructing loricae. However, abundance of these particles generally decreases as they move away from the shore (Mangesh, 2000). Other protozoans present in the samples belong to three different groups namely radiolarians, acantherians and foraminifers. Collectively their numerical abundance was 9% during winter monsoon, 8% during inter monsoon and 7% during summer monsoon.

7.3.2. Temporal and spatial (vertical) variations

During the present study, maximum average column density of microzooplankton was observed during spring intermonsoon (701 x 10^4 m^{-2}) followed by summer (575 x 10^4 m^{-2}) and winter monsoon (350 x 10^4 m^{-2}). Column biomass showed similar distribution with maximum biomass (228 mgC m^{-2}) during inter monsoon followed by summer (152 mgC m^{-2}) and winter monsoon (103 mgC m^{-2}). This seasonal pattern of distribution was similar to the observation made by Mangesh *et al.*, (1996) along the western Arabian Sea and Revelante and Gilmartin (1983) in the northern Adriatic Sea and found great variability in abundance between relatively mixed and stratified periods as observed in the present study. In their studies abundance of microzooplankton during stratified condition was much higher than the mixed period. A study by Suzuki and Taniguchi (1998) also reported large temporal and spatial variability in abundance of microzooplankton in the western Pacific. Suzuki and Taniguchi (1998) also reported great temporal variability in microzooplankton abundance in north Pacific, Subtropical North Pacific and off eastern Australia. Availability of food concentration as well as the temperature is reported to be the key factors, which influence microzooplankton distribution (Heinbokel 1978 b; Taniguchi & Kawakami 1983; Verity 1986 b; Godhantaraman, 2001). During the present study maximum sea surface temperature was found during spring intermonsoon. However, phytoplankton standing stock during the period (Avg.13.8 mg m^{-2}) was lesser than summer monsoon (18.14 mg m^{-2}). Hence, higher average microzooplankton abundance during spring intermonsoon could be explained by the higher temperature and increased abundance of smaller phytoplankton during strongly stratified periods as suggested by (Cushing, 1989; Yentch & Phinney (1995); Aksnes and Egge, (1991); Pomeroy, 1974; Johnson and Sieburth (1979); Platt (1983); Li *et al.*, 1983). During spring intermonsoon stratification of water column in the Bay of Bengal was maximum and 1μM contour of nitrate was found below 50m. According to the recent understanding, this is the ideal condition where cyanobacteria and smaller diatoms dominate the phytoplankton standing stock and

Pathway 2 of the food web substantially dominates over pathway 1 (Figure 7.1). Two blooms of cyanobacterium, *Trichodesmium erythraeum* observed in the oceanic regions of the Bay of Bengal during the present study give biological evidence for the strong stratification prevailed during the period. Marked increase in the ciliate abundance during spring intermonsoon compared to the other two seasons provide further support to the observation by Cushing, 1989, Yentch and Phinney (1995) that during stratified conditions smaller sized diatoms and cyanobacteria dominate the phytoplankton standing stock which result in the increase of microzooplankton. Available information on the feeding requirement suggests that ciliates could not feed efficiently on large sized phytoplankton and usually prefers phytoplankton, which is smaller than their lorica diameter (<40μm) (Revelante & Gilmartin (1983), Paranjape (1990), Rassoulzadegan *et al.*, (1981). A recent study by Bernard and Rassoulzadegan (1993) observed that many tintinnid ciliates consume mostly *Synechococcus* (cyanobacteria), nanoplankton and picoflagellates for their nutrition. Hence optimum temperature and availability of smaller phytoplankton during the period could be the reason for the observed increase of microzooplankton abundance during spring intermonsoon. But confirmation of this hypothesis can only be done after the seasonal measurement of phytoplankton cell size using Flow cytometry.

