Studies on Secondary production in the Bay of Bengal:- A Seasonal approach with special emphasis on planktonic decapods

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Under the
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by

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Declaration

I hereby declare that the thesis entitled "Studies on Secondary production in the Bay of Bengal:-A Seasonal approach with special emphasis on planktonic decapods" is an authentic record of the research carried out by me, under the supervision of Dr. C. Revichandran, Scientist-EII, National Institute of Oceanography, Regional Centre, Kochi-18 in partial fulfilment of the requirement for the Ph.D degree of the Cochin University of Science and Technology under the faculty of Marine Sciences and that no part of this has been presented before for any other degree, diploma or associateship in any university.

Kochi-18
04/01/2010

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Certificate

I hereby certify that the thesis entitled "Studies on Secondary production in the Bay of Bengal:-A Seasonal approach with special emphasis on planktonic decapods" submitted by Jayalakshmi K. J., Research Scholar (Reg.No.2898), National Institute of Oceanography, Regional Centre, Kochi-18, is an authentic record of research work carried out by her under my supervision, in partial fulfilment of the requirement for the Ph.D degree of Cochin University of Science and Technology under the faculty of Marine Sciences and that no part thereof has been previously formed the basis for the award of any degree, diploma or associateship in any university.

Kochi - 18
04/01/2010

Dr. C. Revichandran
(Supervising guide)

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Chapter 1

INTRODUCTION

The oceans occupy three-fourth of the earth's surface and are a vast reservoir of living and nonliving resources. It directly or indirectly provides food and livelihood to millions of people in the coastal states and elsewhere. Developing countries, like India, earn considerable revenue through the exploitation and marketing of marine living resources. United Nations Convention on Law of the Sea (UNCLOS) has set forth rights and obligations of the nations and furnishes international regulations to pursue sustainable development of marine and coastal areas. An essential pre-requisite for the effective management and utilization of these resources is the scientific knowledge on the biological production and its optimum exploitation of the ecosystem.

1.1 Biological production

Biological production is the incorporation of new organic matter into the living tissue (*ie, biomass elaboration*). It can be quantified by tropho-dynamic approach to the foodweb. In the marine ecosystem, the photosynthetic components (phytoplankton) constitute the lower trophic level, comprising the primary producers. Zooplankton constitutes the secondary producers. The next levels consist of tertiary producers such as fishes and top level predators. The balance of marine ecosystem is maintained by two controlling mechanisms namely 'bottom-up' and 'top-down' control. In bottom-up control, the supply of nutrients determine the production (classical food chain), whereas in the top-down control the filter feeding microzooplankton which effectively grazes the microbial community gets finally connected to the classical food chain (Microbial loop). The classical food chain dominates in the eutrophic waters and microbial food web in oligotrophic waters (Fig. 1). Mostly, only 10% of energy is transferred between trophic levels, and these results in a rapid decline in biomass in each successive level (Fig. 2). The size of organisms generally increase towards higher trophic level, but there will be a reduction in their fecundity rate and numerical abundance lead to the consequent reduction in biomass.

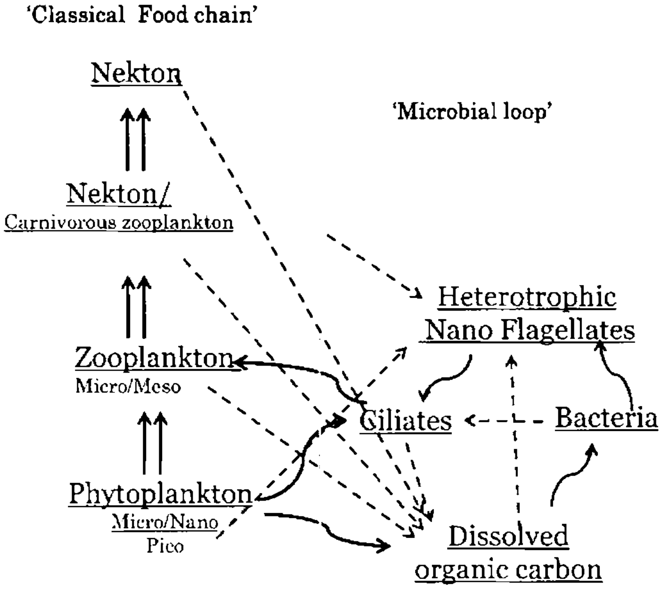
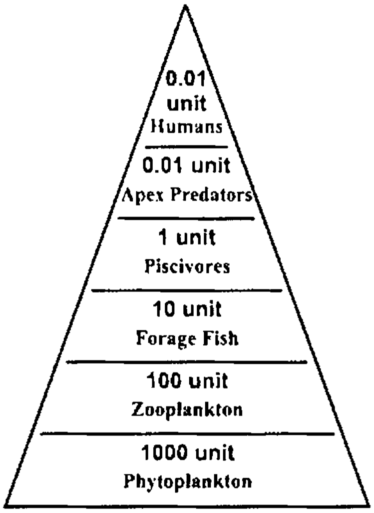


Fig. 1 Marine food web structure with microbial loop

Zooplankton (secondary producers), affect the ocean carbon budget as consumers and regulators of phytoplankton, as prey for other animals and through generation of sinking organic matter. Their role is important because they reflect the magnitude of primary production and it also provides information on tertiary production (fishery potential). Detectable changes in the abundance or species composition of zooplankton may reflect fundamental changes in the ocean environment affecting phytoplankton (Clark, 1992). Zooplankton are tiny, floating or drifting heterotrophic animals which ultimately depend on phytoplankton for their dissolved or particulate foodstuffs (Burkill *et al.*, 1993; Lenz *et al.*, 1993; Landry *et al.*, 1995). Generally, zooplankton are capable of independent movement vertically (vertical migration), whereas their horizontal movement is primarily determined by water currents. These animals inhabit all layers of ocean down to the greater depths (Banse, 1964). They play a pivotal role in ocean biogeochemical fluxes (Banse, 1995) through export of material from euphotic zone (Dam *et al.*, 1995; Le Borgne and Rodier, 1997). The vertical transfer of carbon from surface waters to the deeper waters and sediments through food webs, physical mixing, transport and gravitational settling are referred to collectively as the "biological pump". The overall effect of the biological pump is the sinking of atmospheric carbon dioxide (CO_2) in surface waters, thereby resulting in the drawdown of atmospheric CO_2 along a concentration gradient from the atmosphere to the surface waters of the ocean (Longhurst, 1991; Seigenthaler and Sarmiento, 1993). Therefore, the structure of zooplankton community has profound effect on the carbon cycle, composition and sinking rate of particles. Many of the zooplankton are relatively short-lived, they are capable of high growth rates and they respond quickly to environmental perturbations.



If transfer efficiency is 10%

Fig. 2 Energy pyramid in the successive trophic levels.

1.2 Zooplankton classification and composition

From the beginning of quantitative plankton research as early as 100 years ago, Schutt (1892) made the first attempt to classify zooplankton based on their size. Though their size ranges from a few µm (tiny flagellates) to 2 m (giant jelly fishes), the earliest, most simple and acceptable categorization was micro, meso and macroplankton. Afterwards many alterations or revisions were made by the planktonologists in the basic categorization. Sieburth *et al.*, (1978) put forward an accordant system of size classification which became widely accepted by researchers and is greatly in use (Table I). According to his classification, the zooplankton ranges over five size-classes, from nanoplankton to megaplankton. Heterotrophic nanoflagellates having 2-20 µm constitutes nanoplankton. Other protozoans like ciliates belong to the next size class, the microzooplankton (20-200 µm). Mesozooplankton size varies from 0.2 to 2 mm, comprising of copepods, ostracods, decapods, chaetognaths etc. The next two size categories are macrozooplankton (2-20 cm) and megazooplankton (20-200 cm) which includes large jelly fishes, siphonophores, scyphozoans, pyrosoma *etc.*

Table 1 Size classification of zooplankton (Sieburth *et al.*, 1978).

Name	Size spectrum	Example
Nanoplankton	2 to 20 µm	Nanoflagellates
Microzooplankton	20 to 200 µm	Ciliates, dinoflagellates *etc.*
Mesozooplankton	0.2 to 20 mm	Copepods, ostracods, larval forms of decapods, fish larvae *etc.*
Macrozooplankton	20 mm to 20 cm	Hydromedusae, ctenophores, euphausiids etc
Megazooplankton	20 to 200 cm	Jelly fishes, pelagic tunicates, pyrosoma *etc.*

Based on their mode of life, zooplankton are classified into holoplankton, meroplankton and tycoplankton (Raymont, 1983; Omori and Ikeda, 1992). Species spending their whole life as plankton in the pelagic realm are termed as holoplankton (copepods, ostracods, chaetognaths, siphonophores *etc.*). Animals which spend the early part of their life as plankton are grouped under meroplankton (decapod larvae, fish larvae and other invertebrate larvae). Meroplankton either grows into swimming capability as nekton or settles to the seafloor becoming benthos (Lenz, 2000). The tycoplankton occur predominantly in shallow waters, especially in estuaries, and includes animals such as mysid and other crustaceans that spend part of the day/night cycle as plankton and also includes benthic species that are swept into suspension from the bottom by strong currents or storms, such as some harpacticoid copepods, gammarid amphipods, cumaceans, isopods *etc.* (Raymont, 1983).

Generally, the dominant zooplankton groups are categorised into crustacean plankton and gelatinous plankton. The crustacean plankton are represented by the following taxa, *ie,* Cladocera, Ostracoda, Copepoda, Mysida, Amphipoda, Euphausiacea and Decapoda. The second abundant group is gelatinous plankton, which includes Cnidaria (hydromedusa, siphonophores and scyphomedusae), Ctenophora, and Tunicata (pyrosoma, doliolods, salps and appendicularians). Other groups, not belonging to crustacean or gelatinous zooplankton are pteropods, chaetognaths, fish larvae *etc.* Copepoda under Crustacea is the most successful zooplankton taxon which mostly accounts for ~75 to 80% of zooplankton community, and has a cosmopolitan distribution.

The history of investigation on zooplankton in the Indian Ocean dates back to 1857, when the ship *Novara* engaged 52 stations along 40°S eastward upto 80°E meridian, along 85° meridian northwards upto Madras and eastward upto Sumatra. In the later half of 20th century, full coverage of the area was brought out during International Indian Ocean Expedition (IIOE), on the distribution and zoogeography of various groups (UNESCO, 1965-72, IOBC, 1968-73, 1969-73, Zeitschell, 1973; Rao, 1979; Panikker and Rao, 1973, UNESCO, 1988). Later some lacunas were identified due to the inadequacy of coverage or insufficiency of samples. However, IIOE studies have provided the most extensive data on zooplankton and formed a baseline for further investigations. After IIOE, several studies were carried out in the Indian Ocean including the Arabian Sea (AS) and the Bay of Bengal (BoB) (Qasim, 1977; Nair *et al.*, 1977; Peter and Nair, 1978). The general hydrography and circulation of the BoB have been studied by (Varkey *et al.*, 1996). Being a more biologically productive basin, the AS has been well studied in its physical, chemical and biological aspects during the last two decades including the carbon flux studies (JGOFS 1990). In contrast to the AS, the biological oceanographic studies, especially on the plankton community, in the BoB is very limited (Achuthankutty *et al.*, 1980; Nair *et al.*, 1981; Rakesh *et al.*, 2006). Recent studies have revealed that BoB lacks seasonality in phytoplankton biomass (chlorophyll *a*) and primary production as observed in its counterpart, the AS (Madhu, 2004). Jyothibabu (2004) and

Jyothibabu *et al.,* (2006, 2008) have elucidated the importance of microzooplankton and their role in the overall biological production in the BoB. Significance of various physical processes and their relevance in the biology were considered by PrasannaKumar *et al.,* (2004a) and Muraleedharan *et al.,* (2007). Studies on secondary production, abundance and composition of mesozooplankton in the BoB were attempted by Panikkar and Rao (1973); John and Radhakrishnan (1977); Achuthankutty *et al.,* (1980); Nair *et al.,* (1981); Krishnakumari and Gowsamy (1993) and Madhuprathap *et al.,* (2003). Muraleedharan *et al.,* (2007) depicted characteristic features of the summer monsoon and prevailing physico-chemical features, and their influence on biological aspects. Even though so many studies were carried out in the BoB, information on the seasonal variability of mesozooplankton standing crop and its composition is still fragmentary. Since the oceanographic features of northern Indian Ocean undergo seasonal and annual changes, the strategy adopted for the present study is to cover all the seasons both horizontally and vertically to understand the pattern of variation. Only a multidisciplinary study can explain the biological production, particularly the primary and secondary production and its implications on the ecosystem.

1.3 Bay of Bengal: General characteristics

Biological productivity in the northern Indian Ocean is amongst the highest of all the oceans on the planet (Baars and Oosterhuis, 1997). The BoB is a unique basin located in the northern Indian Ocean (5 to 23°N and 80 to 100°E), and it is connected to the Pacific Ocean through the Strait of Malacca and the Australian seaways. It is a semi enclosed basin covering an area of 4.087×10^6 km^2 which accounts for 0.6% of the world oceans (La Fond, 1966), surrounded by the Indian peninsula and Sri Lanka in the west, and Andaman and Nicobar Islands and Myanmar in the east. Though, the basin is located in the monsoon belt, it comes under the influence of semiannual seasonality (Ramage, 1971) due to the differential heating and cooling of the land and sea. During winter monsoon (November to February), the winds are weak (~5 m/s) blowing from the northeast. This wind brings cool and dry continental air to the BoB. In contrast, during summer monsoon (June to September) the strong (~10 m/s) southwest winds bring humid maritime air into the BoB. The surface circulation of the basin reverse semi annually which is not strictly in accordance with the wind reversal. The reversal of surface circulation brings about marked changes in the hydrography of the upper waters. During the winter monsoon, when the winds are still northeasterly, the current along the western boundary reverses and flows northward. This is called East Indian coastal current (EICC), which peaks during March-April (spring intermonsoon), when the winds are weak and possess anticyclonic curls (Shetye *et al.*, 1993).

The special feature of the basin is the very high fluvial inputs through some of the largest rivers of the world (Milliman and Meade, 1983) like the Ganga and the Brahmaputhra. The other major Indian rivers that drain into the BoB are the Mahanadi in the northern, the Godavari and the Krishna in the central, and the Cauveri in the southern region. There are also a number of minor rivers flowing through the various geological formations of the Indian subcontinent and draining in to the Bay (Fig. 3). Subramanian (1993) estimated that rivers of Indian subcontinent alone contribute about 13.86×10^6 tonnes of terrigenous material annually to the BoB. The excessive river run off (1.625×1012 m^3y^{-1}) into the BoB (Subramanian, 1993) and rainfall leads to a positive water balance (P-E=0.8 m y^{-1}, Ramanathan and Pisharody, 1972). Run off from the Indian rivers to the BoB plays a critical role in the process of monsoon intensification by creating and sustaining low a salinity layer on top of the BoB (Rajamani, 2005). The riverine influx is one of the main source of nutrients for the biological production in the oceanic surface layers (Ittekkot *et al.*, 1991; Honjo *et al.*, 1987; Jennerjahn and Ittekkot, 1999). The sediment load associated with riverine input appears to scavenge biogenic material from the surface layer into the deep with higher sinking fluxes in the BoB (Nair *et al.*, 1989; Ittekkot *et al.*, 1991; Haake *et al.*, 1993; Ramaswami and Nair, 1994; Unger *et al.*, 2003). Due to the rapid sinking rate of particles, most of the nutrient is unavailable to the biotic community and thus, the BoB is traditionally considered as a less productive system (Radhakrishna *et al.*, 1978; Bauer *et al.*, 1991; Brock *et al.*, 1991; PrasannaKumar *et al.*, 2001a, 2002; Madhupratap *et al.*, 2003; Madhu *et al.*, 2006). Upwelling in the BoB is very weak, but cyclonic storms enhance local chlorophyll biomass and primary production (Rao and Sastry, 1981; Madhu *et al.*, 2002; Vinayachandran and Mathew, 2003). However, the massive freshwater influxes result in strong vertical stratification, which impedes the vertical transfer of nutrients to the surface, leading to low biological production.

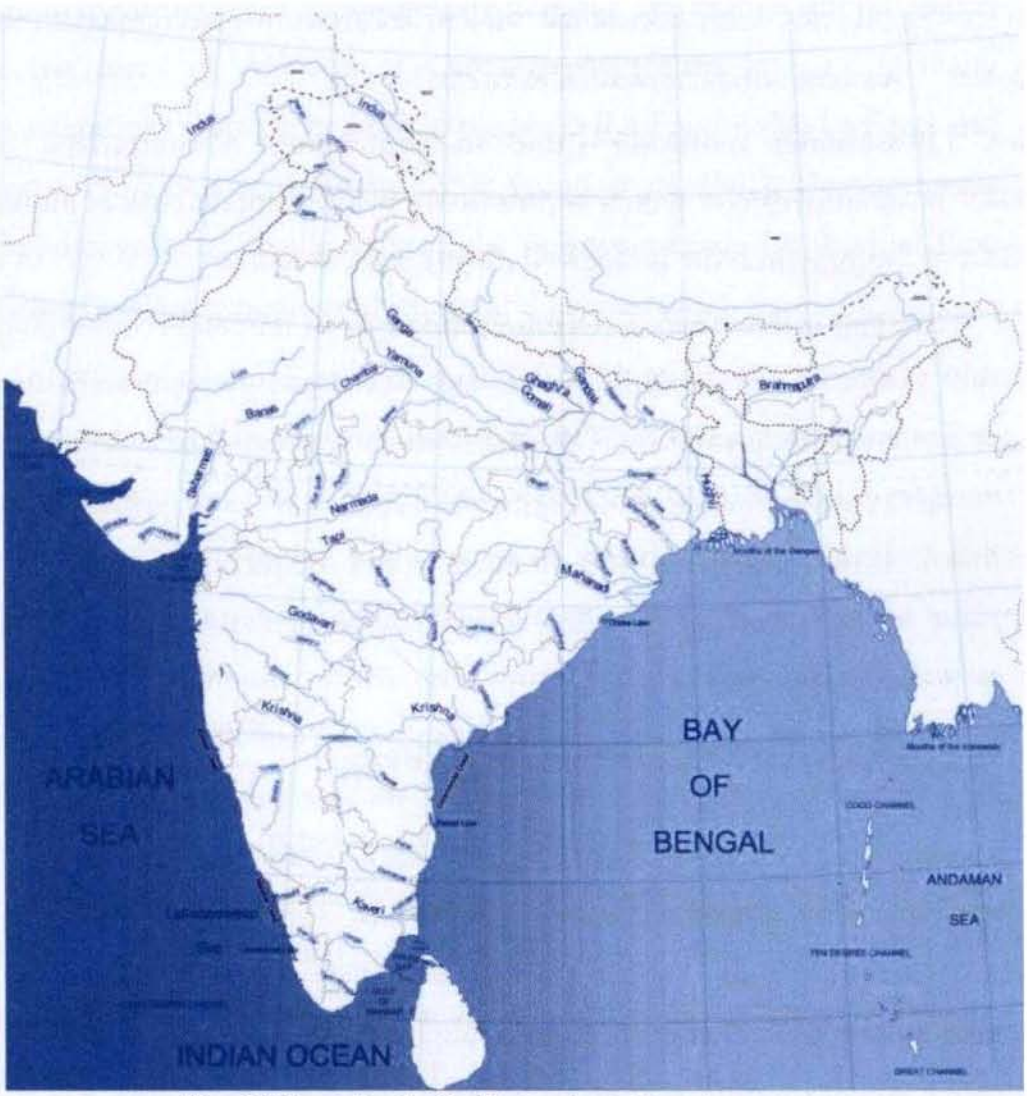


Fig. 3 Rivers in the Indian subcontinent

Depending on the monsoon (arrival and retrieval) and its associated environmental characteristics, the northern Indian Ocean experiences seasonality. The four seasons addressed are:-

1. **Spring intermonsoon (March to May):** The water column becomes more stabilised by thermal stratification. Hot weather prevails with occasional violent local storms accompanied by violent winds, torrential rain, *etc.*
2. **Summer monsoon (June to September):** Characterized by southwesterly winds and resultant heavy rainfall; bulk of annual rainfall in India is received during these months.
3. **Fall intermonsoon (October):** Intensity of rainfall becomes much less. Low pressure zones are developed, which sometimes intensify into cyclonic storms. Generally a season of transition.
4. **Winter monsoon (November to February):** A period when sea surface loses heat to the atmosphere; consequently, surface water becomes colder, bringing heavy rain, particularly in the northern regions of the BoB.

1.4 Previous studies in the Bay of Bengal

The oceanographic study of the basin began in the later part of the 19th century, with the expeditions of *Novara* (1857-59) and *Valdivia* (1898-99). Later, the *John Murray expedition* (1933 -1934) onboard the Egyptian vessel *Mahabiss* provided information on oceanographic features of the basin. Sewell (1925, 1928, 1929, 1932) analysed and documented the data collected onboard *RMIS Investigator* in several reports of the *Memoirs of Asiatic Society of Bengal*. His reports on surface temperature distribution in relation to wind forcing and plankton studies formed classic literature in the history of Indian marine research.

In 1950s, Prof. La Fond studied the physical oceanography, nutrient chemistry and sediment in the BoB which formed another important step in the progress of oceanography in India. The studies got published in the form of *Memoirs of Oceanography.* Since late 1950, many investigations were carried out in the basin (La Fond, 1954; La Fond and Sastry, 1957; Balaramamurthy, 1958; Varadachari, 1961). Measurements of photosynthetic productivity in the BoB were made for the first time during *Galathea* expedition (Neilsen and Jensen, 1957).

The most significant study in the 20th (1962-1965) century was International Indian Ocean Expedition (IIOE). It was a comprehensive programme, including fish and plankton distribution, primary production, and benthic populations in addition to the physical and chemical parameters of Indian Ocean. Considering the BoB alone, prior to IIOE, the amount of scientific work was meager but there after considerable work has been done from time to time. The objective of IIOE study was to survey the Indian Ocean, investigating its physical, chemical and biological oceanography, marine geology and marine geography. Earlier lack of systematic survey and limited number of cruises in the BoB had created lacunae, especially in the northern region. After IIOE, oceanographic programmes like Indian Ocean Experiment (INDEX, 1979), Bay of Bengal Process Studies (BOBPS, 2000- 2006), Bay of Bengal Monsoon Experiment (BOBMEX) *etc.* intensively explored the basin to understand the various oceanographic processes. The prevailing rough weather conditions during monsoon months (storms, cyclones, etc) make it difficult to carry out continuous oceanographic observation in the BoB. Among the recently implemented programmes, Bay of Bengal Process Study (BOBPS) and Marine Research on Living Resources Phase I (MR–LR) are the two programmes which have spatial and seasonal coverage in the BoB. BOBPS notably parameterised two longitudinal sections (one parallel to the coast and the other along the central region 87°E) of the Bay.

1.5 Aim and Scope of the study

The fishery potential of the basin can be effectively estimated through the assessment of successive trophic levels. Zooplankton standing stock was therefore taken into consideration as an index of commercial fishery. In India, it is a fact that the marine resources provides livelihood for a good percentage of the population. According to a recent study, the estimated demand for marine fish for human consumption alone is placed at 5 million tonnes by the year 2020 (CMFRI, 1997). The concept of Exclusive Economic Zone (EEZ) and its sustainable exploitation and management has recently got more attention in developing countries like India to meet their future protein needs. The Indian EEZ has an area of 2.02million km^2 covering the east and west coasts including the island systems. The BoB occupies an area of 5,15,500 km^2 of the total EEZ of the country. Four states and one Union Territory of India, viz, West Bengal (157 km), Orissa (476 km), Andhra Pradesh, Tamil Nadu and Pondicherry (938 km) share the eastern coastline and continental shelf areas of 20,0000, 5,000, 31,000 and 35,000 km^2 respectively. Coastal population of these maritime states and Union Territory depend directly or indirectly on this basin for their livelihood, and thus BoB play an important role in the economy and development of India. The BoB supports a rich marine life, which mainly consists of fishes and crustaceans, besides other resources like molluscs, corals, sponges, echinoderms, seaweeds *etc.*

To enrich the country's economy through proper management of marine living resources around Exclusive Economic Zone, Govt. of India implemented a multidisciplinary project entitled "Marine Research on Living Resources" (MR-LR) during IXth and Xth five year plans (MR-LR I and MR-LR II respectively) through leading scientific institutions of the country. The Kochi Regional Centre of National Institute of Oceanography was identified as the nodal agency of this project to evaluate the physico-chemical and biological features of the seas around India for the purpose of formulating proper management of resources in the EEZ of the country. The present study forms a part of the MR-LR II.

The earlier studies had emphasized the presence of classical and microbial foodweb along the basin on a seasonal scale (Gauns *et al.*, 2005 and Jyothibabu *et al.*, 2006). In both the food webs, mesozooplankton play an important role and thus ultimately determine the overall biological production. The present study is accordingly an attempt to explore the spatial and temporal variations of hydrographical and biological parameters in the BoB, particularly on secondary production.

The main objectives of the study are;

1. to study the seasonal variations in the biological productivity and associated ecology of the BoB.

2. to examine the spatial and temporal distribution of secondary producers especially mesozooplankton and their role in the biological production.
3. to study the composition of mesozooplankton community and contribution of different mesozooplankton taxa.
4. to evaluate the diurnal variation in the mesozooplankton standing stock.

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Chapter 2

MATERIALS AND METHODS

The present study is part of a multidisciplinary project entitled *"Marine Research on Living Resources (MR-LR) Assessment Programme"* conducted by National Institute of Oceanography, Regional Centre, Kochi and funded by Centre for Marine Living Resources and Ecology (CMLRE), Ministry of Earth Sciences (MoES). This programme (2nd phase), initiated in 2003, with an aim to assess and evaluate the 'Environment and productivity patterns in the Indian EEZ' by the simultaneous collection of physical, chemical and biological oceanographic parameters from the seas around India including the Arabian Sea, Bay of Bengal and the Andaman Sea. The samplings were done onboard *FORV Sagar Sampada* (Plate I) during 4 seasonal cruises conducted along the Bay of Bengal.

2.1. Sampling

Seasons selected for the present study were spring intermonsoon (March to May), summer monsoon (June to September), fall intermonsoon (October) and winter monsoon (November to February). A total of 34 stations were sampled along 6 transects (11°N and 20.5°N) with 2° latitudinal and 1° longitudinal interval from the continental shelf to the oceanic boundary of the EEZ (Fig. 4). In each transect the stations near and far to the coast were designated as diurnal stations, where 24 hr (6hr interval) observations were carried out. Stations having depth less than or equal to 200 m were selected as coastal stations, and those deeper than 200 m were selected as oceanic stations (Table II).

Methodology adopted for sampling was JGOFS (Joint Global Ocean Flux Studies, 1995) - India protocol, to ensure compatibility to the recent set of data generated in the Indian Ocean region (UNESCO, 1994). Hydrographical and biological samples were collected from the upper 1000 m at oceanic stations and upto near bottom in coastal stations. At diurnal stations, mesozooplankton samples were collected at 6hr intervals to assess the diel variation in biovolume. Water samples for chlorophyll *a* and microzooplankton were also carried out from these stations before sunrise (dawn) for the comparison of coastal and oceanic variability.

Plate I Fisheries Oceanographic Research Vessel Sagar Sampada.

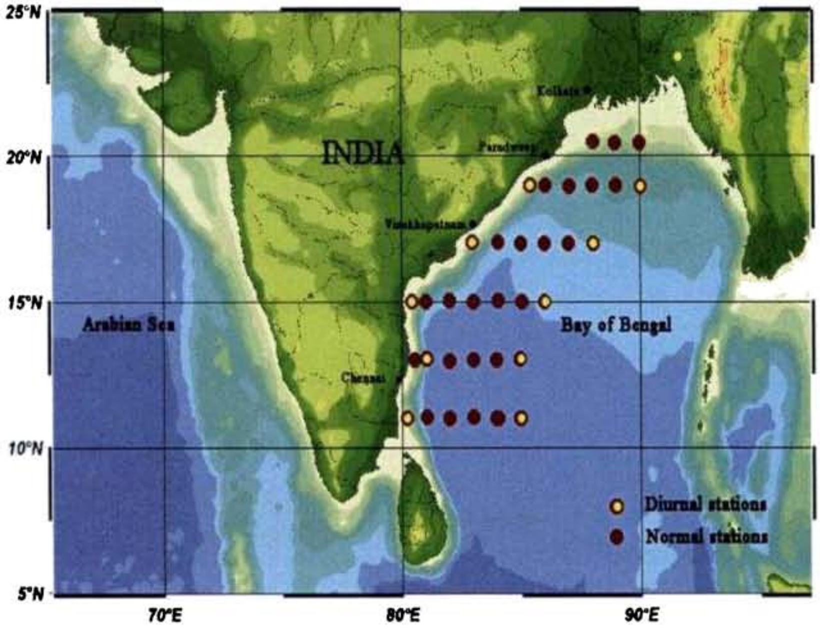

Fig. 4 Station locations of the study region

Table II Inventory of sampling

Seasons	Month/ year	Latitude (°N)					
		11	13	15	17	19	20.5
Spring intermonsoon	February - March 2005	√	√	√	√	√	√
Summer monsoon	July 2003	√	√	√	√	x	x
Fall intermonsoon	October 2006	√	√	√	√	√	√
Winter monsoon	December 2005 - January 2006	√	√	√	√	√	x

'√' indicates the latitudes where all sampling were done, and 'x' indicates latitudes which were not covered due to bad weather conditions

2.2 Hydrography

2.2.1 Physical Parameters

A Seabird CTD (*SBE Model 911 PLUS*, Sea-Bird Inc.) was used to record temperature (accuracy ± 0.001°C) and salinity (conductivity ± 0.0001 S/m) profiles with a bin size of 1 m (Plate II). These data were subjected to quality check by seabird data processing software. Salinity was measured using CTD and calibrated against water samples collected from discrete depth using Autosal (Guildline 8400A) onboard. The preferred international convention is sugested to use no units for salinity (IAPSO) and sigma *t* (Pond & Pickard 1989) which is followed in the present study. The skin layer temperature was measured using a bucket thermometer (accuracy ±0.1°C) at each station. The mixed layer was taken as the depth at which the density increases 0.2 from the surface. The thermocline depth was determined as the depth at which temperature attained 15°C.

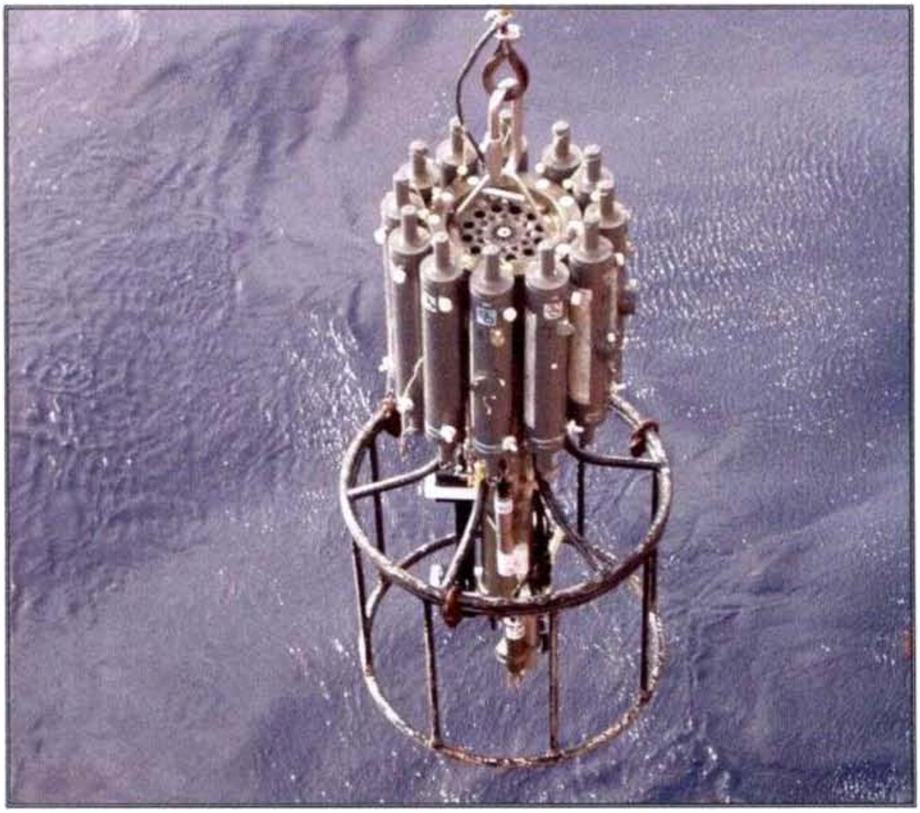

Plate II Seabird CTD attached with Niskin water sampler.

2.2.2 Chemical parameters

Water samples from discrete depths were collected using Niskin bottles (capacity : 1.8 litres) attached to the CTD rosette from 12 predetermined depths (surface, 10, 20, 30, 50, 75, 100, 150, 200, 300, 750 and 1000 m) with remotely operated closing mechanism. The samples were estimated for dissolved oxygen, nitrate, phosphate and silicate according to the standard procedures.

Dissolved oxygen (DO) was estimated by Winkler's titration method (Grasshoff *et al.*, 1983) with visual end point determination. Water samples were collected in 125 ml clean glass bottles without trapping air bubbles. Samples were immediately fixed by adding 0.5 ml of Winkler A (mangnous chloride) and 0.5 ml of Winkler B (alkaline potassium iodide) solution and mixed well before precipitation. The dissolved oxygen was later analyzed after acidification by titration against standard sodium thiosulphate using starch as indicator. The concentration was calculated as

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

N = normality of thiosulphate, S = titre value for sample

b_m = mean titre value for blank, V = volume sample bottle (125 ml)

A = volume of sample titrated (50 ml)

Dissolved oxygen (DO) concentration is expressed in $\mu M\ l^{-1}$.

On board autoanalyser (SKALAR) was used to estimate the dissolved inorganic nutrients such as nitrate, phosphate and silicate (Grasshoff *et al.*, 1983). For the estimation of nitrate (NO_3), the sample was first reduced to nitrate by passing through a reducing coloumn filled with copper amalgamated cadmium granules. The reduced nitrate ie., nitrite (NO_2) then reacts with sulphanilamide in an acid solution. The resultant diazonium compound got coupled with N-(1-Naphtyl)-ethylenediamine dichloride to form a coloured azo dye, and the absorbance was measured spectrophotometrically at 543nm. The concentration of reactive nitrate is given in µM 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 to 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.

2.3 Biology

2.3.1 Chlorophyll *a*

For the estimation of chlorophyll *a* (chl. *a*), water samples (1 litre) were collected from seven discrete depths (surface, 10, 20, 50, 75, 100, and 120 m) and filtered through a GF/F filter (47 mm dia. pore size 0.7 µm). The filters were extracted with 10ml of 90% acetone and analyzed the pigments, using spectrophotometer (Perkin-Elmer UV/Vis at 640 nm). Chlorophyll *a* (mg m^{-2}) in the upper 120 m was calculated by integrating the values obtained in the discrete sampling depths.

Satellite derived chl. *a* values were also used for the present study. SeaWiFS L3 binned data was processed by SeaDAS and correlated with *in-situ* chlorophyll *a* measurements. The appropriate correction factor was applied to the SeaWiFS data and plotted for the distribution pattern of chlorophyll *a* during the study period

2.3.2 Microzooplankton

Water samples (5 - 8 liter) were collected from seven discrete depths (0.5, 10, 20, 50, 75, 100 and 120 m) for microzooplankton. The samples were filtered through a 200 µm bolting silk to eliminate mesozooplankton and the filtrate was carefully collected into black polythene bottles. Subsequently, 3 - 8% of acid Lugol's Iodine was added to the samples, concentrated by gravity settling and siphoning procedure to 100 ml and preserved in 1 - 3% acid Lugol's solution. Prior to the microscopic analysis, the samples were allowed to settle for 2 days, transferred to the Sedgwick Rafter counting chamber, and observed under an inverted microscope, with phase contrast optics at 100 - 400X magnification. The organisms present in the samples were categorized into five groups viz., heterotrophic dinoflagellates, ciliates, metazoa, radiolarians and foraminifera. The abundance of microzooplankton at discrete depths (up to 120 m depth) was integrated, to get the column values, using the formula (a0+a10)/2* (d10-d0)+...........n, where 'a0' is the abundance at depth 0 m (d0) and 'a10' is the abundance at depth 10 m (d10).

2.3.3 Mesozooplankton

The mesozooplankton samples were collected by Multiple Plankton Net (HYDRO-BIOS; Weikert and John, 1981). This sampler (Plate III) is based on the principle of opening and closing a series of individual plankton nets in succession. The system consists of a main powered Deck Command Unit and square shaped stainless steel frame (0.25 m^2) with canvas part to which five net bags are attached (mesh size - 200 μ). The net bags are opened and closed by means of an arrangement of levers which are triggered by a battery powered Motor Unit. The towing was vertical from upper 1000 m water column with a hauling speed of 1 m/s. Five different depth strata sampled were : 1000 - 500, 300-500 m, bottom of thermocline layer to 300 m, thermocline layer and finally mixed layer.

Plate III Multiple Plankton Net (MPN) sampler.

Biovolume

The term biovolume denotes the amount of living matter present in the mesozooplankton sample. The value obtained is used to evaluate the secondary productivity. The fixation and preservation of the sample was done by the standard protocols (Steedman, 1976; Harris et al., 2000). The biovolume is estimated by volumetric (displacement volume and settling volume) method. In this method the zooplankton sample is filtered through a piece of clean, dried netting material. The mesh size of netting material should be the same as the mesh size of the net used for collecting the samples. The interstitial water between the organisms are removed with blotting paper. The filtered zooplankton are then transferred with a spatula to a measuring cylinder with a known volume of 4 % formalin - seawater solution. The displacement volume is obtained by recording the volume of fixative in the measuring jar displaced by the zooplankton. Larger zooplankton (>500 μ) such as medusae, ctenophores, salps, siphonophores and fish larvae should be removed from the sample prior to biovolume determination. The volume of gelatinous zooplankton is taken separately. The total biovolume would be the biovolume of these forms plus the biovolume of the rest of the zooplankton. The value obtained by displacement volume (DV) method is converted in to the unit volume by using the following formula,

$$\text{Biovolume} = DV / VWF$$

$$VWF = DH \times A$$

Where,

DV = Displacement Volume

VWF = Volume of Water Filtered

DH = Difference in depth of haul

A = Mouth area of the net (0.25 m^2)

The biovolume is expressed in ml m^{-3}.

After the measurement of biovolume, zooplankton samples were preserved in 4 % formalin-seawater in the suitable plastic containers for the later qualitative studies (composition and abundance).

Abundance

Mesozooplankton sorting was carried out manually. For enumeration, subsamples or aliquots of 10 to 25% is usually examined. Subsamples were taken depending on the abundance of organisms for detailed study. The subsampling was done by using Folsom plankton splitter or stempel pipette. Folsom plankton splitter is made up of plastic material having a drum with internal partition. The sample to be subsampled is poured into the drum and the drum is rotated slowly back and forth. The internal partition will divide the sample into two equal halves that are finally poured in to collection tray. The fraction may be poured again into the drum for further splitting. The process is repeated until the desired fraction is obtained for counting. The splitter is thoroughly rinsed to recover the organisms, which may be sticking onto the wall of the drum.

The sample was primarily sorted into 25 to 30 taxonomic groups, according to the standard identification manuals (Newell and Newell, 1973; Todd and Laverack, 1991; ICES, 1947). The estimated abundance (density) for the different groups were represented as no. m^{-3}. The abundance and relative abundance of each group was calculated using the formula

$$\text{Abundance} = \frac{\text{No. of individuals of the particular taxa}}{\text{VWF}}$$

$$= \text{No. of particular taxa in the unit volume (no. m}^{-3}\text{)}$$

$$\text{Relative abundance} = \frac{\text{No. of specimens in the particular taxa}}{\text{Total no. of organisms}} \times 100$$

$$= \text{Percentage of particular taxa (\%)}$$

The number obtained for each taxa in the subsample are converted to 100% and are presented as no. m^{-3}.

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Chapter 3

RESULTS

3.1 Spring Intermonsoon (SIM)

3.1.1 Hydrography

During spring intermonsoon (SIM), the BoB was characterised by relatively less saline and cool waters, and showed marked north-south variations in the hydrographical and biological characteristics. The Sea Surface Temperature (SST) varied between 25.8 and 29.1°C (av. 27.8 ± 0.87°C) at northern (20.5°N; 90°E) and southern regions

(11°N; 81°E) respectively. SST dropped about 3.29°C from south to north. The Sea Surface Salinity (SSS) showed a south to north increase (29.7 to 33.9 ; av.32.5 ± 1.2), and the maximum SSS (33.9) was observed at 13°N;84°E and minimum (29.7) at 20.5°N;89°E. Isopycnals were shoaled towards the northern region with less dense waters. The sigma-*t* ranged from 18.87 to 21.4 (av. 20.6 ± 0.65). The coastal and oceanic variation was also pronounced along the southern transacts (11 and 13°N) compared to other transects. The average MLD and thermocline layer depths observed were 24.7 ± 18 and 182.8 ± 49.5 m respectively. The deepest MLD (90 m) was recorded at 13°N;84°E in the south, and it was much shallower (7 m) at 17°N;86°E in the north. The thermocline depth gradually deepens from north (70 m; 19°N;90°E) towards the south (270 m; 13°N;82°E). The northern region was characterised with shallow MLD, having less saline cool surface waters, and the condition was reverse towards the southern region (Fig. 5 and 6).

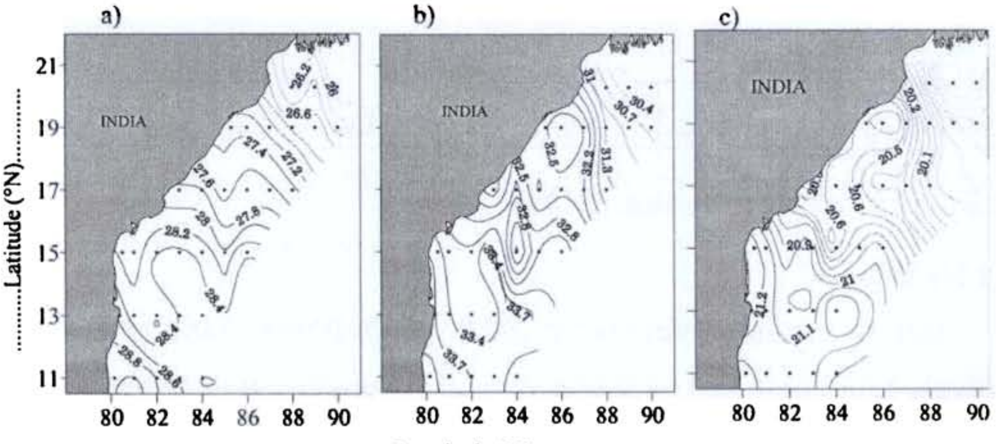


Fig. 5 Spatial distribution of a- sea surface temperature (°C), b- sea surface salinity and c- sigma *t* during spring intermonsoon.

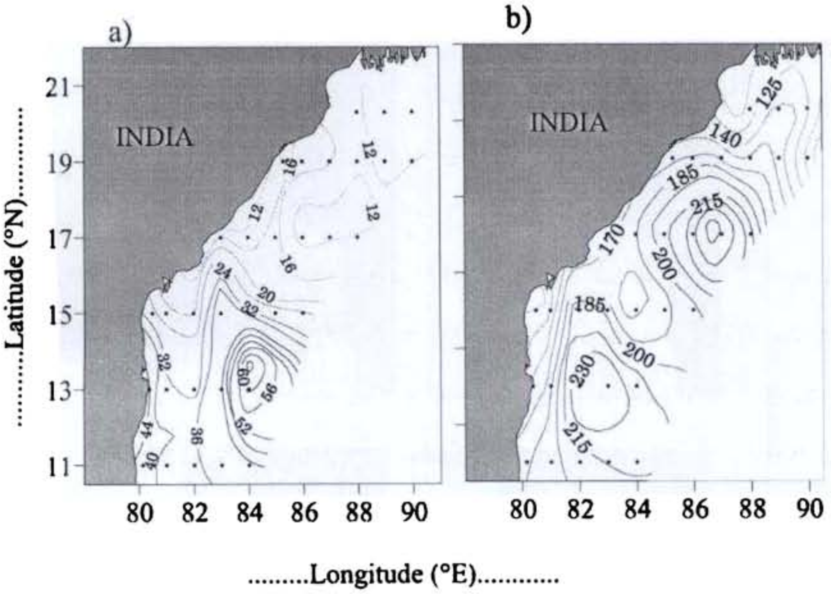


Fig. 6 Spatial distribution of a- MLD (m) and b- thermocline depth (m) during spring intermonsoon.

During this season, concentration of dissolved oxygen (DO) was ranged between 205 and 259 µM l^{-1} (av.227 ± 19) and the northern region (20.5 and 19°N) showed a well oxygenated (>220 µM l^{-1}) surface waters (Fig. 7). The average concentration of nutrients such as nitrate, phosphate and silicate in the surface waters were 0.462 ± 0.32, 0.6 ± 0.2 and 0.47 ± 0.57 µM l^{-1}, respectively. The concentration of nitrate in the surface waters of southern coastal region was relatively higher (0.8 µM l^{-1}) than in the north (Fig. 7b). The phosphate concentration varied between 0.32 and 1.3 µM l^{-1} (Fig. 7c). Similarly silicate concentration ranged from 0.45 to 6.5 µM l^{-1}.

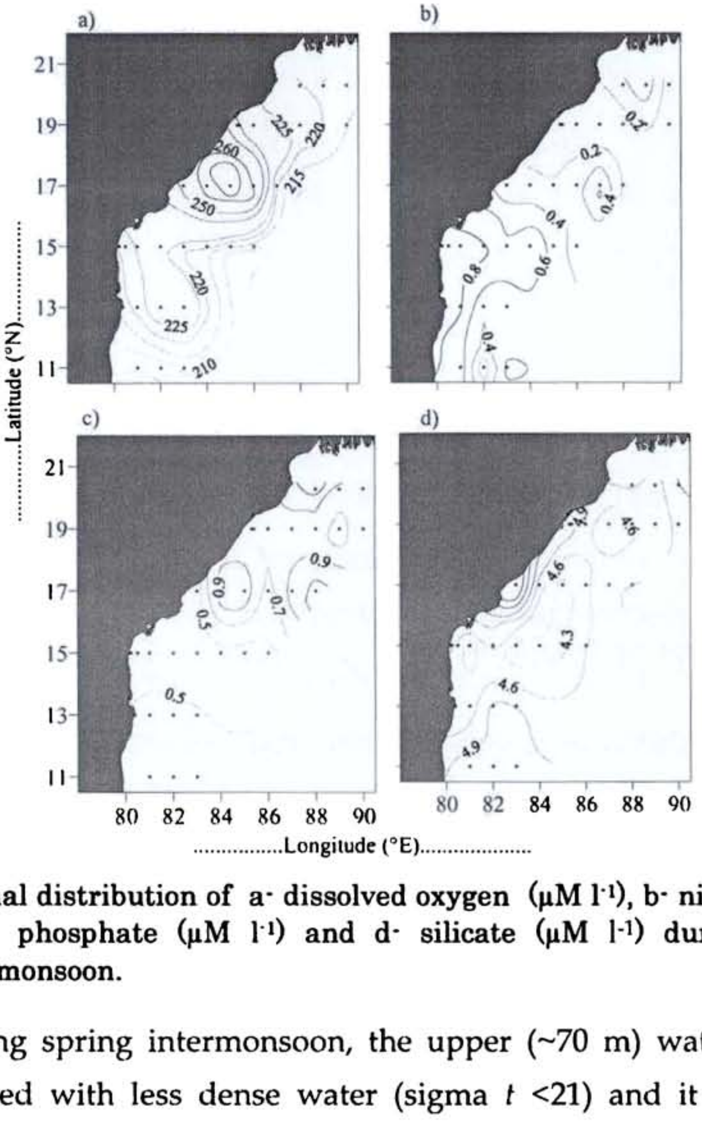


Fig. 7 Spatial distribution of a- dissolved oxygen (µM l-1), b- nitrate (µM l-1), c- phosphate (µM l-1) and d- silicate (µM l-1) during spring intermonsoon.

During spring intermonsoon, the upper (~70 m) water column was stratified with less dense water (sigma *t* <21) and it was more obvious towards the north (Fig. 8). Some physical process were active in the subsurface waters because of the strong stratification in the upper water column. Doming of 26°C isotherm from 70 m to 40 m was noticed at 88°E;19°N. Salinity, dissolved oxygen and nitrate contours showed same pattern along the transect. DO concentration in the upper 50 m was >220 µM l^{-1} and at 19°N;88°E an upward shifting of 175 µM l^{-1} isoline was observed from 70 m to 50 m (Fig. 8).

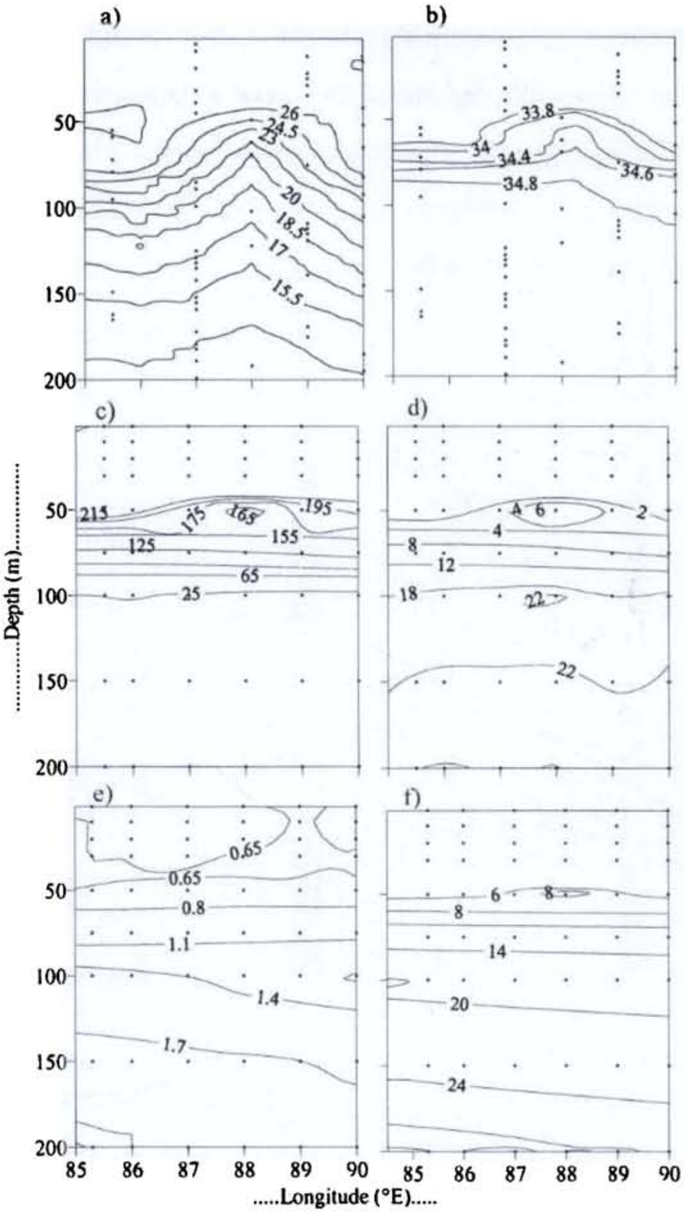


Fig. 8 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}), d- nitrate (µM l^{-1}), e- phosphate (µM l^{-1}) and f- silicate (µM l^{-1}) along 19°N transect during spring intermonsoon.

Vertical distribution of temperature and salinity along 17°N was characterised by downsloping of isotherm (26°C) and isohaline (34.4) from

~55 m in the coastal regions to 100 m towards the oceanic stations (86°E) (Fig. 9). In the upper 50 m, the DO, nitrate, phosphate and silicate concentrations were >220 µM l^{-1}, <2 µM l^{-1}, <1.2 µM l^{-1} and <6 µM l^{-1} respectively.

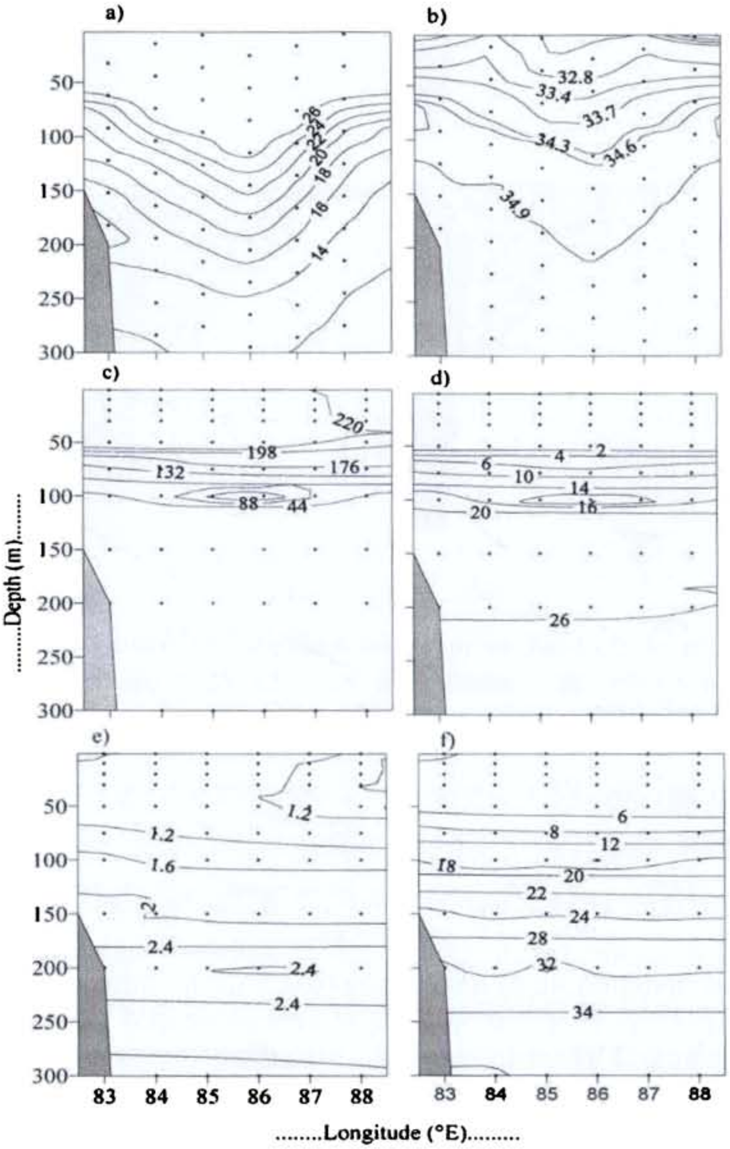


Fig. 9 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}), d- nitrate (µM l^{-1}), e- phosphate (µM l^{-1}) and f- silicate (µM l^{-1}) along 17°N transect during spring intermonsoon.

Vertical distribution of temperature and salinity along 15°N transect showed a subsurface upsloping at 84°E. The surface waters of both coastal and oceanic stations was characterised by less saline (33.3), low oxygenated (>200 µM l^{-1}) and nutrient rich (nitrate >2 µM l^{-1}) waters. Isothermal layer (26°C) was at 45 m in the coastal stations and 70 m in the oceanic stations (Fig. 10).

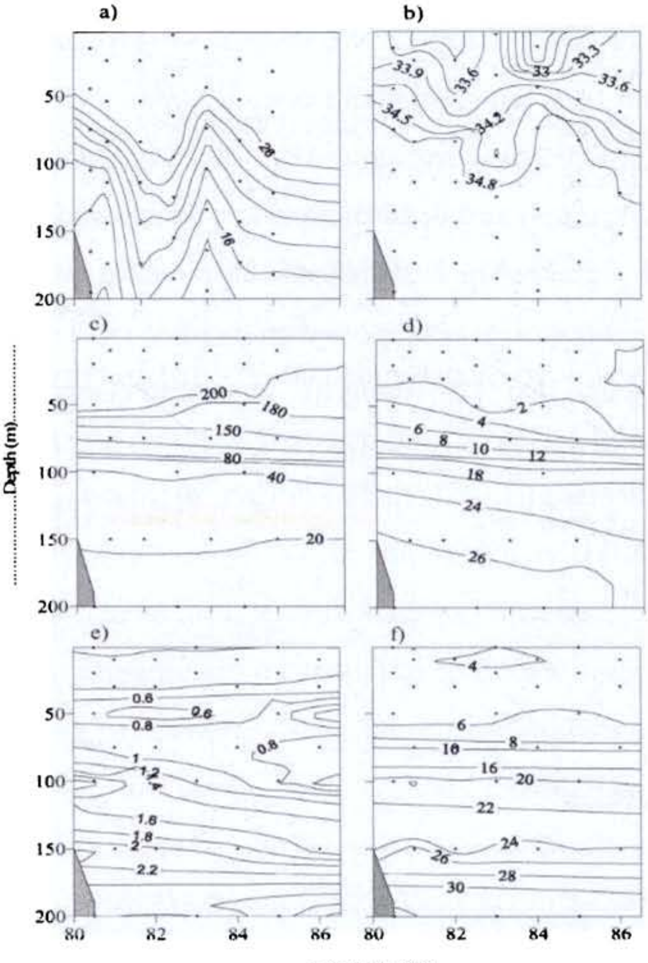


Fig. 10 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}), d- nitrate (µM l^{-1}), e- phosphate (µM l^{-1}) and f- silicate (µM l^{-1}) along 15°N transect during spring intermonsoon.

3.1.2 Biology

Chlorophyll *a* : During SIM, the concentration of chlorophyll *a* (chl. *a*) showed pronounced variation both in the surface as well as column waters. In the surface waters, chl. *a* ranged between 0.10 and 0.41 (av.0.19 ± 0.11) mg m^{-3} in the coastal and 0.10 to 0.22 mg m^{-3} (av. 0.19 ± 0.05) in the oceanic waters with an increase towards the north (Fig. 11). Along 13, 15 and 17°N transects, the variation in surface chl. *a* concentration between coastal and oceanic stations was less (0.10 mg m^{-3} along 13°N and 0.21 mg m^{-3} along 15 and 17°N). Along 19°N, the coastal station (0.42 mg m^{-3}) sustained more chl. *a* concentration than the oceanic station (0.21 mg m^{-3}). The SeaWiFS satellite observation for the distribution of chl. *a* concentration also supported an increase (>0.2 mg m^{-2}) towards the northern regions (Fig. 12). Along the south and central region of the bay (south of 17°N) the chl. *a* concentration was below 0.17 mg m^{-2}.

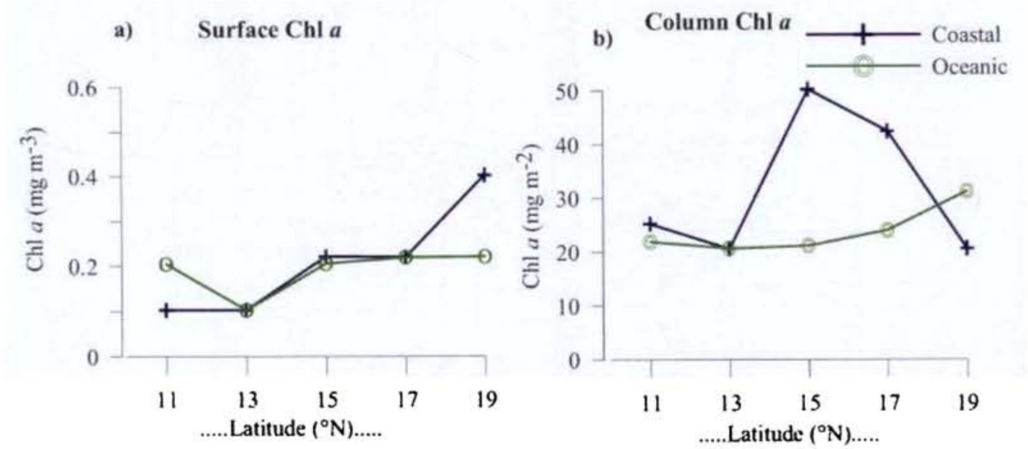


Fig. 11 Latitudinal distribution of a- surface (mg m^{-3}) and b- column chlorophyll *a* (mg m^{-2}) in the coastal and oceanic waters during spring intermonsoon.

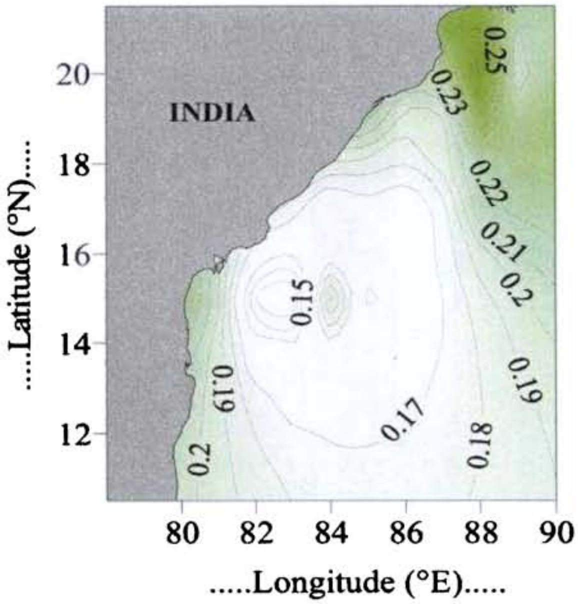


Fig. 12 Spatial distribution of chlorophyll *a* (SeaWiFS) during spring intermonsoon.

Microzooplankton: Total abundance of microzooplankton showed pronounced variations between the coastal and oceanic as well as southern and northern regions (Fig. 13). Higher abundance of microzooplankton was noticed along the southern transects (11 and 13°N) both in the coastal and oceanic stations. Among coastal stations, 13°N transect sustained maximum abundance (96,437 no. m^{-2}) followed by 11°N (79,062 no. m^{-2}). Along 15°N, the oceanic regions showed more abundance (59,687 no. m^{-2}) than coastal (39,062 no. m^{-2}). The heterotrophic dinoflagellates (HDF) were found to dominate in the microzooplankton community both in coastal (44%) as well as oceanic (48%) stations (Fig. 14).

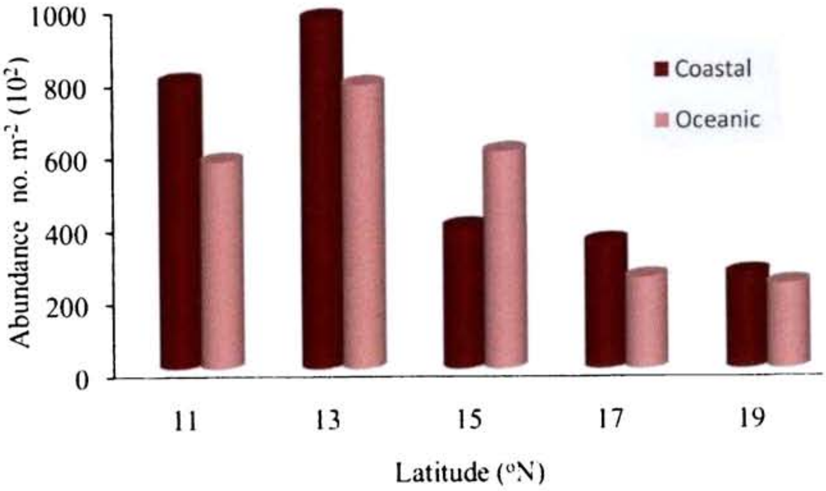


Fig. 13 Latitudewise distribution of total abundance of microzooplankton (no. m^{-3}) in the coastal and oceanic stations during spring intermonsoon.

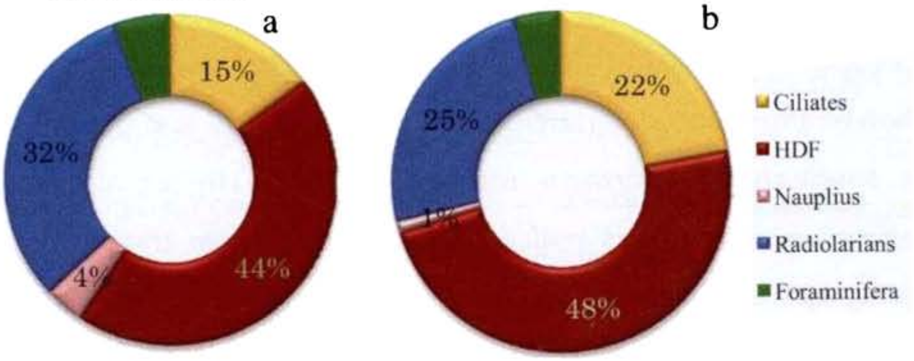


Fig. 14 Percentage composition of microzooplankton (no. m^{-3}) groups in the a- coastal and b- oceanic stations during spring intermonsoon.

Mesozooplankton: The average mesozooplankton biovolume in the MLD and thermocline layer was 0.3 ± 0.49 ml m^{-3} and 0.14 ± 0.16 ml m^{-3} respectively during this season. Relatively higher biovolume was observed in the oceanic region than in coastal waters. The maximum biovolume of 1.7 ml m^{-3} was recorded along 17°N transect at 88°E (oceanic station)

(Fig. 15). The southern and central BoB were characterised by low mesozooplankton biovolume (<0.3 ml m^{-3}) whereas in the northern region, the biovolume was comparatively more. Towards the deeper depths the biovolume recorded were <0.1 ml m^{-3}.

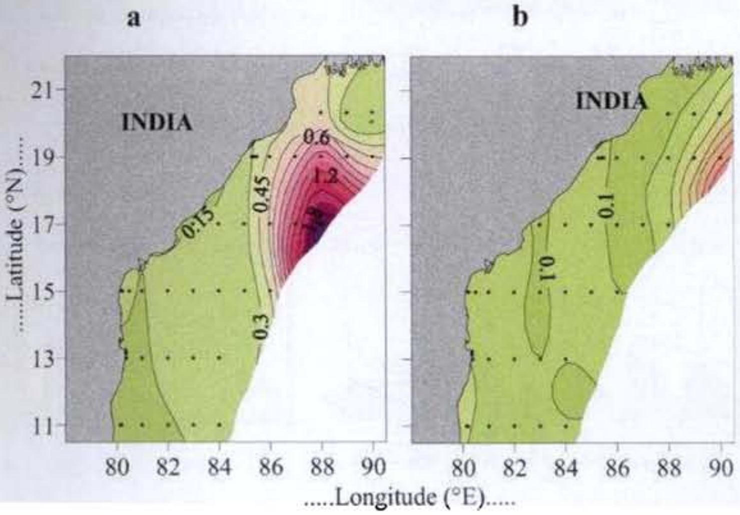


Fig. 15 Distribution of mesozooplankton biovolume (ml m^{-3}) in the a- MLD and b- thermocline layer during spring intermonsoon.

The latitudinal distribution of mesozooplankton standing stock showed that, the southern transects were sustained low biovolume with an average of 0.25 ± 0.19 ml m^{-3}. At the coastal stations along 11°N transect (80°E), the mesozooplankton biovolume was 0.22 and 0.39 ml m^{-3} in the MLD and thermocline layer respectively. Along 13 and 15°N transects, the variations of biovolume between the coastal and oceanic stations were not prominent. But, along 17°N, biovolumes recorded in the oceanic stations (87 and 88°E) were relatively more (1.7 and 1.6 ml m^{-3} respectively) compared to coastal stations especially in the mixed layer (Fig. 16).

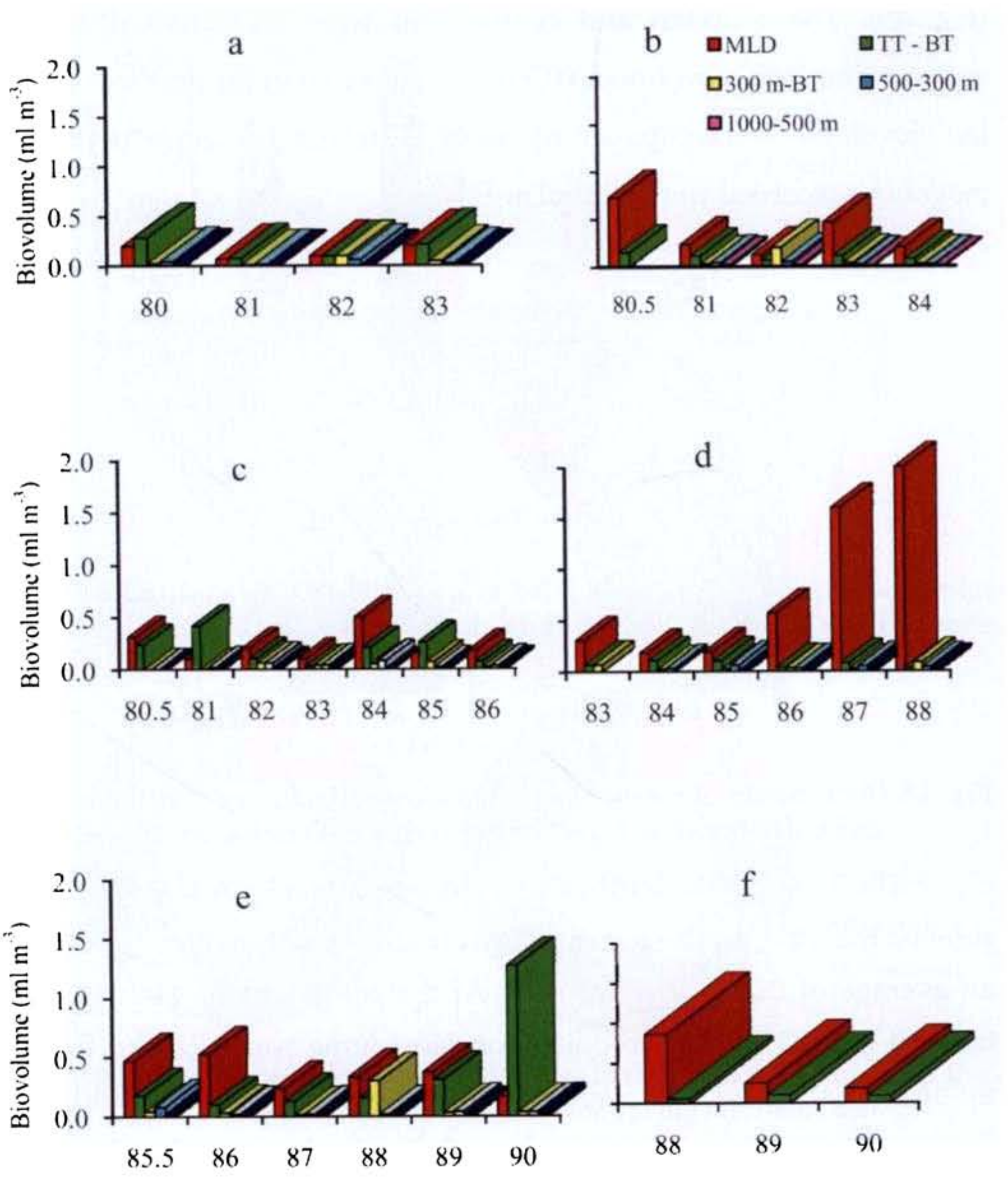


Fig. 16 Latitudinal distribution of mesozooplankton biovolume (ml m^{-3}) along a- 11°N, b- 13°N, c- 15°N, d- 17°N , e- 19°N and f- 20.5°N transects during spring intermonsoon.

The variations in the distribution of biovolume between the coastal and oceanic waters were not pronounced during this season. Occasionally, the oceanic stations sustained relatively high biovolume (>1 ml m^{-3}) than the coastal waters, and this was prominent along 17°N transect. Among coastal stations, the highest biovolume (0.8 ml m^{-3}) in the MLD was recorded at 20.5°N transect. In the oceanic stations, the biovolume in both the MLD and thermocline layer was <0.4 ml m^{-3} except in the MLD at 17°N where it was 1.6 ml m^{-3} (Fig. 17). In the thermocline layer the biovolume was <0.4 ml m^{-3} irrespective of coastal and oceanic waters.

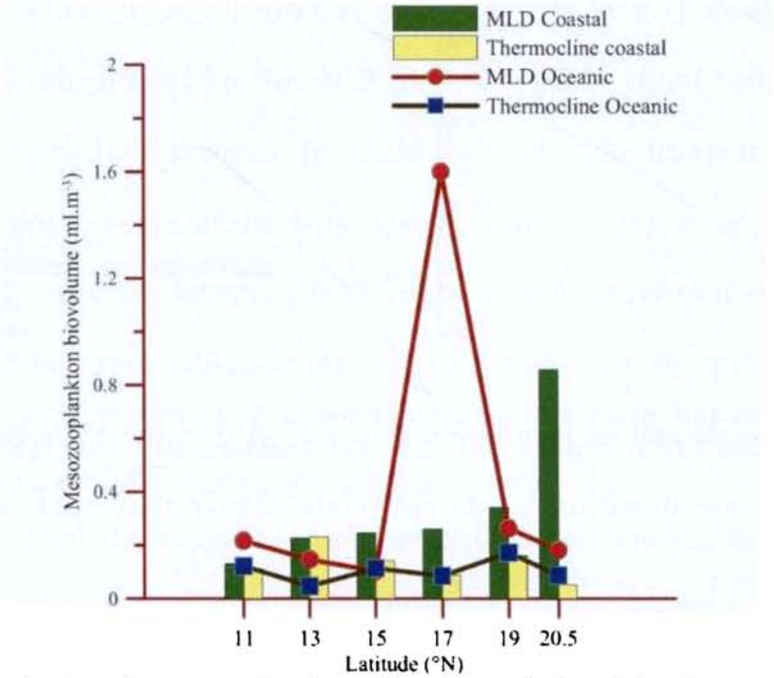


Fig. 17 Variation of mesozooplankton biovolume (ml m^{-3}) in the coastal (bar plot) and oceanic (line plot) stations during spring intermonsoon.

The diurnal variation of mesozooplankton biovolume was only marginal during this season except at few stations. In the coastal station of 13°N transect, relatively higher biovolume (0.73 ml m^{-3}) was observed during the evening hours (an increase of ~0.5 ml) than the rest of the collections especially in the MLD. The diurnal variation of mesozooplankton biovolume at the oceanic stations along the southern and middle transects was relatively low, in the MLD. But, along 17°N transect, ~1 ml increase of mesozooplankton biovolume (1.6 ml m^{-3}) was observed during night haul than those of the other hauls (0.31, 0.33 and 0.44 ml m^{-3} during dawn, day and dusk respectively) in the MLD of oceanic stations. Southern transects sustained more biovolume of mesozooplankton in the thermocline layer during night in the coastal stations. The diurnal variability of biovolume in the thermocline layer along oceanic region was not so prominent (Fig. 18). Along the 15^{0}N transect, the night time biovolume was relatively higher than that recorded in other times.

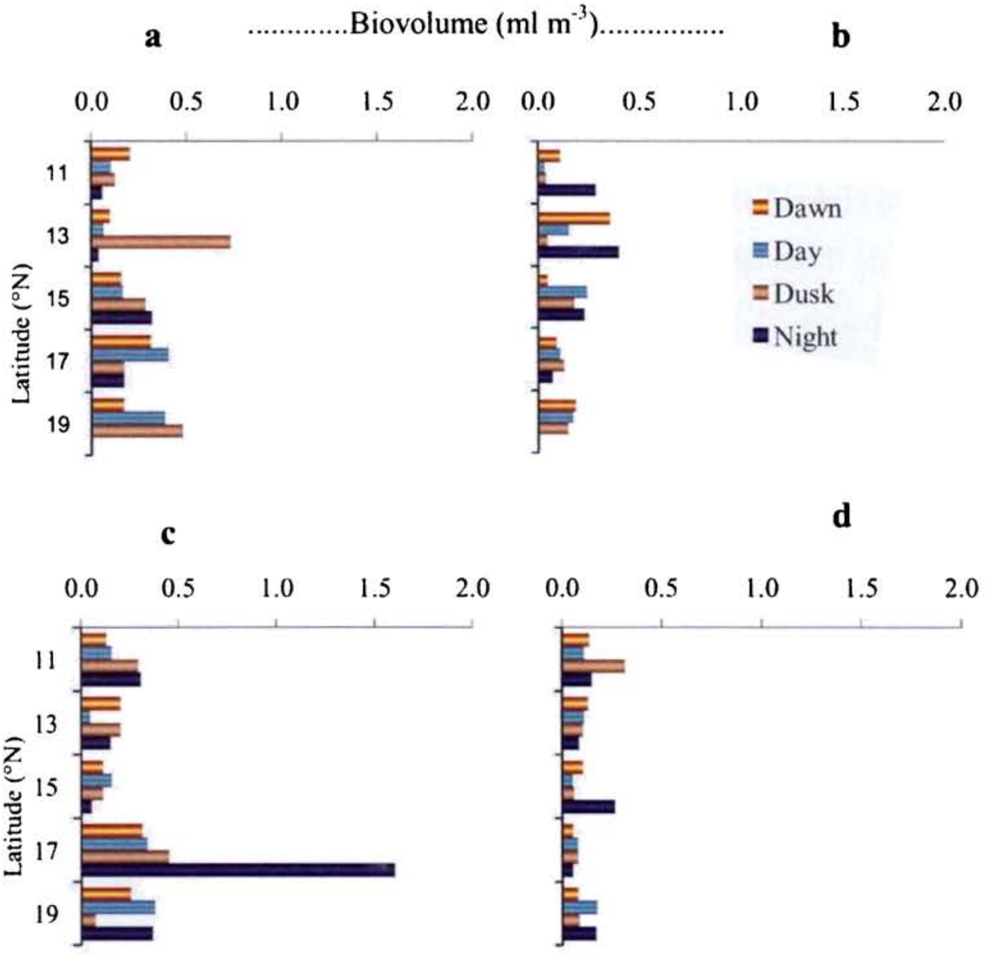


Fig. 18 Diurnal variation of mesozooplankton biovolume (ml m^{-3}) in the MLD and thermocline layer in the coastal (a&b) and oceanic stations (c&d) during spring intermonsoon.

The total abundance of mesozooplankton taxa showed remarkable variation between the northern and southern regions. Mixed layer depth showed relatively higher abundance (317 ± 309 no. m^{-3}) than the thermocline layer (231 ± 217 no. m^{-3}). Maximum abundance of mesozooplankton (2,451 no. m^{-3}) was observed in the MLD at 17°N;88°E (oceanic station) during this season. Among coastal stations, the maximum abundance (2,378 no. m^{-3}) was noticed at 13°N;80.5°E followed by 15°N;80.5°E (867.3 no. m^{-3}) in the MLD. The maximum abundance (106 no. m^{-3}) in the thermocline layer was observed at 15°N;81°E (coastal station) (Table III).

Table III Total abundance of mesozooplankton (no. m^{-3}) in various depth strata during spring intermonsoon.

Latitude (°N)	Longitude (°E)	Mesozooplankton abundance (no. m^{-3}) in different depth strata				
		MLD	Thermocline	BT-300 m	300-500 m	500-1000 m
11	80	326	235	35	-	-
	81	258	165	11	12	10
	82	131	217	34	23	4
	83	353	140	38	25	8
	84	465	148	31	12	2
13	80.5	2,378	674	114	-	-
	81	179	78	2	44	18
	82	28	16	22	21	4
	83	683	284	20	29	13
	84	144	158	26	13	6
15	80.5	867	622	24	-	-
	81	207	1061	1	18	16
	82	87	379	18	7	17
	83	145	77	10	51	15
	84	395	541	22	10	5
	85	251	147	28	16	21
	86	255	94	3	14	21
17	83	404	212	135	-	-
	84	185	342	4	22	9
	85	210	28	61	77	13
	86	95	37	3	4	2
	87	948	161	62	63	24
	88	2,451	14	18	28	7
19	85	309	279	27	-	-
	86	677	298	49	86	23
	87	145	235	64	42	25
	88	105	119	38	21	16.7
	89	792	305	93	65	35
	90	109	446	68	38	11
	85	309	278	27	-	-
20.5	88	435	274	-	-	-
	89	273	122	55	-	-
	90	1,795	598	-	-	-

The dominant taxon of mesozooplankton community was Copepoda, and its contribution ranged from 81 to 96%. Maximum abundance (96%) was recorded at the coastal station along 15°N transect. In the thermocline layer the contribution of copepod was ranged from 65% to 98% along 15 and 11°N transects respectively. Along the oceanic waters, the variations in the percentage contribution of copepod between the MLD and thermocline layer was only marginal. In the MLD, the percentage ranged between 69 and 96 % along 20.5 and 13°N transects respectively in the oceanic stations (Fig. 19).

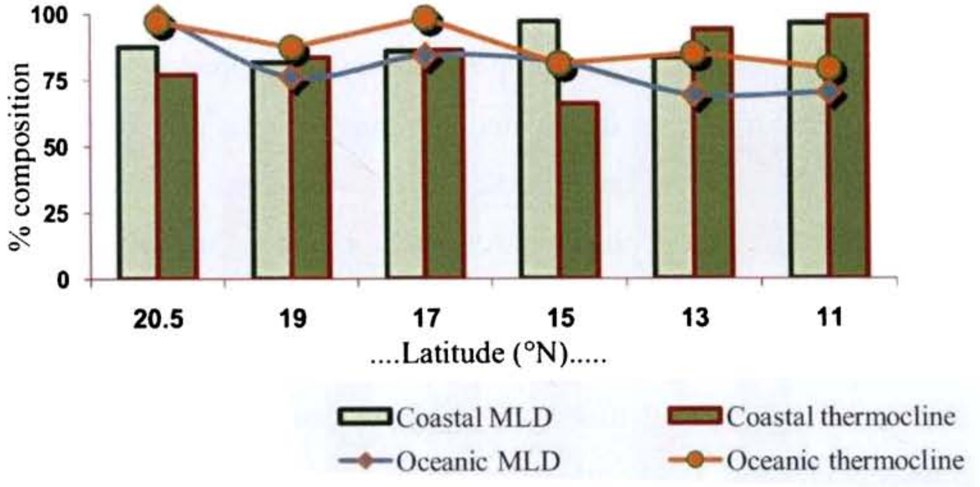


Fig. 19 Percentage composition of copepod in the MLD and thermocline layer in the coastal and oceanic stations during spring intermonsoon.

The non-copepod members of the mesozooplankton were dominated by chaetognaths and copelates in the coastal waters irrespective of depth strata in. In the MLD, chaetognaths (40 to 49%) dominated in all transects except 15 and 13°N where the dominant taxa were copelates (47%) and foraminiferans (61%) respectively (Fig. 20). In the MLD, copelates was the second dominant group among non-copepod members of the mesozooplankton along the northern (20.5 and 19°N) transects. The relative abundance of ostracods in the MLD ranged between 7 and 11% almost all transects except 11°N (25%). Gastropods (14%) and heteropods (13%) were reported from 17°N transect especially in the MLD. In the thermocline layer, the ostracods contributed 18 to 76% in the coastal region. Other major groups observed in the thermocline layer were chaetognaths, euphausiids, copelates *etc.* Decapods were present along the southern transects (11 and 13°N; 15% and 22% respectively) in the thermocline layer.

In the oceanic areas, compositions of non-copepod members of mesozooplankton were dominated by chaetognaths and ostracods in MLD and thermocline layer particularly towards the southern region. Along 20.5°N transect, the dominant group was siphonophores (49%), followed by ostracods (20%) and chaetognaths (14%) in the MLD. In the oceanic stations, abundance of copelates were noticed only at 19°N;88°E both in the MLD, and thermocline layer among. Along the southern transects (13 and 11°N), the major taxa were chaetognaths, ostracods and decapods in the MLD. In the thermocline layer the percentage contribution of ostracods varied from 71 to 19% along 11°N and 15°N respectively (Fig. 21).

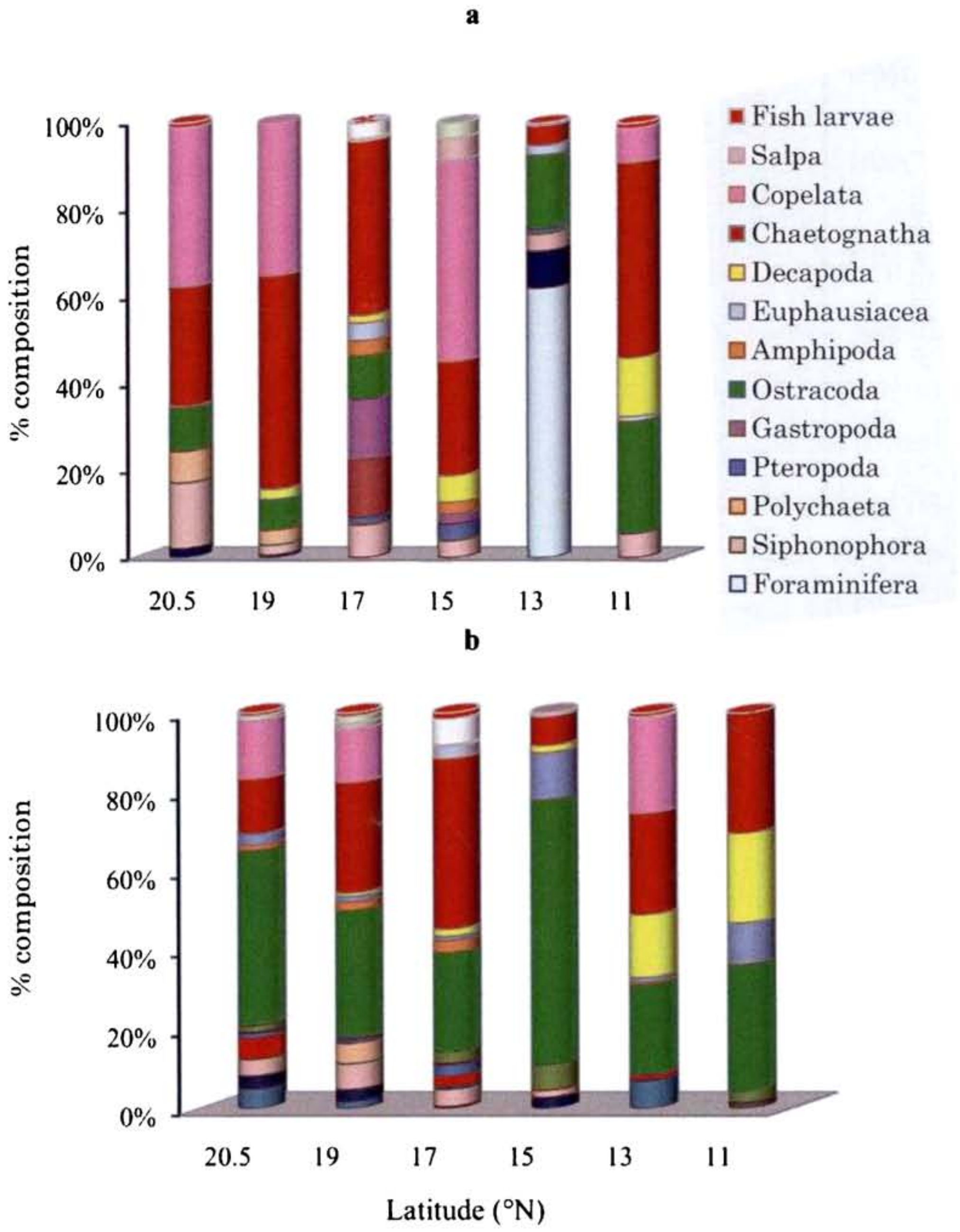


Fig. 20 Percentage composition of non-copepod taxa in the a- MLD and b- thermocline layer in the coastal stations during spring intermonsoon.

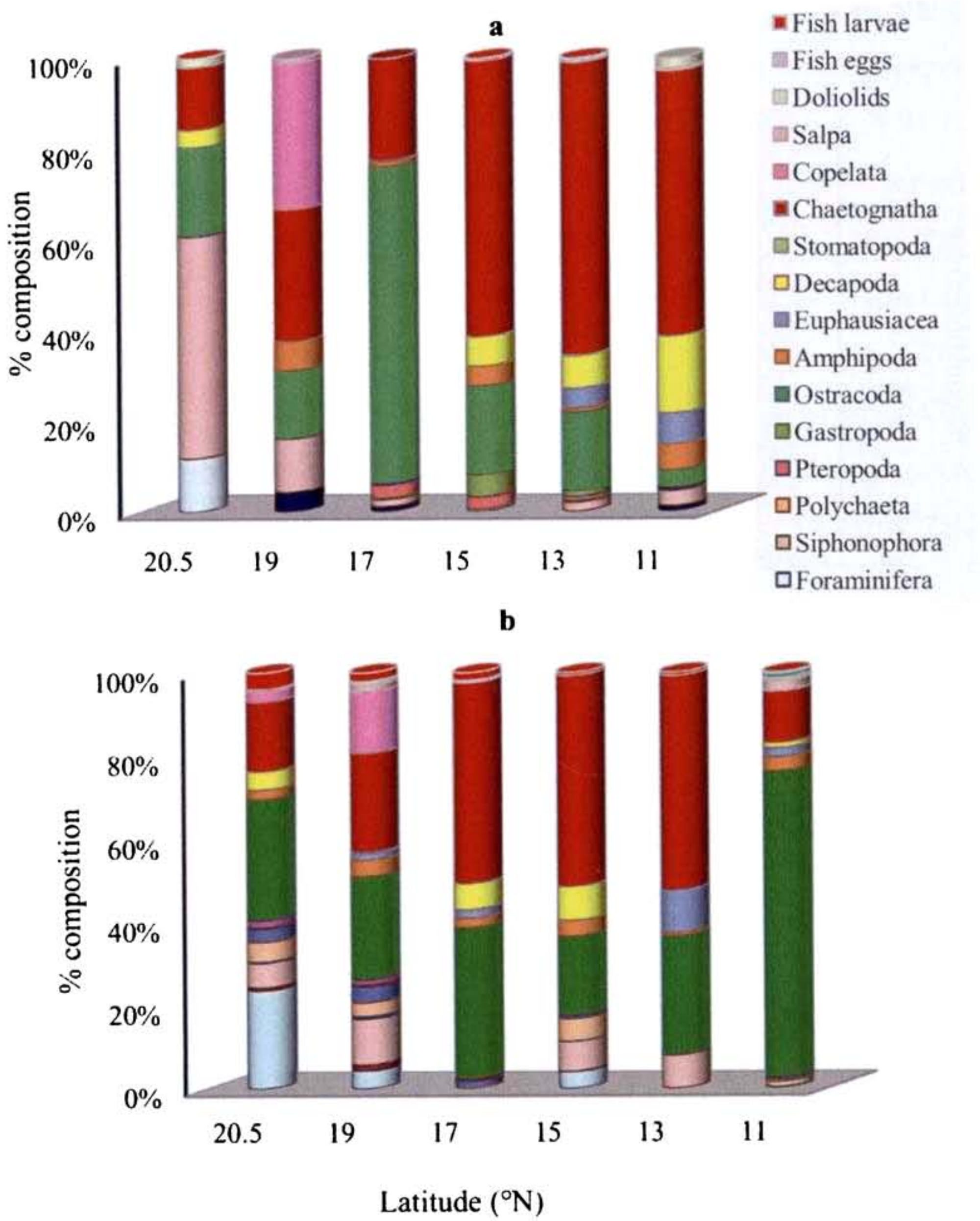


Fig. 21 Percentage composition of non-copepod taxa in the a- MLD and b-thermocline layer in the oceanic stations during spring intermonsoon.

3.2 Summer Monsoon (SM)

3.2.1 Hydrography

During SM, SST ranged between 26.7 and 29.2°C (av. 28.1 ± 0.7°C); whereas SSS varied between 32.9 and 34.2 (av. 33.8 ± 0.58) (Fig. 22). The sigma *t* in the surface waters ranged between 20.6 and 22.4 (av.21.2 ± 0.6). Isopycnals were meridionally arranged with less dense surface waters towards the oceanic region. Along 17.5°N transect, 1°C drop in temperature was observed from coastal to oceanic regions and the lowest value (26.7°C) recorded at 17.5°N;84°E. The average MLD observed during this season was 44.9 ± 19.1 m. MLD was varied from 18 m to 81 m throughout the area during this season and the maximum MLD was observed at the southern open ocean region (15.5°N;84°E) and the minimum was at the coastal waters along 15.5° and 13.5°N. Coastal waters were characterised by relatively cool (~27.3°C), high saline (~34.3) waters with shallow MLD (~19 m) whereas towards the open ocean region, the MLD deepens with relatively low temperature and salinity (Fig. 23).