Summer monsoon showed higher surface density of microzooplankton (Avg. 175 x 10^4 m^{-2}) compared to inter monsoon (Avg. 43 x 10^4 m^{-2}) and winter monsoon (Avg. 43 x 10^4 m^{-2}). Surface biomass of microzooplankton also showed similar trends with higher concentration during summer (46 mgC m^{-2}) followed by spring intermonsoon (17 mgC m^{-2}) and winter monsoon (13 mgC m^{-2}). During summer, phytoplankton biomass was mostly confined to the surface layers due to light limitation and relatively higher temperature and this could be the reason for the higher abundance of microzooplankton at the surface during the season. But due to limitation of light, phytoplankton biomass in the deeper depths were considerably less during the period and this in turn resulted in low microzooplankton abundance at deeper depths. On the contrary during winter,

microzooplankton abundance decreased considerably in the surface layers of the northern region even though the phytoplankton biomass at the surface was relatively higher than spring intermonsoon. This could be due to the low temperature at the surface layers of the northern transects. Temperature limitation on the abundance of microzooplankton is mainly reported from the temperate regions. Recently, Godhantaraman *et al.*, (2001) found that 6°C temperature drop during winter compared to the summer resulted in substantial reduction in the ciliate abundance in the Japanese waters. Though, the SST in the northern region showed only around 3°C drop at the surface during winter compared to the other seasons, it caused considerable reduction in the abundance of ciliates. Low temperature (3 - 4°C drop compared to the other season) in the surface along with low phytoplankton standing stock in deeper waters could be the reason for the low microzooplankton column abundance and biomass in the northern region which ultimately resulted in low average values for the entire area.

It is logical to consider that during summer monsoon higher density of microzooplankton at the surface was due to the increased phytoplankton biomass and optimum temperature at the surface. This means that the two key factors, which are reported to be limiting microzooplankton distribution, were optimum during the season. Decrease in microzooplankton abundance towards depth is apparently due to the low concentration of phytoplankton biomass due to the limitation of light.

A study by Leaky *et al.*, (1996) described that ciliate abundance was largely dependant on phytoplankton standing stock in the central and northwestern Arabian Sea. If this happens during winter monsoon, naturally microzooplankton abundance in the northern Arabian Sea (north of 17°N) would be high due to the higher phytoplankton biomass existing in that region resulting from winter convection. Interestingly, Mangesh (2000) reported only an average minimum of microzooplankton column density in the AS especially in the northern region during winter monsoon. This conveys the fact that temperature limitation on microzooplankton abundance is also apparent in the northern regions of the Arabian Sea during winter.

Generally, vertical distribution of microzooplankton during different seasons showed high concentrations in the upper layers (75m - surface). With in the upper layers clear seasonal fluctuations were found, which was corresponding to the distribution of phytoplankton standing stock. During summer and winter monsoon higher numerical abundance was found at the upper 20m water column below which it decreased with increasing depth. This could be due to the concentration of phytoplankton biomass in the surface layers during the season. During inter monsoon higher microzooplankton abundance and biomass was found at relatively deeper depths (50 – 75m) and was corresponding to the higher phytoplankton standing stock at respective depths. Close associations between vertical distribution of ciliate abundance and phytoplankton chlorophyll a was reported globally by many earlier researchers (Beers and Stewart 1970 & 1971, Lynn and Montagnes, 1991), which support the present observation. Statistical analysis showed that during different seasons number of species of ciliates decreased steadily from spring intermonsoon to winter through summer reducing to nearly 50 % of the species, with 62 % richness, 67 % concentration, and 78% species diversity.

Vertical distribution of different groups of microzooplankton showed variations during different seasons. During winter and summer monsoon dinoflagellates showed a decreasing trend from the surface. This indicates the higher range of tolerance of dinoflagellates to temperature during winter. Interestingly, ciliates showed more or less uniform distributional pattern during winter with very low abundance in the surface layer, which points out that during the season ciliate distribution in the surface layers were severely limited by the relatively low temperature particularly in the northern regions. Numerical abundance of ciliates during the season were comparable with the densities of other protozoans and micro metazoans, which usually represented in very low densities through out the study. During summer monsoon ciliates showed a decreasing trend in abundance from surface to bottom in almost all the stations. This could be due to the higher concentration of phytoplankton biomass at the surface layers.

Distribution of dinoflagellates showed increased densities in the subsurface layers during spring inter monsoon compared to the other two seasons. But the change in the distribution of ciliates was more prominent during the period. During the season ciliate concentration in the 20 - 75m water column increased considerably compared to the other seasons. At many stations other protozoans and micrometazoans also showed higher densities in the subsurface layers. This apparently is due to the higher concentration of phytoplankton biomass at the deeper depths.

Inferences from statistical analysis shows that maximum number of species, diversity and concentration of microzooplankton was during spring intermonsoon. This supports the general pattern of microzooplankton distribution during spring intermonsoon.