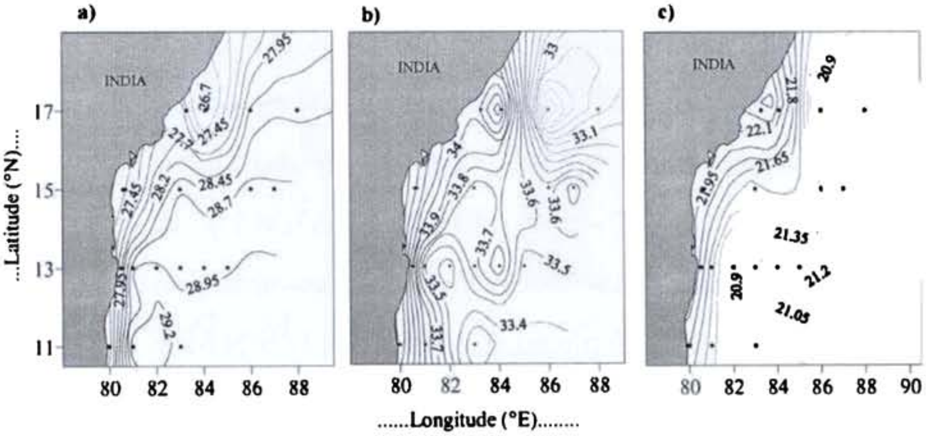


Fig. 22 Spatial distribution of a- sea surface temperature (°C), b- sea surface salinity and c- sigma *t* during summer monsoon.

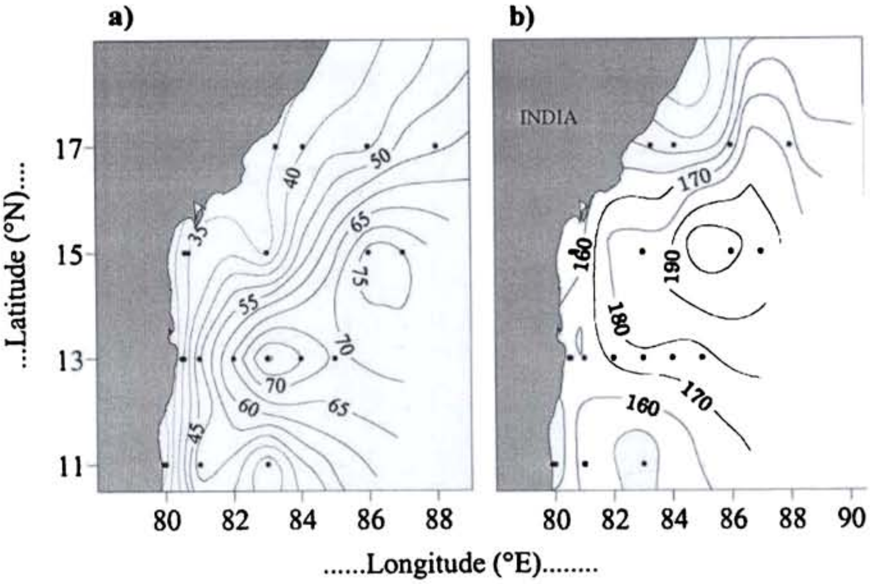


Fig. 23 Spatial distribution of a-MLD (m) and b- thermocline depth (m) during summer monsoon.

Unlike spring intermonsoon, summer monsoon exhibited wide variation in the chemical parameters of the surface waters such as dissolved oxygen (180 to 213 μM l^{-1}; av. 194.7 ± 15.2 μM l^{-1}), nitrate (0.02 to 8 μM l^{-1}; av. 0.7 ± 1.7 μM l^{-1}), phosphate (0.2 to 1.0 μM l^{-1}; av. 0.5 ± 0.26 μM l^{-1}) and silicate (0.8 to 5.7; av. 3.1 ± 1 μM l^{-1}). Along the coastal waters, the concentration of DO in the upper water column was <200 μM l^{-1} (Fig. 24) whereas at 11.5, 13.5 and 15.5°N, the surface waters were characterised with very low concentration of DO (<196 μM l^{-1}) and high concentration nutrient (NO_3 - 2 μM l^{-1}; PO_4 - 0.6 μM l^{-1}; SiO_4 - 3 μM l^{-1}). At the oceanic stations, the surface waters had relatively higher concentration of dissolved oxygen (>200 μM l^{-1}) and depleted nutrients. At 17.5°N;84°E, the surface waters were characterised with low dissolved oxygen (<190 μM l^{-1}) and high nutrient concentration (NO_3 >2 μM l^{-1}) to a greater extent than the adjacent stations due to the upward injection of subsurface waters to the surface. This indicates the presence of cold core eddy along the transect.

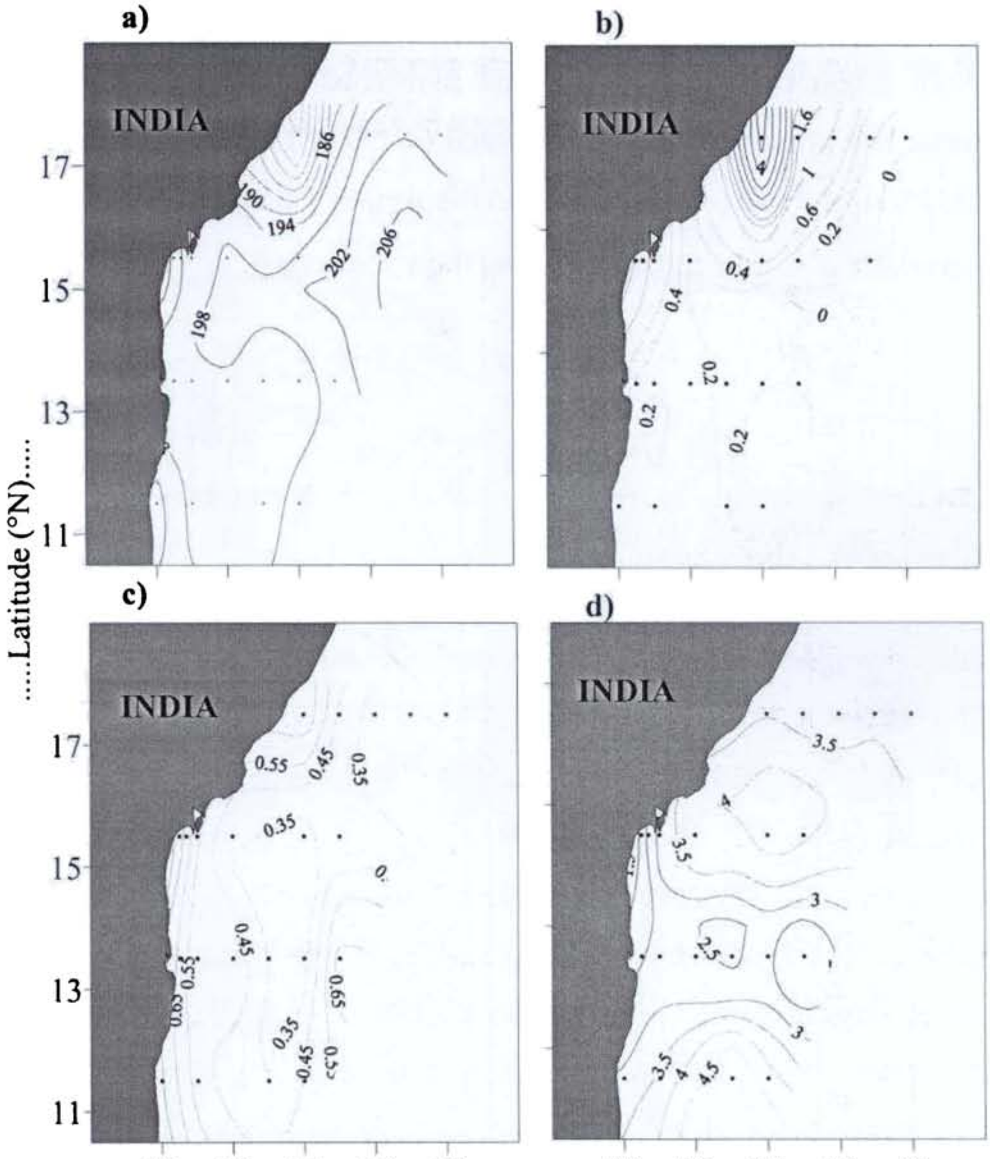


Fig. 24 Spatial distribution of a- dissolved oxygen (µM l^{-1}), b- nitrate (µM l^{-1}), c- phosphate (µM l^{-1}) and d- silicate (µM l^{-1}) during summer monsoon.

During summer monsoon, doming of isolines of temperature (27°C) and salinity (34.6) was evidenced in the coastal waters off 13°N transect and this upsloping was observed from subsurface (~30 m) to surface (Fig. 25), with origin from 11.5 to 15.5 and it reached maximum at 13.5°N transects. The presence of less oxygenated (< 190 µM l^{-1}) and nitrate rich (>2 µM l^{-1}) subsurface (~30 m) waters in the surface (~5 m) layers indicates the signatures of coastal upwelling along these transects.

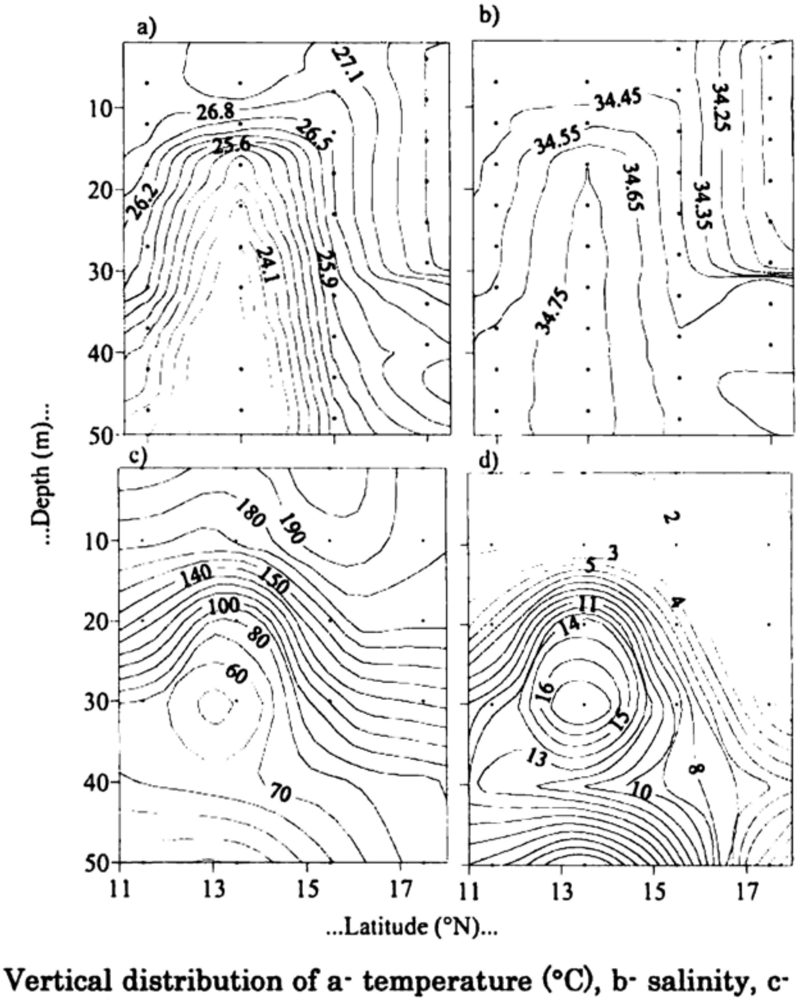


Fig. 25 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}) and d- nitrate (µM l^{-1}) in the coastal waters during summer monsoon.

Doming of temperature (27°C) and salinity (34.4) contours were observed (at 84°E) from the subsurface (~50 m) to the surface at 17.5°N. DO and nutrients also showed similar kind of distribution at this station. These specialized features observed at this station evidence the persistence of a cold core eddy in the region (Fig. 26).

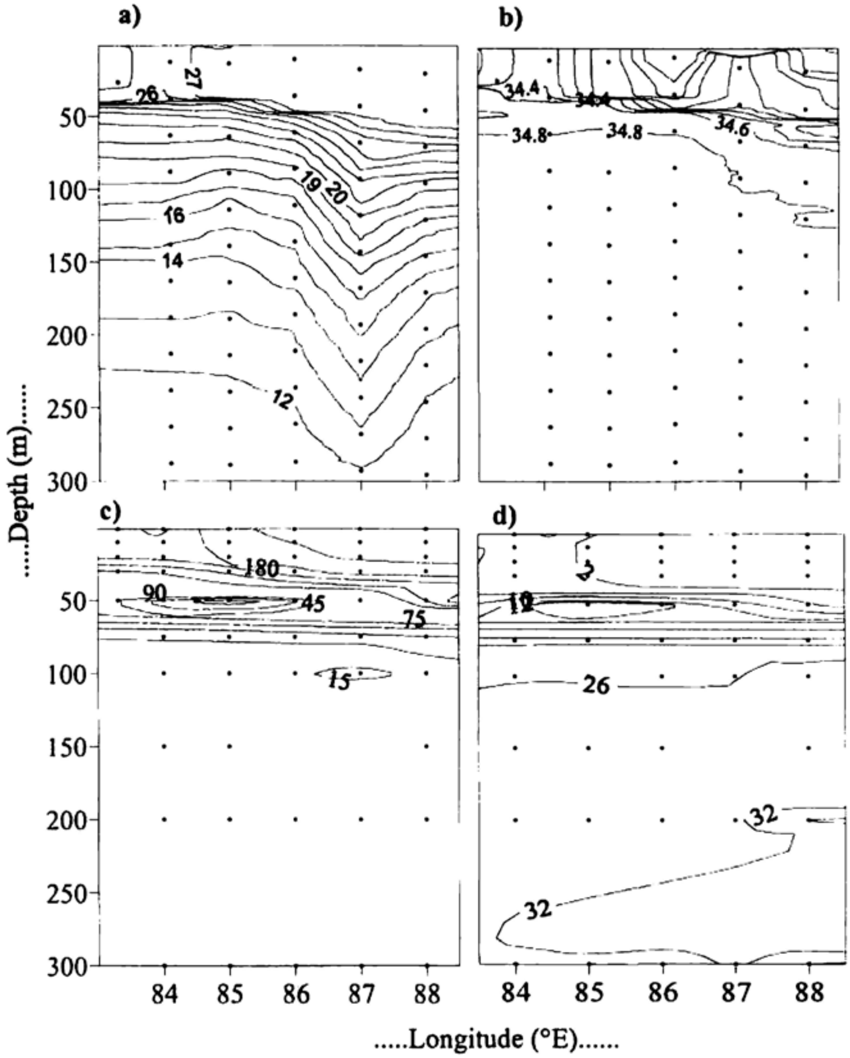


Fig. 26 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (μM l^{-1}), and d- nitrate (μM l^{-1}) along 17.5°N transect during summer monsoon.

3.2.2 Biology

Chlorophyll *a*: Chlorophyll *a*, an index of phytoplankton biomass showed prominent spatial variation during SM both in the surface as well as column waters. The satellite derived chl. *a* (SeaWiFS) also showed more or less similar values as observed *in-situ*. The coastal waters in the southern (11.5°N) and middle region (15.5°N) sustained relatively high chl. *a* concentration as compared to the northern regions. Surface chl. *a* in the coastal waters, varied from 0.12 to 0.14 mg m^{-3} whereas in the oceanic regions, the values ranged from 0.13 to 0.16 mg m^{-3} (Fig. 27). The integrated column chl. *a* concentration for the upper 120 m, showed relatively higher values at the coastal as compared to oceanic waters. Maximum concentration of column chl. *a* (13 mg m^{-2}) was recorded between 15.5 and 13.5°N whereas the minimum (9 mg m^{-2}) was recorded at 11.5°N transect. The SeaWiFS chl. *a* distribution showed an exceptionally higher concentration at 17.5°N;84°E than oceanic region (Fig. 28).

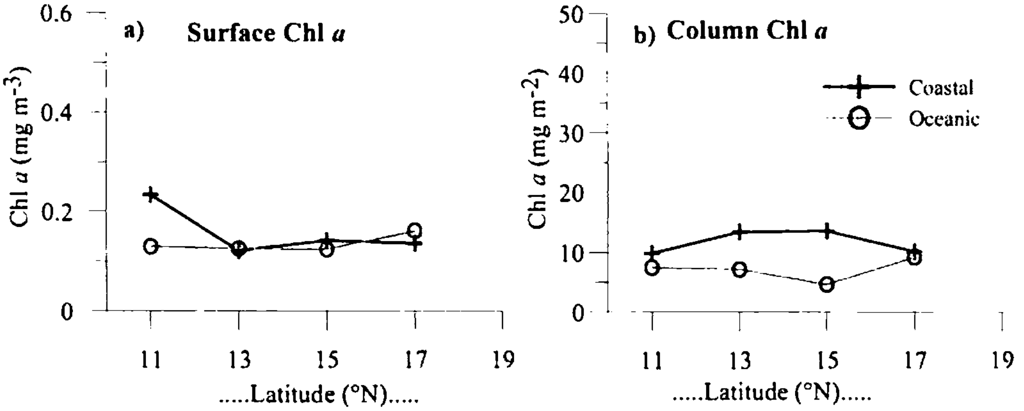


Fig. 27 Latitudinal distribution of a- surface (mg m^{-3}) and b- column chlorophyll *a* (mg m^{-2}) in the coastal and oceanic waters during summer monsoon.

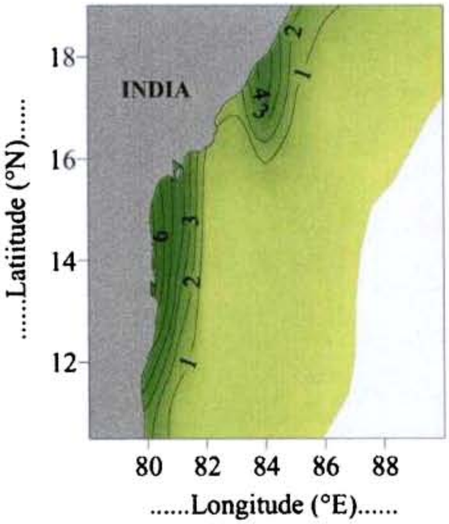


Fig. 28 Spatial distribution of chlorophyll *a* (SeaWiFS) during summer monsoon.

Mesozooplankton: During SM, distribution of mesozooplankton biovolume showed remarkable variations both vertically and horizontally. In the MLD, the average biovolume was 0.36 ± 0.27 ml m^{-3} and in thermocline layer it was 0.16 ± 0.24 ml m^{-3}. The coastal waters sustained higher biovolume in almost all the stations and the maximum biovolume in the MLD was observed at 13.5°N; 83°E (2.7 ml m^{-3}) followed by 1.08 ml m^{-3} at 17.5°N;84°E (Fig. 29). In the thermocline layer, the maximum biovolume (1.8 ml m^{-3}) was observed at 17.5°N;84°E followed by 0.89 ml m^{-3} at 13°N;80.5°E. All other stations sustained relatively low biovolume (<0.15 ml m^{-3}) in the thermocline layer. In the deeper layers viz., 1000-500 m, 500-300 m and 300 m -BT, the biovolume recorded were ranged from 0.01 to 0.3 ml m^{-3} and the variations between the depth strata were meager.

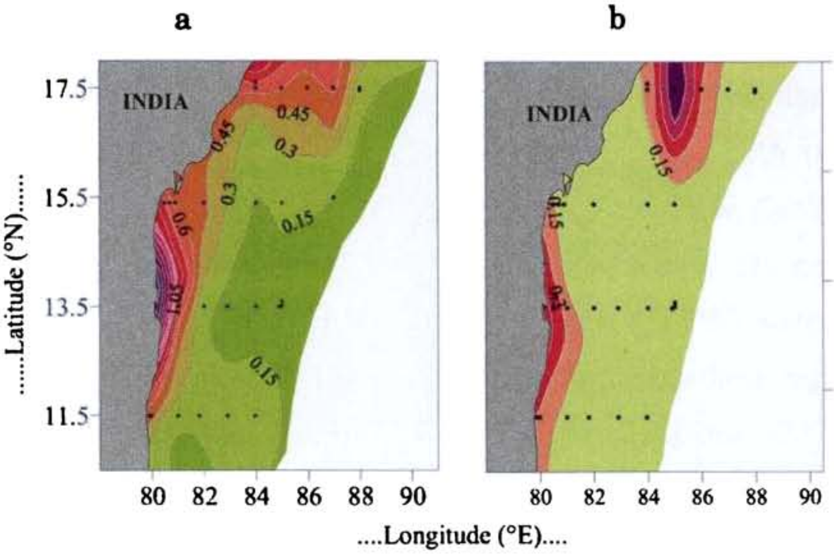


Fig. 29 Distribution of mesozooplankton biovolume (ml m^{-3}) in the a- MLD and b- thermocline layer during summer monsoon.

Latitude wise distribution of mesozooplankton biovolume is given in Fig. 30. In general, the biovolume distribution showed decreasing trend towards the deeper depths with maximum values recorded in the MLD followed by thermocline layer. Along 11.5°N transect, the variation of biovolume distribution from the coastal to oceanic stations were meager. Maximum biovolume in the above transect was observed at 80°E both in the MLD (0.33 ml m^{-3}) and thermocline layer (0.25 ml m^{-3}). Coastal stations along 13.5°N sustained relatively higher biovolume (2.2 ml m^{-3}) during this season, while other stations of this transect had low biovolume towards the oceanic as well as deeper waters. Along 15.5°N the average mesozooplankton biovolume was 0.32 ± 0.18 ml m^{-3}. Oceanic stations along 17.5°N transect especially at 84°E sustained more biovolume (2.01 ml m^{-3}) of mesozooplankton in both the MLD and thermocline layers.

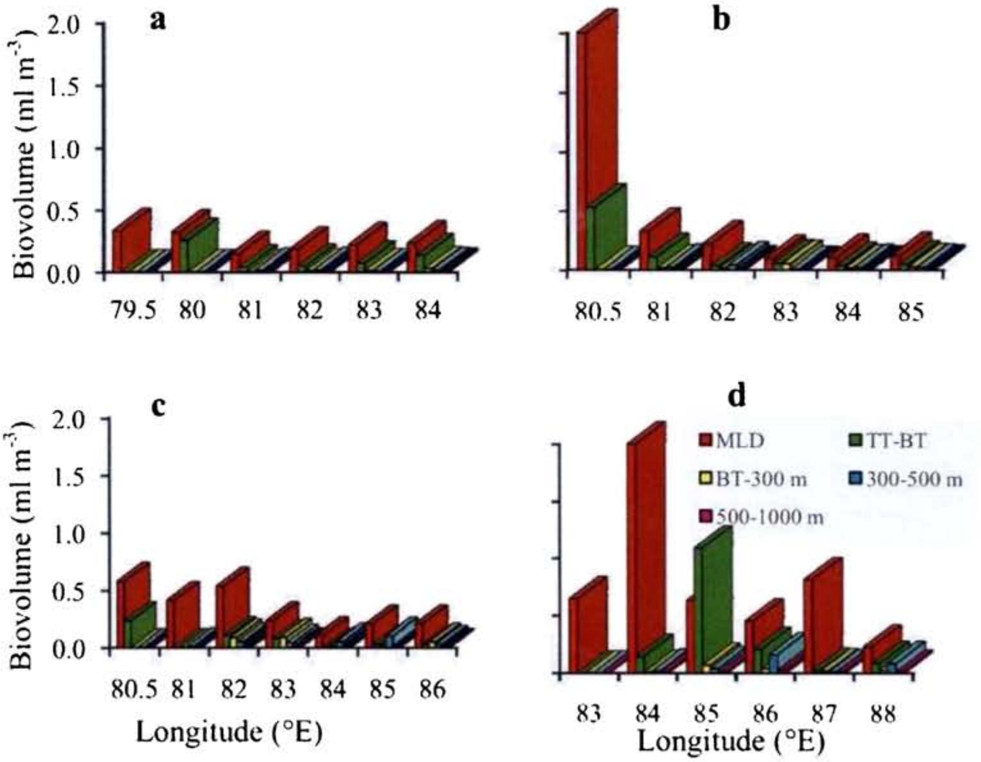


Fig. 30 Latitudewise distribution of mesozooplankton biovolume (ml m^{-3}) a-11.5°N, b- 13.5°N, c- 15.5°N and d- 17.5°N during summer monsoon.

The latitudinal variation of biovolume was very prominent during this season. The coastal stations were found to be sustain relatively higher biovolume than the oceanic stations. Among the coastal stations, the maximum biovolume of 2.7 ml m^{-3} was observed along the 13.5°N (Fig. 31) in the MLD and 0.58 ml m^{-3} in the thermocline layer. The lowest biovolume (0.32 ml m^{-3}) in the MLD was observed along 11.5°N transect. In oceanic stations along 11.5°N and 17.5°N, the biovolume in the MLD was observed to be more (0.25 ml m^{-3}) when compared to the oceanic stations of the other two transects(<0.1 ml m^{-3}). In the oceanic stations, biovolume in the thermocline showed similar pattern of distribution in the MLD.

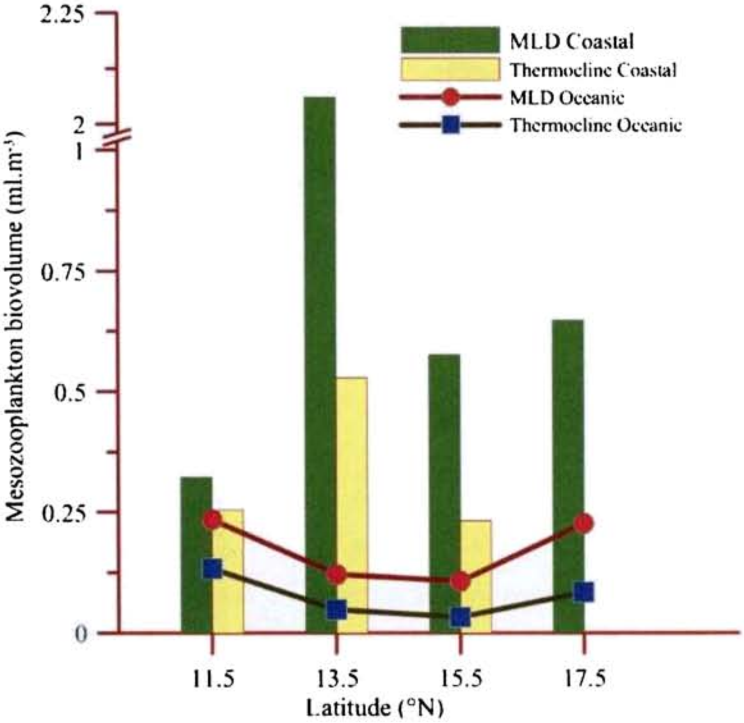


Fig.31 Variation of mesozooplankton biovolume (ml m^{-3}) in the coastal (bar plot) and oceanic (line plot) stations during summer monsoon.

Diurnal observation along 11.5°N, was not carried out during this season due to the non availability of the ship time. At the coastal station along 13.5°N transect, the biovolume was relatively higher in the MLD as compared to other transects and showed marked diurnal variation. At night, the biovolume recorded was higher at the coastal stations along 13.5 (2.8 ml m^{-3}) and 15.5°N (0.9 ml m^{-3}) transects, as compared to 17.5°N (Fig. 32). In the thermocline layer, the morning and night collections had more biovolume compared to noon and evening collections along 13.5°N.

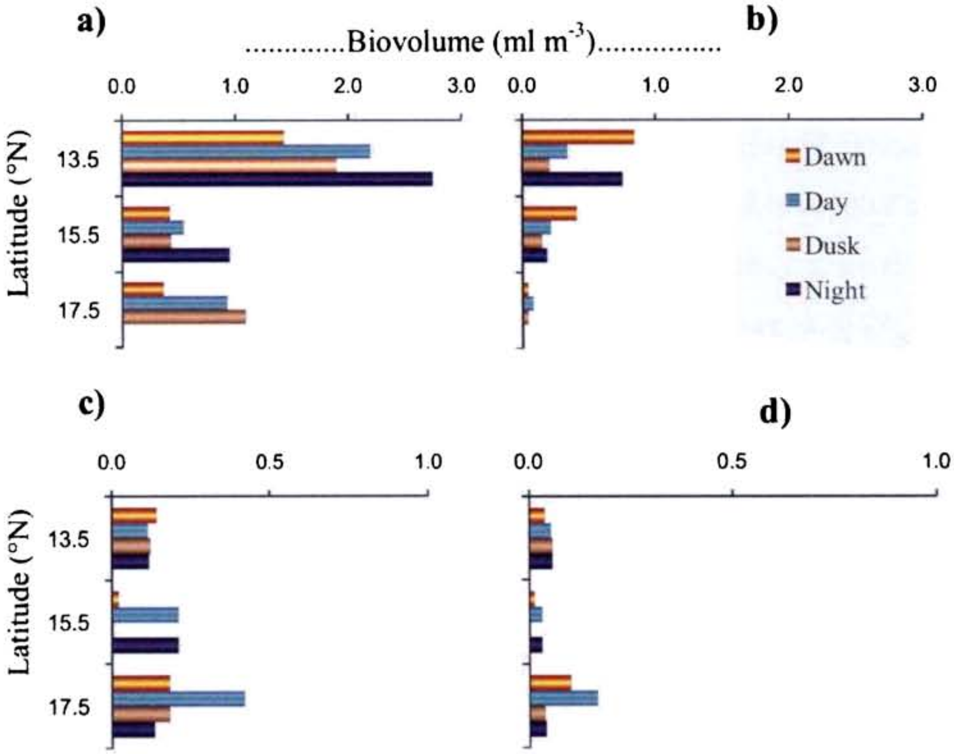


Fig. 32 Diurnal variation of mesozooplankton biovolume (ml m^{-3}) in the MLD and thermocline layer in the coastal (a&b) and in the oceanic stations (c&d) during summer monsoon.

The average abundance of mesozooplankton during this season in the MLD was 1,031 ± 1,274 and in the thermocline layer it was 163 ± 180 no. m^{-3}. In the lower layers viz., 300 m -BT, 500-300 m and 1000-500 m, the average abundance were 14 ± 17, 20 ± 18 and 6.4 ± 6 no. m^{-3} respectively. The mesozooplankton abundance during SM showed marked variation both in horizontal and vertical distribution. Maximum abundance of 5,559 no. m^{-3} was observed along 13.5°N at 80.5°E, and the dominant taxa in the MLD at this station were copepods (2,630 no. m^{-3}) followed by fish eggs (1,845 no. m^{-3}) and copelates (680 no. m^{-3}). The next abundance of mesozooplankton was noticed at 17°N;84°E (Table

IV). Between the coastal and oceanic stations, the variation of total abundance was very prominent especially along 11.5 and 13.5°N transects. The abundance at coastal station along the above transects were 1,064 and 5,559 no.m^{-3} and density in oceanic stations were 669 and 353 no.m^{-3} respectively.

Table IV Total abundance of mesozooplankton (no. m^{-3}) in the various depth strata during summer monsoon.

Latitude (°N)	Longitude (°E)	Mesozooplankton abundance (no. m^{-3}) in different depth strata				
		MLD	Thermocline	BT – 300 m	300-500 m	500-1000 m
11.5	79.5	1,065	-	-	-	-
	80	667	455	-	-	-
	81	289	217	2	2	2
	82	472	252	3	3	1
	83	430	92	7	3	4
	84	669	141	18	5	5
13.5	80.5	5,559	742	-	-	-
	81	392	47	7	5	2
	82	200	26	15	20	5
	83	190	23	16	6	1
	84	238	14	16	8	3
	85	354	104	30	10	4
15.5	80.5	1,583	338	-	-	-
	81	1,024	-	14	16	17
	82	1,286	325	74	74	6
	84	572	68	49	43	14
	85	339	50	13	51	2
	86	421	65	34	34	9
	87	489	221	8	18	2
17.5	83	1,571	-	-	-	-
	84	4,379	425	5	8	16
	85	1,379	14	3	58	10
	86	556	235	7	20	12
	87	979	117	5	39	26
	88	669	117	27	25	8

The contribution of various taxa to the total abundance of mesozooplankton also showed variation both horizontally and vertically. Copepod formed the major component in almost all stations. The average copepod abundance during this season was 78 ± 15% (Fig. 33), and it ranged from 57 to 82%. Relatively lower abundance (57%) of copepod was recorded from the coastal station along 13.5°N in the MLD. Among non-copepod members the dominant taxa were chaetognaths, copelates, decapods, ostracods etc. These taxa showed pronounced variations between the coastal and oceanic stations.

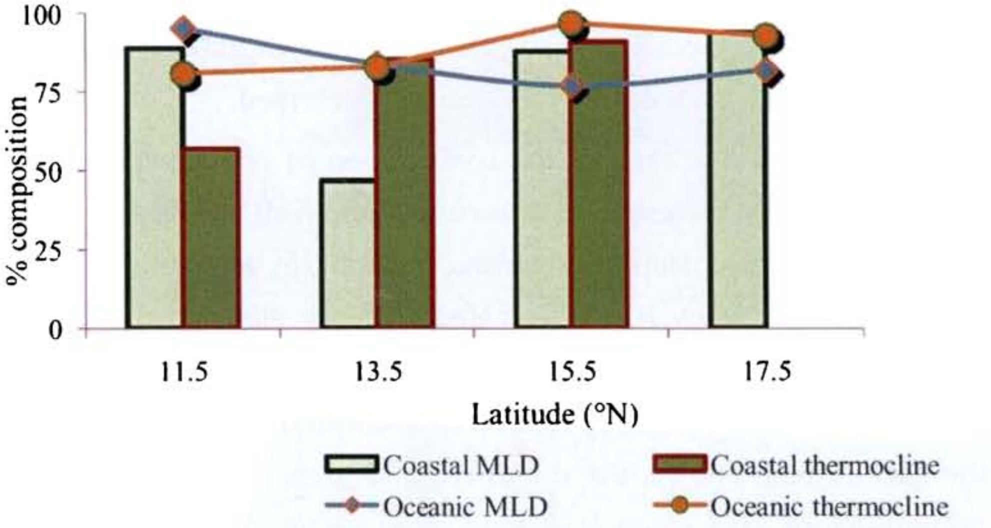


Fig. 33 Percentage composition of copepods in the coastal and oceanic stations in the MLD and thermocline during summer monsoon.

Among non-copepod components, in the coastal stations especially, along the southern transects (13.5°N in the MLD and 11.5°N in the thermocline) were characterised by high abundance of fish eggs (63% and 90% respectively). The highest abundance of ostracods (50.46%) in the coastal stations were noticed in the MLD along 11.5°N transect and all other transects were with > 11% (Fig. 34). Towards the northern side, along 15.5 and 17.5°N transects, the major groups were copelates (27% each), chaetognaths (16% and 30%), and decapods (15% and 17%). Representations of other taxa like polychaets, siphonophores *etc.* were not prominent.

In the thermocline layer at the coastal station along 11.5°N transect, 90% of the non-copepod groups were contributed by fish eggs (Fig. 34). Good representation of ostracods (27%) euphausiids (25%) and copelates (24%) were observed in the thermocline layer at the coastal station along 13.5°N. Along 15.5°N transect, the major groups observed in the thermocline layer were copelates (27%), chaetognaths (24%), doliolids (14%) ostracods (9%) and decapods (6%) in the coastal stations, and the other groups were only meagerly represented.

At the oceanic stations the composition of non-copepod taxa of mesozooplankton presented a different picture in all transects. Fish eggs were not observed from the oceanic stations in any of the depths. Foraminiferans were noticed in the oceanic stations of southern transects with a contribution of 21% in the MLD and of 19% in the thermocline layer; this group was not present in the coastal stations. In the MLD along 11.5°N, the dominant taxa were chaetognaths (27%), foraminiferans (21%), copelates (18%) and gastropods (14%) (Fig. 35). Chaetognaths contributed about 66% and 47% along 13.5°N and 17.5°N transects respectively. Along 15.5°N transect the dominant taxa in the oceanic station were siphonophores (34%) followed by foraminiferans (28%) and chaetognaths (24%). In the thermocline layer, chaetognaths were the dominant taxa in the oceanic stations along all the transects (33, 36, 35 and 63% along 11.5, 13.5, 15.5 and 17.5°N respectively) (Fig. 35b). Along 13.5 and 15.5°N transects, ostracoda (33% and 36%

respectively) formed a major component in the mesozooplankton. Percentage contribution of other groups like euphusiids, siphonophores, polychaetes *etc.* were negligible in the thermocline layer along the oceanic station of the 15.5 and 17.5°N transects.

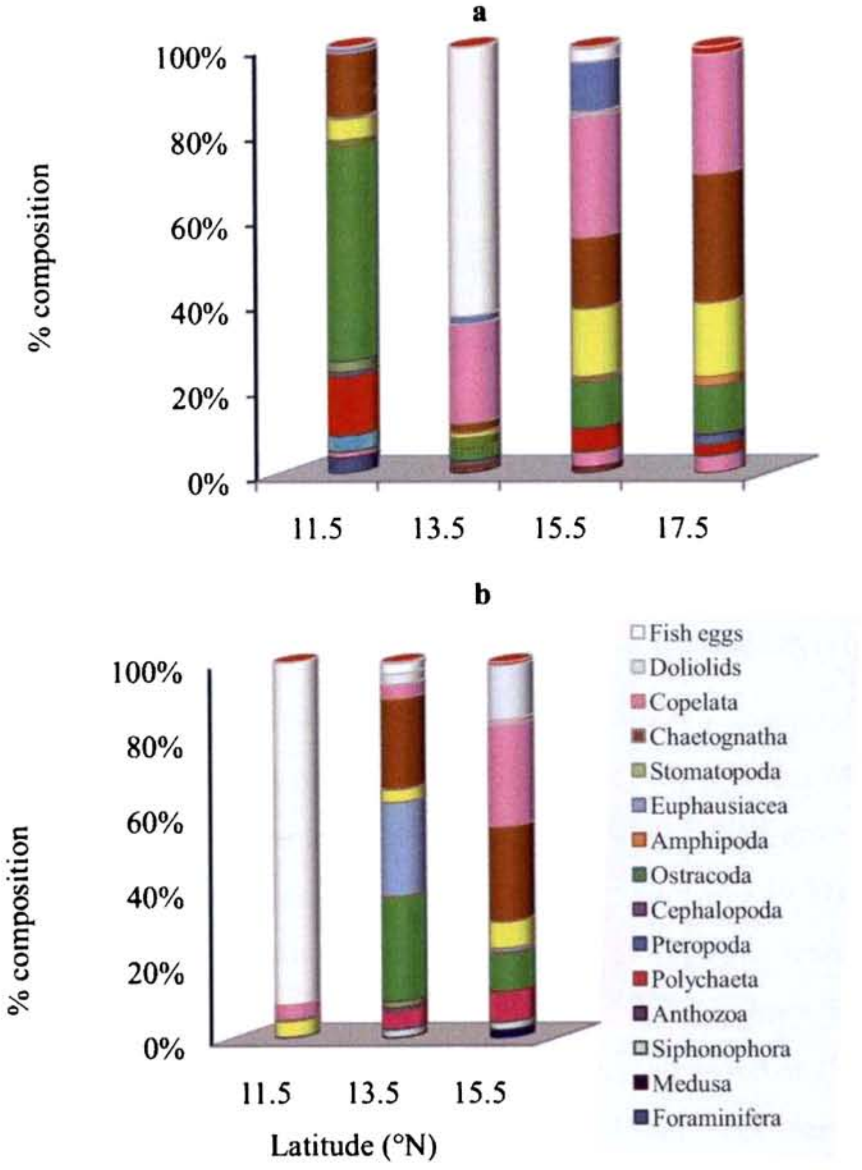


Fig. 34 Percentage composition of non-copepod taxa in the a- MLD and b- thermocline layer in the coastal stations along different transects.

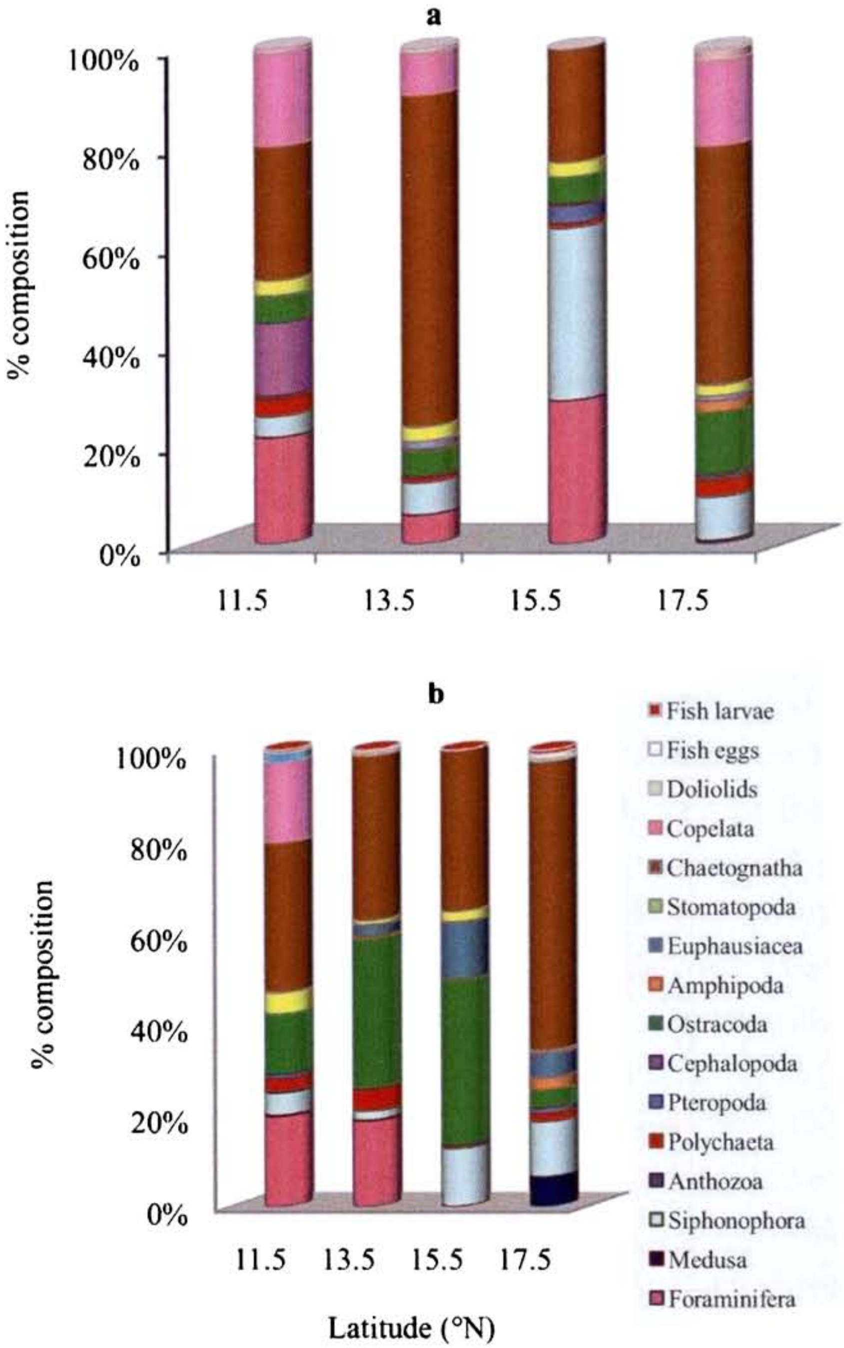


Fig. 35 Percentage composition of non-copepod taxa in the a- MLD and b- thermocline layer in the oceanic stations along different transects.

3.3 Fall intermonsoon (FIM)

3.3.1. Hydrography

Fall intermonsoon is considered as the short transitional period between the two monsoons (summer monsoon and winter monsoon). The average wind speed during this season was 4.8 ± 2.5 ms^{-1}. Warm surface (SST >28°C) waters prevailed in the entire region during this season. SST ranged from 28.5 to 28.9°C along northern transects, and 28.9 to 29.5°C along southern transects, with ~0.5°C variation between northern and southern transects. The average SST was 29.05 ± 0.38°C. As like the distribution of SST, SSS also showed a gradual increase towards the southern region. An increase of 2 was observed in the SSS from north to south. The average SSS noticed during this season was 32.47 ± 1.4. Maximum salinity (34) was recorded from the oceanic station (85°E) along 13°N transect. The sigma *t* of surface waters ranged from 18.5 to 20.5 with an increasing trend from north to south (Fig. 36).

The average MLD and thermocline layer depth observed during this season was 20 ± 11 m and 165 ± 16 m respectively. The MLD and thermocline depth deepened towards the central and southern region of the Bay during this season. Towards the north (20.5 and 19°N) and the coastal region of middle transects (17 and 15°N), the waters were characterised with shallow MLD (<14 m) and thermocline layer (<150 m) (Fig. 37). The deepest MLD (47 m) was recorded at 13°N; 82°E where the thermocline depth extended to 188m. The samples for dissolved oxygen and nutrients were not taken due to technical problems encountered during the cruise.

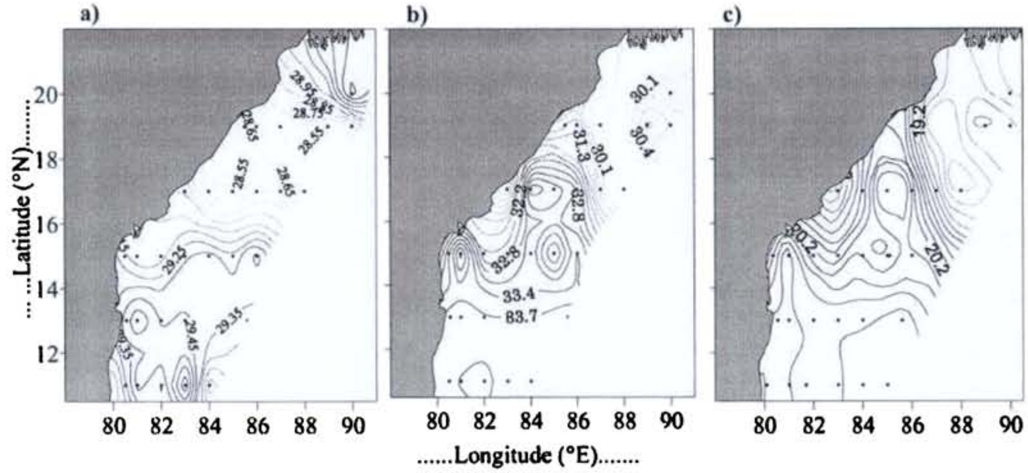


Fig. 36 Spatial distribution of a- sea surface temperature (°C), b- sea surface salinity and c- sigma *t* during fall intermonsoon.

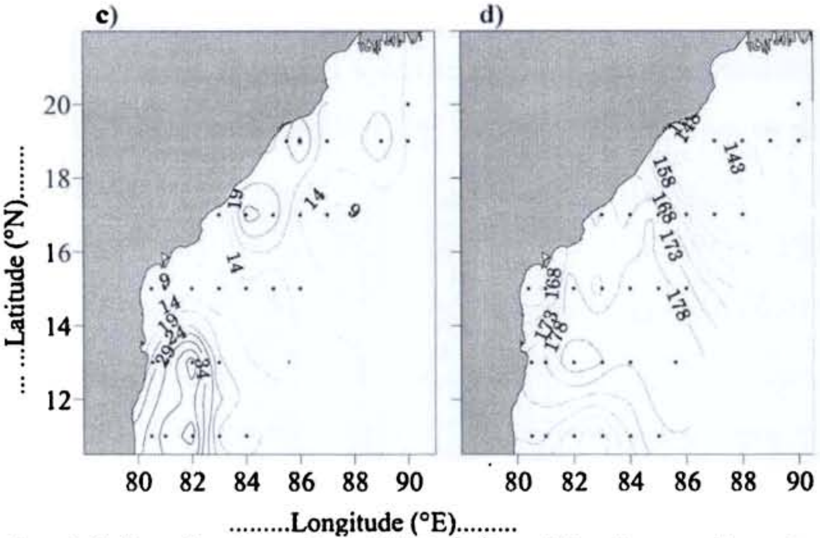


Fig. 37 Spatial distribution of a- MLD (m) and b- thermocline depth (m) during fall intermonsoon.

On analysing the latitudewise vertical distribution, an upsloping of temperature contours along the 15°N transect was observed during this season. 26°C isotherm shifted from 80 m to 50 m at 81°E and 34.4 isohaline intruded to the surface at the same station. This peculiar feature indicates the prevalence of coastal upwelling along the transect (Fig. 38).

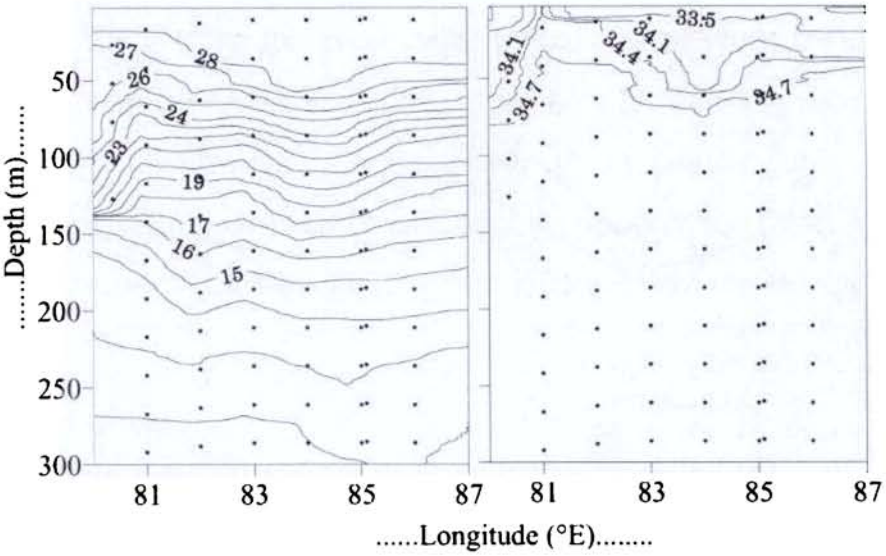


Fig. 38 Vertical distribution of temperature (°C) and salinity along 15 °N transect during fall intermonsoon.

3.3.2 Biology

Chlorophyll *a* : During FIM, the coastal regions sustained more chl. *a* concentration than the oceanic. The average concentration of surface chl. *a* in the coastal stations was 0.24 ± 0.10 mg m^{-3}, and in the oceanic stations it was 0.20 ± 0.79 mg m^{-3}. An increase in the surface as well as column values of chl. *a* was observed from the south to north (Fig. 39). The column chl. *a* concentration ranged from 7 to 31 mg m^{-3} (av.19.7 ± 9.6) along the coastal stations and 9 to 23 mg m^{-3} (av. 17.7 ± 5.6) along the oceanic stations. The SeaWiFS satellite observation supported *in situ* results. In the coastal station, maximum surface and column values of chl. *a* were observed towards the northern transects (17 and 19°N). The average values of surface chl. *a* concentration along the coastal and oceanic stations were 0.24 ± 0.0005 and 0.2 ± 0.0002 mg m^{-2} respectively (Fig. 40).

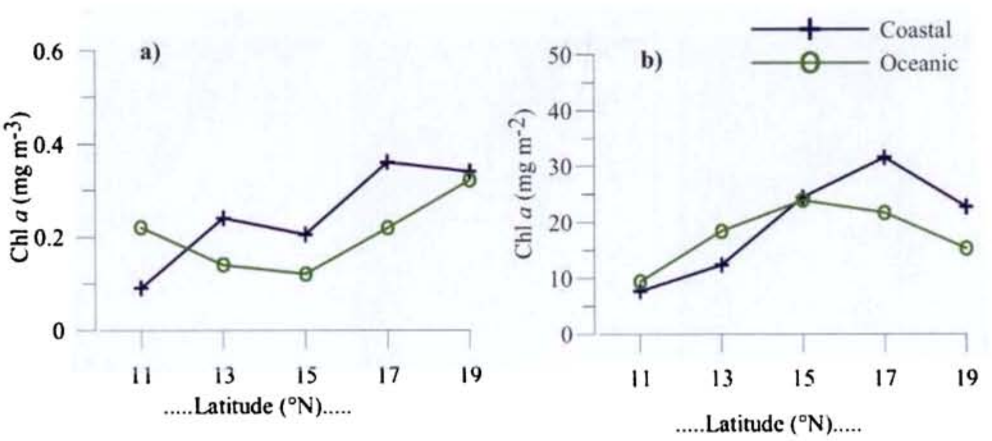


Fig. 39 Latitudinal distribution of a- surface (mg m^{-3}) and b- column chlorophyll *a* (mg m^{-2}) in the coastal and oceanic stations during fall intermonsoon.

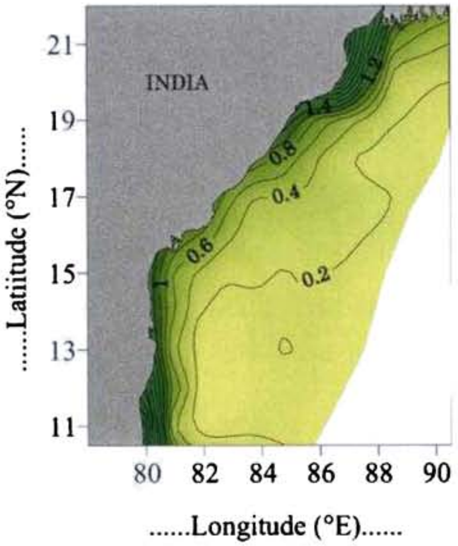


Fig. 40 Spatial distribution of chlorophyll *a* (SeaWiFS) during fall intermonsoon.

Microzooplankton: Variations in the total abundance of microzooplankton was observed between the coastal and the oceanic waters during FIM. Coastal stations had a higher abundance than the oceanic stations except along 11°N transect (Fig. 41). The lowest abundance (<800 no. m^{-2}) was reported from the northernmost transect

(19°N). Along 17°N, the variation of abundance between the coastal (26,5313 no. m^{-2}) and oceanic station (21,563 no. m^{-2}) was very prominent (Fig. 42). Heterotrophic dinoflagellates (58%) and ciliates (57%) dominated in the coastal and oceanic stations respectively. Other groups recorded were radiolarians and nauplii. Foramenifera were completely absent.

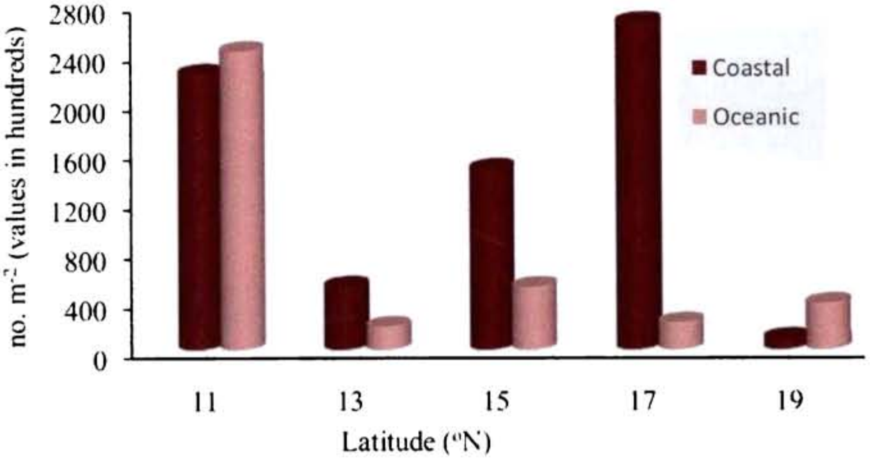


Fig. 41 Latitudewise distribution of total abundance of microzooplankton (no. m^{-2}) in the coastal and oceanic stations during fall intermonsoon.

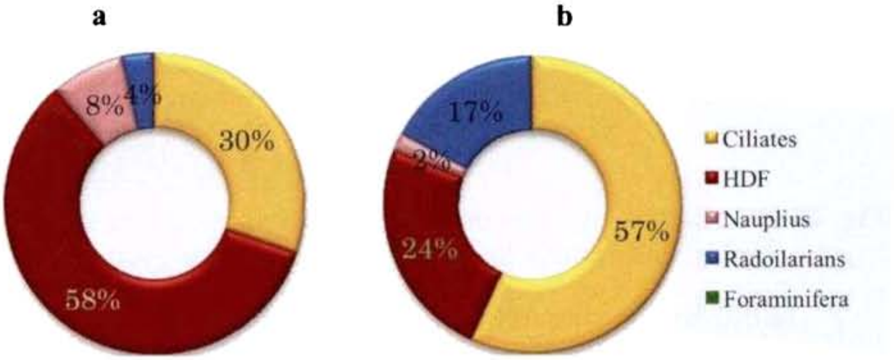


Fig. 42 Percentage composition of microzooplankton groups in the a- coastal and b- oceanic stations during fall intermonsoon.

Mesozooplankton: Mesozooplankton biovolume in the MLD ranged from 0.1 to 2.1 ml m^{-3} (av.: 0.55 ± 0.5), and in the thermocline layer it was from 0.1 to 0.5 ml m^{-3} (av. 15 ± 0.1). In the MLD, maximum biovolume (2.1 ml m^{-3}) was observed at the coastal station (83°E) along 17°N transect. In the southern regions, the biovolume recorded in the MLD and thermocline was low (<0.2 ml m^{-3}). North of 15°N, an increas of volume was observed especially along the coastal stations (Fig. 43). Towards the deeper depths the biovolume of mesozooplankton ranged from 0.002 to 0.19 (av. 0.04 ± 0.03), 0.004 to 0.22 (av. 0.04 ± 0.03) and 0.016 to 0.04 (av. 0.01 ± 0.009) ml m^{-3} in the 300 m -BT, 500-300 m and 1000-500 m depth strata respectively.

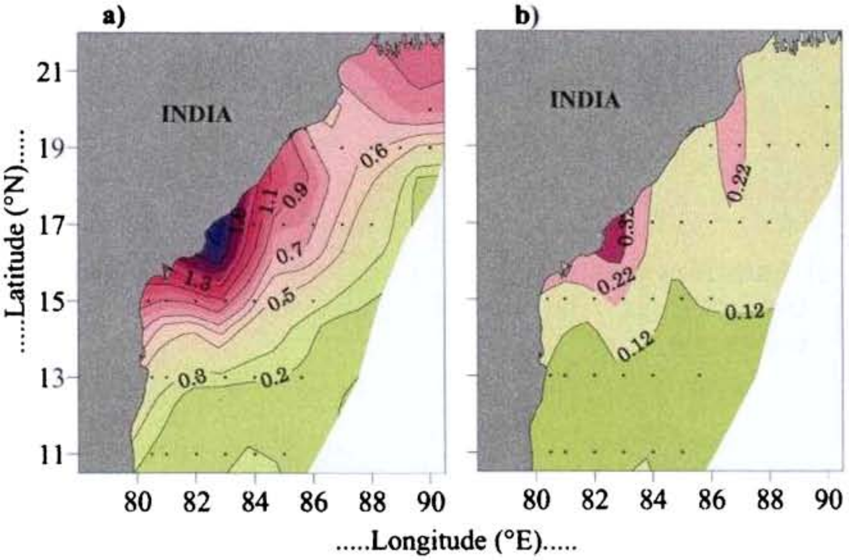


Fig. 43 Distribution of mesozooplankton biovolume (ml m^{-3}) in the a- MLD and b- thermocline layer during fall intermonsoon.

Latitudewise showed that, the distribution of biovolume at 15, 17 and 19°N transects were higher. Along 11°N and 13°N transects, the biovolume was in the range of 0.2 to 0.73 ml m^{-3} in the MLD (Fig. 44).

Towards the northern region, the variation of biovolume between coastal and oceanic stations were not prominent. All stations had biovolume >0.5 ml m^{-3} in the MLD with maximum of 2.4 ml m^{-3} at 17°N; 83°E and it was <0.5 ml m^{-3} from thermocline to the deeper depths.

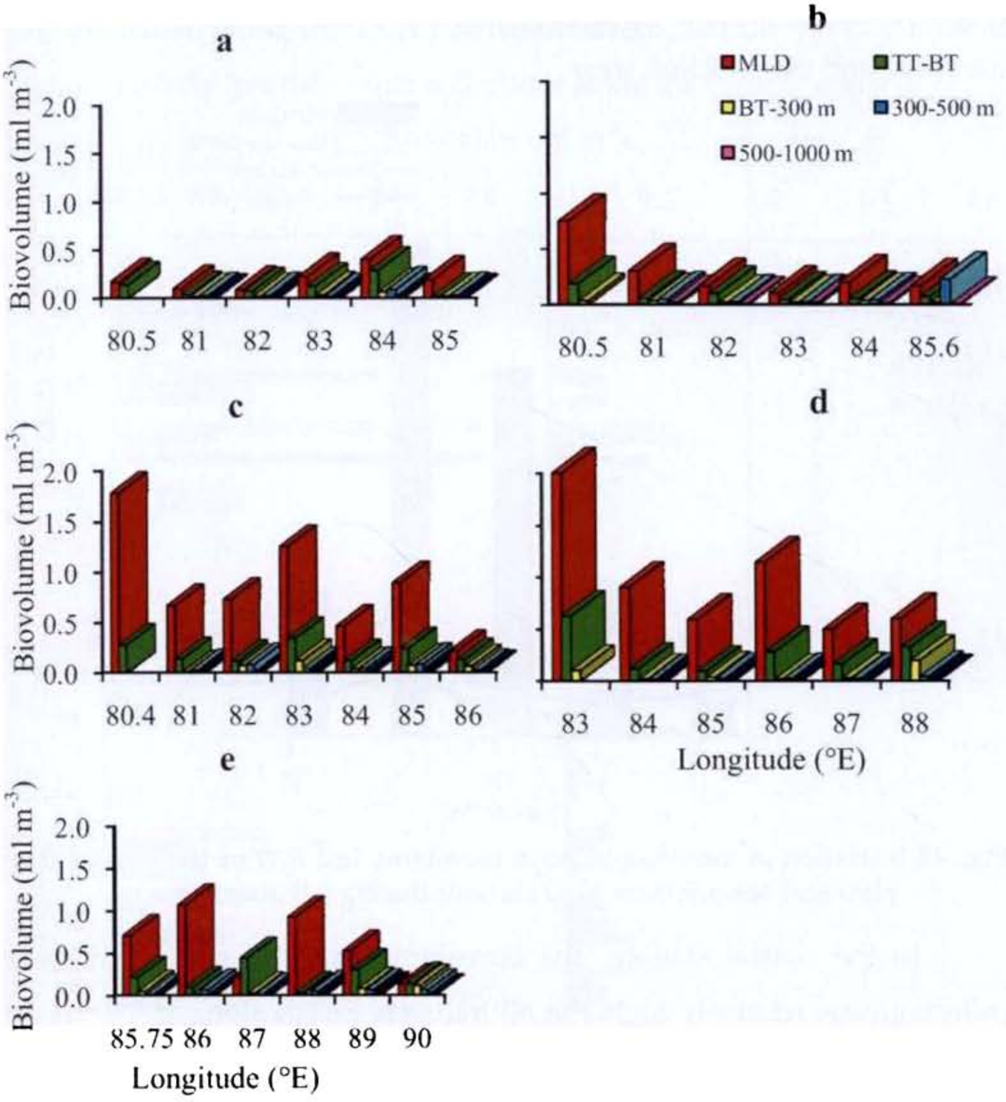


Fig. 44 Latitudinal distribution of mesozooplankton biovolume (ml m^{-3}) along a- 11°N, b- 13°N, c- 15°N, d- 17°N , and e- 19°N transects during fall intermonsoon.

In the coastal and oceanic regions, from 17°N to 11°N, the distribution of biovolume showed a decreasing trend in the MLD and thermocline layer. Coastal stations sustained five times higher biovolume than the oceanic station along the 17°N transect in the MLD (Fig. 45). At the oceanic stations, variations were only marginal between the MLD and thermocline layer.

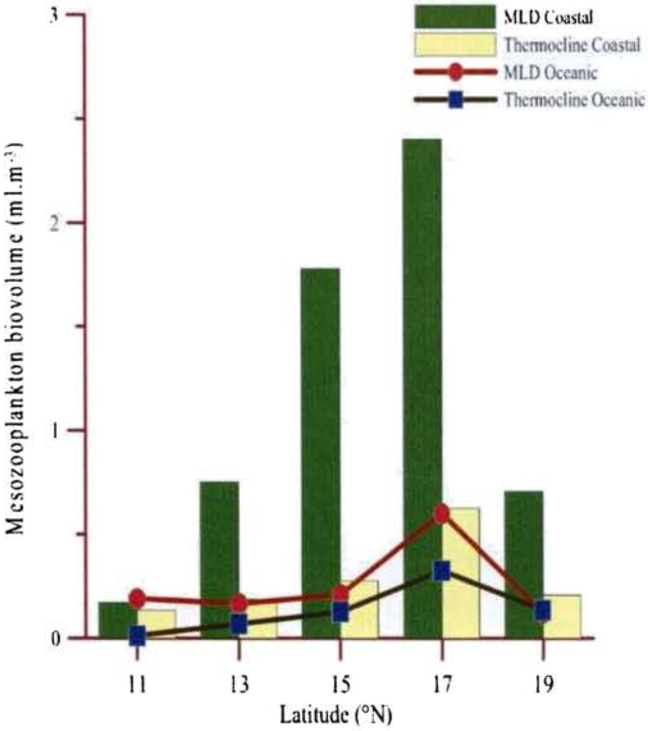


Fig. 45 Variation of mesozooplankton biovolume (ml m^{-3}) in the coastal (bar plot) and oceanic (line plot) stations during fall intermonsoon.

In the coastal stations, the biovolume recorded during morning collection was relatively higher at all transects except along 15°N. In the MLD along 15°N, the biovolume (>1.5 ml m^{-3}) was more in the day hauls than the night collections (<1 ml m^{-3}). At the coastal station along 17°N transect, the diurnal variation of biovolume was not pronounced in the MLD. In the thermocline layer, variations between diurnal collections were not substantial but the day collections, sustained slightly higher value. In the oceanic regions, the variation in time series collection was not significant either in the MLD and thermocline layer (Fig. 46). Maximum biovolume (1 ml m^{-3}) was recorded during early morning hours at the open ocean station along the 15°N. Biovolume recorded during day time was comparatively less than other collections along the oceanic regions.

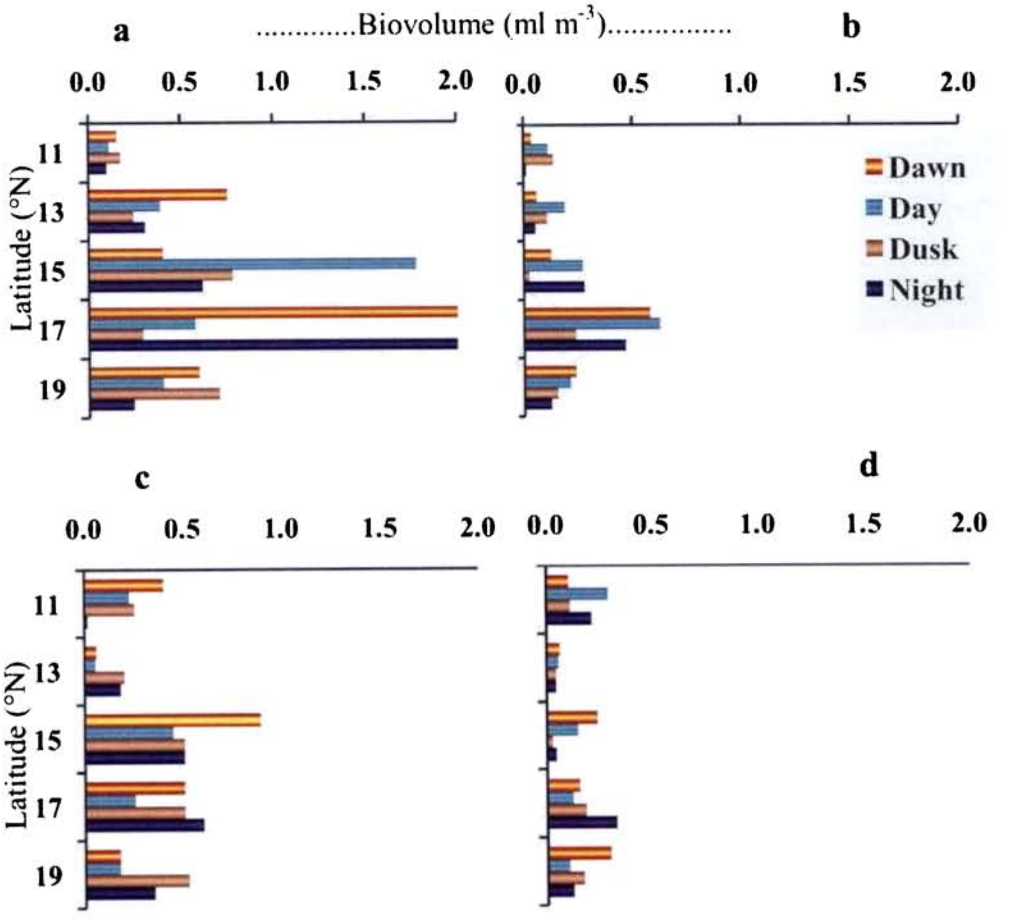


Fig. 46 Diurnal variation of mesozooplankton biovolume (ml m^{-3}) in the MLD and thermocline layer in the coastal (a&b) and in the oceanic stations (c&d) during fall intermonsoon.

Similar to biovolume, the total abundance of mesozooplankton showed an increasing trend from south to north Table V. Maximum abundance (3,186 no. m^{-3}) was observed in the MLD at 17°N;86°E followed by (1,529 no. m^{-3}) at 88°E along the same transect. Average abundance of mesozooplankton in the MLD was 998 ± 974 no. m^{-3}. Highest abundance in the thermocline layer was 984 no. m^{-3} and it was recorded from the 15°N;84°E. In the thermocline layer, the average abundance recorded was 246 ± 197 no. m^{-3}. Towards the deeper layers the abundance was comparatively less (<100 no. m^{-3}) with an exception in the 300 m-BT at the 15°N;84°E where it was 234 no. m^{-3}.

Table V Total abundance of mesozooplankton (no. m^{-3}) in the various depth strata during fall intermonsoon.

Latitude (°N)	Longitude (°E)	Mesozooplankton abundance (no. m^{-3}) in different depth strata				
		MLD	Thermocline	BT – 300 m	300-500 m	500-1000 m
11	80.5	426	216			
	81	3	65	10	10	2
	82	125	203	7	21	1
	83	226	196	3	2	1
	84	500	123	6	16	1
13	80.5	2,194	39			
	81	263	164	52	57	20
	82	88	134	6	34	1
	83	35	102	11	26	1
	84	369	129	17	44	1
	85	282	85	11	13	1
15	80.5	1,503	477			
	81	286	83	9	5	4
	82	805	199	48	43	1
	84	4,215	984	234	149	0
	85	149	139	7	23	4
17	83	1,108	512	33		
	84	715	98	6	14	22
	85	1,192	323	95	11	29
	86	3,186	319	37	10	29
	87	267	310	3	38	1
	88	1,529	898	49	19	26
19	85	997	331	97		
	86	1,013	304	6	39	1
	87	438	353	14	5	1
	88	518	28	3	54	17
	89	243	444	8	16	1
	90	1,403	221	42	57	17

Copepoda was the dominant group with an average of 82 ± 5% during this season. Maximum contribution of copepods (98%) was recorded in the coastal sations along 11°N transect. Along the northern transect (19°N), especially in the oceanic station, the contribution of copepods was relatively less (73% and 48%) in the MLD and the thermocline layer respectively (Fig. 47).

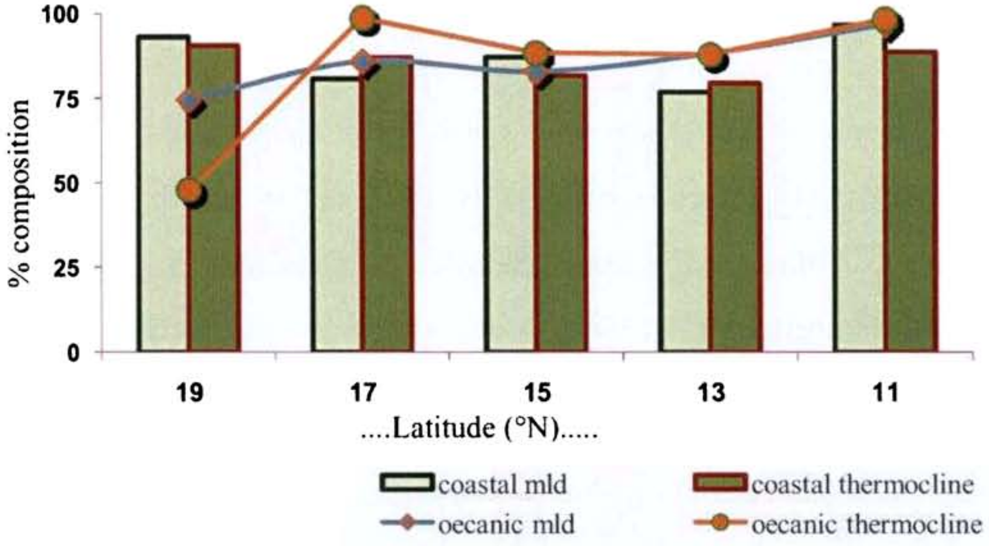


Fig. 47 Percentage composition copepods in the coastal and oceanic stations in the MLD and thermocline layer during fall intermonsoon.

Among the non-copepod members of mesozooplankton, the dominant taxon was Chaetognatha in both MLD and the thermocline layer in the coastal stations (Fig. 48). Copelates were the second abundant group after copepods in the MLD almost all transects except 19°N. Other components of mesozooplankton were decapods, euphausiids, doliolids *etc.* during this season. Percentage composition of chaetognaths ranged between 26 to 46% in the MLD and 20 to 51% in the thermocline layer in the coastal waters. Pteropods contributed 25% along the 19°N transect in the MLD while along other transects, the contribution was negligible. In the coastal waters, the representation of ostracods (6%) was reported only from 15°N. Eupahusiids were observed both in the MLD and thermocline layer and their percentage ranged from 2 to 10% in the MLD and 7 to 51% in the thermocline layer. Salps (19%) and doliolids (14%) were recorded only in the coastal waters along 11°N transect from the MLD. Amphipods were present in the MLD (16%) towards north of 15°N transect and also in the thermocline layer (5-16%).

As like coastal stations, oceanic stations had higher abundance of Chaetognatha and Copelata in the MLD, and thermocline layer along all transects but 11°N. In the MLD, contribution of Copelata (33 to 51%) was higher than Chaetognatha (5 to 40%), and *vice versa* in the thermocline layer (Fig. 49). Large colonies of Pyrosoma were observed in the study region especially towards the deeper layers *viz*. 1000-500 m, 500-300 m and 300 m -BT.

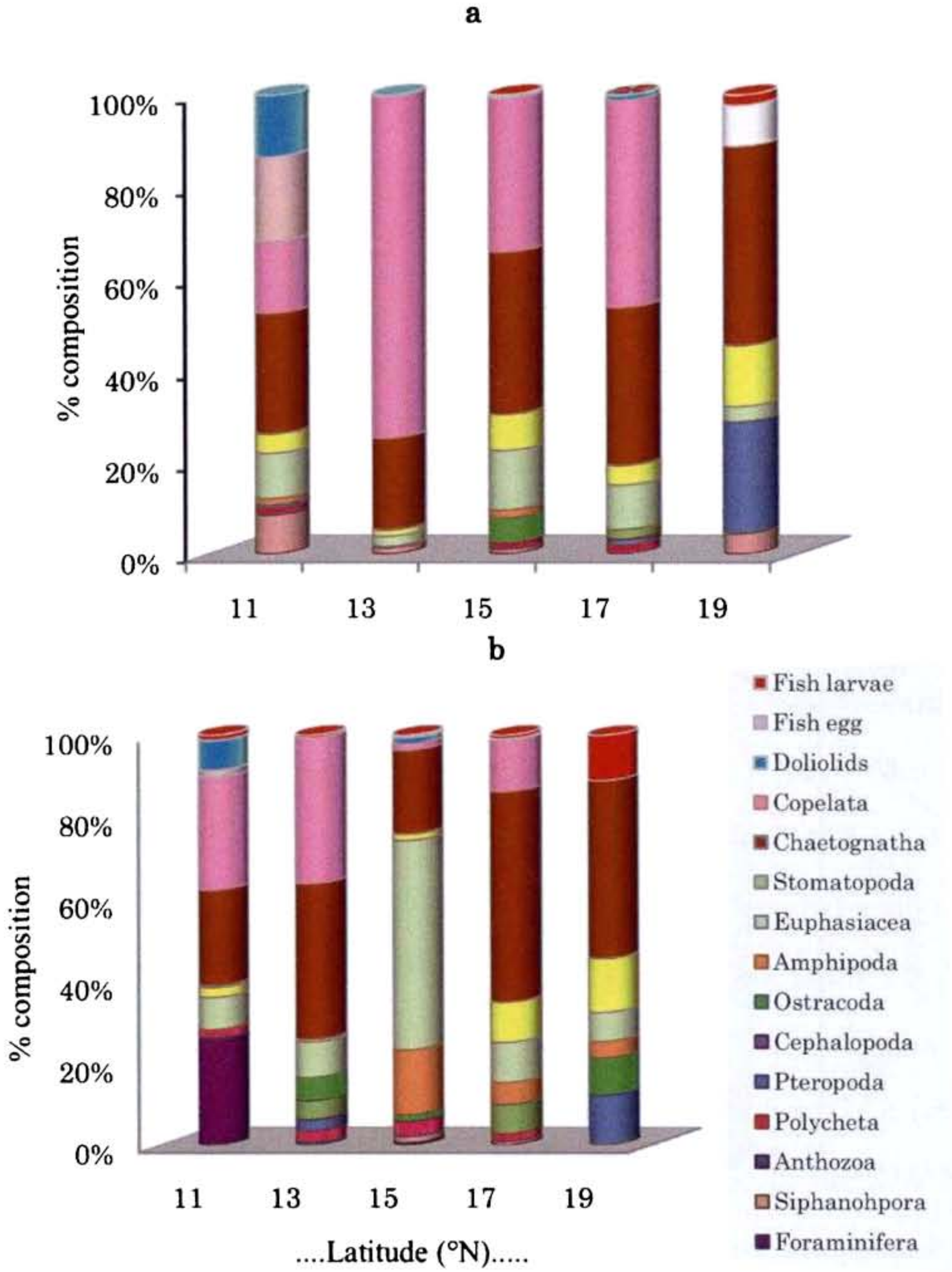


Fig. 48 Percentage composition of non-copepod taxa in the a- MLD and b- thermocline layer in the coastal stations during fall intermonsoon.

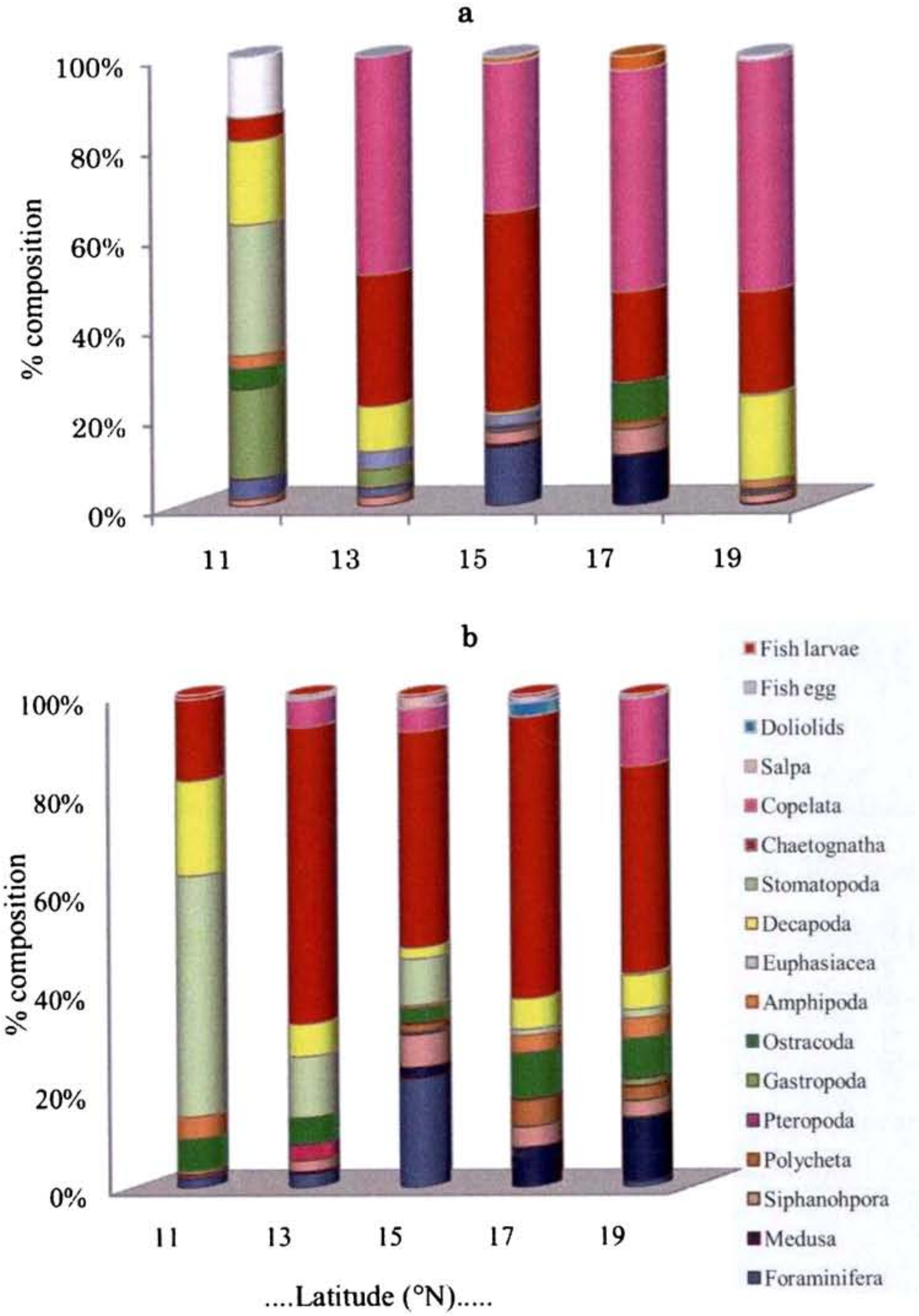


Fig. 49 Percentage composition of non-copepod taxa in the a- MLD and b- thermocline layer in the oceanic stations during fall intermonsoon.

3.4 Winter Monsoon (WM)

3.4.1 Hydrography

During this season, the BoB experienced north-westerly winds with an average wind speed of 7.2 ± 5 ms^{-1}. The maximum wind speed of 10.4 ms^{-1} was observed towards the oceanic region along 17°N transect. Distribution of temperature during this season varied widely between the northern and southern regions as well as coastal and oceanic regions. The average SST recorded during this season was 26.6 ± 0.54°C. The oceanic region of the central bay was characterised with warmer waters (>27°C) than the southern and northern region (Fig. 50). The lowest surface temperature (25.8°C) was observed at the coastal station (80.5°E) along the 13°N. Towards the north, the region had cold (25.2°C) and less saline (31.5) waters (20.5°N;89.5°E). The average SSS during this season was 32.8 ± 1.05. High saline waters (34.08) prevailed in the surface waters, between 11 and 13°N transect at 82 and 83°E respectively. The less saline (28.7) water was observed towards the northern tip of the bay. Sigma *t* during this season was found to be ranging from 18.5 to 22.2 (av. 21.02 ± 0.8). The minimum MLD (11 m) was observed in the 20.5°N and 13°N transects. The oceanic regions were characterised by relatively deep MLD (>45 m) and thermocline layer (>160 m) (Fig. 51).

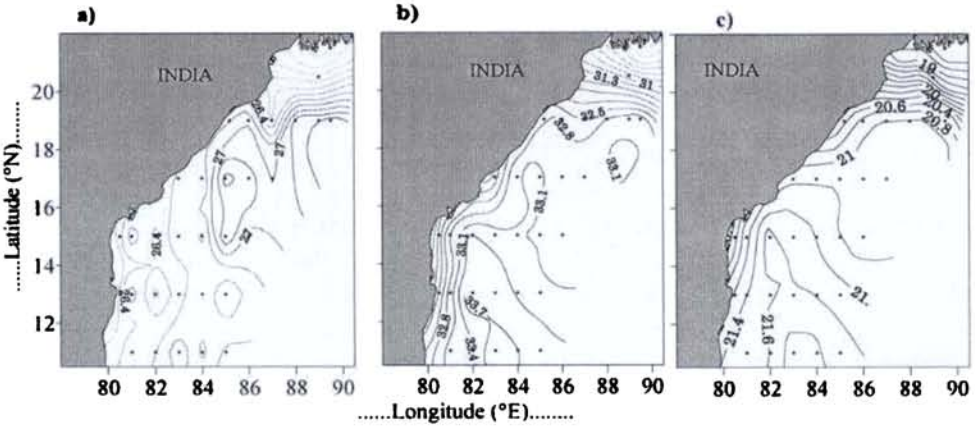


Fig. 50 Spatial distribution of a- sea surface temperature (°C), b- sea surface salinity, and c- sigma *t* during winter monsoon.

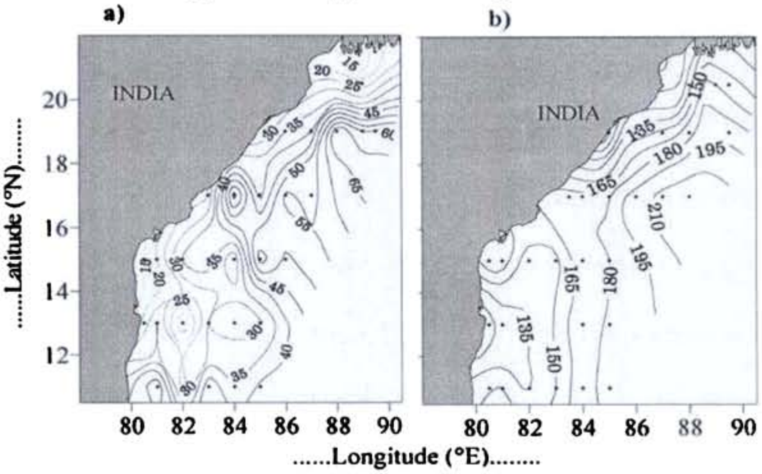


Fig. 51 Spatial distribution of a- MLD (m) and b- thermocline depth (m) during winter monsoon.

The surface layers were characterised with well oxygenated waters having average concentration of 211 ± 8.8 µM l^{-1}. The northern transects contained higher concentration of dissolved oxygen than the southern transects. Maximum concentration of DO (233 µM l^{-1}) was observed at 13°N;83°E and the lowest (196 µM l^{-1}) at 17°N;84°E. The surface waters were enriched with nutrients along the 13°N and 15°N transects. (Fig. 52). Along 19 and 20.5°N transects, the surface waters were characterised with less concentration of nitrate (<0.2 µM l^{-1}) and high concentration of silicate (>5 µM l^{-1}).

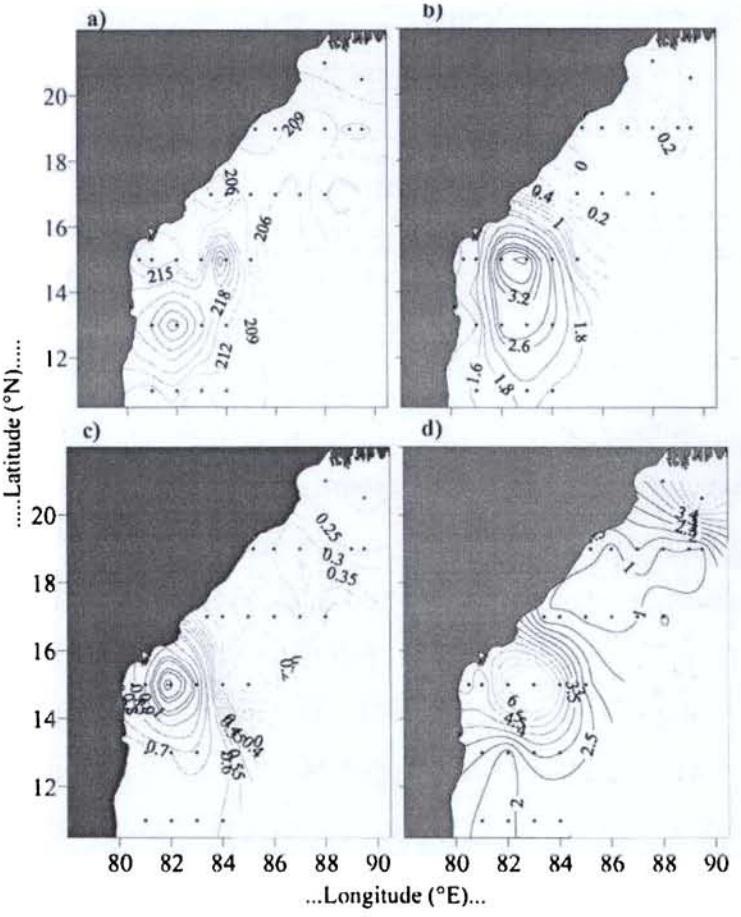


Fig. 52 Spatial distribution of a- dissolved oxygen (µM l^{-1}), b- nitrate (µM l^{-1}), c- phosphate (µM l^{-1}) and d- silicate (µM l^{-1}) during winter monsoon.

The northernmost transect (20.5°N) was experienced thermal inversion in the upper 75 m depth strata. Variation of temperature between the surface and subsurface layer was (depth at which the inversion observed) ~ 2°C. The average SST observed along the transect was 26 ± 0.2°C. Temperature inversion was observed from 40 to 65 m where the temperature (28°C) was 2°C higher than that of the surface layers (Fig. 53). This particular feature along the transect may be due to the heavy fresh water influx, in the northern region of the BoB.

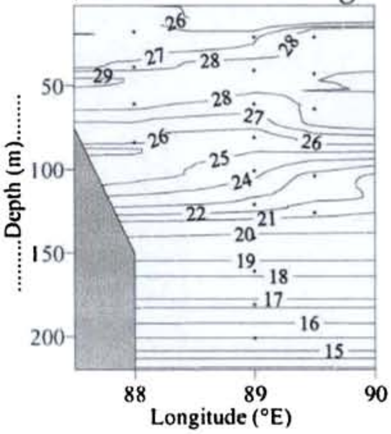


Fig. 53 Vertical distribution of temperature (°C) along the 20.5 °N transect during winter monsoon.

Along 19°N transect, doming of temperature (27°C) and salinity (34.4) contours were observed from 100 m to 65 m at 87°E. The oxycline (195 μM l^{-1}) and nutricline also followed the similar pattern of distribution along the transect (Fig. 54). The nitrate concentration along the transect was >2 μM l^{-1} in the upper 50 m water column. The MLD deepened towards the oceanic region from coastal waters, and the depth ranged from 25 m (coastal) to 66 m (oceanic). The depth of thermocline shifted upward (130 m) at 19°N;87°E from the coastal (150 m) and oceanic region (190 m).

The vertical distribution of physico-chemical parameters along 13°N transect was not similar to other transects. At 83°E, upsloping of temperature (26°C) and salinity contours (33.8) was observed from 75 m to the surface. The presence of a cold gyre was evident from the distribution of physico-chemical parameters in the region. The core of the gyre was identified at 83°E with 1° extension towards the periphery (Fig. 55). The surface waters were characterised with low DO (<195 µM l^{-1}), and high nutrient concentration (NO_3 - >2 µM l^{-1}).