7.3.3. Microzooplankton herbivory

Herbivory studies during winter monsoon at four locations in the surface waters (5m) of southern Bay of Bengal indicated that herbivory ranged between 1.8 – 7.9 $\mu gC\ l^{-1}\ d^{-1}$ (Avg.5$\mu gC\ l^{-1}\ d^{-1}$), which indicated that major portion of (average 72%) of the phytoplankton standing stock was grazed by microzooplankton. In deeper depths (40m), herbivory ranged between 3.3 – 4.8 $\mu gC\ l^{-1}d^{-1}$ (Avg. 4$\mu gC\ l^{-1}\ d^{-1}$) and on an average 63% of the phytoplankton standing stock was grazed daily by microzooplankton. This result agrees with the earlier works from the different parts of the world oceans, which revealed that microzooplankton grazing is highly important for the transfer of primary organic material to the higher trophic levels.

James and Hall (1998) studied the grazing rates of microzooplankton on total phytoplankton, picophytoplankton and bacteria in Sub Tropical, Sub Tropical Convergence and Sub Antarctic waters in winter and spring of 1993. They found that the grazing impact on total chlorophyll *a* standing stock and phytoplankton production ranged from 10 - 92% in winter and 4 - 57% in spring, respectively. The abundance of microzooplankton was generally higher in spring than winter. Grazing by microzooplankton is known to be quantitatively significant (Burkill *et*

al., 1987; 1993 a & b; Verity, 1990, 1993 a&b) because of their key role in the microbial system where they graze on particles of varying sizes. This allows the incorporation of a greater proportion of the primary production into the food chain. Microzooplankton is capable of consuming a significant proportion of primary production (Frost, 1991), which is reported to be of 40-70% of the total primary production (Riley *et al.*, 1965; Beers and Stewart, 1970) in the tropical Pacific. Indeed, field experiments have demonstrated that microzooplankton consumes between 10 and 75% of daily primary production (Garrison, 1991; Pierce and Turner, 1992). Similar studies (Capriulo and Carpenter, 1983; Cosper and Stepien, 1982) have shown that certain components of the microzooplankton community alone would have consumed 20-100% of primary production. Burkill (1982), Capriulo and Carpenter (1983) and Verity (1987) found that the tintinnids are responsible for the consumption of ~30% of the annual primary production, a value of the same order of magnitude as those consumed by copepods. In the present study the relationship between ambient chlorophyll *a* concentration and herbivorous activity showed a linear relationship ($r = 0.921$, $n = 8$, $p < 0.05$), which indicates the dependency of microzooplankton on phytoplankton biomass.

7.3.4. Some ecological aspects of microzooplankton

7.3.4.1. Relationship with phytoplankton standing stock

In the present study, correlation between microzooplankton biomass and chlorophyll *a* during different seasons showed significant linear relationship ($p < 0.05$) during all the seasons. During all the seasons dinoflagellates and ciliates had linear relationship to phytoplankton biomass and the magnitude changed during different seasons. During winter and summer monsoon when higher concentration of chlorophyll *a* was available in relatively shallower depth, dinoflagellates were more closely related to phytoplankton biomass compared to the ciliates. Higher linear relationship between ciliates and phytoplankton during spring intermonsoon could due to the increased abundance of smaller phytoplankton during the season, which is proved as the preferential food of ciliates. During the present study, dinoflagellates were relatively more concentrated in the surface layers through out

the year. But ciliates proliferate in deeper depths when sufficient phytoplankton biomass is available in deep, which was clear from the vertical distribution during spring intermonsoon.

7.3.4.2 Symbiotic associations with cyanobacteria

Symbiotic associations were found in three genera of dinoflagellates namely *Ornithocercus*, *Histioneis* and *Parahistioneis*. These dinoflagellates hosted clusters of cyanobacteria - rod, ovoid or spherical shaped (*Synechococcus* and *Synechocystis*, Norris 1967 and Taylor 1982 & 1990) located between the 'lists' the cells. Normally *Synechococcus* and *Synechocystis* (Cyanobacteria) inhabit extracellularly is referred as phaeosomes (Taylor, 1982; Norris, 1967). But the ecological advantage of these associations in the waters of nitrogen limitation received scientific attention recently (Gordon, 1994).