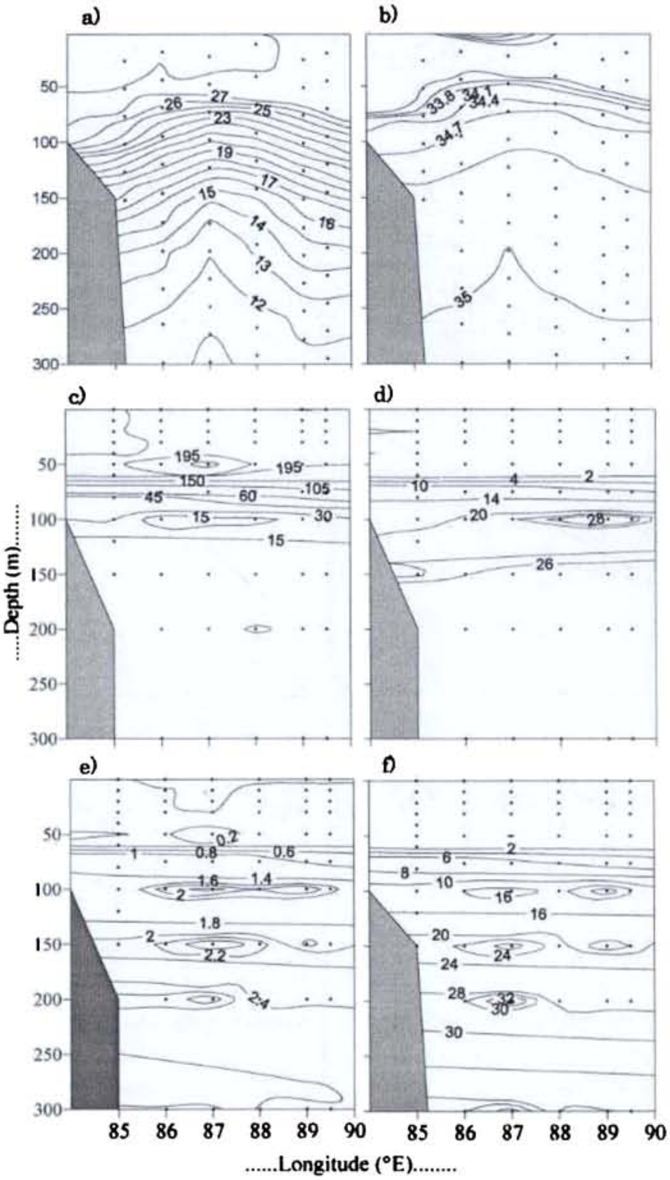


Fig. 54 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}), d- nitrate (µM l^{-1}), e- phosphate (µM l^{-1}) and f- silicate (µM l^{-1}) along 19°N transect during winter monsoon.

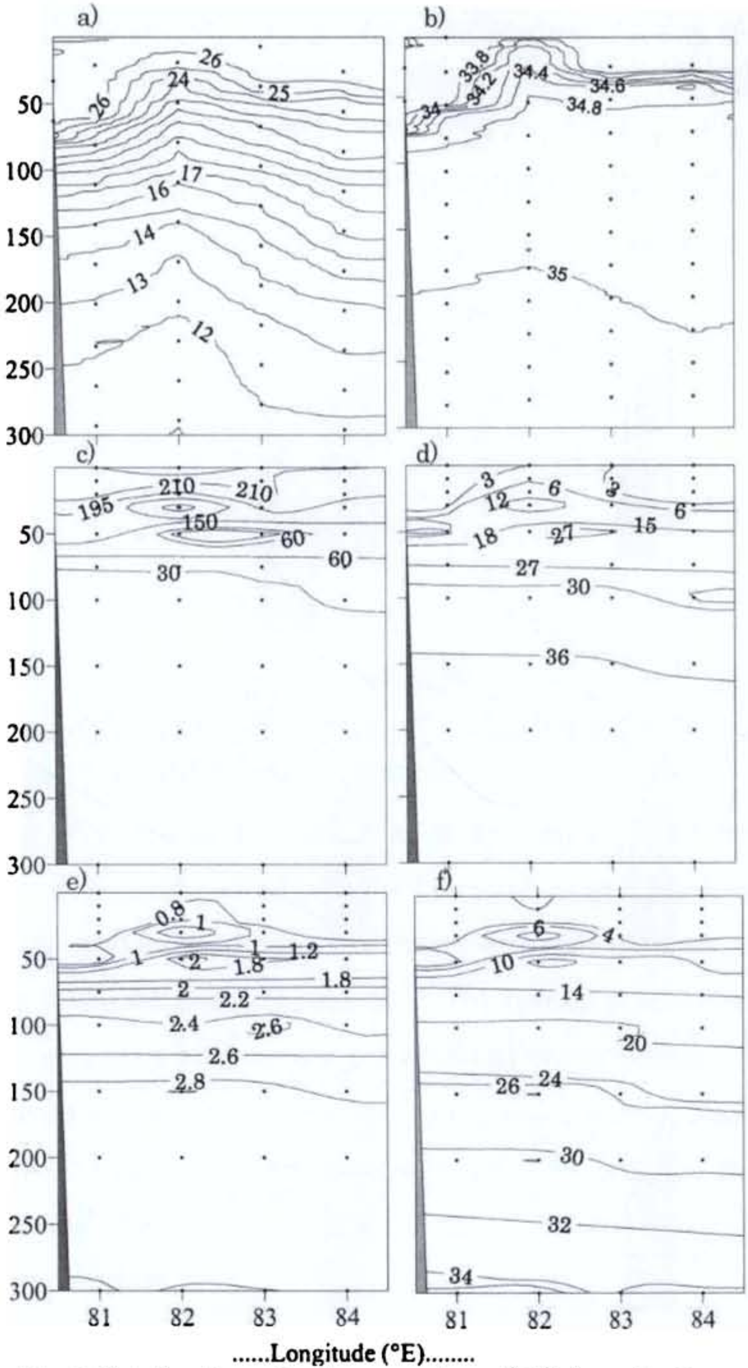


Fig. 55 Vertical distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}), d- nitrate (µM l^{-1}), e- phosphate (µM l^{-1}) and f- silicate (µM l^{-1}) along 13°N transect during winter monsoon.

3.4.2 Biology

Chlorophyll *a* : In the surface, the chlorophyll *a* concentration was in the ranged from 0.16 to 0.31 mg m^{-2} in the coastal and 0.07 and 0.5 mg m^{-2} in the oceanic stations. The average chl. *a* concentration during this season was 0.22 ± 0.13 mg m^{-2}. In the euphotic depth (upper 120 m) the column chl. *a* concentration was in the range of 6 to 25 mg m^{-2}. Variation of column chl. *a* concentration between the coastal and oceanic regions were marginal in all transects except 15°N (Fig. 56). The SeaWiFS chl. *a* distribution showed that the northern transect had higher concentration than the southern and middle transects. Towards the southern transects, the oceanic stations had more concentration than the coastal stations (Fig. 57).

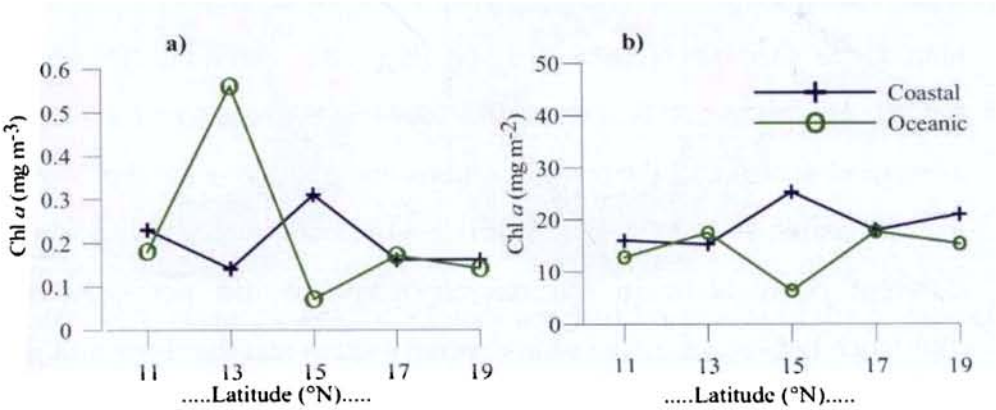


Fig. 56 Latitudinal distribution of a- surface (mg m^{-3}) and b- column chlorophyll *a* (mg m^{-2}) in the coastal and oceanic waters during winter monsoon.

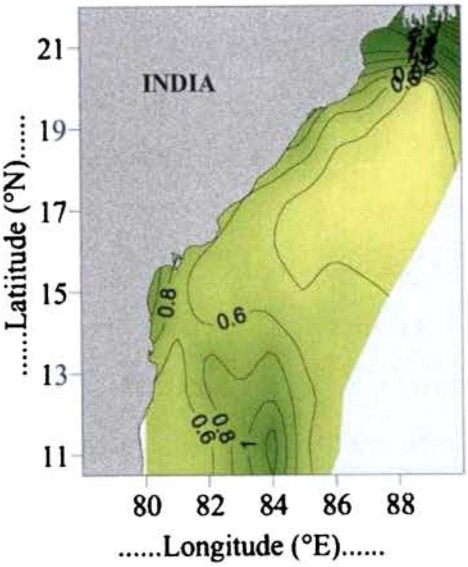


Fig. 57 Spatial distribution of chlorophyll *a* (SeaWiFS) distribution during winter monsoon.

Microzooplankton: Total abundance of microzooplankton showed a decreasing trend from south to north. The oceanic station sustained more abundance than the coastal stations (Fig. 58). Variations between the coastal and oceanic station were prominent in the southern transects. The average abundance in the coastal stations was 52,188 ± 9,888 no. m^{-2}, and in the oceanic stations it was 99,750 ± 44,843no.m^{-2}. The composition of different components in the microzooplankton did not show much difference between the coastal and oceanic stations. The dominant group was heterotrophic dinoflagellates (HDF) (35%) followed by ciliates (25%) and radiolarians (18%) (Fig. 59). Absence of foraminiferans were observed along the coastal stations, whereas it contributed 8% in the oceanic stations

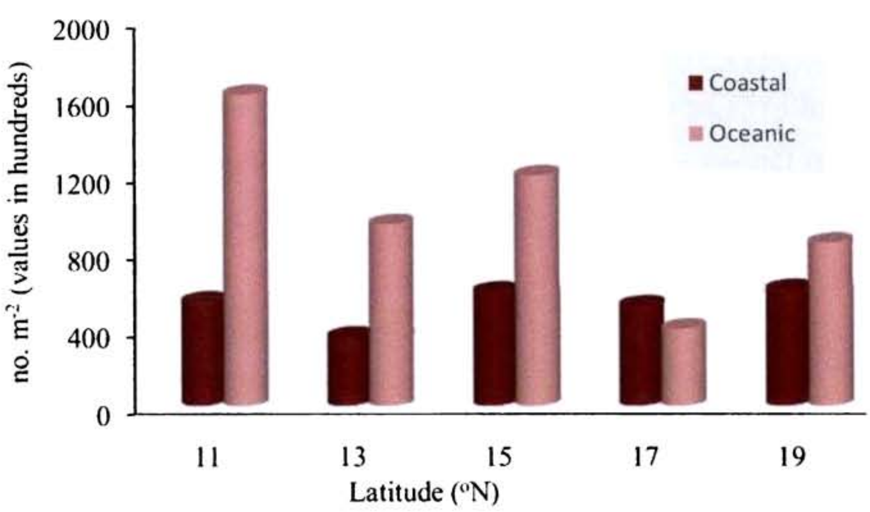


Fig. 58 Latitudewise distribution of total abundance of microzooplankton (no. m^{-2}) in the coastal and oceanic stations during winter monsoon.

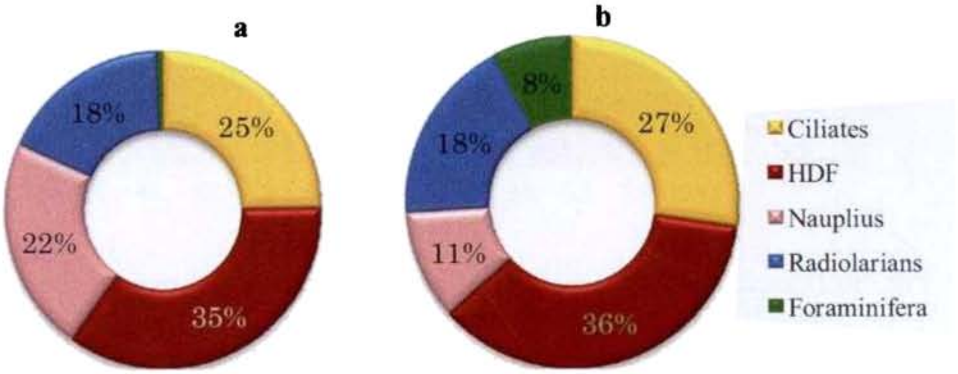


Fig. 59 Percentage composition of microzooplankton groups in the a- coastal and b- oceanic stations during winter monsoon.

Mesozooplankton : During WM, the mesozooplankton biovolume showed pronounced variation between the southern and northern regions. The region south of 15°N, sustained higher biovolume in the upper layers than the other transects. Variation of mesozooplankton biovolume between the MLD and thermocline layer was also appreciable during this season. The average biovolume in the

MLD was 0.59 ± 0.35 ml m^{-3} during this season. In the MLD and thermocline layer, the biovolume ranged from 0.2 to 1.92 ml m^{-3} and 0.01 to 0.69 ml m^{-3} respectively (Fig. 60). Maximum biovolume (1.92 ml m^{-3}) in the MLD was observed at 15°N;81°E. The average biovolume in the lower layer are 0.06 ± 0.03 in the 300 m-BT, 0.04 ± 0.004 in the 500-300 m and 0.01 ± 0.006 ml m^{-3} in the 1000-500 m.

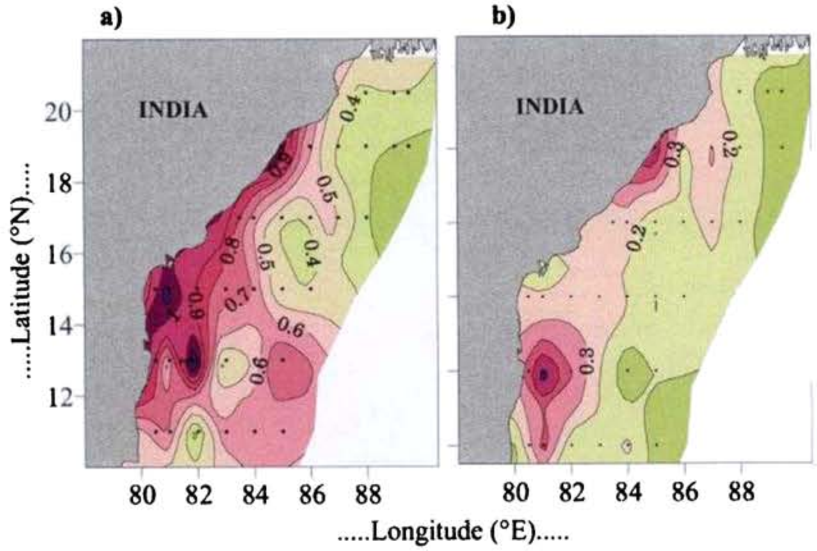


Fig. 60 Distribution of mesozooplankton biovolume (ml m^{-3}) in the a- MLD and b- thermocline layer during winter monsoon.

The transectwise variation of mesozooplankton biovolume was very prominent during this season. Along 11°N transect, the variation of biovolume in the MLD between the coastal and oceanic stations was marginal (av. 0.72. ± 0.32 ml m^{-3}). Distribution of biovolume towards the deeper waters showed a decreasing trend. An exceptional increase of biovolume in the 500-300 m (1 ml m^{-3}) depth strata was observed at 15°N;82°E station during this season (biovolume in the MLD was 0.6 ml m^{-3} at this station) (Fig. 61). In the northern region (17 and 19°N), the observed biovolume was much less (<0.5 ml m^{-3}) in all stations except in the coastal station.

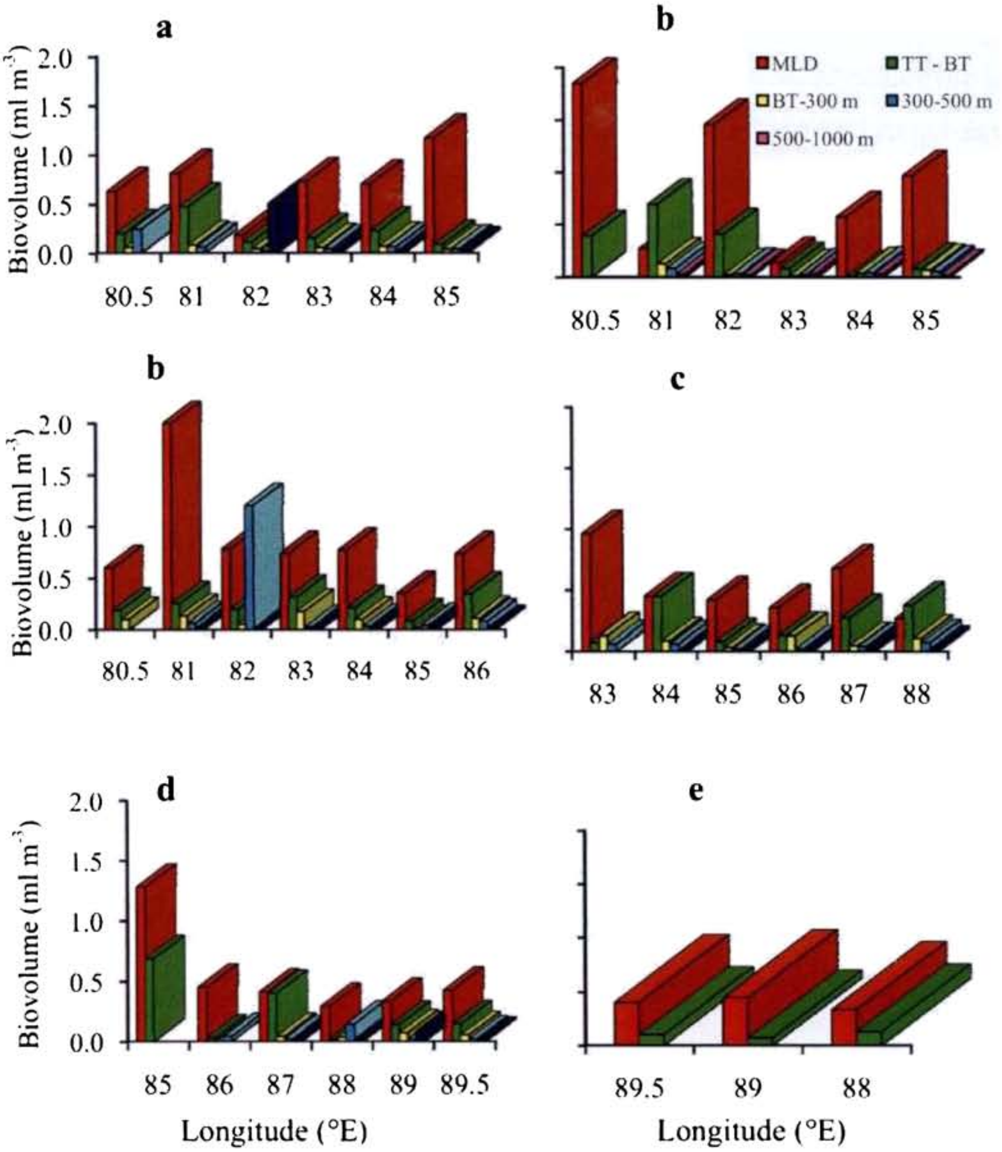


Fig. 61 Latitudinal distribution of mesozooplankton biovolume (ml m^{-3}) along a-11°N, b- 13°N, c- 15°N, d- 17°N, e- 19°N and f- 20.5°N transects during winter monsoon.

During WM, disparity of mesozooplankton biovolume between coastal and oceanic stations was more evident. MLD sustained more biovolume as compared to thermocline layer irrespective of the stations. In the coastal stations, the maximum biovolume (1.8 ml m^{-3}) was noticed along the 13°N, followed by 19°N (1.3 ml m^{-3}) transect (Fig. 62). In the oceanic stations of the southern region, the biovolume in the MLD was much higher in the than that of northern region. Maximum biovolume among the oceanic stations were observed along 11°N transect (1.2 ml m^{-3}), and minimum along 17°N (0.28 ml m^{-3}).

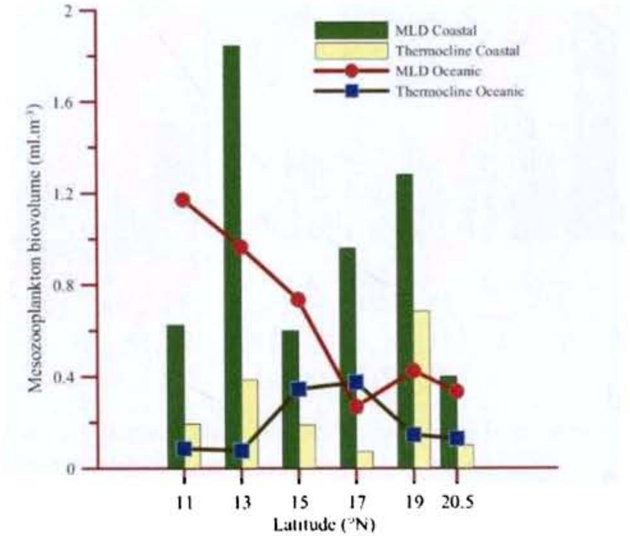


Fig. 62 Variation of mesozooplankton biovolume (ml m^{-3}) in the coastal (bar plot) and oceanic (line plot) during winter monsoon.

Diurnal variations of biovolume in the coastal and oceanic stations were not pronounced during this season (Fig. 63). Along the southern transects (11 and 13°N) in the MLD of the coastal stations, the night hauls were having relatively higher biovolume as compared to other hauls (an increase of 0.2 and 0.4 ml m^{-3} respectively), whereas in the middle and northern transects, the evening collections showed more biovolume than others. In the thermocline layer, the increased biovolume was observed at night time in the coastal station along 13°N transec. Towards the oceanic regions, during evening collection, the volume was slightly higher. Along 13°N transect, the diurnal variation of biovolume was only marginal. The distribution pattern of biovolume in the thermocline layer did not showed any specific pattern as in the MLD.

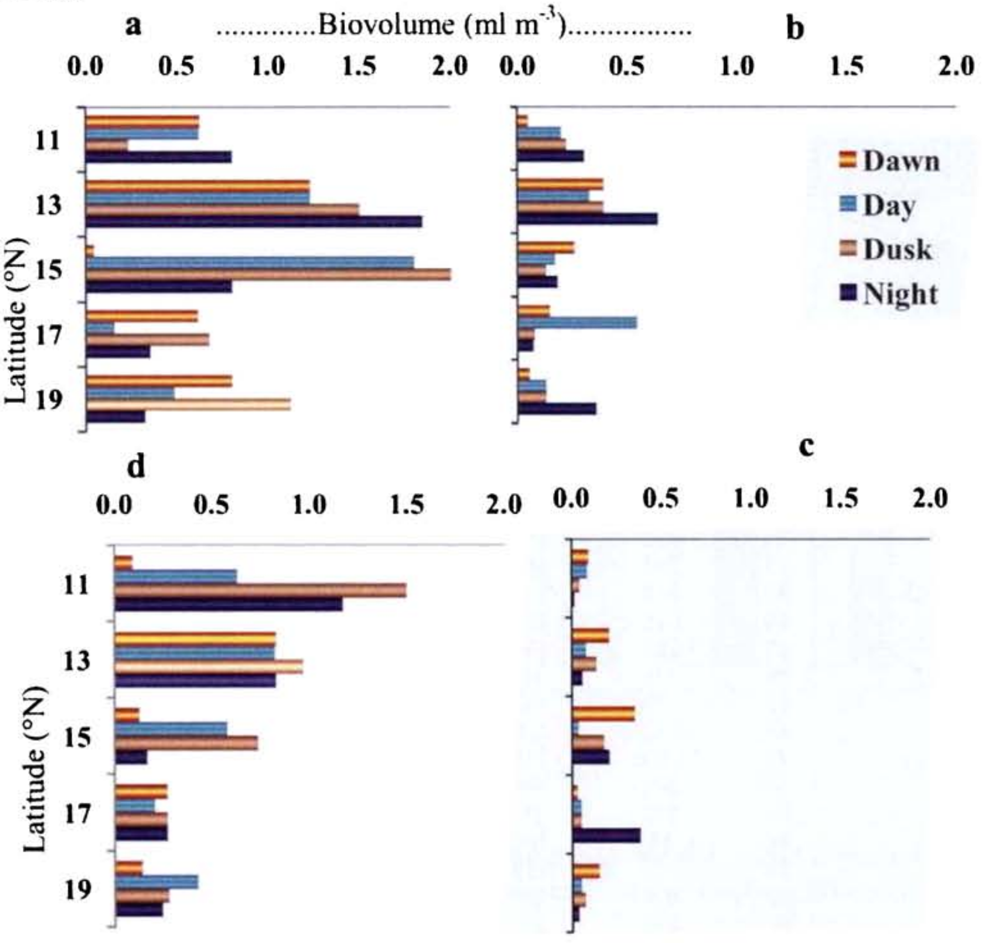


Fig. 63 Diurnal variation of mesozooplankton biovolume (ml m^{-3}) in the MLD and thermocline layer in the coastal (a&b) and oceanic stations (c&d) during winter monsoon.

During WM, the average abundance of mesozooplankton in the MLD was 546 ± 616 no. m^{-3} with maximum (4,288 no. m^{-3}) at 11°N;83°E. The second abundance was observed at the coastal station along 17°N transect. The mesozooplankton abundance was higher in the coastal than the oceanic stations except at 11°N. In the thermocline layer the maximum (1,294 no. m^{-3}) abundance was recorded at 19°N;85°E. In the deeper strata, the abundance of mesozooplankton was gradually decreasing (av. 32 ± 25 no. m^{-3}; Table VI).

Table VI Total abundance of mesozooplankton (no. m^{-3}) in the various depth strata during winter monsoon.

Latitude (°N)	Longitude (°E)	Mesozooplankton abundance (no. m^{-3}) in different depth strata				
		MLD	Thermocline	BT – 300 m	300-500 m	500-1000 m
11	80.5	296	68	53	-	-
	82	582	120	23	20	25
	83	4,288	428	47	15	10
	84	582	498	41	10	4
	85	646	26	78	4	12
13	80.5	649	188	32	15	10
	81	71	128	37	7	1
	82	844	19	21	11	10
	83	322	17	7	9	3
	84	284	4	33	6	38
	85	272	88	42	19	13
15	80.5	1,029	308	87	-	-
	81	753	145	12	11	3
	82	592	169	37	100	2
	83	566	316	33	12	0
	84	989	203	38	11	8
	85	284	167	20	1	7
	86	345	56	44	9	6
17	83	1,296	46			
	84	3,138	128	36	29	9
	85	1,200	158	43	8	4
	86	391	94	41	50	-
	87	327	88	39	24	10
	88	64	109	19	33	4
19	85	586	155	-	-	-
	86	378	35	0	25	-
	87	275	85	-	11	-
	88	110	104	29	18	38
	89	274	123	16	11	23
	90	245	143	6	3	2
20.5	88	251	110	-	-	-
	89	171	155	-	-	-
	89.5	359	136	-	-	-

Copepoda was the dominant taxon in the mesozooplankton composition during this season. The average percentage composition of copepods recorded during this season was 85 ± 4%. Variation of percentage contribution of copepod was meager between the coastal and oceanic stations. The layer wise distribution also followed the similar trend. Along the 13°N transect, an exceptional decrease (24%) in copepod occurrence was observed in the MLD (Fig. 64) at the oceanic stations.

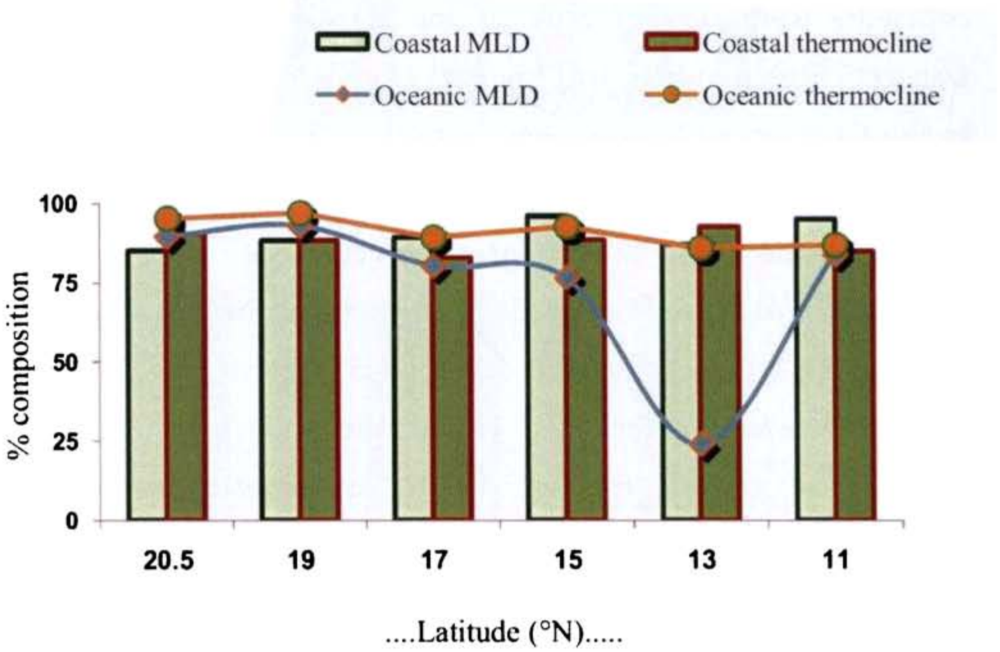


Fig. 64 Percentage composition of copepods in the coastal and oceanic stations in the MLD and thermocline during winter monsoon.

Among non-copepod members of mesozooplankton, the dominant taxon was Chaetognatha, (50 to 80%) both in the MLD and thermocline layer irrespective of coastal and oceanic waters. The maximum percentage of chaetognaths (83%) in the MLD was recorded from the coastal station along 19°N transect. Other major taxa along the coastal stations were siphonophores, euphausiids, amphipods etc. In the MLD, the contribution of copelates was negligible, except along the 19°N transect where it contributed to about 38% (second dominant taxa). In the thermocline layer, copelates were present only at the coastal stations along 19°N transect. Siphonophore was the next abundant group after copelates in the thermocline layer as well as in the MLD (Fig. 65). Maximum abundance of siphonophores (26%) was observed in the MLD at the coastal station along 17°N transect. Occurrence of ostracods (5 to 15%) in the MLD and thermocline layer was confined to the southern (13 and 11°N) and northern most (20.5°N) transects during this season. Decapoda contributed 13% in the MLD at 17°N and their contribution ranged from 2 to 9% in other transects. The representation of fish larvae ranged from 1 to 3% in the MLD and thermocline along the coastal stations.

Towards the oceanic region, the contribution of non-copepod mesozooplankton taxa showed great variability between the MLD and thermocline layer. Chaetognatha (25 to 67%) dominated in both MLD and thermocline layer followed by copelates and ostracods in almost all transects except the northernmost (20.5°N). Other dominant taxa were siphonophores, euphausiids *etc.* in the MLD (Fig. 66). Ostracods was reported from the thermocline layer and its contribution ranged from 7 to 67%.

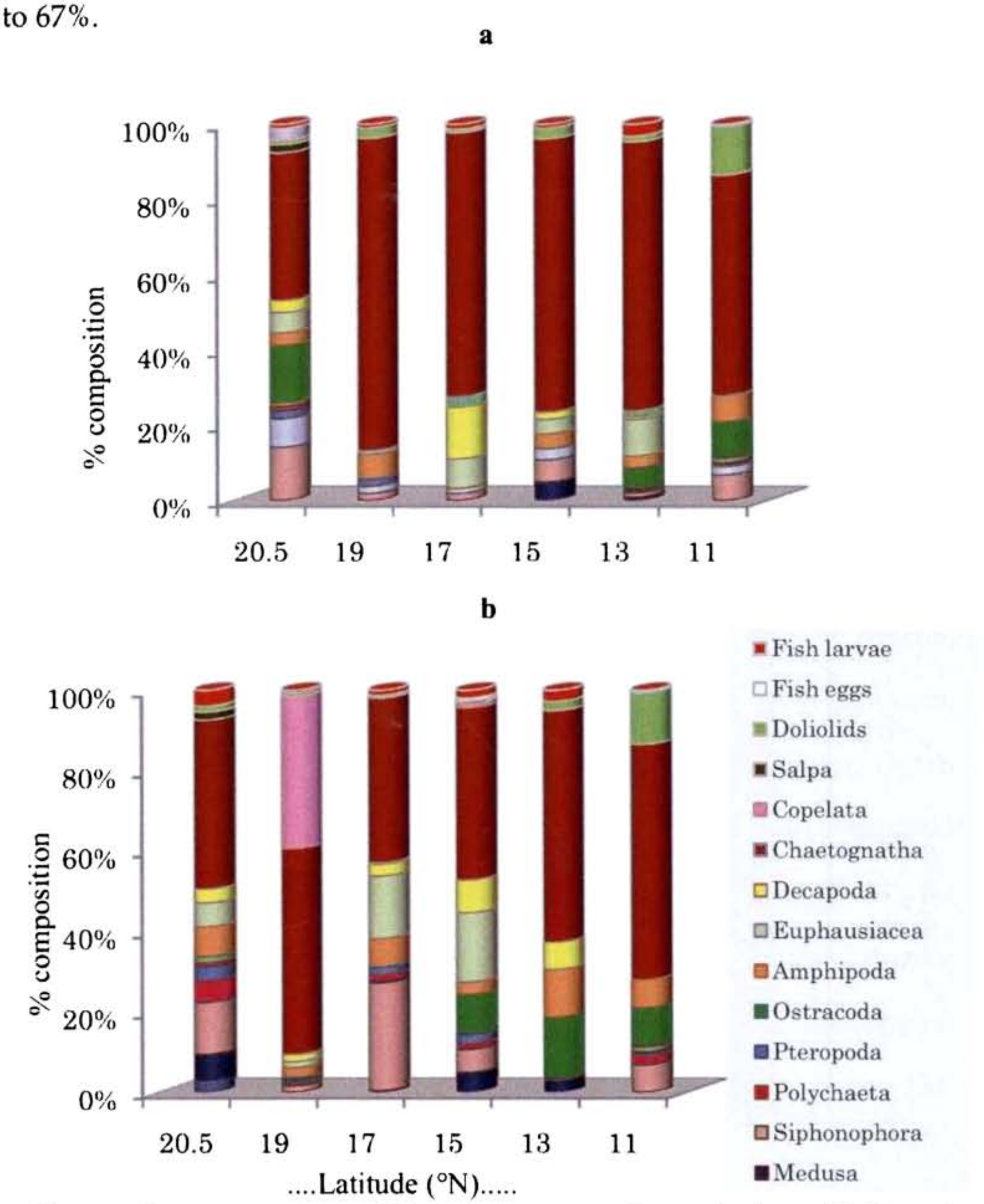


Fig. 65 Percentage composition of non-copepod taxa in the a- MLD and b- thermocline layer in the coastal stations during winter monsoon.

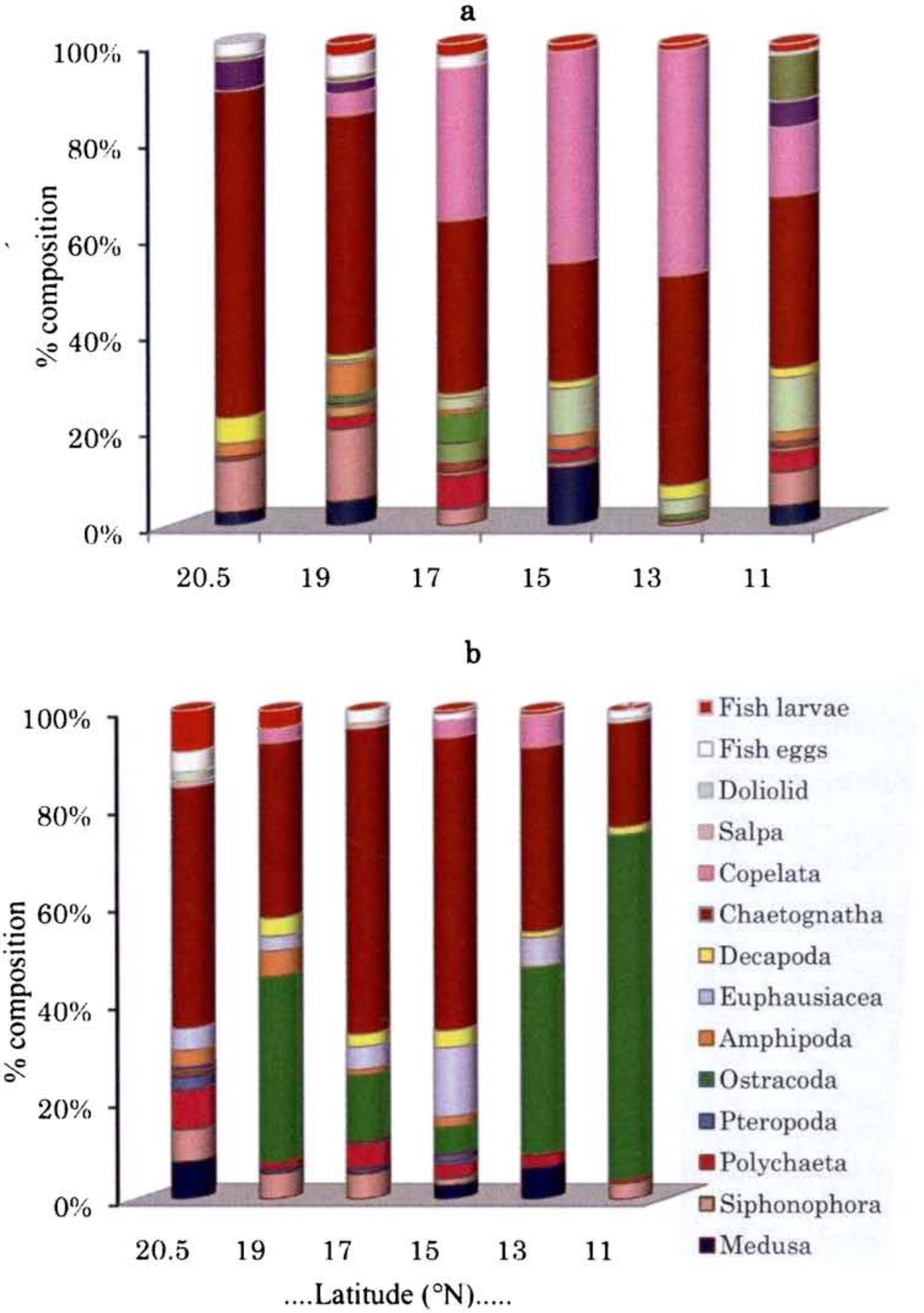


Fig. 66 Percentage composition of non-copepod taxa in the- MLD and b- thermocline layer in the oceanic stations during winter monsoon.

3.5 Seasonal comparison

The seasonal variations in hydrographic as well as biological characteristics of the BoB were pronounced during the study period. The mean surface temperature recorded were 27.8 ± 0.8, 27.1 ± 0.9, 29.1 ± 0.3 and 26.6 ± 0.5 during SIM, SM, FIM and WM respectively. The seasonal variation of SSS was relatively less than that of SST, but between northern and southern region the variation was prominent. The mean values of SSS recorded were 32.5 ± 1.2, 32.7 ± 0.58, 32.8 ± 1.8 and 32.4 ± 1.1 during SIM, SM, FIM and WM respectively. Maximum surface salinity (~34.4) was recorded during SM in the coastal waters. During SM, the northern transects (19 and 20.5°N) were not sampled due to bad weather. During FIM, salinity patterns were same both in the coastal as well as oceanic stations, with a difference of ~2.5 between the south and north transects. Monsoon seasons were charectrised with deep MLD (mean depth 44.12 ± 19.7 and 36.6 ± 18.8 m during SM and WM respectively) compared to intermonsoon months (25.2 ± 18.6 and 19.6 ± 11.5 m during SIM and FIM respectively) (Fig. 67). The deepest MLD (81 m) was observed during SM along 13°N transect at 83°E. The mean dissoved oxygen concentration in the surface layer was 194 ± 15, 227 ± 19 and 211 ± 11 μM l^{-1}during SM, SIM and WM respectively.

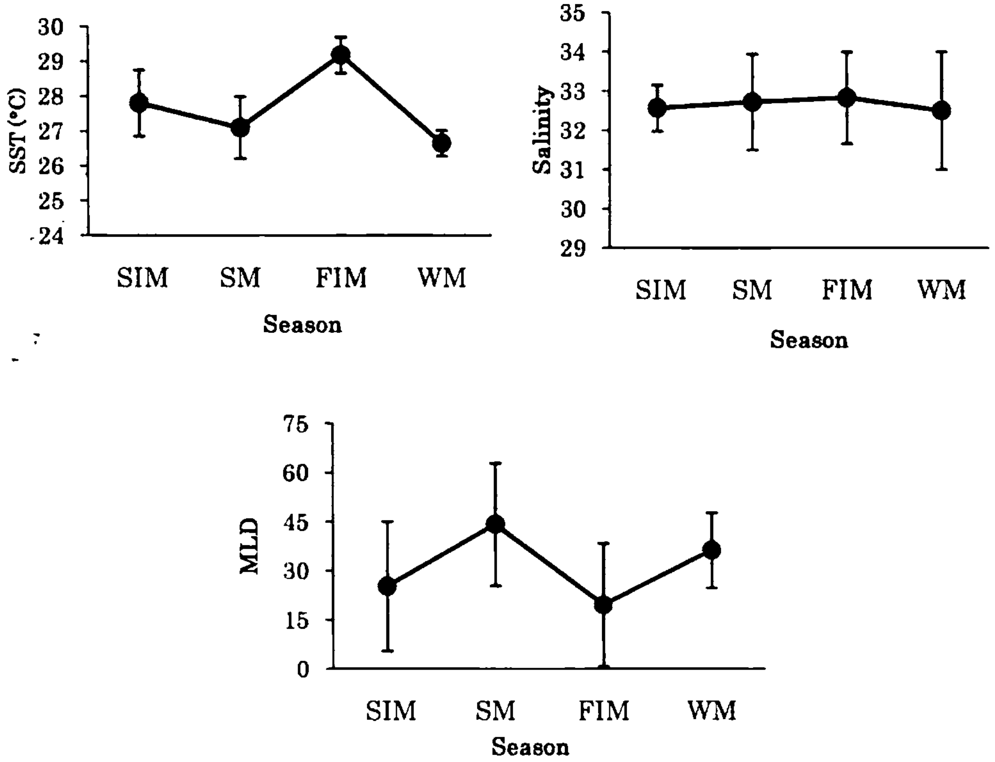


Fig. 67 Mean sea surface temperature (°C), sea surface salinity and MLD (m) recorded during different seasons.

During intermonsoon months, the variation of biological parameters between the northern and southern region were prominant especially along the coastal waters. Along the northern region, the chl. *a* concentrations was higher compared to southern region. Northern and southern as well as coastal and oceanic variation of the chl. *a* concentration was only marginal during monosoon months. In the oceanic regions, the varibility between season was not prevalant. But, an exceptional high value (0.56 mg m^{-3}) of chl. *a* was observed at the oceanic stations along the 13°N transect during WM (Fig. 68). During SIM, subsurface chlorophyll maximum was observed in the coastal staions along 15 and 17°N at 50 m and oceanic stations along 19°N at 120 m (Fig. 69).

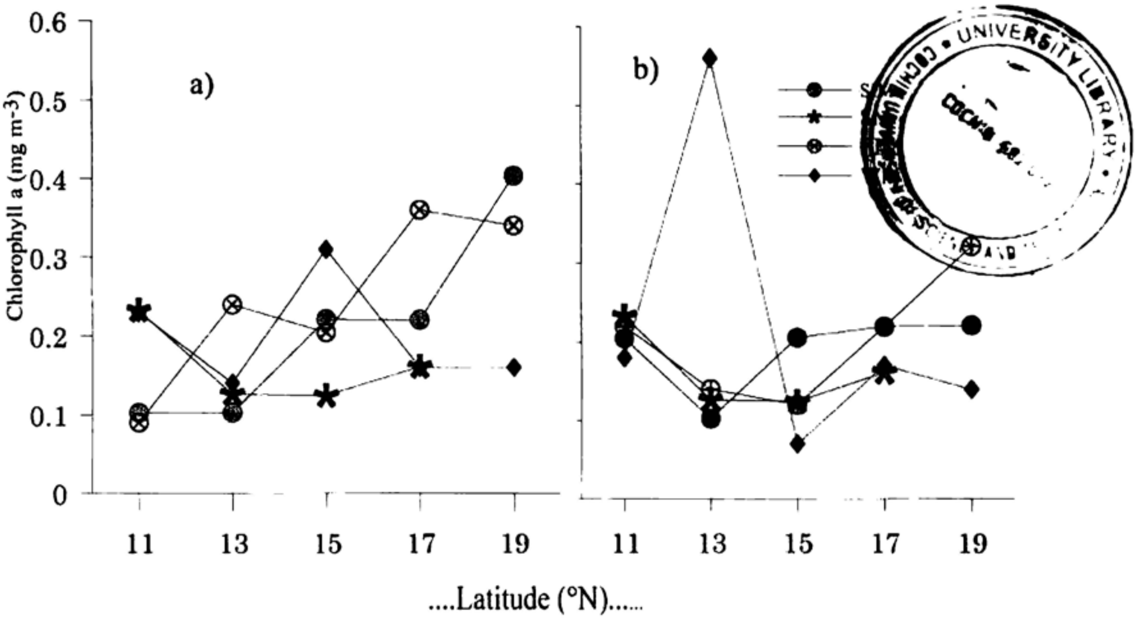


Fig. 68 Distribution of chlorophyll*a* (mg m^{-3}) in the a- coastal and b- oceanic station during different seasons.