During the present study, the percentage occurrence symbiotic association was maximum (97%) during spring intermonsoon, relatively less during winter (13%) and summer (11%). More over the abundance of these heterotrophic genera increased five times during spring intermonsoon compared to the other season. This seasonal shift in the frequency of occurrence of this association is directly linked to the oligotrophy of the water column arisen from strong and prolonged stratification during intermonsoon. In the Bay of Bengal, stratification of water column is maximum during spring intermonsoon where nitracline was usually below 50m depths.

Normally cyanobacterial cells dominate in the nitrate depleted (strongly stratified) environment (Gordon, 1994; Johnson and Sieburth., 1979; Platt, 1983) and *Trichodesmium* is one among them, which proliferate in such environments. During the present study also, two blooms of *Trichodesmium erythraeum* were observed at different regions of the study area, which is an indication of the oligotrophic nature of the water column.

The possible ecological advantage of the symbiotic association between heterotrophic dinoflagellates and cyanobacterium during prolonged oligotrophic

condition is very significant (Norris, 1967). *Ornithocercus, Histeonis* and *Parahisteonis* are heterotrophic organisms, which live osmotrophically (by absorbing dissolved organic compounds) (Droop, 1974). During the period of prolonged nitrogen limitation, abundance of cyanobacterial cells increases in the water column and the dinoflagellates allow them to inhabit between their girdles. By doing this heterotrophic dinoflagellates get organic substances from the cyanobacteria and in turn the latter get a micro environment which is relatively reducing and thought to be advantageous to carry out the nitrogen fixation.

7.3.5. Comparison with microzooplankton and mesozooplankton biomass

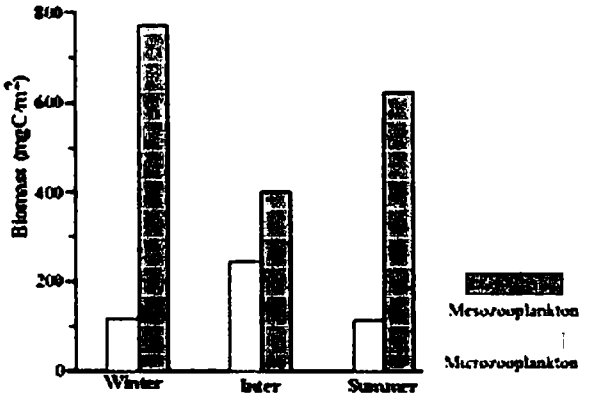


Figure 7.2. Comparison of biomass between microzooplankton and mesozooplankton during different seasons

During the present study, comparison between microzooplankton and mesozooplankton biomass convey some interesting results. During summer and winter mesozooplankton biomass was markedly higher. But during these seasons microzooplankton biomass was relatively less. But during intermonsoon period mesozooplankton biomass was considerably low although microzooplankton biomass was maximum during the season.

Present observation is contrary to the observation by Madhupratap *et al.*, (1996) in the Arabian Sea that high mesozooplankton biomass is supported by increased microzooplankton biomass during spring intermonsoon. But from the

present study it become obvious that, although microzooplankton biomass increases during intermonsoon spring, it is not sufficient enough to support higher mesozooplankton biomass especially in conditions of strong stratification. A logical reason for the present observation could be drawn from the observations of Cushing (1989) and Yentch & Phinney (1995) (Figure. 7.1) which suggest that in stratified conditions food web is more complex (pathway 2) and hence primary organic carbon reaches higher trophic level less efficiently (Azam *et al.*, 1983). The consequence of pathway 2 is the distribution of photosynthetic carbon at multitrophic levels (widely dispersed) with a long residence time in the upper layers of the ocean. Though the Bay of Bengal is oligotrophic through out the year there are some regions that are moderately productive during summer and winter due to the upwelling process, river runoff and eddies which becomes evident in the present study. But during spring intermonsoon entire region was strongly stratified and hence the latitudinal variations of primary productivity was minimum during the period. From these observations it could be concluded that due to the relatively mixed surface layers during summer and wintermonsoon traditional pathway (Pathway 1) of the food web dominates (Figure 7.1) in the Bay of Bengal (at least in some regions). This results in the efficient transfer of primary food to the mesozooplankton and could be the possible reason for the higher mesozooplankton biomass during summer and winter monsoon. Another reason for higher mesozooplankton biomass during summer and winter may be due to the river water plumes as suggested by Parson and Kessler (1986) and Madhupratap *et al* (1993). These results suggest that in the Bay of Bengal, microzooplankton could not be considered as an alternative source when phytoplankton biomass and productivity remain low, instead as a key component, which transfers organic carbon from smaller sized phytoplankton and bacteria to mesozooplankton through out the year but more crucial during spring intermonsoon when water column is strongly stratified. Presently, global implications of the two pathway systems (Figure 7.1) are of major concern to ocean ecologists and geochemists. In regions where pathway two dominates, the transfer of photosynthetic carbon is complex due to the