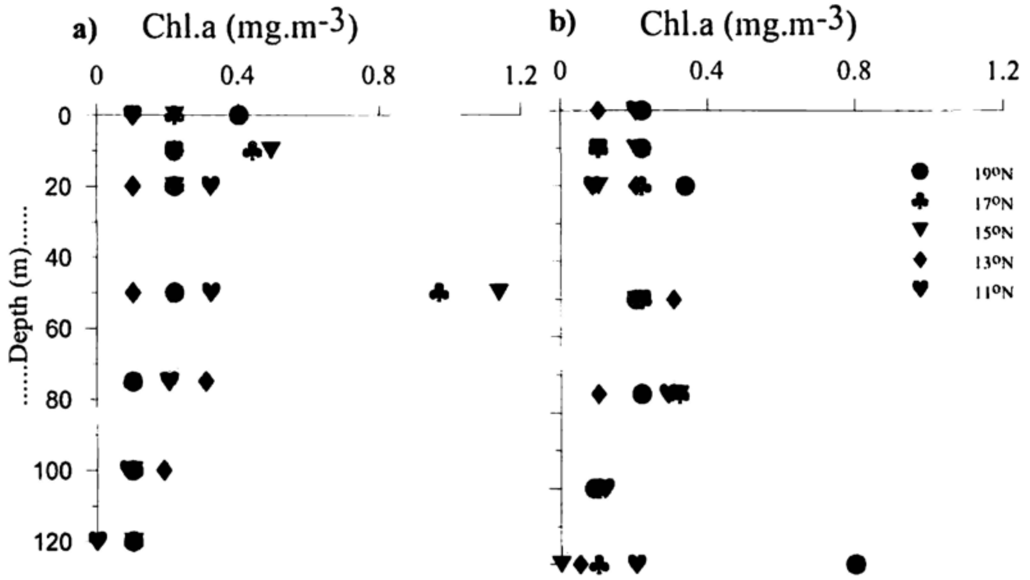


Fig. 69 Vertical distribution of chlorophyll *a* in the a- coastal and b- oceanic staions during spring intermonsoon.

Microzooplankton commuity was dominated by HDF along the coastal as well as oceanic stations during all the seasons except FIM where the dominant group was ciliates (>50%; Fig. 42). During SIM, radiolarians were the second abundant group both in the coastal and oceanic waters whereas in other seasons ciliates occupied the second position.

The mean mesozooplankton biovolume during WM (0.66 ml m^{-3}) and FIM (0.62 ml m^{-3}) was almost similar in the MLD. The variation of biovolume between the different depth strata were more pronounced. In the uppermost layer (MLD), the biovolume was comparatively more than other depth strata irrespective of seasons. Higher biovolume was observed during WM than SM. The lowest biovolume in th MLD and thermocline layer was observed during SIM (0.36 and 0.15 ml m^{-3} respectively). North-south and coastal-oceanic variability of biovolume was well marked during all the four seasons. In general, the seasonal variation of mean volume of mesozooplankton standing stock was only marginal except during SIM (Fig. 70).

In the total abundance and percentage composition of mesozooplankton also showed variability between seasons. A special feature observed during intermonsoon months, especially during FIM was the occurrence of large colonies of pyrosoma in the deeper layers mostly along the oceanic regions irrespective of north-south variability (Plate IV). Copepod was the abundant taxon during all the four seasons. Abundance of fish eggs (>50% of non-copepod taxa) were observed in the coastal stations during SM. Chaetognaths and copelates were the dominant groups irrespective of seasons(Plate V). Planktonic decapods were also an important component of mesozooplankton during the study period.

Plate IV Colonies of pyrosoma observed during fall intermonsoon

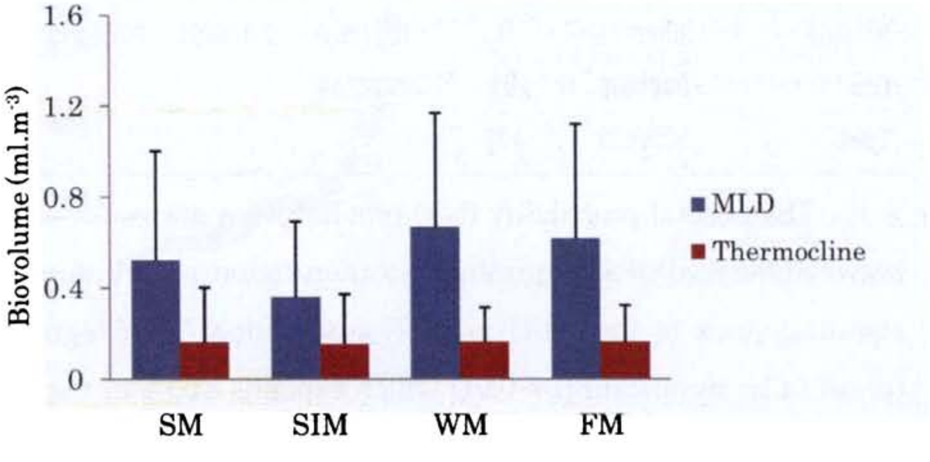


Fig. 70 Mean mesozooplankton biovolume (ml m^{-3}) in the MLD and thermocline layer during different seasons.

Data on total abundance of mesozooplankton in thermocline layer was analyzed using two factor ANOVA to test the significance of difference between seasons and stations (Table VII). Wherever the effects are found to be significant, least significant difference were calculated and significantly important seasons and stations were identified. This was significant between season ($P < 0.05$) FIM and SIM having significantly higher zooplankton compared to summer and winter. There is significant difference between stations ($P<0.05$) coastal stations along 15°N transect is having significantly higher mesozooplankton as compared to station oceanic stations along the same transect which was having significantly lower mesozooplankton abundance.

Table VII ANOVA of mesozooplankton abundance between stations and seasons.

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Stations	1738449	31	56079.01	1.584487	0.047724	1.574698
Seasons	309677.8	3	103225.9	2.916601	0.038313	2.702509
Error	3291506	93	35392.54			
Total	5339633	127				

The normal probability (NP) plot has been drawn for each season between the SeaWiFS chlorophyll a concentration and mesozooplankton standing stock in the MLD to analyse variation. The regression was found to be significant ($P < 0.01$) which explains 81.5% of the variability during summer monsoon. Regression of mesozooplankton biovolume on chlorophyll *a* is 81.5% (Fig. 71). During FIM, the regression in NP plot of the biovolume on chl. *a* wass significant ($P<0.01$) 71% of the variability is explained by the regression (Fig. 72).

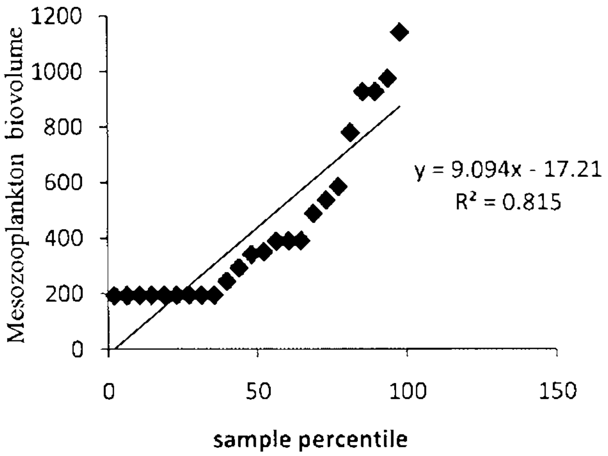


Fig. 71 Normal probability plot between mesozooplankton biovolume and chlorophyll *a* during summer monsoon.

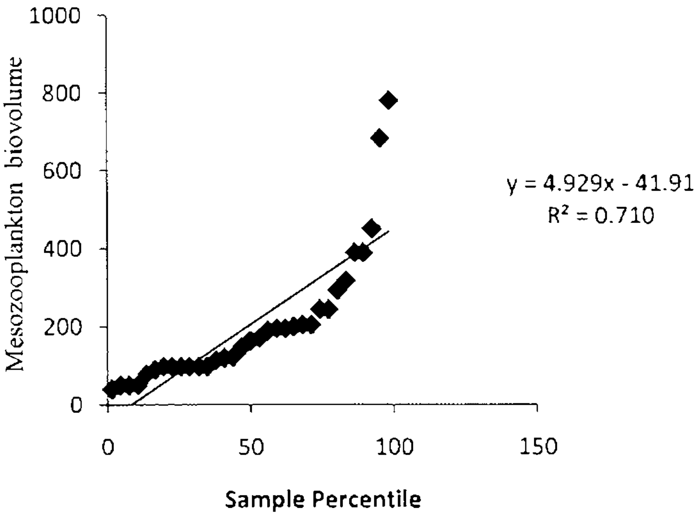


Fig. 72 Normal probability plot between mesozooplankton biovolume and chlorophyll *a* during fall intermonsoon.

3.6 Mesozooplankton response to various physicochemical processes

3.6.1 Upwelling: During the study period, signatures of upwelling were observed during SM (coastal, 13°N;80.5°E) and SIM (open ocean, 15°N; 84°E). The biological responses to the upwelling process during the two seasons were different. During SM, signatures of upwelling were observed in the surface with less saline, cool and low oxygenated waters. Maximum mesozooplankton biovolume (>2 ml m^{-3}) during SM was recorded from the upwelling station (Fig. 30) but the chl. *a* concentration did not showed much variation at the particular station compared to others along the transect (Fig. 27). The mesozooplankton biovolume was higher also in the thermocline layer (~0.5 ml m^{-3}). The highest of mesozooplankton in the MLD and thermocline layer during SM was recorded from this station. In the MLD, the total abundance of mesozooplankton was 5,559.48 no. m^{-3} and 742 no. m^{-3} in the thermocline layer (Table IV). The percentage composition of various mesozooplankton taxa were also showed variations in the upwelling regions during SM. Copepods contributed about 57% in the MLD and 81% in the thermocline layer (Fig. 33). Among non-copepod members of mesozooplankton 63% was contributed by fish eggs in the MLD of upwelling station. Other major groups noticed during this season were chaetognaths (27%) and copelates (8%) in the MLD. In the thermocline layer ostracods (27%) and euphausiids (16%) were the main components.

Unlike the SM, upwelling observed during SIM was remained in the subsurface layers due to the fresh water spreading along the central and oceanic regions of the basin during the period. The prevalence of subsurface upsloping of temperature contours from 80 m to 50 m was an evidence of oceanic upwelling along the transect (15°N;84°E). Variation of chl. *a* concentration and mesozooplankton biovolume between the upwelling station and the adjacent station were only marginal. A slight increase in the biovolume was observed in the upwelling station along the transect during FIM. The total abundance of mesozooplankton also showed a slight increase in the MLD (395 no. m^{-3}) and thermocline layer (541 no. m^{-3}) compared to adjescent oceanic stations along the transect. While comparing the coastal upwelling observed during SM, with open ocean upwelling observed during SIM, it is obvious to say that the coastal upwelling was more pronounced and strong and exerted more influence on the biological production.

3.6.2 Cold core eddy: Cold core or cyclonic eddies are very common in the BoB and it is considered that, this process is a mechanism of nutrient injection in the surface waters especially in the oceanic region. In the present study three cyclonic eddy circulations were observed along northern BoB. During SIM and WM the cyclonic circulation was observed along 19°N transect at 88°E and during SM it was observed along 17°N at 84°E. Upsloping of temperature (26°C) and salinity (33.8) from 100 m to 50 m at 19°N;88°E indicates the presence of cold core eddy during SIM. The Vertical profile of dissolved oxygen and nutrients also followed the similar trend and support the formation of cyclonic eddy during the period (Fig. 8). The upper water column found to be highly stratified with fresh water runoff from the northern rivers. SeaWiFS satellite derived chl. *a* distribution showed relatively higher values at this station than the adjacent stations. The mesozooplankton biovolume in the MLD and thermocline layer did not show any difference from the adjacent stations. An increased biovolume (0.5 ml m^{-3}) in the lower layer (300 m-BT depth strata), was observed at this station. The analysis of mesozooplankton abundance did not show any difference from adjacent stations.

Unlike SIM, the cyclonic eddy observed during SM (17°N;84°E) was more pronounced and the characteristics were extended to the surface waters (Fig. 26). The profiling of physico-chemical parameters displayed the presence of eddy in the region. SeaWiFS satellite observation showed high concentration of chl. *a* at the eddy region (Fig. 28). The mesozooplankton biovolume (1.08 ml m^{-3}) and total abundance of mesozooplankton in the MLD (Fig. 30) and thermocline layer showed considerable increase at the eddy station compared to the adjescent stations along the transect. The total abundance of mesozooplankton in the MLD was 4,379 no. m^{-3} and thermocline was 424 no. m^{-3} at the eddy station which were higher than recorded form the other stations along the same transect. Copepods contributed about 80% in the MLD and among non-copepod members chaetognaths (47%) copelates (21%) decapods larvae (12%) *etc.* were the dominant forms.

During WM, the eddy was noticed at 19°N;87°E, with uplifting of temperature (27°C) and salinity (33.8) contours from 100 m to 55 m (Fig. 54). Similar to SIM, the eddy circulation observed during WM was suppressed beneath by the strong stratified upper layers. The circulation may not be strong enough to break the barrier layer in the top. The chl. *a* concentration (SeaWiFS) showed strong gradients towards the northern region including the location of eddy (Fig. 57). The mesozooplankton biovolume in the MLD and thermocline layer was almost similar (0.4 ml m^{-3}) (Fig. 60). The pattern in the total abundance and the composition of the mesozooplankton followed the similar as other stations along the transect.

3.6.3 Cold gyre: During WM, towards the oceanic region along 13°N transect a well mixed upper water column was observed at 82°N with isothermal layers at 15 m whereas the adjacent station the same was observed at 60 m. The uplifting of physical parameters like salinity, sigma *t* and temperature were clearly depicts an unusual upward lifting of these properties from the adjacent stations proving the presence of a cold gyre at the station. The chemical parameters showed the similar trend as that of physical parameters. The upper 50 m water column was prevailed with less oxygenated and nutrient rich waters along the transect. The spatial extension of cold gyre can be seen from Fig. 73.

Response of biological parameters especially chl. *a* and mesozooplankton biovolume to the prevailing environmental conditions of the cold gyre region was more prominent. Distribution of chl. *a* along 13°N transect was found to be higher along the oceanic station both in the onboard sampling (Fig. 56) and SeaWiFS satellite observation. The increased chl. *a* concentration is reflected in the distribution of mesozooplankton biovolume along the cold gyre region. In the MLD and thermocline layer, the biovolume was >1 and >0.5 ml m^{-3} respectively at the 13°N;82°E where the core region was located (Fig. 60). The peripheral region of the gyre was sustained with low biovolume (>0.5 ml m^{-3}).

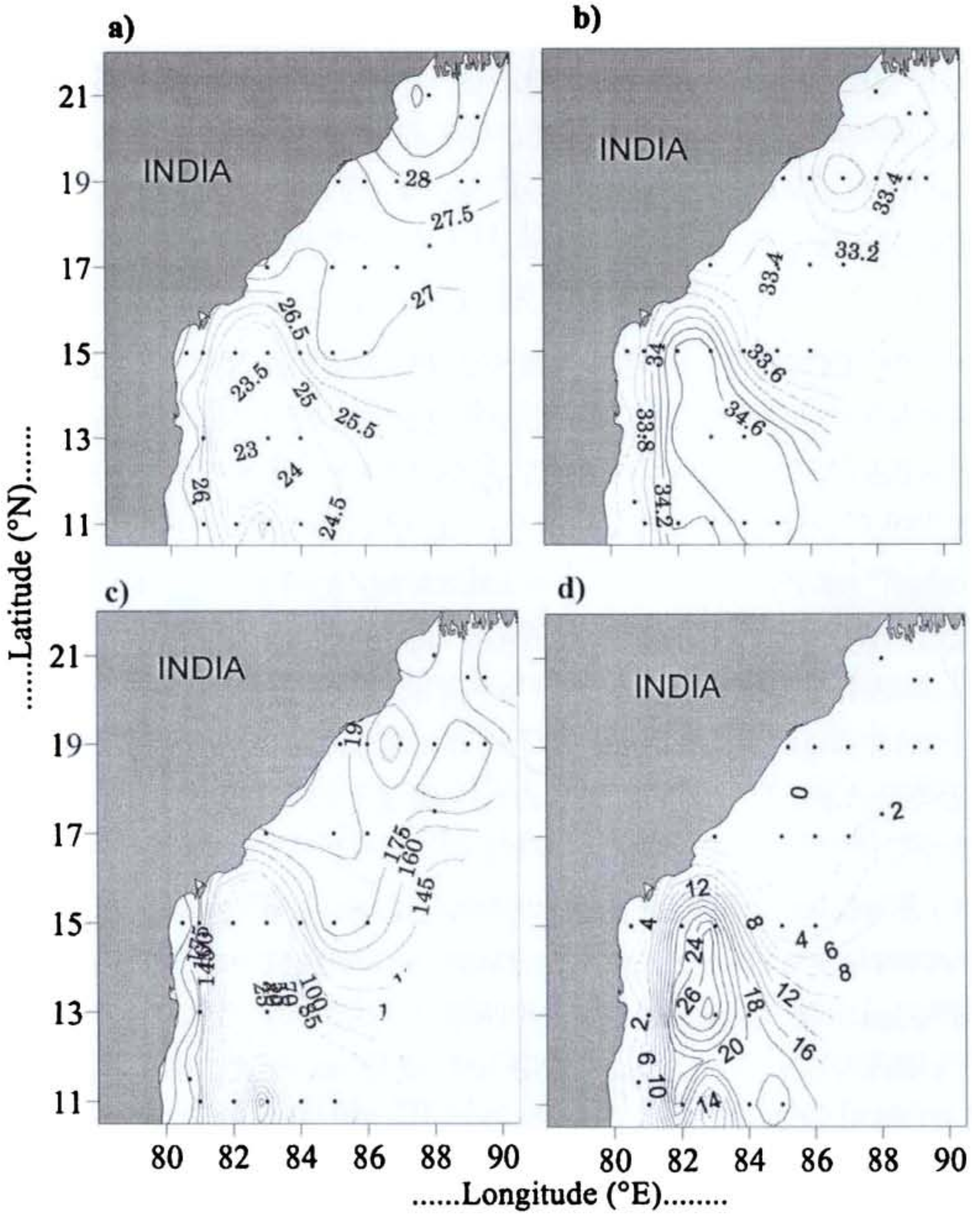
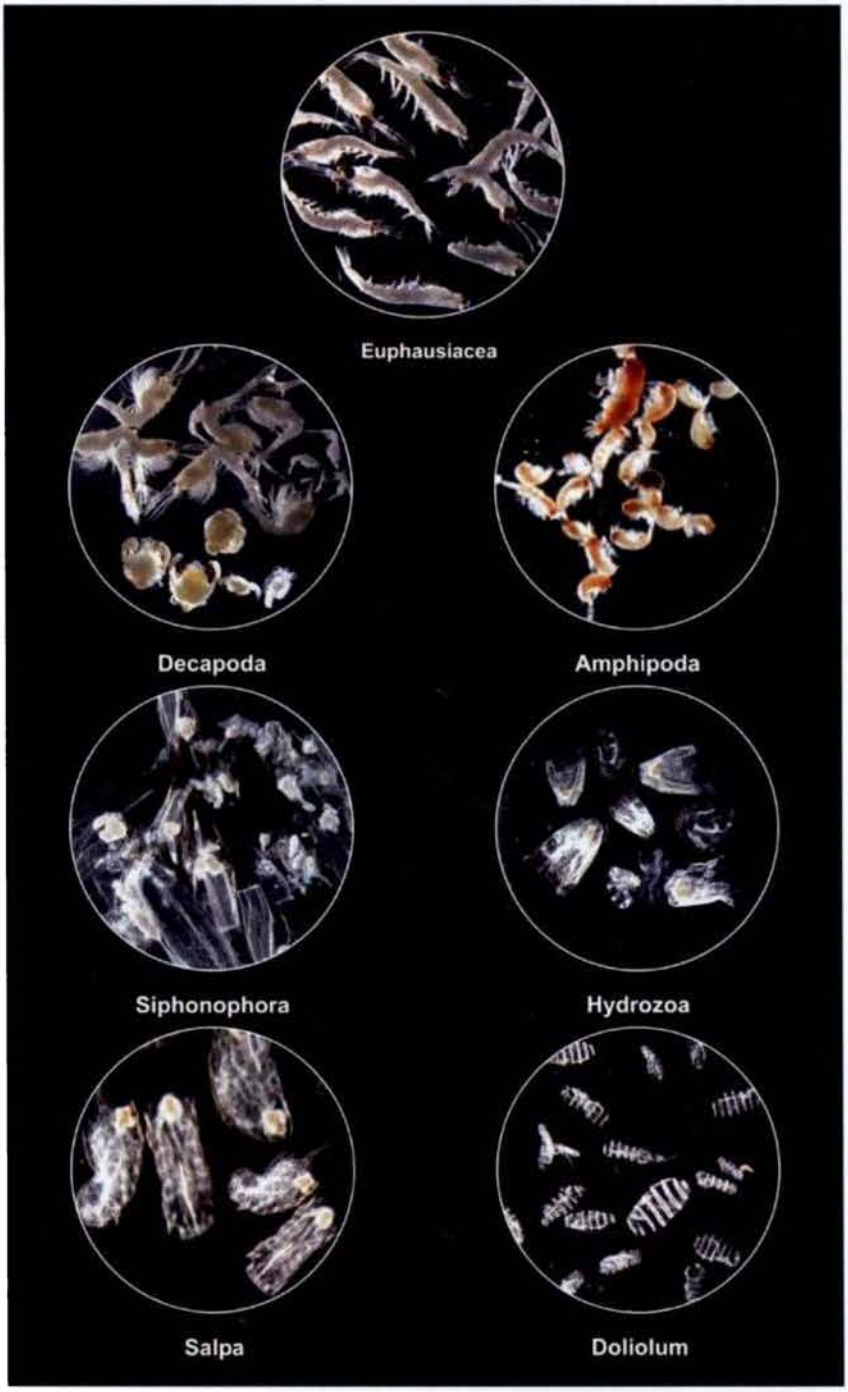


Fig. 73 Spatial distribution of a- temperature (°C), b- salinity, c- dissolved oxygen (µM l^{-1}) and d- nitrate (µM l^{-1}) at 50 m during winter monsoon.

Plate V- Various mesozooplankton taxa under the microscope



Various mesozooplankton taxa under the microscope

Various mesozooplankton taxa under the microscope

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Chapter 4

DISCUSSION

The Bay of Bengal, being a typical tropical basin situated in the monsoon belt experiences an annually reversing wind pattern which greatly influences the physicochemical and biological environment. The BoB lacks strong upwelling due to weak wind pattern, and the highly stratified upper water column resulting from heavy freshwater influx, makes the basin a unique ecosystem. According to earlier researchers, the BoB is a less productive basin than its western counterpart the Arabian Sea (Qasim, 1977; Radhakrishnan *et al.*, 1978; PrasannaKumar *et al.*, 2002; Madhuprathap *et al.*, 2003). The unavailability of nutrients in the surface waters due to upper layer stratification, heavy sediment flux and the cloud coverage which limit the growth of primary producers and thus results in low biological production.

Spring Intermonsoon

Spring intermonsoon (SIM), a transition phase between the winter and summer monsoon is characterised with comparatively low biological production than other seasons. The average sea surface temperature during this season was 27.8 ± 0.87°C, with the maximum along the southern and the central BoB, and the minimum along the northern region. The relatively high temperature during this period could be linked to the maximum solar radiation available during these months. Warming of surface waters is a general feature during this period (Varkey *et al.*, 1996). According to Shetye *et al.*, (1993), the poleward western boundary current known as East Indian Coastal Current (EICC) carried warmer waters to the south. Contrary to the previous observation, the northern region of the BoB was characterised with cool surface waters during the present study period. This may be the outcome of the heavy fresh water influx to the Basin. Salinity pattern and the chemical properties of surface waters also supported the prevalence of riverine discharge in the northern area during this season. In the present study, variation of salinity between the southern and northern BoB was very prominent. The average salinity recorded in the surface waters was 32.5 ± 1.2 with a minimum of 30.4 along 20.5°N transect, which gradually increasing towards the central and southern region. Relatively high saline waters observed at the coastal stations along the southern region may be due to the low input of fresh water, which does not dilute the water column. The EICC pushes the low saline water away from the coast, resulting in the dispersal of high saline water along the coastal regions. The shallow MLD (8-13 m) and thermocline depth in the head of the Bay indicate the strong influx of fresh water and its mixing in the region. The observation during SIM suggests that there is a settling phase after strong winter monsoonal activities of winds and currents which churn up the entire BoB. The influence of fresh water influx during the active winter may persist up to the early months of SIM, which gets gradually spread the cool less saline waters to the south and central BoB and finally makes the region more stratified during the months of April - May. The sampling of the present study was done during the early month of SIM, which was advantageous to understand the transitional characteristics of the BoB from active WM to SIM. Researchers like PrasannaKumar *et al.*, (2004b); Gauns *et al.*, (2006); Jyothibabu *et al.*, (2006) had studied the particular environmental conditions that prevailed during SIM in terms of physicochemical and biological aspects. Along 19°N transect, towards the oceanic region, an upheaval of temperature and salinity contours indicated the existence of a cold core eddy at 88°E. Weak wind pattern and strong stratification preserved the eddy in the subsurface layer.

The chlorophyll *a* concentration recorded during the present study was comparatively more than in the previous studies (Gomes, 2000; Jyothibabu *et al.*, 2006). The value ranged from 0.10 to 0.41 (av. 0.19 ± 0.11) mg m^{-3} in the coastal and oceanic stations, with an increasing trend toward the northern transects. Relatively high concentration of surface chl. *a* along the northern regions may be because of the proliferation of phytoplankton community due to nutrient enrichment through riverine influx. Along the southern region, the low values of surface chl. *a* were either due to the slow dissemination of nutrient rich water or complete utilisation of nutrients by the phytoplankton community in the surrounding waters of influx region. Column chl. *a* concentration at the coastal waters along 15 and

17°N transects were comparatively high, with maximum concentration at the intermediate depth (50 m). This subsurface increase of phytoplankton standing stock (chl. *a*) is a special feature during this season probably due to the prevalence of stratified upper layers. Generally SIM was characterised by subsurface chlorophyll maximum 60 to 120 m (Gomes, 2000; Madhuprthap *et al.*, 2003; Gauns, *et al.*, 2005; Jyothibabu *et al.*, 2006). Stratified nature of the water column coupled with increased solar radiation may extend the euphotic zone below the nitracline which may enable the phytoplankton to grow in the subsurface water (Bhattathiri *et al.*, 1996; PrasannaKumar *et al.*, 2000). Warm SST and low salinity lead to strong stratification, preventing the entrainment of nutrients in to the surface water all through the year, resulting in low primary production (Gauns, *et al.*, 2005). Another interesting feature noted in the chl. *a* distribution during this season was the variation in surface and column values between coastal and oceanic stations along 19°N transect. The coastal station of this transect possess high chl. *a* concentration in the surface waters and low concentration in the upper 120 m water column. The reverse was observed at the oceanic stations. This condition also confirmed the availability of nutrient rich surface waters in the coastal region. According to Sen Gupta and Naqvi (1984); Rao *et al.*, (1994); Madhuprathap *et al.*, (2003) the riverine inflow does not bring quantifiable nutrients into the open sea. In other words, as the nutrient rich riverine influx water move away from its source (from coastal to oceanic), the phytoplankton community along the coastal waters may utilise the nutrients or it may get lost to deeper waters due to fast vertical sinking. Increased chl. *a* concentration in the water column at the oceanic stations along 19°N can be explained by examining the vertical distribution of the chl. *a* that showed an increase in availability of phytoplankton standing stock (120 m depth), which validates the presence of both stratification and subsurface cyclonic eddy in that region. Gomes (2000) reported high chl. *a* and primary production during this season in small pockets where eddy like structures were located.

A high abundance of total microzooplankton during SIM was reported in earlier studies (Gauns *et al.*, 2005; Jyothibabu, 2006). In the present study the total availability of microzooplankton community was relatively lower than during the other two seasons. Microzooplankton being the main controlling factor in the oligotrophic waters in enhancing the microbial food web might not have been fully established in the region at the time of observation. It may be possible that either the condition was not purely oligotrophic due to some locally enhanced biological production, especially in the northern regions, by means of fresh water discharge or eddy circulation, or it could be a transitional phase between the more productive season to a stable oligotrophic condition. The coastal and oceanic regions along the southern transect harboured relatively more microzooplankton, and this may be due to the changeover of classical food web to the microbial food web. Heterotrophic dinoflagellates (HDF) dominated the composition, both in the coastal and oceanic regions. According to Gauns (2000) and Jyothibabu (2004), HDF are the common and dominant group in the study region, and they can withstand or overcome the oligotrophic condition or may possibly have a better chance of survival due to the numerous specialised mechanism for heterotrophy (Gains and Elbrachter, 1987; Hansen, 1991, 1992; Lessard, 1991). According to Huntsman *et al.*, (1980), occurrence of dinoflagellates is a characteristic of stratified water column.

Mesozooplankton was sparsely distributed during this season. The southern and central BoB sustained very low volume of mesozooplankton both in the MLD and thermocline layer. The low volume of mesozooplankton standing stock during this season may be due to the strong stratification which prevents the nutrient injection and resultant biological production. The coastal and oceanic variability in the mesozooplankton standing stock was not prominent along the 11,13 and 15°N transects but in 17 and 19°N transects, the oceanic stations sustained more volume of mesozooplankton. Along the 19°N transect the oceanic stations were characterised by the presence of a subsurface cold core eddy which can uplift the nitracline to the upper layers. Relatively increased chl. *a* concentration and mesozooplankton standing stock along this region might be linked with the cold core eddy. According to Gomes *et al.*, (2000) and PrasannaKumar *et al.*, (2004a), even though the upper layers of the BoB are so stably stratified, eddy pumping is a possible mechanism for transferring nutrients into the euphotic zone, resulting in an increased biological production. PrasannaKumar *et al.*, (2007) reported an increase in chl. *a* concentration due to the nutrient enrichment by cyclonic eddy in the Bay of Bengal.

Summer monsoon

Summer monsoon is the period of maximum fresh water influx to the east coast from the northern as well as southern rivers. Thus the sinking flux of biogenic matter is several fold high during this season (Ittekot *et al.*, 1991). Meridionally arraged isotherms, isopycnals and isohalines showed severe influx of fresh water along the coastal regions especially along the region between 11 and 15°N. These transects were also characterized by shallow MLD (<20 m) and thermocline layer (<150 m) along the coastal regions. Presence of high saline, cold, nutrient rich waters along the 13°N transect is an evidence of coastal upwelling. During SW monsoon, due to favourable current and southwesterly wind, moderate upwelling occurs along the southeast coast of India (Murthy and Varadachari, 1968; Naqvi *et al.*, 1979). According to Suryanarayana *et al.*, 1991 due to the influence of favourable wind forcing, the isopleths of salinity and temperature lift up, leading to upwelling near the coast from about 80 m depth in the area between 16 and 14°N. Shetye *et al.*, (1991) observed a narrow band of upwelling along the southeast coast during summer monsoon. Anand *et al.*, (1968) and Murthy and Varadachary (1968) reported upwelling during premonsoon and southwest monsoon periods with more intensity due to the marked lowering of surface temperature near the coast of Waltiar. Upwelling is obviously accompanied by marked changes in the physical and chemical properties of the water column and these are reflected by similar micro- and mesoscale changes in zooplankton assemblages (Pagès and Gili, 1991; Pagès, 1992; Gibbons and Buecher, 2001). Surface chl. *a* concentration ranged from 0.15 to 0.25 mg m^{-3} during this season along the coastal region and the results were remarkably comparable with the values reported by Madhu *et al.,* (2002). The enhancement of nutrients in the surface waters by upwelling results in high plankton production during early summer monsoon months. Increased concentration of chl. *a* along the coast indicates the production of more phytoplankton cells which reproduce rapidly, utilising the favourable conditions due to the coastal upwelling. Mesozooplankton standing stock and total abundance also showed an increasing trend along the southern region during the period. Aggregation or swarming of mesozooplankton in the upwelling regions were reported by Madhupratap and Haridas, (1990) from the southwest coast of India during summer monsoon. Generally during upwelling season, the mesozooplankton groups tend to get aggregated and patchy within the upwelled waters (Peterson, 1998; Escribano *et al.,* 2002; Hutching *et al.,* 2006; Abraham, 1998; Giraldo *et al.,* 2002). The maximum abundance of mesozooplankton during this season was noticed from the coastal station along the 13°N transect (5,559 no. m^{-3}). Coastal processes like upwelling can effectively augment the biological production due to the expansion of classical food chain (Muraleedharan *et al.,* 2007). High abundance of fish eggs observed in the upwelling region indirectly supports the prevalence of high phytoplankton production. Spawning activity of many fishes, associated with the seasonal phenomenon like upwelling, may be due to the availability of more favourable environment for gravid females for breeding and feeding, or the availability of small phytoplankton cells which form the food for the first feeding larval stages thus accelerates survival rate. The composition of various mesozooplankton taxa were entirely different along the coastal stations of southern transects, the non- copepod community was dominated by filter feeders like ostracods in the MLD and ostracods, euphausiids and copelates in the thermocline layer. The active predators like chaetognaths were least represented, which indicates that the region was dominated by primary consumers, not by the secondary consumers. This may be due to need of minimum switchover time between the successive trophic levels.

During SM, the hydrographical and biological conditions along 17°N transect was relatively different from the other transects. Cyclonic eddy circulation was observed along the transect with its centre at 84°E. The station was characterised by cool, high saline water which was evidenced by the upheaval of isolines. The dissolved oxygen and nutrient concentration also showed shifting of deep water towards the surface. The nitrate concentration in the surface layer of the eddy region clearly indicates an increase (eutrophic) composed of the adjacent stations. Thus the enriched nutrient condition at the eddy region triggers primary and secondary production respectively. Concentration of the chl. *a* was nearly double at the eddy station compared to the other stations along the transect, resulting in similar variation in mesozooplankton biovolume in the MLD. The high chl. *a* concentration may be attributed to the increased phytoplankton production due to the mixing of the deep nutrient rich water in the photic zone due to the eddy process. Cyclonic eddy promotes isotherm elevation acting as a localized upwelling with high primary production in their core (Aristegai *et al.*, 1997). This in turn supports the increased biovolume of mesozooplankton in eddy region, with higher food availability. Hernandez-Leon *et al.*, (2001) reported accumulation of zooplankton biovolume around cyclonic eddy and resultant in high feeding and increased growth rate. Though the eddy forcing was more distinct in the surface waters, its impacts on mesozooplankton biovolume in the mixed layer was more prominent than in the thermocline layer. Copepoda, the main grazers of productive environment, dominated along the transect. This is a typical example of efficient utilization of the biotope with the changing environmental factors in an ecosystem. The other dominant groups were fish eggs and chaetognaths. The presence of fish eggs in the mixed layer was an indication of the spawning activity of fishes in the region. This might be due to the prevailing physical condition of the cyclonic eddy which may retain the eggs by floatation or the enhanced phytoplankton production to attract the adult fish for feeding and breeding, and at the same time the newly hatched larvae are exposed to abundant food supply. Abundance of large zooplankton groups in the cyclonic eddy region is also reported from the BoB by Madhupratap *et al.*, (2003). Large zooplankton between the size of 1000-2000 μm fraction were detected in the cyclonic eddy region (4.58mg dry weight/m^3) in the Algerian basin (Riandey *et al.*, 2005) which may be feeding on large herbivorous copepods. He also noticed the higher abundance of ostracods, doliolids, fish larvae and salps in the cyclonic eddy region.

The cumulative effect of fresh water influx, coastal upwelling and localized phenomenon like cyclonic eddy are congenial for the overall biological production of the basin, and most of the time the high cloud cover during summer monsoon was not limiting the average production.

Fall intermonsoon (FIM)

FIM, the short transitional period between the two monsoonal seasons, was characterized by the interim heating of the basin due to the high SST (>28°C) in the entire region. Both salinity (<30) and temperature were found to be increasing from northern to southern regions. MLD and thermocline layer were deepening towards the southern and central BoB. The vertical thermal structure along the 15°N transect showed prevalence of cool high saline surface waters along the region which indicates the presence of coastal upwelling in the region. Data on chemical parameters were not available during the study period due to some technical snags. But, from the published results of PrasannaKumar *et al.*, (2007), the central BoB was characterized with shoaling of nitrate contours towards the northern region. According to them, in the upper 20m, the nitrate concentration was below detectable level; 1 µM nitrate isopleths was located close to 50 m, shoaled to about 25m in the south (south of 15°N) under the influence of doming, while in the north it shoaled shallower than 10 m. Silicate also showed similar trend in distribution in their study. The northern region was observed to be less saline (19°N) with relatively cool water with salinity <30, and this condition may be due to the persisting effect of run off during summer monsoon from the large perennial rivers in the northern region.

The distribution of surface as well as integrated column values of chl. *a* concentration showed an increasing trend towards the northern region both in the coastal and oceanic waters. Maximum concentration of chl. *a* during this season was noticed along the 19°N transect. Low salinity waters along the head of the bay indicated strong freshwater influx and oceanic precipitation. According to PrasannaKumar *et al*., (2007) there is a time lag between the precipitation and the freshwater discharge peaks. Precipitation peaks in July (Narvekar and PrasannaKumar, 2006) and river discharge peaks in August. This increased nutrient input along the northern transect even during fall intermonsoon sustained more chl. *a* concentration in the head region of the bay. Increased column values of chl. *a* along the 15 and 17°N transect were due to the increased subsurface concentration at 50 m depth. The signature of coastal upwelling observed in the coastal stations along 15°N transects was not intensive due to the stratified nature of the region. Even then, relatively higher chl. *a* concentration along the coastal regions may be either due to the weak upwelling that prevailed during the season or the sustenance of nutrients along the regions due to the strong upwelling experienced during the preceding summer monsoon.

The total abundance of microzooplankton was relatively high along 11 and 17°N transect during FIM. Along 11°N transect, the variability of microzooplankton abundance between the coastal and oceanic stations were only marginal. But along 17°N transect the coastal station sustained more abundance than the oceanic waters. Ciliate population was more numerous along the oceanic (57%) stations whereas heterotrophic dinoflagellates (58%) dominated along the coastal stations. The increased abundance of ciliates along the oceanic stations can be related with the availability of preferential food and warm water condition (Heinbokel, 1978; Gothantaraman and Krishnamurthy, 1997) during the season. The ciliates can most effectively graze smaller phytoplankton cells which are most abundant in the stratified oligotrophic waters. Unlike ciliates, the increased abundance of heterotrophic dinoflagellates in the coastal waters may be linked with the abundance of large phytoplankton cells along the coastal regions which is markedly preferred by the heterotrophic dinoflagellates.

Mesozooplankton standing stock during this season was relatively plentiful and comparable with the monsoon seasons. Southern transects (11 and 13°N) were characterized by low volume than the other transects (15, 17 and 19°N). Maximum biovolume during this season was recorded from the coastal stations along 17°N followed by 15°N transects. Coastal and oceanic variability along the transects (except 11 and 13°N) were not well marked, with relatively higher biovolume along oceanic stations (≥0.5 ml m^{-3}). Increased mesozooplankton biovolume observed in the coastal as well as oceanic stations towards the north of 15°N transect was probably because of higher primary production as indicated by the increased chl. *a* concentration along the region. The SeaWiFS chl. *a* distribution map showed more or less uniform concentration in the coastal as well as oceanic waters.

Practically no information is available on the mesozooplankton standing stock during FIM, and hence the present study is of importance. Earlier researchers have put forward a general concept of limited biological production in the BoB during intermonsoon months (Gauns *et al.*, 2005; Jyothibabu *et al.*, 2006; PrasannaKumar *et al.*, 2007). But the results of the present study necessitates a reconsideration of these concepts, as it give baseline data on the biological features, especially on mesozooplankton standing stock during FIM. The increased chl. *a* concentration and mesozooplankton biovolume observed in the present study may be linked with enrichment of surface waters due to the persistent runoff from the northern rivers preceding summer monsoon. The peak of river discharge along the bay is seasonal and is greater during the latter half of the summer monsoon (PrasannaKumar *et al.*, 2007).

The diurnal variability in the mesozooplankton standing stock was not pronounced during the season except along 15 and 17°N transects. At the coastal stations along 15°N, the biovolume during day time was relatively more and this can be related with more phytoplankton standing stock in the illuminated surface waters during the day time. Along 17°N transect, the biovolumes during morning and night collections were relatively more than of the day collections. On analyzing the vertical distribution of chl. *a* (50 m) and microzooplankton

(20 m) abundance at this station, it showed a subsurface increase in both. The variability in biovolume of mesozooplankton can be explained through the availability of preferred food item in the subsurface layers during the day hours and grazing of phytoplankton cells in the surface waters during dark hours. Along 15°N also, the subsurface waters were characterized with increased concentration of both phytoplankton (chl. *a*) and microzooplankton standing stock, but when compared to 17°N the values were too low. The total abundance of mesozooplankton during FIM showed an increasing trend from the north to south, with maximum abundance along the coastal stations in the 17°N transect. Like biovolume distribution, the total density also exhibited marginal variability between the coastal and oceanic station in the MLD and thermocline layer. Lower depths viz., 300-BT, 500-300, and 1000-500 m showed more abundance especially along 13, 15 and 17°N transects and this may be due to the presence of pyrosomes. Large pyrosoma colonies were very common in the deeper layers during this season. Gauns *et al.*, (2005) reported the abundance of colonies of pyrosomes in the deeper waters during FIM. There is a possibility that these filter feeders exert a grazing pressure on both phytoplankton and smaller zooplankton (Madhupratap, 2003) Dominance of active predators like chaetognaths and filter feeders like copelates in the MLD reflects the presence of dominance of preys and small organisms.

Winter Monsoon (WM)

During this season, the entire study region was characterized with cool surface waters (<27°C) of low salinity especially towards the northern region where the isopycnal were shoaled with low dense surface waters. Shallow MLD and thermocline depths were also observed along the northern regions. These features clearly indicate the presence of freshwater influx along the northern bay during this season. The entire coastal region from north to south was characterized by colder and less saline waters with shallow MLD and thermocline which deepens towards the oceanic stations, and this indicates the fresh water influx along the entire coast, and its effect decreases towards oceanic region. Moreover, considerable decrease in the SST was observed towards the northern region, and this is due to the decreasing atmospheric temperature (winter cooling). According to Shetye *et al.*, (1996), surface temperatures were lower in the north, and along the coast and all over the Bay temperature inversions suggested cooling of surface waters by northeasterly winds. As in the Arabian sea, winter cooling did not lead to convective mixing and enrichment of the upper layers due to the intense stratification of waters caused by the less saline water of the upper layer (Banse, 1984). The distribution of hydrographical features suggests that the northern and coastal bay is under the influence of riverine run off. Shetye *et al.*, (1993) noted that discharge from the Ganga and Brahmaputra decreases the SST in the northern bay during winter. Varkey *et al.*, (1996) computed the seasonal runoff for both monsoon seasons and found that during winter the runoff is reduced to $103.8 \mathrm{x} 10^9 \mathrm{m}^3$ from its summer value of $943 \mathrm{x} 10^9 \mathrm{m}^3$. In spite of such reduction in runoff during winter, a hydrographic survey carried out by Shetye *et al.*, (1996) during winter monsoon reported fresh water induced surface layer stratification in the northern Bay of Bengal. The winter cooling caused by surface heat loss (Hastenrath and Lamb, 1979) and the resulting convective mixing in the northern Bay is found to be confined to a thin surface layer. Temperature inversion was observed along the northernmost transect (20.5°N) in the study. The surface layer with temperature of < 26°C and ~2°C increase (28°C isotherm) was noticed from 40 to 70 m deep. Temperature inversion during winter is reported by Varkey *et al.*, (1996) and Thadathil *et al.*, (2002). But due to the strong salinity stratification this inversion layer is embedded within the Barrier layer (Thadathil *et al.*, 2007).

The vertical structure of physico-chemical parameters along 19°N transect showed an upsloping of temperature and salinity contours from 100 to 60 m, which evidences the subsistence of subsurface cold core eddy with its centre at 86°E. Even though, the eddies are possible mechanism of nutrient injection in the oceanic waters (PrasannaKumar *et al.*, 20004a), the strong salinity stratification prevents the uplifting of subsurface water to the surface. Persistence of subsurface cold core eddy during winter monsoon was reported by many researchers (Jyothibabu *et al.*, 2008; Madhuprtap *et al.*, 1990 PrasannaKumar *et al.*, 2004a)

Along 13°N transect, towards the oceanic station at 82°E, the surface waters were characterized with shallow MLD and thermocline with relatively cool and high saline water, and its tongue extended towards north and south (15°N and 11°N respectively). The spatial extension of this feature can be successfully traced out from the distribution of physico-chemical parameter at 75 m depth. It confirms the presence of a basin scale phenomenon cold gyre along the regions.

The biological production during this season showed a more remarkable variation than in the other seasons. The chl. *a* distribution showed great variability between the coastal and oceanic stations, especially along the southern transects. Among the coastal stations maximum chl. *a* distribution was observed along the 15°N transect, and this increased concentration is assumed to be due to the addition of nutrients in to the surface waters through river run off. Among the oceanic stations, along 13°N transect, an increased concentration was noticed obviously because of the prevalence of subsurface nutrient rich water in the surface due to the cold gyre. The satellite imagery of chl. *a* distribution agreed with the result obtained from the onboard collection. Along 19°N transect, the concentration of chl. *a* in the surface waters was relatively low, but it was relatively high for the integrated column value. This disparity may be due to the prevalence of cyclonic eddy in the subsurface water column. Normally the eddy features result in appreciable enhancement of biological production through pumping of nutrients into the euphotic zone (McGillicudy and Robinson, 1997). According to Gomes *et al.*, (2000), the primary production in the shelf region of northern BoB is higher in the winter monsoon than the intermonsoon and summer monsoon season. The increased transparency and river runoff are considered as the reasons for increased production during winter.

Microzooplankton abundance during this season was comparatively lower than in the other seasons with relatively greater abundance towards the oceanic stations. Jyothibabu *et al.*, (2008) reported strong seasonality in the abundance of microzooplankton and suggested that during monsoon period, availability of nutrients in the surface waters facilitates the classical food chain than the microbial food web.