interactions at the multitrophic levels. The consequence is that carbon becomes widely dispersed with long residence time in the upper layers of the ocean. In regions where pathway 1 dominates, the photosynthetic carbon is transported directly to the primary herbivore in a straight shot.

During the present study microzooplankton density and biomass was maximum during spring intermonsoon (most stratified period). This is a common observation in many other parts of the world ocean during strong and prolonged stratification (Mangesh *et al.*, 1996; Mangesh, 2000; Revelante & Gilmartin, 1983; Suzuki & Taniguchi, 1998). The opinions of Marshall (1973) found that copepods and other zooplankton are unable to crop small sized algae efficiently further signify the trophic importance of microzooplankton in the Bay of Bengal. Results from the grazing studies showed that >60% of the daily primary productions are consumed by microzooplankton during winter monsoon in the southern region. From the above discussion it can be concluded that even though the total abundance and biomass of microzooplankton in the BOB is less compared to AS, the trophic role played by them is crucial by transferring the organic carbon from small sized phytoplankton and bacteria to mesozooplankton which is significant in the context of the general oligotrophy of the BOB. Being the first study on microzooplankton from the open waters of Bay of Bengal, the present observations are also relevant as base line information from these regions. Hence future studies on this subject should include the phytoplankton cell size measurements using Flow cytometry and also the seasonal fluctuations in the grazing pressure of microzooplankton on phytoplankton biomass along with the routine qualitative and quantitative measurements of microzooplankton.

Chapter 9

Summary and conclusion

A study of the microzooplankton community along the east coast of India in relation to environmental parameters is presented. Paucity of information from Indian waters and the upsurge of interest on these organisms in recent years around the globe are the reason for selecting this topic.

Most of the available literature on microzooplankton community from the Indian waters covers tintinnids, normally from the estuarine and very coastal environments along east coast of India. Present study is the first of its kind, which addresses microzooplankton as a heterogeneous community consisting of ciliates, heterotrophic dinoflagellates, sarcordines and micrometazoans. Moreover photomicrographs of all identified species of microzooplankton (135 species) are presented in the thesis that will be of help to future researchers on this particular group.

During sampling, microzooplankton were collected from 17 stations along 6 latitudinal transects from the EEZ of India along the east coast of India during three cruises of FORV *Sagar Sampada* representing winter monsoon (November – February), spring intermonsoon (March – May) and summer monsoon (June – September). From each station 7 discrete standard depths were selected up to a depth of 150 m (surface, 10, 20, 50, 75, 100, 120 and 150m) and altogether around 350 samples of microzooplankton were collected and analysed during the study.

Other biological parameters like phytoplankton standing stock (chlorophyll *a*), primary production and mesozooplankton biomass were also studied along with environmental parameters like temperature, salinity, dissolved oxygen, nitrate, silicate and phosphate.

During the study, winter monsoon showed marked latitudinal variations in sea surface temperature (SST) with minimum in the northernmost transect (20.5°N) due to the increasing intensity of winter towards north. Sea surface salinity showed clear coastal – offshore variations where low saline waters (<30 psu) prevailed

along the entire coast due to the heavy river discharge in to the bay from Indian peninsula. Minimum value of sea surface salinity (SSS) was observed at the coastal stations along 15,19 and 20.5°N where the salinity was considerably influenced by the Krishna (near 15°N) and Ganges - Mahanadi (19 and 20.5°N) river discharges. During the period, fluctuations of mixed layer depth were mostly related to the intensity of salinity stratification.

The vertical salinity structure in the upper layers showed clear frontal structures (2-5 psu gradients in the upper layers) towards the coast especially along the transects which were near to the river mouths due to the freshwater discharges. Higher attenuation coefficient (low transparency) was found along the coastal transect due to high suspended and particulate materials arisen from the river discharge. During winter monsoon, due to atmospheric cooling in the northern region, low saline surface layers attains low temperature but fails to impart it to the deeper waters due to the lack of sinking which results in strong thermal inversion. Another significant feature during the period was the subsurface cold core eddy with high salinity, nutrient, and low dissolved oxygen waters, which was mostly intense below the surface layers and the reason is reported to be the peculiar circulation pattern during the period. The eddy signatures were more prominent along the middle stations of the study area and 1 μM contour of nutrients (nitrate and silicate) was found at relatively shallow depths (~40m) in these stations.

During winter monsoon, surface chlorophyll *a* varied from 0.01 – 0.2 mg m^{-3} and in most of the stations maximum phytoplankton biomass was in the upper 50m water column. Maximum column chlorophyll *a* (16 mg m^{-2}) was found at the middle station along 15°N where the eddy signatures were prominent. Maximum primary production was found at the coastal station along the same transect (15°N). But the enhanced standing sock of phytoplankton observed in the present study at the location of the eddy (16 mg m^{-2}) was moderate compared to the other productive upwelling regions of the southwest coast (88 mg m^{-2}) and winter convective regions (34 mg m^{-2}) of the northwest coast of India.

Vertical distribution of primary production during the season showed higher values below the surface (10m depth) in most of the stations. This finding differs from the opinion of Qasim (1977) that through out the year maximum primary productivity in the Bay of Bengal is occurring at the surface due to the lack of photo inhibition. Average mesozooplankton biomass during the period was maximum (776 mgC m-2) among different seasons. Higher zooplankton biomass was found in the southern region, and this could be due to the relatively higher primary production and phytoplankton biomass existing in the region during the season.

During spring intermonsoon, spatial variability of SST was minimum due to the maximum solar radiation during the period. Strong East Indian Coastal current (EICC), which flows poleward during the season pushes the low saline waters away from the coast and hence low saline waters were found about 200 – 400km away from the coast. Warm and low saline waters in the oceanic regions provide stratified surface layers and shallow MLD along most of the oceanic regions. Strong stratification that inhibits surfacing of nutrients from deeper waters (below 50m) results in the absence of nutrients in the surface layers during the period.

During the period, chlorophyll *a* at the surface varied from 0.01 – 0.03 mg m^{-3}, which was relatively lower than the other two seasons and this could be mostly due to the strong and prolonged stratification in the surface layers during the season. Latitudinal variations of chlorophyll *a* and primary production were minimum during the season, which further indicate the lack of strong physical processes that could alter the stratification of the surface waters.

Primary production values at the surface varied from 1-12.3 mgC m^{-3} d^{-1}. Similar to winter monsoon, upper 20m water column had maximum primary production during the period. Zooplankton biomass was considerably less in the entire study area (Avg. 406 mgC m^{-2}) and this was explained by the recent understanding on the seasonal variations in the cell size of phytoplankton proposed by Cushing (1989) and substantiated by Yentch & Phinney (1995) using flow cytometry measurements.

Warmer SST was observed during summer monsoon compared to winter monsoon. Relatively low saline waters were present in the northern region due to the maximum rainfall and river runoff along these regions during the period. MLD showed north – south gradients due to the influence of freshwater and was relatively thicker along the southern region (30 - 60m).

Signatures of upwelling such as relatively colder waters at the surface layers, shallow mixed layer and nitracline (upsloping of isolines) near to the coast were observed along 15°N due to the prevailing southwesterly winds that give rise to southeastward Ekman transport at the surface. But the upwelled waters found during the study remained as a narrow band as reported by Shetye *et al.*, (1993).

During summer monsoon, chlorophyll *a* at the surface was relatively higher and varied from 0.09 – 0.8 mg m^{-3} and higher concentration was found in the surface layers and below 20m there was a decrease with increasing depth due to the limitation of light. During the season, maximum column chlorophyll *a* was found along 15°N where upwelling was found towards the coastal region where maximum phytoplankton standing sock was observed (45.8 mgC m^3 d^{-1}).