Mesozooplankton biovolume during winter showed remarkable variation between the north and south. Coastal stations sustained more biovolume than the oceanic station in all transects except along 15°N transect. But coastal and oceanic variability during this season was comparatively less prominent than in the other seasons. Along 13°N transect, the coastal stations possess more volumes of mesozooplankton standing stock (>1.5 ml m^{-3}) followed by the oceanic stations at 82°E along the same transect in the MLD and thermocline layer. Along 11 and 15°N transects, the biovolume showed an increasing trend towards the oceanic stations. The increased mesozooplankton biovolume is presumably due to the cumulative effect of cyclonic gyre circulation which favours the appearance of cold deep-waters in the surface (upwelling) which fertilises the upper layers and the addition of nitrate in to the surface because of fresh water runoff or oceanic precipitation. Unger *et al.*, (2003) observed that during north east monsoon along southeastern region of BoB, the biological production depends on both riverine input and surface circulation pattern, characterised by cyclonic eddies and associated upwelling. In northern region, comparatively low biovolume was recorded than the southern transect. Relatively higher biovolume was obtained at the coastal stations than at the oceanic stations. Here, river runoff alone contributes to the nutrient supply which was easily available to the coastal region (thus more biological production) whereas towards the oceanic region the nutrient level gets dissipated, and this may be due to dilution effect, strong stratification or vertical sinking or the combined effect of all. Along 20.5°N transect, the mesozooplankton biovolume was comparatively low may be because of the strong thermal inversion

The diurnal variability in the mesozooplankton standing stock in the MLD and thermocline layer was only marginal. The total abundance of mesozooplankton was more towards the southern region, possibly due to the enriched condition and food availability. Copepods dominated in the mesozooplankton composition along all transects irrespective of layers except thermocline layer along 13°N transect. Among the non copepod members, the dominant taxa were Chaetognatha, Copelata, Ostracoda, *etc*. The abundance of filter feeders like ostracods and copelates and active predators like chaetognaths may be an indication of availability of a variety of food during this season which allows partitioning of the food.

Seasonal variation

The seasonal variability of physicochemical and biological parameters were more pronounced in the BoB. The monsoon seasons were characterised by cool surface waters with relatively deeper MLD than the inter monsoon months, and it gets reflected in the distribution of mean temperature. The variability in the mean salinity between seasons was only marginal. This may be due to the cumulative effect in the distribution of hydrographical feature between the north and south BoB which was not reflected in the average value. The average production between the seasons remains more or less same due to the prevalence of freshwater discharge during most of the time of the year and various physical processes such as upwelling, cyclonic eddy, cold gyre, etc.

The biological responses to the various physical processes depended on the seasons in which they occur. Upwelling signature was observed along 13°N during SM and 15°N during SIM. SM upwelling supported more biological production whereas SIM upwelling was weak and in buried nature due to the strong stratification. Cyclonic eddy, observed during summer, injects nutrients into the surface layers whereas during SIM and WM, the eddy was in buried nature and triggered comparatively more biological response in the oceanic waters. The coastal process like upwelling enhances the classical food chain and results in biological production, whereas the oceanic processes like oceanic upwelling, cyclonic eddy, gyres, etc enhances the production based on the new nitrate (new production), but amount to comparatively less than the coastal production. Localised effects of physical processes were observed in the biological production such as subsurface chl. *a* maxima and subsequent increase in mesozooplankton biovolume. During winter monsoon the presence of cold gyres along the southern transect greatly influenced the overall biological production during this season. The combined effect of freshwater discharge and cold gyres makes the region biologically more productive.

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Part II Planktonic decapods

Chapter 1

INTRODUCTION

1.1 Classification
1.2 Previous studies
1.3 Scope of the study

Planktonic decapods contribute about 60% of the non-copepod members of the plankton community. It includes larval forms of many economical and uneconomical decapod crustaceans (meroplankton) and holoplankton. Studies on planktonic decapods are meager and those available are confined to certain species, which are commercially important along coastal regions. An inventory of seasonal occurrence of planktonic decapods is of prime importance because it includes larval forms of various commercially important crustaceans which form an index of the future decapod fishery. The presence of decapod larvae in the pelagic realm is very important as rich food sources for planktivorous fishes (Morgan, 1990). The success of any fishery is mainly dependent on the survival of its larval stages. A thorough knowledge of the various aspects of the larval behaviour and ecology is quite essential for assessing the potential of decapod fishery resources.

1.1 Classification

The class Crustacea includes a variety of decapod organisms such as shrimps, prawns, crabs, lobsters, cray fishes, brachyurans, etc. In due course of the systematic study, a number of classifications have been proposed by eminent researchers. Recently, Martin and Davis (2001) published an updated classification of recent crustaceans For the present study, this classification is followed

Phylum : Arthropda

Subphylum : **Crustacea** Brunnich, 1772
  Class: **Malacostraca** Latreille, 1802
    Subclass: **Eumalacostraca** Grobben, 1892
      Superorder : **Eucarida** Calman, 1904
        Order :**Decapoda** Latreille, 1802
          Suborder :**Dendrobranchiata** Bate, 1888
            Superfamily:**Penaeoidea** Rafinesque, 1815
            Superfamily :**Sergestoidea** Dana, 1852
          Suborder : **Pleocyemata** Burkenroad, 1963
            Infraorder : **Stenopodidea** Claus, 1872
            Infraorder : **Caridea** Dana, 1852
            Infraorder : **Thalassinidea** Latreille, 1831
            Infraorder : **Anomura**
            Infraorder : **Brachyura** Latreille, 1802

1.2 Previous studies

Planktonic decapods are composed of both meroplankton and holoplankton, the later represented by epipelagic shrimp family, Luciferidae under the superfamily Sergestoidea. Distribution and species composition of *Lucifer* in the plankton samples along the east coast of India were studied by many researchers (Prasad *et al.*, 1952; Prasad and Thampi, 1958; Ganapathi and Ramanamurthy, 1975; Nair *et al.*, 1981; Sarkar *et al.*, 1986; Naomi *et al.*, 2006). An extensive study on the systematics, distribution and abundance of Luciferidae was carried out as part of the International Indian Ocean Expedition (IIOE) (Antony *et al.*, 1989).

Decapod larvae, form a major component in the plankton samples which includes a wide variety of larval forms of coastal and oceanic groups. The larvae captured represent only a small fraction of a greater number of families that live in the unsampled area under normal oceanographic condition (Baez and Martin, 1992) Larval stages are the free swimming phase in the life cycle which differs in form and habits of the adult. The occurrence of pelagic larvae in the life cycle of benthic crustaceans is considered an advantage for the species, since their dispersal improves genetic flow and the colonization of new and remote areas. Furthermore, larval dispersal reduces competition for space, the predation rate of young stages in the adult habitat and osmoregulation problems due to low salinity in estuarine or coastal parental habitats. The fundamental fact which determines the organisation of larvae is the mode of locomotion. In the nauplius stage, the main organ of locomotion is the antenna. In due course of development the locomotor function gets transferred to thorax and in the later stages to the abdomen. This changeover function leading to much of the modification of the larva, is attained through a series of moulting. Decapod development may therefore be regarded as consisting of four phases; 1. Nauplius , 2. Protozoea (both stages have antennal propulsion) 3. Zoea (thoracic propulsion) and 4. Postlarvae (abdominal propulsion) (Gurney, 1942). Mysis stage of decapoda represents the adult ancestor in which the exopod of legs are present and functional. Owing to shortage of research on larval development, the identification of larvae to species is extremely difficult because of great morphological changes between developmental phases, although the changes between larval stages are less pronounced. Penaeid larvae are very delicate and hence form an easy prey to different groups of animals. The survival rate in nature, for *Penaeus duorarum* as calculated by Munro *et al.*, (1968) is less than 0.05% from protozoea I to the post larval stages, which averages 35 days in age.

Studies on decapod larvae (meroplanktonic) in the Indian waters are limited to a few descriptive accounts, based on the pioneer expedition collections (Bate, 1888; Gurney, 1924, 1927, 1942; Heegard, 1966, 1969). Studies of Kemp (1915); Panikkar and Iyer (1939); Menon (1933a,b, 1937, 1940, 1952, 1955); Pillai (1955); Prasad and Thampi (1958); Sankholi, (1967); Shenoy and Sankholi (1967); Williamson (1967, 1970), Subrahmanyam and Rao (1968); Rao (1972); Paulinose (1973); Menon and Paulinose (1973); Ramamoorthy *et al.*, (1975); Suseelan (1976);

Paulinose (1979a, b) have added to our knowledge of decapod larval stages which belong to various genera and family. Paulinose (1979a) studied the IIOE samples and has brought out almost a complete systematic survey of decapod larvae, especially, family Penaeidae. Paulinose, (1974, 1979a,b) described the larval stages *Aristeomorpha foliacea, Funchalia woodwardi, Funchalia balboae, Parapenaues investigatoris, Parapenaeus longipes* and *Parapenaeus fissurus* from samples collected during IIOE (1960-65) from the Indian Ocean. Most of the above studies have outlined the distribution of larvae, post larvae, juveniles and adults of penaieds together with information on their breeding seasons. CMFRI, 1978 published the larval development of eight commercially important decapods in the Indian waters, with an aim to enhance the coastal aquaculture. Hassan (1974) prepared a generic key for the identification of the larvae, including nauplii of the genera *Penaeus, Metapenaeus and Parapenaeopsis*. Muhammed *et al.*, (1970) have described the first post larvae of *Penaues indicus, Metapenaeus monoceros, Metapenaeus affinis* and *Parapenaeopsis stylifera*. Rao (1973) has described the larvae of *Parapenaeopsis stylifera, Metapenaeus affinis, M.monoceros and Penaeus indicus.* Dakin (1938) studied the life history of *Penaeus plebejus* and Morris and Bennet (1951) worked out the life history of *Metapenaeus bennettae* from the Australian waters. Pearson (1939) traced the complete larval series of Penaeus *setiferus* and *Trachypenaeues sonstircua* and the partial life history of *Parapenaeus lingirostris* and *Eusicyonia stimpsoni* from the USA. Cook (1966) gave a generic key to the protozoea, mysis and post larval stages of penaeid shrimps of the same area.

Menon (1933a,b, 1937, 1940) carried out some pioneering work on the decapod larvae of the east coast of India from the coast of Madras. Earlier work reveals that the species diversity and abundance of planktonic decapods in the Bay of Bengal is richer (Paulinose *et al.*, 1987), and there exists marked seasonal variations. Larval distribution in the estuaries and coastal waters are common both in the east and west coasts of India.

Oceanic penaeids like *Solenocera* and *Gennadas,* and their larval stages, are very common in plankton samples. The only description of larval stages of *Solenocera* from the Indian waters is by Menon (1933a) from the Madras coast. Larval development of members of family Benthesecymidae *(Gennadas)* has been described from many areas of the world oceans. Gurney (1924) and Heldt (1938) described protozoea and mysis of *G.elegans* collected from plankton samples. Subramanym and Gunter (1970) reported protozoea of an undetermined species of *Gennadas* from Mississipi coast. Crales and McGowan (1993) reported the occurrence and description of mysis larvae from the coastal waters of south Florida. The described the larval form of this species is not made so far in the Indian waters. The adult specimens of this family were very common in the deep scattering layer (Karuppasaamy et al, 2006). The identification of planktonic stages of penaeid shrimps their species level remains incomplete even today.

Larval forms of the family Sicyonidae were identified and described by Monticelli and Lo Bianco (1900); Lo Bianco (1909); Heldt (1938); Pearson (1939); Gurney (1943); Cook and Murphy (1965); Paulinose (1982).

Studies on the family Caridea were relatively fewer compared to those of Penaeidae. No detailed study on distribution and abundance of caridean larvae in the Indian waters are available even at present. A few studies were carried out to trace the development of carideans by keeping the specimens under captivity and rearing in the laboratory. Characteristics of many families are still unknown to many of the researchers. Description of larval forms of family Processidae were explained by Pillai (1955) from the Travancore waters and later on Jagadisha and Sankoli (1977) from the Karwar by using the laboratory reared specimen of *Processa barnadi* Hayashi. Jagadisha and Sankoli (1977) described the larval development of other families such as Palaemonidae, Alpheidae (Bhuti *et al.*, 1977) *etc.* all from the laboratory-reared specimens. George and Paulinose (1973) reported the presence of *Leptochela roubusta* (family: Pasiphaeidae) form the Indian waters and provided an illustrated note regarding their larval stages. Other earlier studies on *Oplophorus* were by Alcock (1901); De Man (1920; George and Rao (1966) from Indian waters and Gurney and Lebour (1941); Crosnier and Forest (1973) from other oceans. Very recently, Fernandes *et al.*, (2007) described the morphology of Oplophorid and Bresilid larvae from southwestern Atlantic waters. Williamson (1957a, b, 1960) published the preliminary information on the identification of larvae of carideans. Gurnery and Lebour (1941) studied the crustacean larvae from Barmuda and brought out a detailed description of various larval forms including Caridea. Larvae of Pandalidae were described by Lebour (1940). Dos Sanotos and Gonzalez-Gordillo (2004) has published an illustrated key for the identification *Pleocymata* from Portuguese waters. This key is a useful tool for identifying planktonic decapods, mainly in ecological and life history studies.

In India, studies on Thalassinoidea have been mainly undertaken with reference to the deep sea forms (Miers, 1884; Henderson, 1893; Alcock and Anderson, 1894; Anderson, 1896; Alcock, 1901; Borradaile, 1907; Kemp, 1915; Sankholi 1970). Comparatively less work has been done in the east coast, Southwell (1906) has worked on Thalassinids from Ceylon. Gravely (1927) while working on the fauna of Krusadai Island, deals with one species of Callianassidae which he refers to as subgenus *Callindne (=Gebiopsis)*. Chopra (1933) discussed the taxonomic position of *Entrichocheles modestus* of the family Axiidae. Reports on larvae of Anomura and Brachyura were based on the laboratory reared specimen (Paul *et al.*, (1977); Shenoy and Sankoli (1977). Planktonic stages of Brahyuran crabs from the southwestern Iberain coast was explained by Paula (1987) and Rice (1980).

Variability in distribution of planktonic decapods with respect to various physical processes has been studied by many researchers. Baez (1997) collected and studied the distribution and composition of crustacean larvae from northern Chile during El Nino event.

1.3 Scope of the study

An adequate management of fishery resources requires knowledge of the life cycle of the species, and hence plankton studies provide valuable information on the distribution, abundance, and mortality of the larvae and postlarval stages of the corresponding species. In fact, an efficient fishery management depends on the correct estimation of populations and their abundance together with knowledge of their recruitment survival process, as evidenced, strongly by the studies on eggs and larvae of fishes and crustaceans. The plankton samples can provide ample information of the decapod resource in our waters. From our waters, the earlier studies reveal that Bay of Bengal is richer in decapod larvae in the plankton samples compared to the Arabian Sea. In view of the above, this study is essential to explore the planktonic decapod larvae of the EEZ of BoB and adjoining areas with a view to study their pattern of recruitment seasonal variation and population dynamics.

The main objectives are:-

1. to evaluate the qualitative and quantitative abundance of plantktonic decapods in the Bay of Bengal
2. to study the seasonal variation and composition of planktonic decapod in Bay of Bengal.
3. to understand the role of physical processes in the distribution of planktonic decapods in the Bay of Bengal.

Methodology

Planktonic decapods were separated from the zooplankton samples collected during 4 seasons from the BoB. The details of the study region and sampling are given in the Part I. Chapter 2.

The decapods were identified up to species level as far as possible, using the binocular microscope (Nikon Eclipse-E400). The identification of the decapods was done by using the available literature: Gurney (1924, 1927, 1942); Cook (1966); Paulinose (1982); Dos Sanotos and Gonzalez-Gordillo (2004). The abundance of organisms is expressed as no. $100m^{-3}$ using the volume of water filtered by the net.

The nature of abundance was tested using the PRIMER-5 statistical package for calculating the diversity indices and plotting cluster and dominance diagram. Species diversity means absolute number of species present in an environment. It indicates the degree of complexity of a community structure. Diversity is a concise expression of how individuals in a community are distributed with in subsets of groups. Two way ANOVA is applied to compare the diversity indices and the sampling depth strata during each season. The following diversity indices were used in the present study.

1) Margalef's diversity index (Margalef, 1968)

$$D = S-1/\log_e N$$

Where ,

S= No. of species

N= total No. of individuals of all the species in the sample

2) Shannon Wiener diversity index (Shannon and Wiener, 1963)

$H' = \Sigma (P_i \log_e P_i)$ where $P_i = n_i / N$

Where,

Pi=ni/n (Proportion of the sample belonging to the *i*th species.

3) Fisher's diversity index α (Fisher *et al.*, 1943)

$S = \alpha \log (1 + N/a)$

4) Peilou's evenness

$J' = H' / \mathrm{Log}\,(S)$

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Chapter 2

RESULTS

2.1 Spring Intermonsoon (SIM)

During SIM, the presence of planktonic decapods (both holoplanktonic and meroplanktonic forms) in the mixed layer and thermocline layer was observed from all sampling stations (Fig. 1). Towards the deeper depths the number was decreasing or sometimes absent. The average abundance in the mixed layer and thermocline layer was 459 ± 417 and 106 ± 181 no. 100m^{-3} respectively. Stations along the southern transects were found to harbour relatively greater number of organisms especially in the MLD (>300 no. 100m^{-3}). Maximum number of planktonic decapods in the mixed layer (2,036 no. 100m^{-3}) and thermocline layer (1,188 no. 100m^{-3}) was recorded at 13°N;80.5°E. Among the northern stations, higher (1,733 no. 100m^{-3}) abundance was observed at 19°N;88°E. Along 17°N transect the abundance was relatively lower (<300 no. 100m^{-3}), except at 87°E where the density was 444 no. 100m^{-3}. On comparison, the abundance of decapods in thermocline layer was less (~ <100 no. 100m^{-3}) than in the MLD.

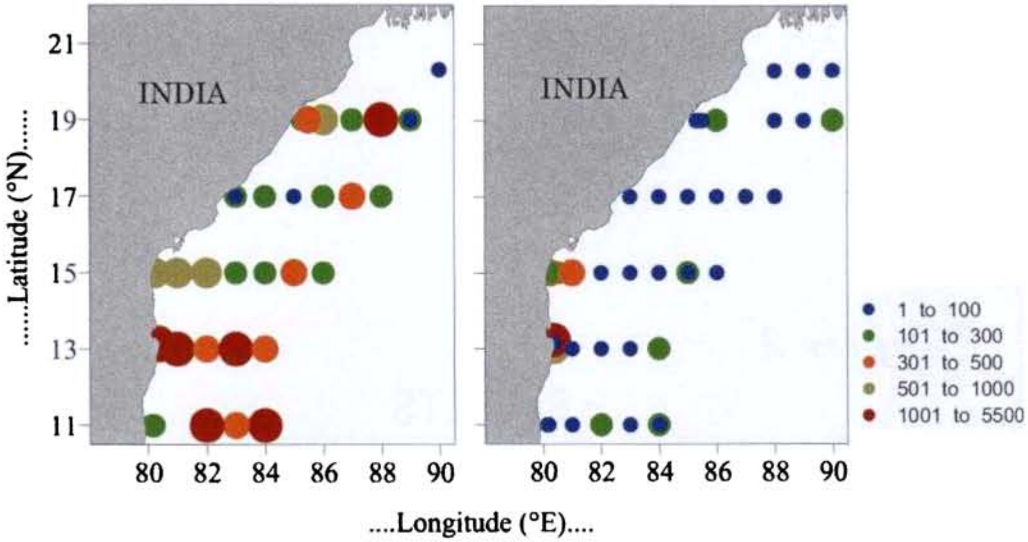

Fig. 1 Spatial distribution of planktonic decapods (no. 100m^{-3}) in the mixed layer and thermocline layer during spring intermonsoon.

Variation in the distribution of decapods between the coastal and oceanic stations was noticeable during this season. Among coastal stations the abundance was relatively higher along 13 (2,036 no. 100m^{-3}) and 15°N (965 no. 100m^{-3}) transects than 11 (292 no. 100m^{-3}) and 17°N (184 no. 100m^{-3}). Oceanic stations had only comparatively lower abundance (<300) than the coastal stations except along 19°N. Among oceanic stations, the highest abundance (1,733 no. 100m^{-3}) was recorded at 19°N;88°E in the mixed layer. The abundance was <300 no. 100m^{-3} in the thermocline layer at all the oceanic stations (Fig. 2)

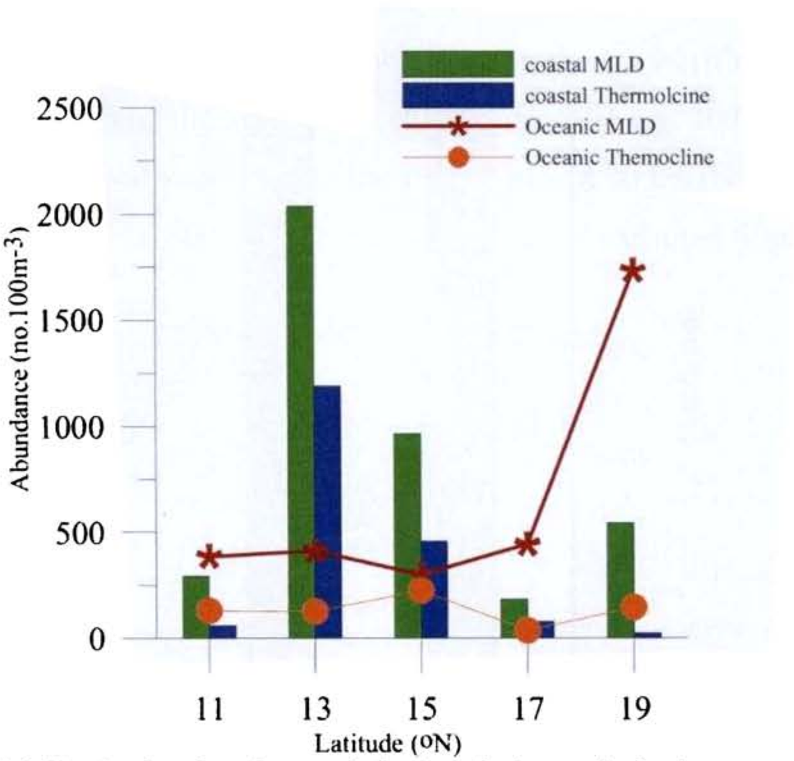

Fig. 2 Variability in the abundance of planktonic decapods in the coastal (bar plot) and oceanic (line plot) stations along different transects during spring intermonsoon.

Of the total abundance of planktonic decapods, the dominant taxa in the mixed layer was Sergestiodea (49%) followed by Brachyura (31%). The relative abundance of other taxa like Caridea and Penaeidea were 19.52% and 3% respectively. Thalassinoidea and Anomura contributed <1% and Stenopodidea was not recorded during this season. In the thermocline layer, the dominant taxa were Brachyura (40%) followed by Caridea (31%) and Sergestiodea (18%). Penaeidea contributed 5% and Anomura 3% in the thermocline layer (Fig. 3).

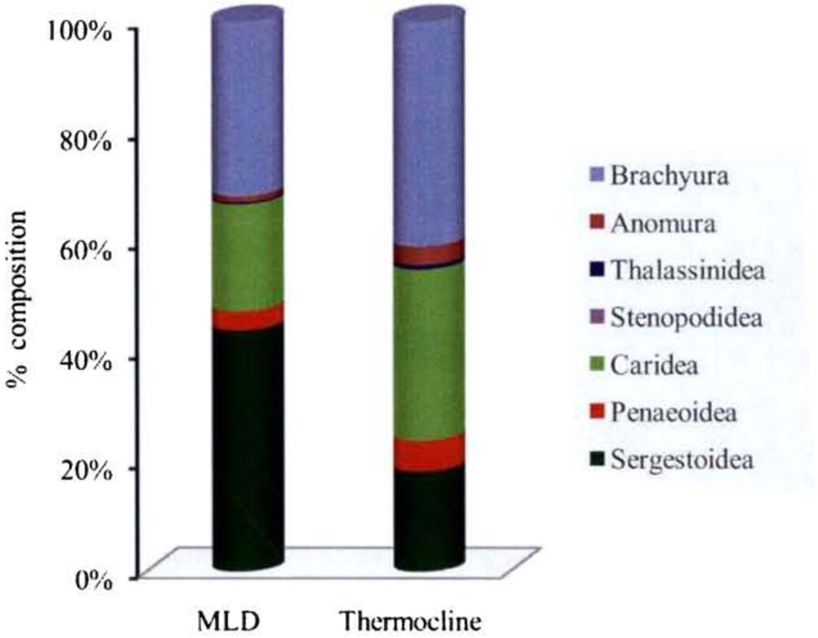

Fig. 3 Relative abundance of various groups of planktonic decapods in the mixed layer and thermocline layer during spring intermonsoon.

Seregestoidea was comprised of sergestids, luciferids and *Acetes*. The abundance of *Acetes* was relatively lower than sergestids and lucifers. Sergestids were represented by larval stages like Elaphocaris, Acanthosoma, Mastigopus and adults of *Sergestes* sp. Larval stages were sparsely (<50 no. 100m^{-3}) distributed in the thermocline layer during this period and were not recorded from the mixed layer. Among larval stages, Mastigopus was dominant (16 no. 100m^{-3}) with maximum abundance at 17°N;89°E, and others were only <10 no. 100m^{-3}. Adults of *Sergestes* sp. were recorded (30 no. 100m$^{-3)}$ in the mixed layer. Luferidae was the dominant family under Sergestoidea with maximum abundance recorded at 13°N;80.5°E (737 no. 100m^{-3}). The distribution of *Lucifer* was more concentrated towards the southern than to the northern region. In the northern region, the maximum abundance (600 no. $100m^{-3}$) was noticed at the coastal station along the 19°N transect. In the thermocline layer the, *Lucifer* was (<50 no. $100m^{-3}$) and sparsely distributed (Fig. 4).

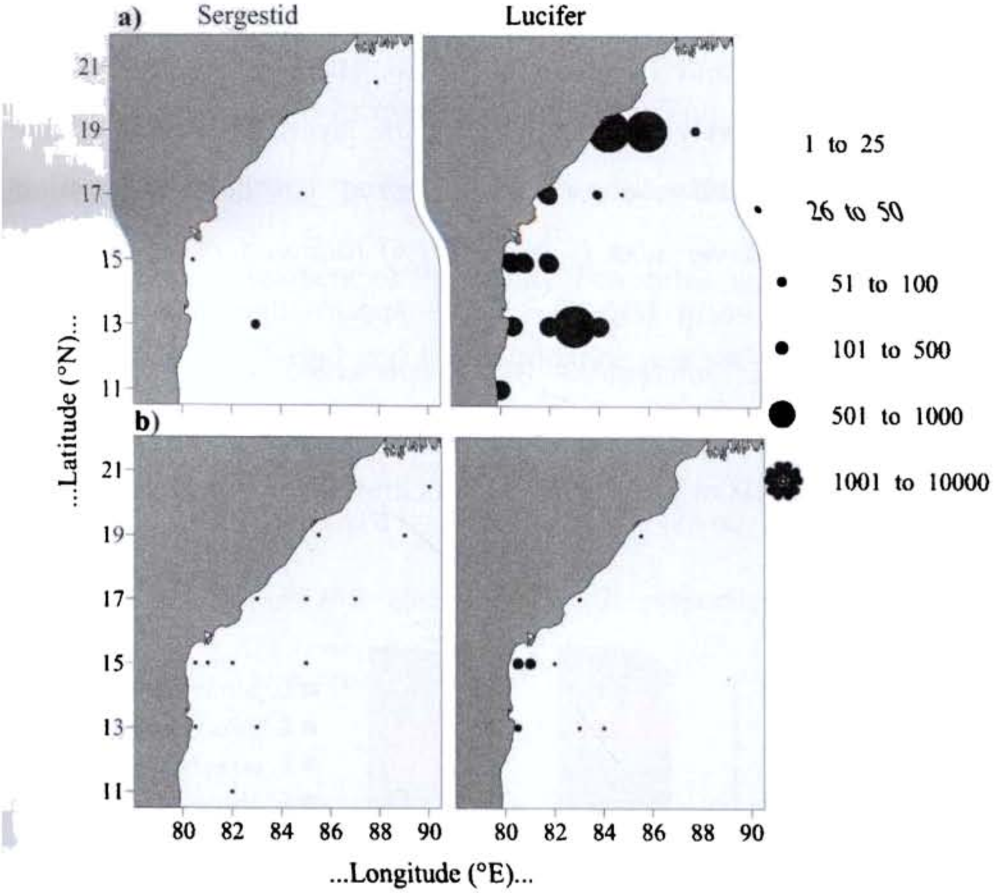

Fig. 4 Spatial distribution of sergestids and *lucifer* (no. $100m^{-3}$) in the a- mixed layer and b- thermocline layer during spring intermonsoon.

Species composition of *Lucifer* showed pronounced variability between the mixed layer and thermocline layer. In the mixed layer, the dominant species was *L. typus* (52%) followed by *L. faxoni* (23%). Maximum abundance of *L. typus* (300 no. $100m^{-3}$) and *L. faxoni*

(220 no. 100m^{-3}) was recorded at the coastal stations along 19°N and 15°N transects respectively. Other species like *L. chacei, L. orientalis* and *L. intermedius* contributed 13 and 4% (both *L. orinetalis* and *L. intermedius*) respectively in the mixed layer. The maximum number of *L. chacei* (300 no. 100m^{-3}) was observed at 19°N;85.5°E and *L. intermedius* (88 no. 100m^{-3}) and *L. orientalis* (40 no. 100m^{-3}) at 15°N;80.5°E and 15°;81°E respectively. In the thermocline layer, the variability in the species-wise abundance was only marginal. The dominant species in the thermocline layer was *L. faxoni* (31%) followed by *L. typus* and *L. hanseni* (18% each) (Fig. 5). Other species like *L. orienetalis, L. penicillifer* and *L. intermedius* were represented by 6, 5 and 2% respectively in the thermocline layer. The maximum abundance of *L. faxoni* (56 no. 100m^{-3}) in the thermocline layer was recorded at 15°N;80.5°E.

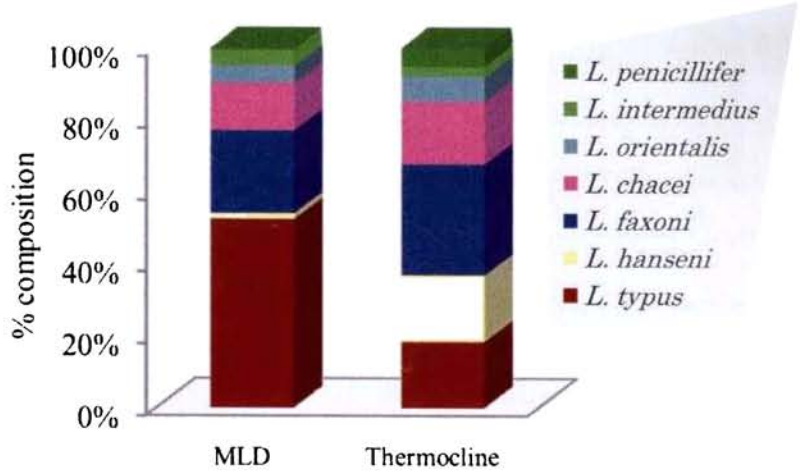

Fig. 5 Species composition of family Luciferidae in the mixed layer and thermocline layer during spring intermonsoon.

The Penaeoidea contributed only 3% of the total planktonic decapod recorded during this season. Among Penaeoidea, family, Benthesicymidae was recorded from 2 stations in the mixed layer and from 5 stations (Fig. 6) in the thermocline layer. The only representative of this family was *Gennadas* sp. (Mysis II) and its maximum density (15 no. 100m^{-3}) recorded in the MLD at 13°N;83°E. In the thermocline layer the abundance was <10 no. 100m^{-3}. Members of the family Penaeidae were also sparsely present during this period and the abundance was <40 no. 100m^{-3}. The dominant species under this family was *Metapenaeopsis barbata* (Mysis II stage) (37 no. 100m^{-3}) followed by *Metapenaeus* sp. (23 no. 100m^{-3}) and were recorded from 15°N;80.5°E and 19°N;85.5°E respectively. *Metapenaeus affinis* (5 no. 100m^{-3}) was present at 20.5;89°E.

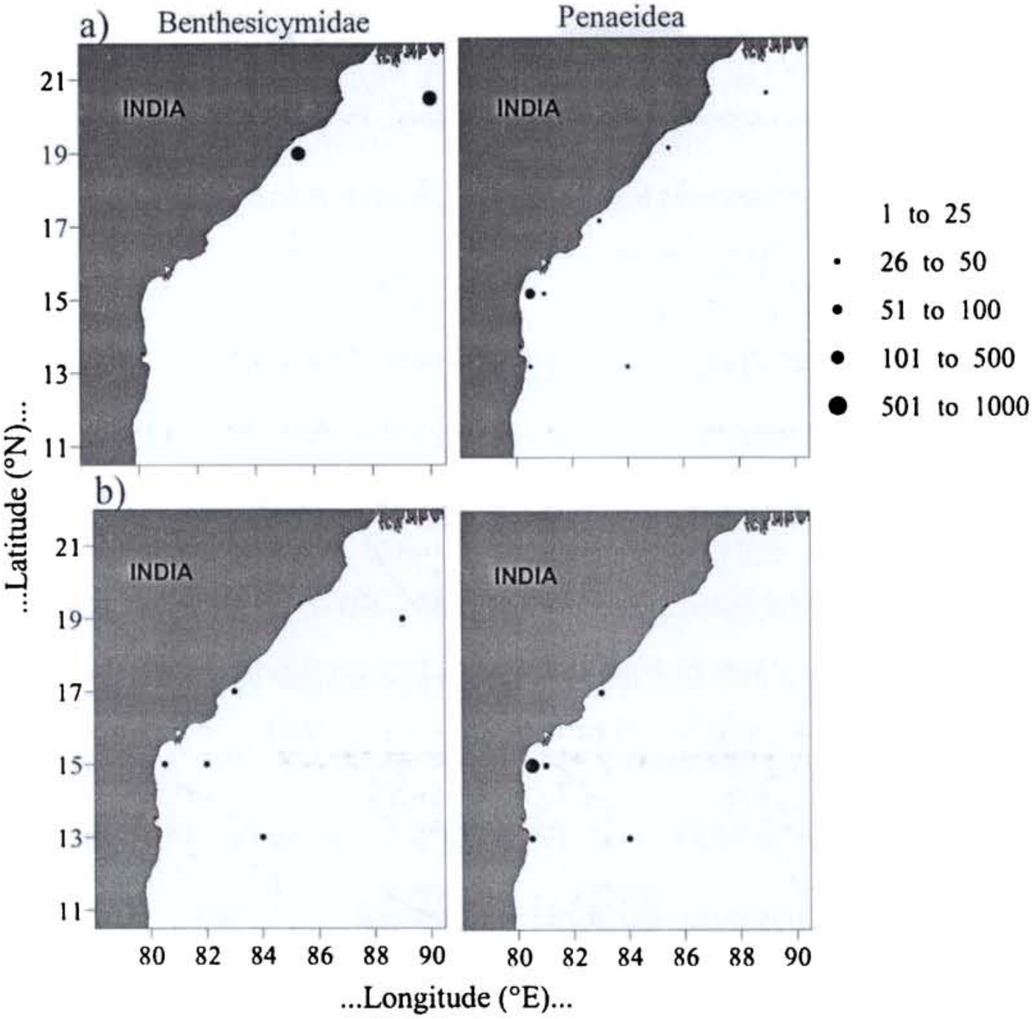

Fig. 6 Spatial distribution of Penaeoidea (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during summer monsoon.

Caridea was the third dominant taxa in the total planktonic decapods in the mixed layer and second dominant in the thermocline layer. Numerical density was more towards the southern region in both the layers, and towards the deeper depth the abundance was very low or nil. Thalassocaridae was the dominant family under Caridea and represented by larval stages and adults. The adult specimens were identified as *Thalassocaris lucida, Thalassocaris obscura and Thalassocaris crinata*. Maximum number of *T. lucida* (30 no. 100m^{-3}), *T. obscura* (136 no. 100m^{-3}), and *T. crinata* (60 no. 100m^{-3}) was recorded at 17°N;83°E, 11°N;80°E and 13°N;84°E respectively in the mixed layer. Zoea IV and V of *T. lucida, T. obscura and T.* sp. were also recorded during this season. The highest abundance of larval population was recorded at 13°N;80.5°E (*T. obscura,* 300 no. 100m^{-3}) followed by 13°N;84°E (Zoea IV of *T. lucida,* 125 no. 100m^{-3}) in the mixed layer (Fig. 7). Other Carideans represented in the mixed layer were *Synalpheus* (27 no. 100m^{-3} at 15°N;80.5°E), *Athnas* (24 no. 100m^{-3} at 13°N;80.5°E), *Erytmocaris* (23 no. 100m^{-3} at 19°N;85.5°E) *Hippolysmata* (12 no. 100m^{-3} at 13°N;80.5°E), and various others were represented <10 no. 100m^{-3}.

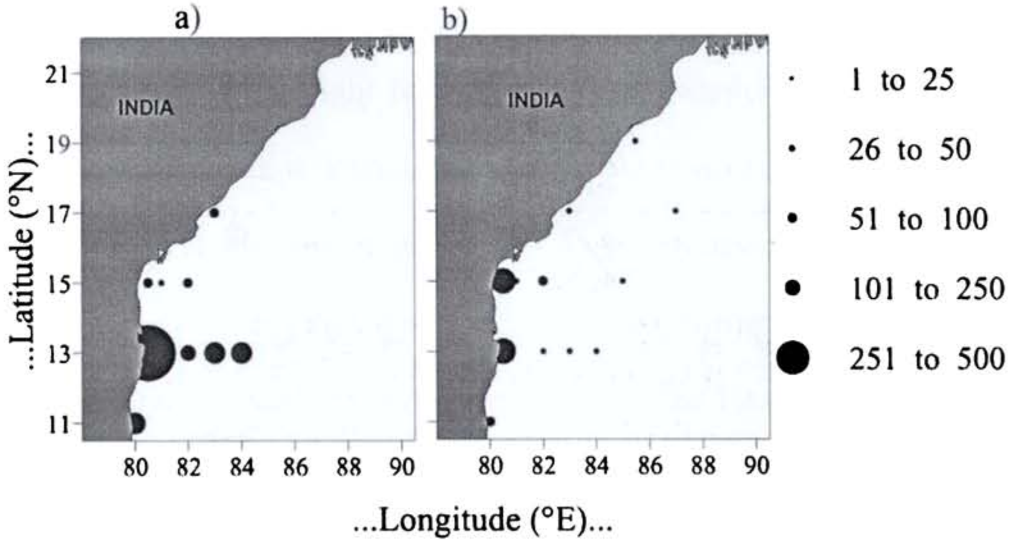

Fig. 7 Spatial distribution of family Thalassocaridae (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during spring intermonsoon.

Brachyura contributed 31% in the mixed layer and 40% in the thermocline layer to the total planktonic decapod. Zoea and megalopa of Brachyuran crab were the two components under Brachyura. Maximum abundance (1,478 no. 100m^{-3}) in the mixed layer and thermocline layer (911 no. 100m^{-3}) were observed at 13°N;80.5°E (Fig. 8). Zoea outnumbered megalopa stage at 13°N;80.5°E where the maximum abundance was observed. Other taxa like Thalassinoidea and Anomura were scanty during this season (<50 no. 100m^{-3}).

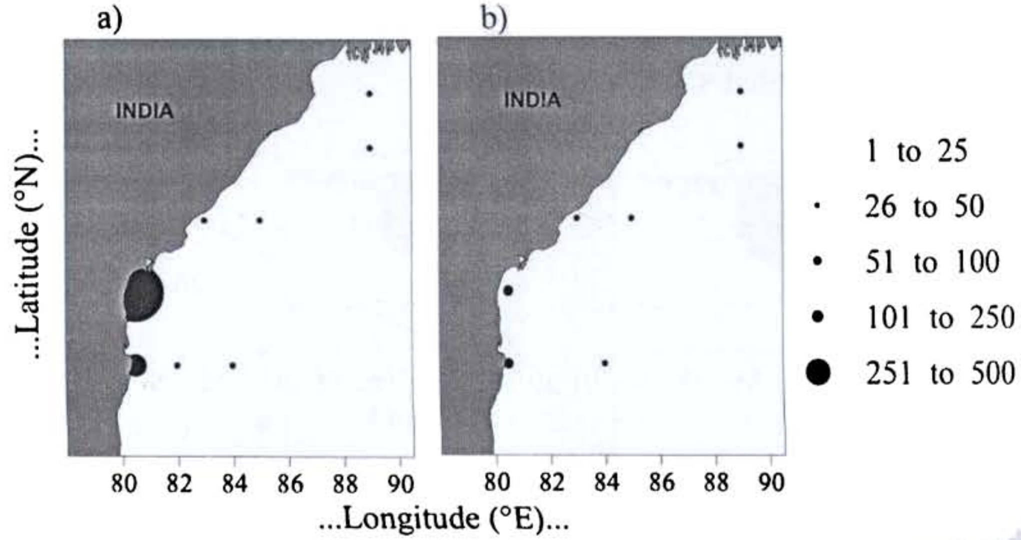

Fig. 8 Spatial distribution of Brachyura (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during spring intermonsoon.

The diurnal variability in the dispersal of planktonic decapod was observed more along the coastal stations than in the oceanic stations. Along 11°N transect the day and night variations in the abundance were not prominent and the abundance along this transect was comparatively lower than other transects. Along 13 and 15°N transects, the decapods were more abundant during night both in the coastal and oceanic stations. At the coastal station along 13°N transect, the abundance of decapods in the MLD during night hauls (2,183 no. 100m^{-3}) was nearly four times more compared to day sampling (558 no. 100m^{-3}). In the deeper layer (300 m-BT), the abundance of planktonic decapods were observed during the night hauls at the coastal station along the 13°N transect. Night time abundance of planktonic decapods in the MLD was noticed at the coastal station along 15°N transect whereas in the thermocline layer the abundance was observed during day hours at the same station. Towards the northern transects, the total abundance was relatively less, and there was thus no significant variability between the day and night samplings (Fig. 9)

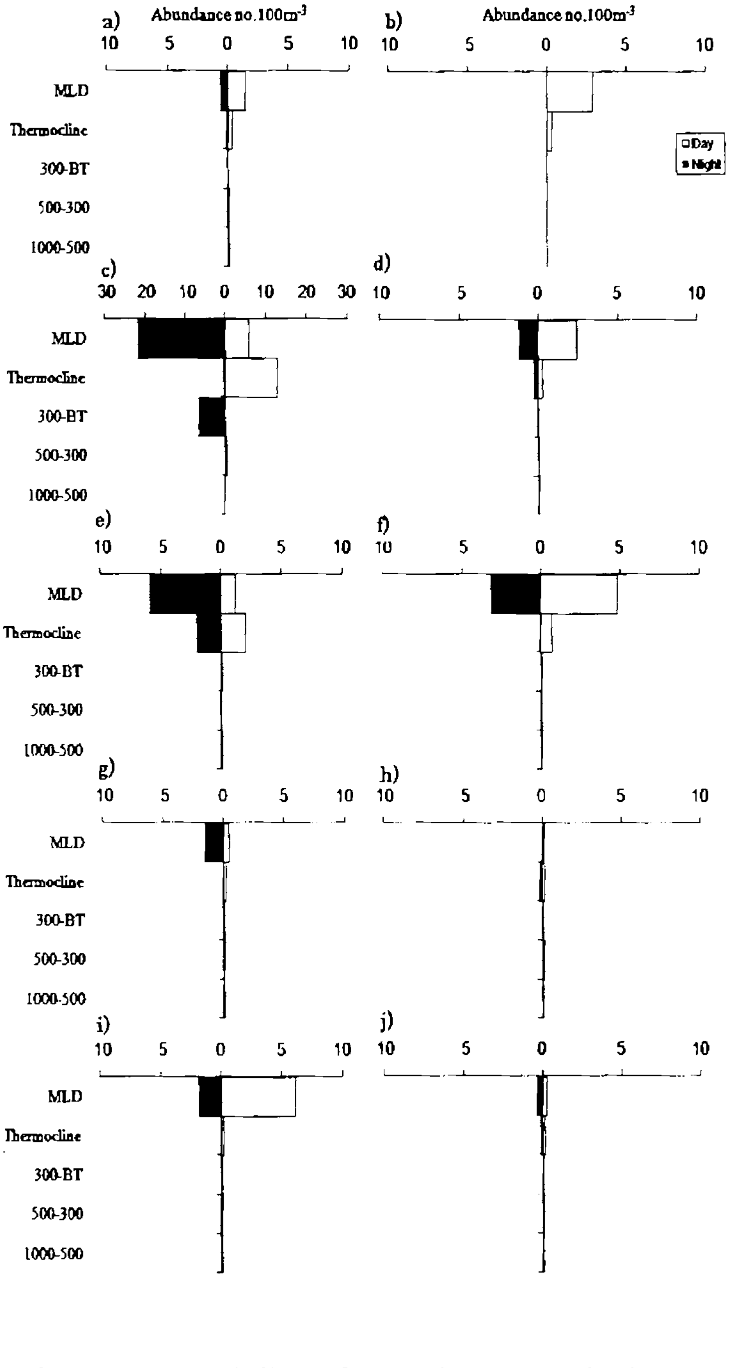

Fig. 9 Diurnal variability of abundance of planktonic decapods during spring intermonsoon in the coastal and oceanic station along 11°N (a&b); 13°N (c&d); 15°N (e&f); 17°N (g&h); and 19°N (i&j) transects (note: scales are not same and the value are in hundreds).

Significant difference (P<0.01) was observed between the various diversity indices and the sampling depth strata (Table I). Thermocline had significantly higher diversity index, compared to other layers. Very high significant difference was observed between the different diversity indices (P<0.001). Fisher's diversity was significantly higher, compared to all others.

Table I ANOVA table between the diversity indices and sampling depth strata.