The phytoplankton standing stock and primary production obtained at the location of upwelling during the present study (45.8 mg m^{-3} and 470 mgC m^{-2} d^{-1} respectively) was considerably lower than the upwelling regions of the Arabian Sea during the same period (88 mg m^{-3} and 1760 mgC m^{-2} d^{-1}) (Bhattathiri *et al.*, 1996). This indicates that the intensity of upwelling and its manifestations on biological productivity is considerably less along the east coast of India compared to the west coast of India.

During the present study the mean attenuation coefficient of the water column during summer (0.084) and winter monsoon (0.070) were considerably higher than intermonsoon spring (0.048), which shows that maximum water column transparency was during spring intermonsoon. Average mesozooplankton biomass during the season was 676 mgC m^{-2} and relatively higher biomass was

found in the northern region, which could be due to the high primary productivity and the influence from river water plumes

During the study, microzooplankton community was composed of both protozoans and some larval stages of invertebrate metazoans. Protozoans were the most dominant group found in terms of abundance and biomass. Protozoans present in the samples were heterotrophic dinoflagellates, ciliates, acantherians, radiolarians and foraminifers. Among these protozoans, heterotrophic dinoflagellates and ciliates were the most common and the individual contributions of sarcordines (radiolarians, acantherians and foraminifers) were minor.

Heterotrophic dinoflagellates were the most abundant group of organisms, which contributed maximum of the microzooplankton community irrespective of seasons. Its percentage contribution to the total numerical abundance of microzooplankton community ranged between 62 and 77%, 48 and 75% and 57 and 73% during winter, inter and summer monsoon respectively. Dominance of dinoflagellates in the microzooplankton community may be due to the diverse and advantageous modes of nutrition of this group, which were discussed in detail.

Ciliates were the second dominant group of organisms in the samples. Its percentage contribution varied 4 - 33%, which was close to the ranges obtained from many other parts of the world oceans. During the study, tintinnid ciliates were the most dominant groups among ciliates followed by aloricates. 35 genera and 78 species of Tintinnid ciliates were identified during the study. Aloricate ciliates were numerically less during the present study compared to tintinnid ciliates and represented by 5 genera and 12 species.

Genus *Tintinnopsis* was the most dominant form among the loricate ciliates in the coastal waters, because this genus requires fine sand grains or mineral flakes for constructing loricae. However, abundance of these particles generally decreases as they move away from the shore. Other protozoans present in the samples belong to three different groups namely radiolarians, acantherians and foraminifers. Collectively their numerical abundance was 9% during winter monsoon, 8% during inter monsoon and 7% during summer monsoon

Temporal variation of microzooplankton showed maximum average column density of microzooplankton during spring intermonsoon (701 x 10^4 m^{-2}) followed by summer (575 x 10^4 m^{-2}) and winter monsoon (350 x 10^4 m^{-2}). Column biomass showed similar distribution with maximum biomass (228 mgC m^{-2}) during inter monsoon followed by summer (152 mgC m^{-2}) and winter monsoon (10^3 mgC m^{-2}).

During the present study maximum sea surface temperature was found during spring intermonsoon, but the phytoplankton standing stock was maximum during summer monsoon (18.14 mg m^{-2}) compared to spring intermonsoon (Avg.13.8 mg m^{-2}). Higher average microzooplankton abundance during intermonsoon is explained by the maximum temperature and increased abundance of smaller sized phytoplankton during strongly stratified periods as suggested by Cushing (1989) and Yentch and Phinney (1995). Two blooms of cyanobacterium, *Trichodesmium erythraeum* observed in the oceanic regions of the Bay of Bengal during the present study give biological evidence for the strong stratification prevailed during the period.

Marked increase in the ciliate abundance during spring intermonsoon compared to the other two seasons provide theoretical support to the observation by Yentch and Phinney (1994) that during stratified conditions smaller sized diatoms and cyanobacteria dominate the phytoplankton standing stock. Available information on the feeding requirement ciliates suggests that it could not feed on large sized phytoplankton and usually prefers phytoplankton, which is smaller than their lorica diameter (nanoplankton). Hence optimum temperature and availability of smaller phytoplankton during the period could be the reason for the observed increase of microzooplankton abundance during spring intermonsoon.

Summer monsoon showed higher surface density of microzooplankton (Avg. 175 x 10^4 m^{-2}) compared to inter monsoon (Avg. 43 x 10^4 m^{-2}) and winter monsoon (Avg. 43 x 10^4 m^{-2}). Surface biomass of microzooplankton also showed similar trends with higher concentration during summer (46 mgC m^{-2}) followed by spring intermonsoon (17 mgC m^{-2}) and winter monsoon (13 mgC m^{-2}). During summer the phytoplankton biomass was mostly confined to the surface layers due

to limitation of light and relatively higher temperature was available at the surface and this could be the reason for the higher abundance of microzooplankton t the surface during the season.

On the contrary during winter, microzooplankton abundance decreased considerably in the surface layers of the northern region even though the phytoplankton biomass at the surface was moderate. This could be due to the low temperature at the surface layers that pronounced in the northern transects where more than 3°C drop of temperature was observed compared to other seasons.

Generally, spatial (vertical) distribution of microzooplankton during different seasons showed high concentrations in the upper layers (75m - surface). Within the upper layers clear seasonal fluctuations were found, which was corresponding to the fluctuations of the chlorophyll distribution. During summer and winter monsoon higher density was found at the upper 20m water column due to the higher concentration of phytoplankton biomass in the surface layers during the season. However during spring intermonsoon higher microzooplankton abundance and biomass was found at relatively deeper depth (50 – 75m) and was corresponding to the higher phytoplankton standing stock at these depths.

Spatial (vertical) distribution of different groups of microzooplankton showed variations during different seasons. During winter and summer monsoon dinoflagellates showed a decreasing trend from the surface. However during winter, ciliates showed more or less uniform distributional pattern with very low abundance in the upper water column. This indicates that during the season ciliate distribution in the surface layers was severely limited by relatively low temperature. During summer monsoon ciliates showed a decreasing trend in abundance from surface to bottom in almost all the stations. This could be due to the higher concentration of phytoplankton biomass at the surface layers. However during spring intermonsoon, ciliate concentration in the 20 - 75m water column increased considerably compared to the other seasons. This was apparently due to the higher concentration of phytoplankton biomass at the deeper layer due to the higher solar radiation during the period.

Herbivory studies during winter monsoon showed that more than 60% of phytoplankton standing stock was grazed daily by microzooplankton along the southeast coast of India. This is the first information ever available on the grazing pressure of phytoplankton on microzooplankton from the Indian waters

Correlation between microzooplankton biomass and chlorophyll *a* during different seasons showed significant positive relationship during all the seasons. However, higher significant relationship between ciliates and chlorophyll *a* during spring intermonsoon could be due to the increased abundance of smaller phytoplankton during the season as suggested by Yentsh and Phinney (1992).

Dinoflagellates were relatively more concentrated in the surface layers throughout the year. But ciliates increased markedly in deeper depths when sufficient phytoplankton biomass was available, which was clear from the vertical distribution during spring intermonsoon.

Symbiotic associations were found in three genera of dinoflagellates namely *Ornithocercus*, *Histioneis* and *Parahistioneis*. These dinoflagellates hosted clusters of cyanobacteria – rod, ovoid or spherical shaped (reported as Synechococcus / Synechocystis) located between the upper and lower lists of the horizontal groove of the cells. The percentage occurrence of symbiotic association was maximum (97%) during inter monsoon spring, relatively less during winter (13%) and summer (11%). More over the abundance of these symbiotic genera increased five times during spring intermonsoon compared to other seasons. This seasonal shift in the frequency of occurrence of this association could be directly linked to the oligotrophy of the water column caused from strong and prolonged stratification during spring intermonsoon.

Comparison between microzooplankton and mesozooplankton biomass showed some interesting results. During summer and winter, mesozooplankton biomass was markedly higher although microzooplankton biomass was relatively less. But during intermonsoon period mesozooplankton biomass was considerably less though microzooplankton biomass was higher during the season.

This suggests that, although microzooplankton biomass increases during intermonsoon spring, it is not sufficient to support higher mesozooplankton biomass especially in conditions, where phytoplankton biomass and productivity are low. This logically indicates that in the Bay of Bengal, microzooplankton can not be considered as an alternative source when phytoplankton biomass and productivity remain low, instead as a key component, which transfers organic carbon from small sized phytoplankton and bacteria to mesozooplankton. This trophic role of microzooplankton is particularly significant in the context of the general oligotrophy of the Bay of Bengal.

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