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Depth strata	0.886674	4	0.221668	7.445917	0.00138	3.006917
Diversity index	1.72187	4	0.430467	14.45955	3.53E-05	3.006917
Error	0.476327	16	0.02977			
Total	3.084871	24				

Cluster analysis was performed to analyse the similarity in the qualitative abundance of planktonic decapods between the coastal and oceanic stations. Higher level (>80%) similarity was observed in the coastal and oceanic stations of 11°N transect (Fig. 10).

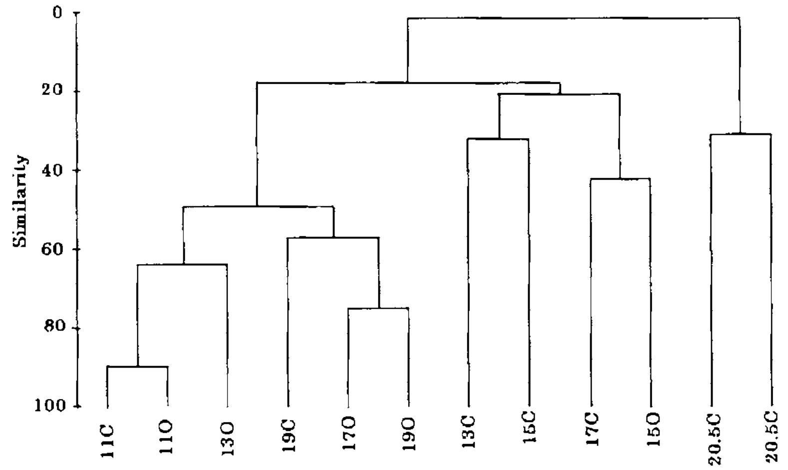

Fig. 10 Dendrogram for grouping the coastal (C) and oceanic (O) stations based on the qualitative abundance of decapods during spring monsoon.

Table II Composition of planktonic decapods during spring intermonsoon ('+'- <50; '++' - 50-100; '+++' - >100 no. $100m^{-3}$ and '-' - not present).

	Sampling Depth strata				
Name of species	**MLD**	**Thermocline**	**300 m-BT**	**500-300 m**	**1000-500 m**
Solenocera sp. *(larvae)*	+	+	-	+	+
Gennadas sordidus		+			+
Gennadas clavicarpus			+	+	-
Gennadas sp.			+	+	+
Gennadas sp. (Zoea & Mysis)	+ +	+		+	+
Sergestes sp. (adult)	+	+			+
Sergestes sp. (Elaphocaris)		+	+		-
Sergestes sp. (Acanthosoma)	+	+			-
Sergestes sp. (Mastigopus)	+	+	+	+	-
Acetes erythreaus			+	+	-
A. sp.		+			-
Acetes sp. (Acanthosoma)		+			-
Lucifer typus	+ + +	+ +			-
Lucifer hanseni	+	+ +			-
Lucifer faxoni	+ + +	+ +			-
Lucifer chacei	+ + +	+ +			-
Lucifer orientalis	+ + +	+			-
Lucifer intermedius	+ + +	+			-
Lucifer penicillifer	+	+	+ +		-
Lucifer sp. (larval stages).	+ + +	+ +			-
Atypopenaeus stenodactylus		+			-
Trachypenaeus sp.		+			-
Metapenaeus sp.	+				-
Metapenaeus dobsoni			+		-
M. affinis	+	+			-
Metapenaeopsis andamanensis			+		-
Metapenaeopsis barbata	+	+			-
Parapenaeopsis stylifera		+			-
Parapenaeopsis sp.	+				-
Parapenaeus investigatoris	+	+			-

Table II Cont.....

Penaeid protozoeae		+			-
Acanthyphyra sp.	+	+	-		-
Alphid sp.		+			-
Alpheus sp.		+	+		-
synalpheus sp.	+	+			-
Athanas sp. *(dimorphus)*	+				-
Automate sp.					-
Thalassocaris lucida	+	+			-
Thalassocaris lucida (Zoea & Mysis)	+	+ + +			-
Thalassocaris obscura	+ + +	+ +	+ + +		-
Thalassocaris obscura (Zoea & Mysis)	+ + +	+ + +	+		-
Thalassocaris crinata	+		+		-
T. sp. *(Zoea & Mysis)*	+ + +	+ + +			-
Hippolysmata sp.	+				+
Eretmocaris sp. (dolichops?)	+				-
Processa sp. (*edulis*?)		+			-
Pontoninae			+		-
Periclimenes grandii	+	+			-
Mesocaris sp.	+				-
Axius sp.		+			-
Callianassa sp.		+			-
Galathea sp.		+			-
Pagurids		+	+		-
Diogenes sp.	+				-
Parapagurus		+			-
Pagurus zoea.		+			-
Albunea sp.		+			-
Dromia sp.			+ + +	+	-
Crab zoea	+ + +	+ + +	+	+	-
Crab megalopa	+ +	+			-
Stomatopoda	+	+	-	-	-

2.2 Summer Monsoon (SM)

During summer monsoon the abundance of planktonic decapods ranged from 2 to 5,087 in the mixed layer and 3 to 816 no. 100m^{-3} in the thermocline layer. The average abundance in the mixed layer was 1,011 ± 1,033, and that in the thermocline layer was 130 ± 215 no. 100m^{-3}. Maximum abundance (5,087 no. 100m^{-3}) in the mixed layer was recorded at 15°N;80.5°E followed by 17.5°N;84°E (3,466 no. 100m^{-3}). Coastal stations possess relatively more abundance than oceanic stations except in the MLD along 17.5°N (Fig. 11). In the thermocline layer, the abundance was more concentrated towards the coastal stations than in the oceanic stations. In 300 m-BT depth strata, the abundance ranged from 2 to 61 no. 100m^{-3}; the maximum abundance (61 no. 100m^{-3}) was recorded at 13.5°N;84°E. In the 1000-500 m and 500-300 m depth strata, the abundance was found to be ranged from 2 to 68 and 1 to 25 no. 100m^{-3} respectively.

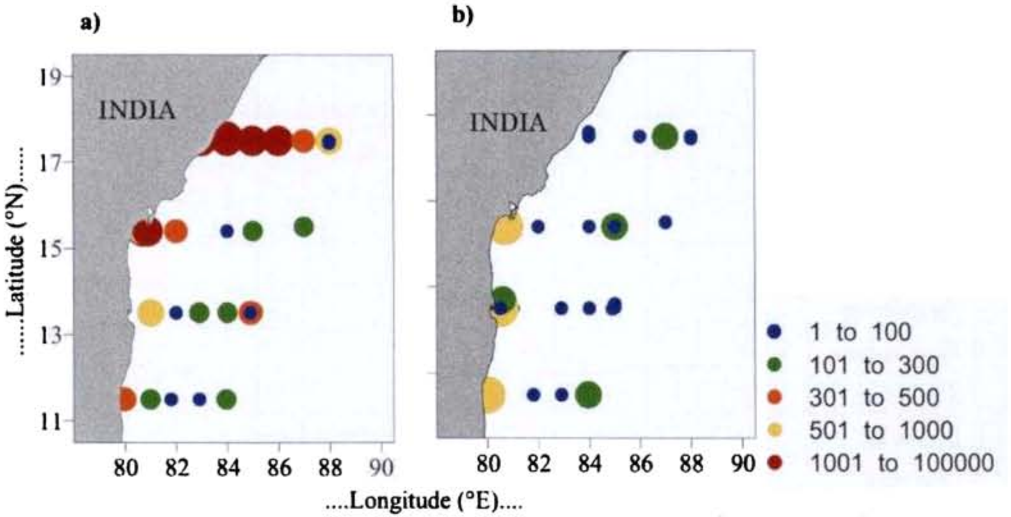

Fig. 11 Spatial distribution of planktonic decapods (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during summer monsoon.

Among the coastal stations, the abundance was maximum along 15.5°N (5,087 no. $100m^{-3}$) transect, followed by 17.5°N (1576 no. $100m^{-3}$) transect in the mixed layer. In the thermocline layer, the maximum abundance (816 no. $100m^{-3}$) was noticed along the 11.5°N transect during this season. Along the oceanic regions, the abundance was quite low both in the mixed layer and thermocline layer. The maximum abundance at the oceanic region was recorded in the mixed layer (616 no. $100m^{-3}$) along 17.5°N transect. In the thermocline layer, the number of planktonic decapods were <100 no. $100m^{-3}$ in almost all oceanic stations with a few exceptions (Fig. 12).

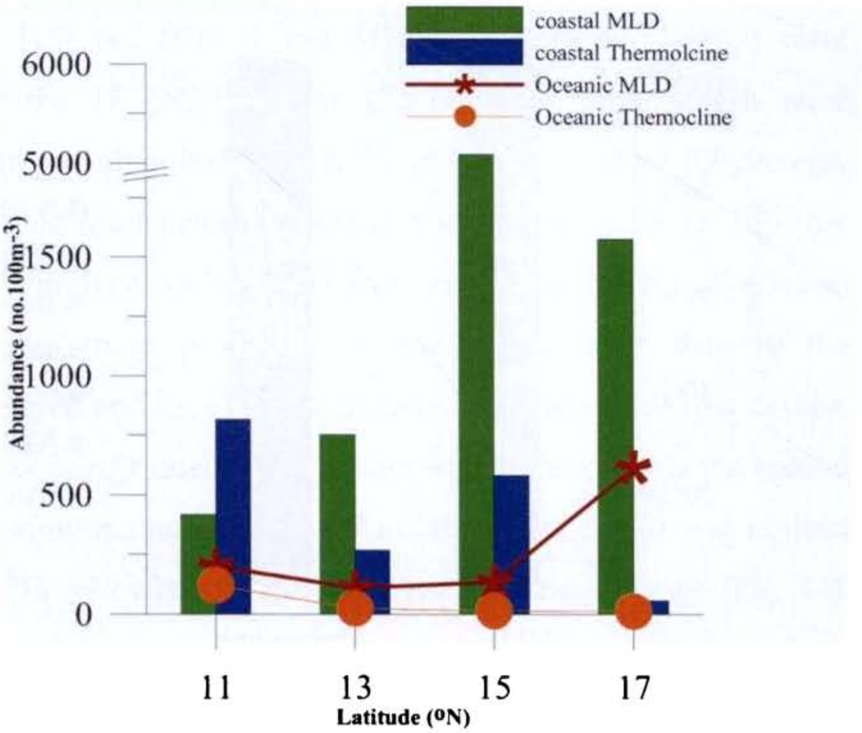

Fig. 12 Variability in abundance of planktonic decapods in the coastal (bar plot) and oceanic (line plot) stations during summer monsoon.

The relative abundance of various groups of planktonic decapods during this season is shown in (Fig. 13). Members of the Sergestoidea dominated both in mixed layer (65%) and thermocline layer (38%). The second dominant group was Caridea which contributed 26% in the mixed layer and 42% in the thermocline layer. Brachyura were also recorded during this season with 4 and 9% in the mixed layer and thermocline layer respectively. The relative abundance of Anomura (1 and 4% in the mixed and thermocline layers respectively) and Penaeoidea (2% in both the layers) were quite low, and Stenopodidea was not recorded during this season.

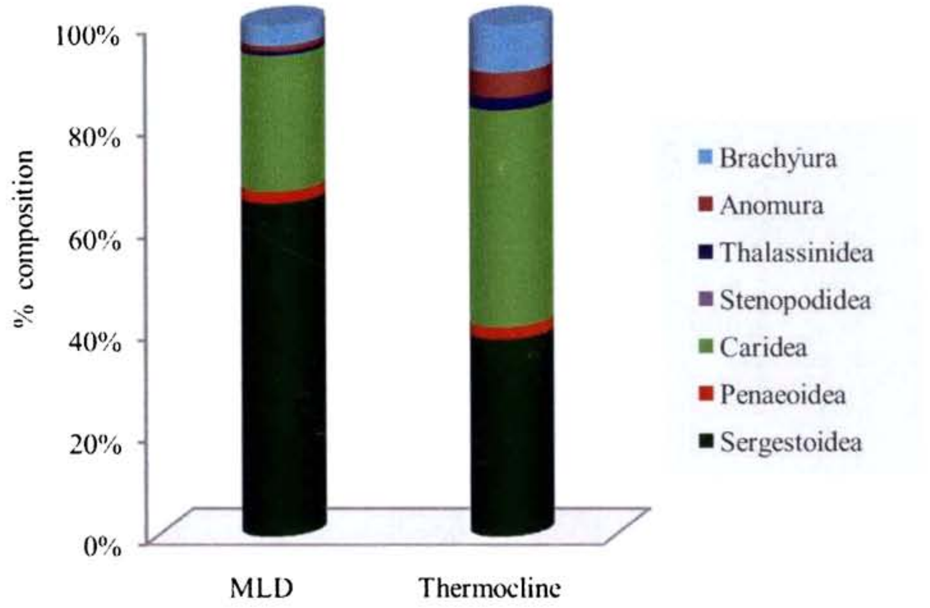

Fig. 13 Relative abundance of various groups of planktonic decapods in the mixed layer and thermocline layer during summer monsoon.

During SM, the dominant taxon was Sergestoidea which composed of both meroplanktonic and holoplanktonic forms. Among meroplanktonic group larval stages (*Elaphocaris, Acanthosoma and Mastigopus*) of sergestids and *Acetes* were observed. The maximum abundance of Sergestids (731 no. 100m^{-3}) during this season was recorded at the coastal station along 17.5°N transect. *Acanthosoma* and *Mastigopus* stages of sergestids were more abundant than the same stages of *Acetes* sp. The abundance of *Elaphocaris* was relatively lesser than the other two stages, and the maximum abundance (38 no. 100m^{-3}) of *Elaphocaris* was recorded at 13.5°N;80.5°E. Maximum number of *Acanthosoma* (457 no. 100m^{-3}) and *Mastigopus* (274 no. 100m^{-3}) were observed at the 17.5°N;84°E. At 13.5°N;81°E , three stages were observed with an abundance of 11, 23 and 35 no. 100m^{-3} (*Elaphocaris, Acanthosoma and Mastigopus* respectively) in the mixed layer. In other stations the abundance of larval stages were >10 no. 100m^{-3}. The larval abundance was more prominent in the mixed layer than in the thermocline layer, and the abundance decreased towards deeper depths. Distribution of *Lucifer* during this season was more towards the coastal stations. Maximum abundance (2,877 no. 100m^{-3}) of *Lucifer* was noticed at 17.5°N;84°E, followed by 13.5°N;83°E (2,634 no. 100m^{-3}) (Fig. 14). Maximum abundance was noticed in the mixed layer followed by thermocline layer, and toward the deeper layers the abundance showed decreasing trend.

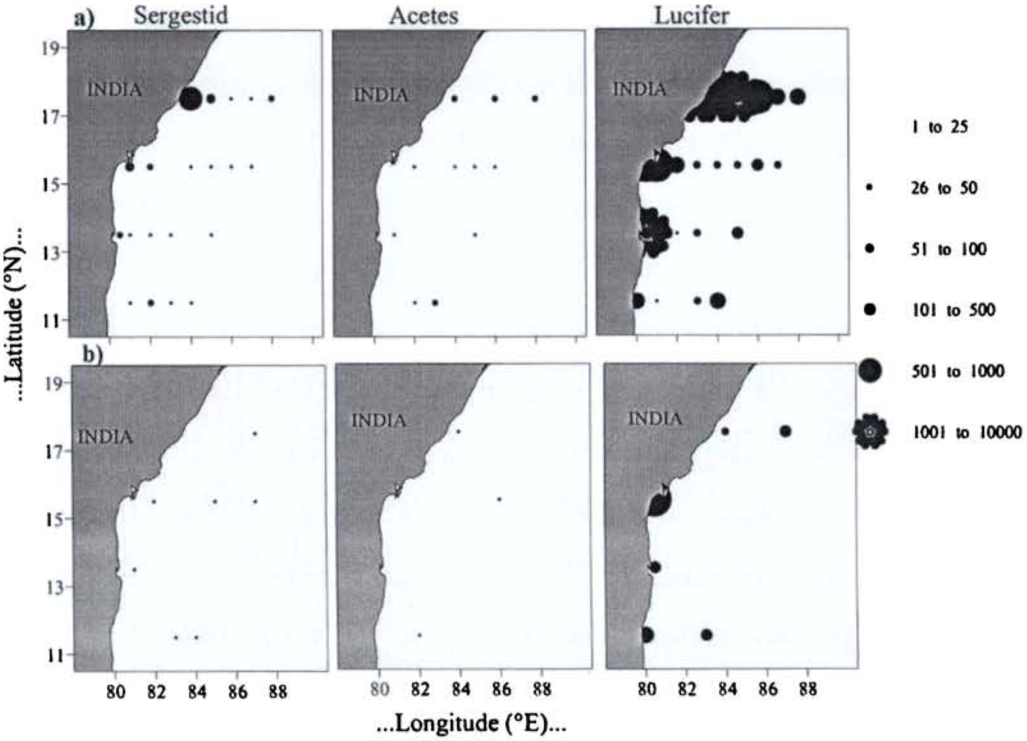

Fig. 14 Spatial distribution of Sergestids, *Acetes* and *Lucifer* (no. $100m^{-3}$) in the a- mixed layer and b- thermocline layer during summer monsoon.

Family Luciferidae (the holoplankton) was represented by 6 species during this season. *Lucifer penicillifer* (40%) dominated in the mixed layer, followed by *Lucifer hanseni* (33%), and the other species accounted for only >10%. In the thermocline layer , the dominant species was *L. hanseni* (38%), followed by *L. faxoni* (25%), *Lucifer chacei* and *L. oreintalis* were not observed in thermocline layer during the study period (Fig. 15). Maximum abundance (2,102 no. $100m^{-3}$) of *L. penicillifer* was recorded at 17.5°N;84°E, and other species reported at this station were *L. chacei* (365 no. $100m^{-3}$) and *L. faxoni* (274 no. $100m^{-3}$). Mysis stages of *Lucifer* were also recorded in mixed layer with maximum abundance (1,142 no. 100m^{-3}) at 13.5°N;80.5°E. Larval abundance of *Lucifer* ranged from 45 to 1,142 no. 100m^{-3}. At the coastal stations, the larval abundance was relatively greater compared to oceanic stations. *Lucifer orientalis* was not recorded during this seasons.

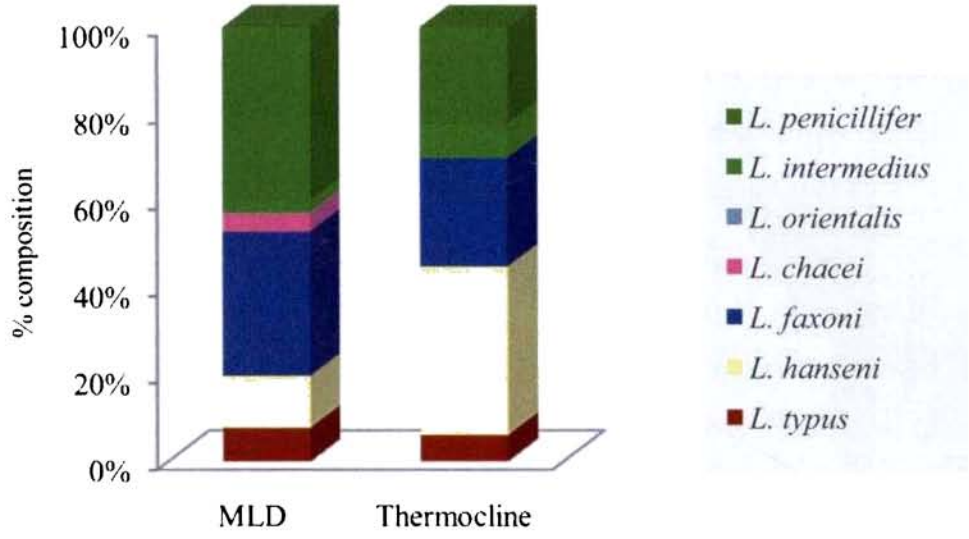

Fig. 15 Species composition of family Luciferidae in the mixed layer and thermocline layer during summer monsoon.

The members of superfamily Penaeoidea contributed only 2% both in the mixed layer and thermocline layer. The dominant families recorded were Solenoceridae, Benthesicymidae and Penaeidae. The total abundance of Penaeoidea was 986 no. 100m^{-3}, of which the mysis stages of Benthesicymidae (*Gennadas* sp.) contributed 50% (494 no. 100m^{-3}), followed by Penaeidae 40% (398 no. 100m^{-3}) and Solenoceridae 8% (85 no. 100m^{-3}). Abundance of Benthesicymidae was relatively more evident towards the northern regions with a maximum of 91 no. 100m^{-3}

at 17.5°N;84°E, followed by 44 no. 100m^{-3} at 17.5°N;86°E, and these were composed of mysis stages of *Gennadas* sp. in the mixed layer. Adult specimens *Gennadas sordidas* also were observed in deeper depth strata (500-300 and 1000-500 m). In 500-300 m depth stratum, the *G. sordidas* were represented by 18 no. 100m^{-3} at 15.5°N;82°E and in 1000-500 m stratum by 3 no. 100m^{-3} at 11.5°N;83°E. Protozoeal stage of genus *Solenocera* (54 no. 100m^{-3}) was recorded from the northern transects (17.5°N; 86°E) (Fig. 16).

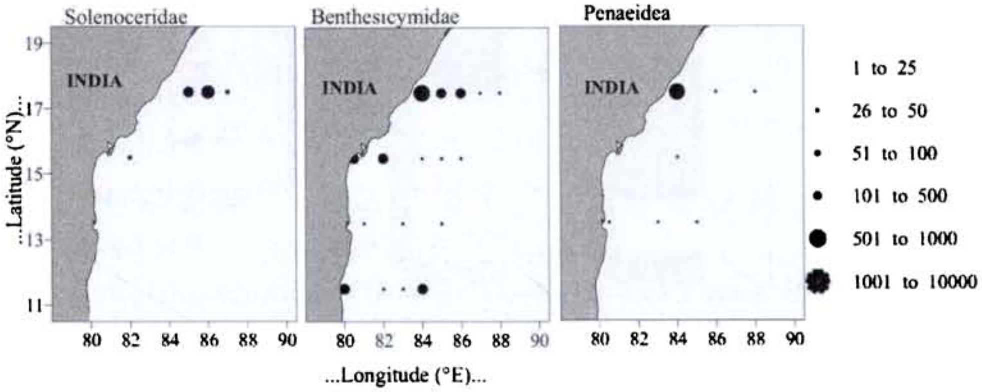

Fig. 16 Spatial distribution of Penaeoidae (no. 100m^{-3}) in the mixed layer during summer monsoon.

Family Penaeidae contributed 40% (398 no.100m^{-3}) under super family Penaeoidea. Protozoeal and mysis stages were the major contributers to the total abundance. Maximum abundance of Penaeidae was represented by mysis II of *Metapenaeus monoceros* (274 no. 100m^{-3}) at station 17.5°N;84°E. Mysis I of *Metapenaues* sp. and *Metapenaeus affinis* (27 and 23 no. 100m^{-3} respectively) were recorded in the oceanic stations of 17.5°N transect. Other representatives of family Penaeidae were mysis stages of *Atypopenaeus stenodactylus* (5 no. 100m^{-3}), *Trachypenaues* *curvirostris* (5 no. 100m^{-3}), *Penaeus monodon* (10 no. 100m^{-3}), *Parapenaeus investigatoris* (5 no. 100m^{-3}) and protozoeal stages of unidentified penaeids (8 no. 100m^{-3}). The presence of larval forms were higher in the mixed layer and thermocline layer, and towards the deeper layers the representation was either low or nil.

The relative abundance of carideans in mixed layer and thermocline layer during this season was 26% and 42% respectively. Mysis III and IV stages of *Leptochela robusta* and *Leptochela* sp. were the major contributors under family Pasiphaeidae. Maximum abundance of pasiphaeids (421 no. 100m^{-3}) were observed at 13.5°N;80.5°E followed by 11.5°N;79.5°E (90 no. 100m^{-3}) (Fig. 17). The abundance of mysis III and IV of *Leptochela robusta* (83 no. 100m^{-3}) was recorded in the mixed layer at the coastal station along 11.5°N transect. Mysis stages of *Leptochela* sp. (421 no. 100m^{-3}) was maximum in the MLD at the coastal station along 13.5°N transect. In the thermocline layer also, larval stages of both *L. robusta* and *L.* sp. were recorded and their density varied from 118 to 373 no.100m^{-3} at 11.5°N;80°E and 13.5°N;80.5°E respectively. The sub-adults of *L. robusta* (88 no. 100m^{-3}) were also recorded in mixed layer during this period.

Thalassocaridea was the leading family and the maximum abundance noticed was 513 no. 100m^{-3} at 13.5°N; 80.5°E, followed by 190 no. 100m^{-3} at 11.5°N;79.5°E. *Thalassocaris* was recorded in almost all stations during this season, especially in the mixed layer. Zoea and Mysis stages of *Thalassocaris obscura, Thalassocaris lucida* and *Thalassocaris* sp. were the under this family. Maximum abundance (4,076 no. 100m^{-3})

of *T.* sp. was rerecorded at 13.5°N 80.5°E in the mixed layer and at 11.5°N;78°E in the thermocline layer (249 no. 100m^{-3}). Zoea III and IV of *T. obscura* were recorded at 13.5°N; 80.5°E with maximum abundance of 133 no. 100m^{-3}. *T. lucida* (45 no. 100m^{-3}), present only at one station (17.5°N;84°E) in the mixed layer.

The occurrence of alpheid shrimps was comparatively less than the other two families. At 13.5°N; 80.5°E, 342 no.100m^{-3} of alpheids were present in mixed layer and their representation in the thermocline was nil.

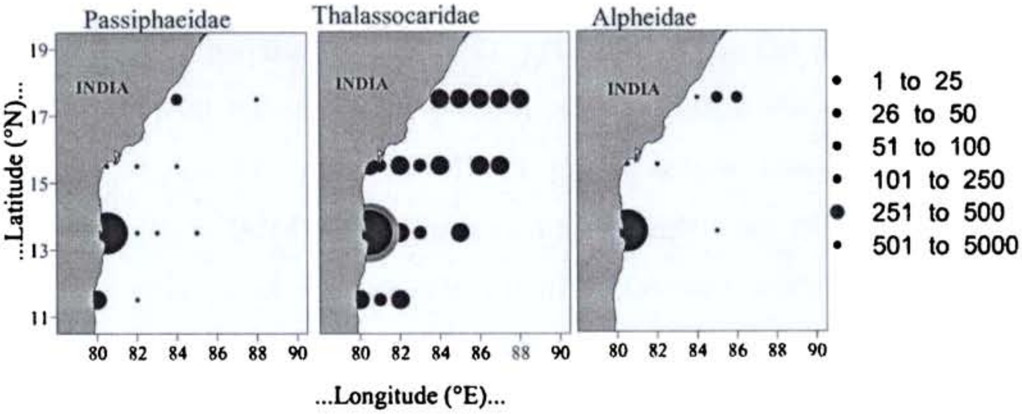

Fig. 17 Spatial distribution of Caridea (no. 100m^{-3}) in mixed layer during summer monsoon

Abundance of Thalassinidea, Anomura and Brachyura were noted only at a few stations (Fig. 18). The relative abundance of Thalassinidea and Anomura was <50 no. 100m^{-3}, except the former at 17°N;84°E and latter at 13.5°N; 84°E (91 and 168 no. 100m^{-3} respectively). Brachyura was represented by larval stages (Zoea and Megalopa) of brachyuran crabs and 39% (537 no. 100m^{-3}) of the total brachyurans were recorded from the 13.5°N;80.5°E (228 and 308 no. $100m^{-3}$ of brachyuran zoeae and megalopae respectively).

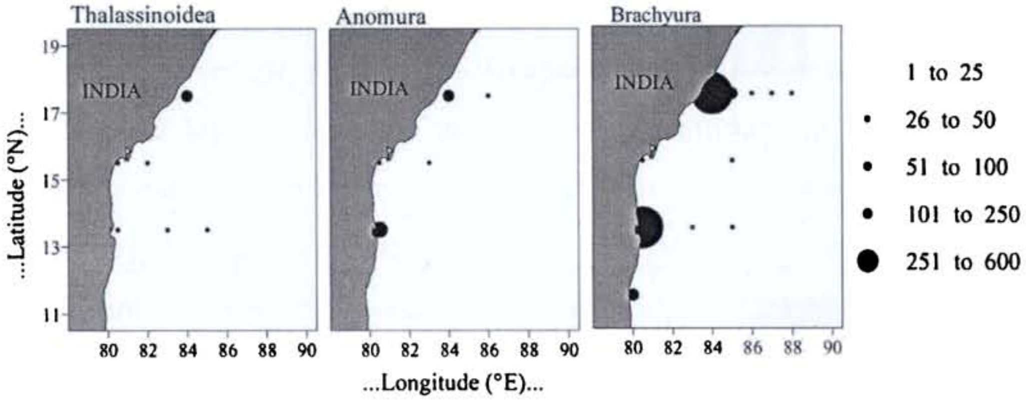

Fig. 18 Spatial distribution of Thalassinidea, Anomura and Brachyura (no. $100m^{-3}$) in mixed layer during summer monsoon.

The diurnal variability of total abundance of planktonic decapods were more pronounced along the coastal stations than oceanic stations. At the coastal station along 11.5°N transect, the day and night variability in the mixed layer (179 and 162 no. $100m^{-3}$ repectively) was not prominent whereas in thermocline layer, abundance increased during night (492 no. $100m^{-3}$). In coastal stations along 13.5, 15.5 and 17.5°N transects, the night (6,891, 577 and 4,977 no. $100m^{-3}$ respectively) samples were rich in planktocinc decapods compared to day (4,188, 281, 558 no. $100m^{-3}$ respectivley) in the mixed layer. Along theses transects, the abundance of decapods in the thermocline layer was quite low, and thus no significant variation showed between day and night samples. At oceanic stations also, the night hauls were having a greater number of decapods (164 no. $100m^{-3}$). The oceanic station along 17.5°N transect showed remarkbale variation in abundance between day and night samples in the mixed layer (Fig. 19).

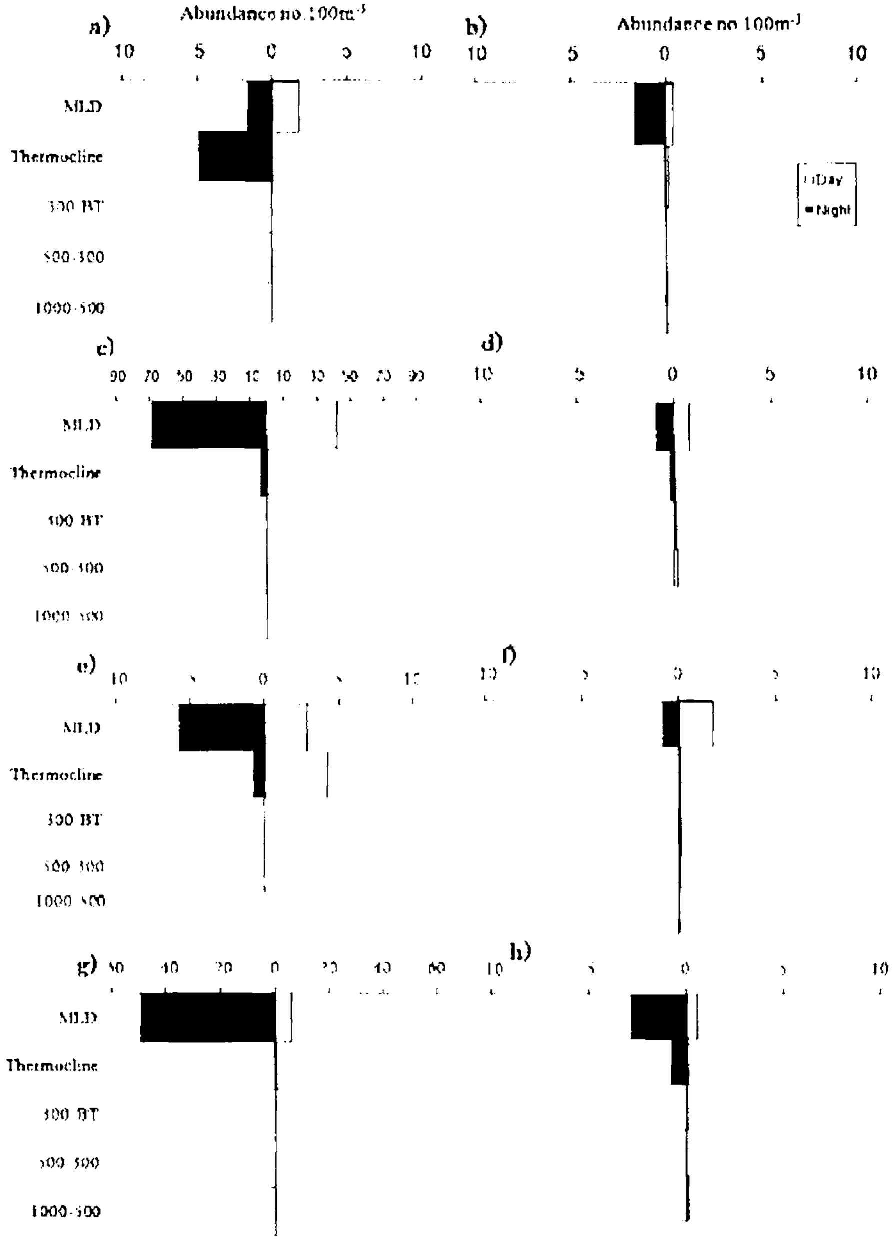

Fig. 19 Diurnal variability of abundance of planktonic decapods during summer monsoon in the coastal and oceanic stations along 11.5°N (a&b); 13.5°N (c&d); 15.5°N (e&f) and 17.5°N (g&h) transects (note: scales are not the same and the value are in hundreds).

On the basis of statistical analysis, the mean diversity of planktonic decapods during this season was 1.25 (Fisher's α), and other diversity indices are given in Table III. Variability between various diversity indices of planktonic decapods between mixed layer and thermocline layer was only marginal. The comparison of different diversity indices with layer during this season, was significant ($P<0.05$). Fisher's index is significantly higher and Shannon weiner's H' is significantly lower compared to all other indices. There is significant difference between layers also (Table IV).

Table III Diversity indices recorded during summer monsoon; d= Margalef's richness index, J' = Pilous evenness, α= Fisher's diversity, and H'= Shannon weiner's species diversity index.

	d	J'	α	H'
Average	0.976	0.785	1.25	0.579
SD	0.45	0.15	0.589	0.217

Table IV ANOVA table between different diversity indices on the sampling layers during summer monsoon.

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Sampling strata	6.709208	4	1.677302	1.57416	0.229171	3.006917
Diversity indices	18.61211	4	4.653028	4.366899	0.014122	3.006917
Error	17.04835	16	1.065522			
Total	42.36968	24				

The coastal and oceanic variability during this season was very prominent. The coastal and oceanic stations form two separate clusters but in low level similarity (Fig. 20). Coastal stations along 15.5 and 17.5°N transects clustered together with > 60% similarity.

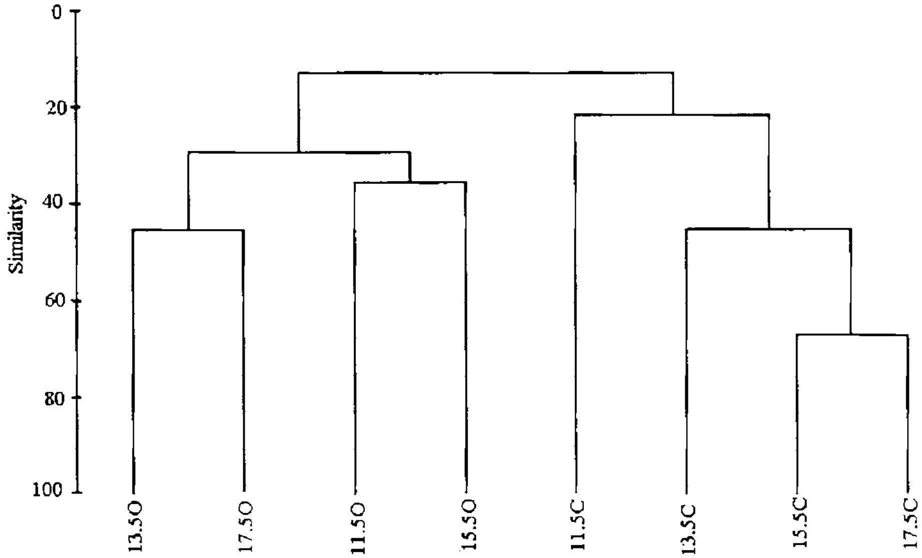

Fig. 20 Dendrogram for grouping the coastal (C) and oceanic (O) stations based on the qualitative abundance of decapods during summer monsoon.

Table V Composition of planktonic decapods identified during the Summer monsoon ('+'- <50; '++' - 50-100; '+++' - >100 no. 100m^{-3} and '-' - not present)

Name of species	Sampling Depth strata				
	MLD	Thermocline	300 m -BT	500-300 m	1000-500 m
Aristaeus alcockii	+	-	-	-	+
Notostomus sp.	-		-	-	+
Solenocera sp.	+		+	+	-
Solenocera sp. *(larvae)*	+ +		-	-	-
Gennadas sordidus	-		+	+	+
Gennadas clavicarpus	-	-	-	-	+
Gennadas sp.	+	+	+	+ +	+
Gennadas sp. *(Zoea &Mysis)*	+ + +	+	+	-	+
Sergestes sp. *(adult)*	+	+	+	+	+
Sergestes sp. *(Elaphocaris)*	+ +	+	-		-
Sergestes sp.(Acanthosoma)	+ + +	+	-		-
Acetes sp.	+	+	+	+	+
Acetes sp.*(acanthosoma)*	+ +	+	-	-	-
Lucifer hanseni	+ + +	+ + +	-	+	+
Lucifer typus	+ + +	+	-		-
Lucifer penicillifer	+ + +	+ + +		-	+
Lucifer faxoni	+ + +	+ + +	-	+	-
Lucifer chacei	+ + +	-	+	-	+
Lucifer intermedius	+ + +	+	-	-	-
Lucifer sp. (larval stages).	+ + +	+ + +		+	+

Table V Cont..................

Atypopenaeus stenodactylus	+			-	-
Penaeus sp.	+				-
P. monodon	+				-
Metapenaeus sp.	+	-			+
Metapenaeus dobsoni	-	+			-
M. affinis	+	+			-
M.monoceros	+ + +			-	-
Metapenaeopsis mogiensis				+	-
Metapenaeopsis andamanensis		+			-
Parapenaeus investigatoris	+	-			-
Penaeopsis sp.	+			-	-
Pelagopenaeus sp.	-	-	-	+	-
Acanthyphyra sp	+	+ +	+	+	-
Pasiphaea sp.	-	+ +	+		
Eupasiphaea sp.	-	+	-	-	-
Parapasipheae sp.	+	+		+	-
Leptochela robusta	+ + +			-	-
Leptochela robusta (zoea & Mysis)	+ + +	+ + +			-
Leptochela sp. *(mysis &z oea)*	+ + +	+ + +			
Alpheus sp.	+	-			-
Unidentified Alpheid.	+ + +	-			-
Thalassocaris lucida	+	+			-
Thalassocaris obsucura	+	+		-	-
Thalassocaris obsucura (Zoea & Mysis)	+ + +	+ + +		+	-
T. sp. *(Zoea & Mysis)*	+ + +	+ + +		+	-
Hippolysmata	+ + +	+		+	-
Crangonid sp.		+			-
Processa sp. (*edulis?*)	+				-
Palaemonid	-	+			-
Pontoninae	-	+			-
Periclimenes grandii	+ +	+			-
Mesocaris sp.	+	-			-
Crangon sp.	-	+			-
Pontocaris sp.	+ + +	-			-
Stenopus sp.	+	-			-
Axiids	+ +	+			-
Callianassa sp.	+ + +	+ +			-
Upogebia sp.	+	-			-
Galathea sp.	-	+			-
Porcellanid zoea	+ +	-			-
Pagurus zoea.	-	+ + +			-
Pagurid megalopa	+ +	+			-
Albunea sp.	+ + +				-
Hippa sp.	-	+			-
Clibanarius sp.	+ +	-	-		-
Crab zoea	+ + +	+	-	-	-
Crab megalopa	+ + +	+ + +	-	+	-

2.3 Fall Intermonsoon (FIM)

During fall intermonsoon the dispersal of planktonic decapods in the BoB was relatively higher compared to other seasons. Northern region sustained more abundance of decapods, which gradually decreased towards the south (Fig. 21). The maximum abundance (4,142 no. 100m^{-3}) was observed at 17°N;83°E, followed by 20.5°N;90°N (3,247 no. 100m^{-3}) in the mixed layer. Along 20.5°N transect, the abundance was >2,000 no. 100m^{-3} both in the mixed layer and thermocline layer. The variability in the abundance of planktonic decapod between the coastal and the oceanic waters along 17 and 19°N transects were comparatively low. Along the 15°N transect, thermocline layer sustained more number of planktonic decapods than the mixed layer with maximum (6,403 no. 100m^{-3}) in the coastal station.

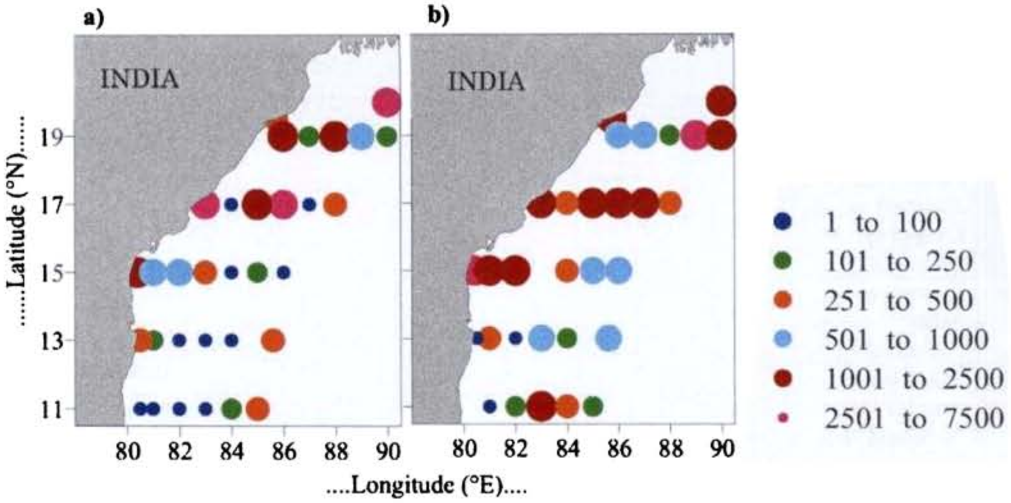

Fig. 21 Spatial distribution of planktonic decapods (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during fall intermonsoon

Along southern transects (11 and 13°N), the variability in the abundance of planktonic decapods between coastal and oceanic stations were low. Maximum abundance was observed in the coastal waters along 15 and 17°N transects. In other transects, the coastal population of planktonic decapods was sparsely distributed. The oceanic stations showed a gradual increase in the abundance towards north both in the mixed layer and thermocline layer and relatively more abundance in the thermocline layer (Fig. 22). Maximum abundance (3,330 no. 100m^{-3}) along the oceanic stations was recorded at 19°N;89°E in the thermocline layer.

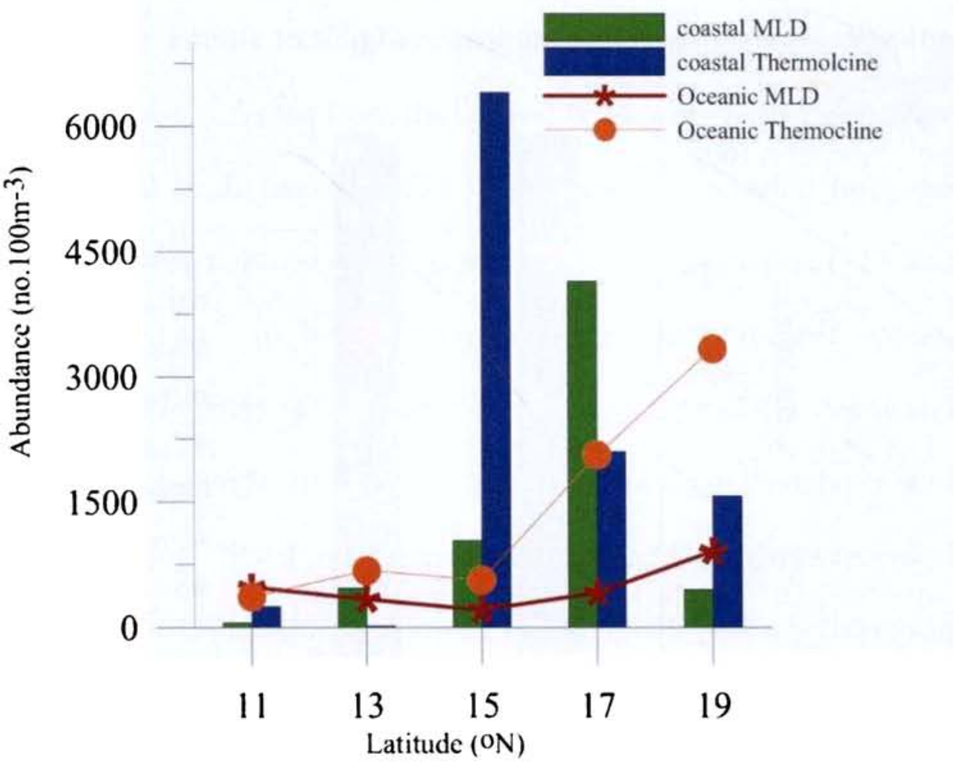

Fig. 22 Variability of abundance of planktonic decapods in the coastal (bar plot) and oceanic (line plot) stations during fall intermonsoon.

Among planktonic decapods, the relative abundance of various groups were more or less similar in the mixed layer and thermocline layer. The dominant component was Sergestoidea (79% and 67%) followed by Caridea both in the mixed layer and thermocline layer (12% and 15% respectively). The relative abundance of Penaeoidea in mixed layer was 2% and thermocline layer was 8%. The abundance of Brachyura were higher in the thermocline layer than mixed layer. Other components; Thalassinoidea, Anomura and Stenopidea were present only <1%, both in the mixed and thermocline layers (Fig. 23). Towards deeper waters the abundance was negligible or absent.

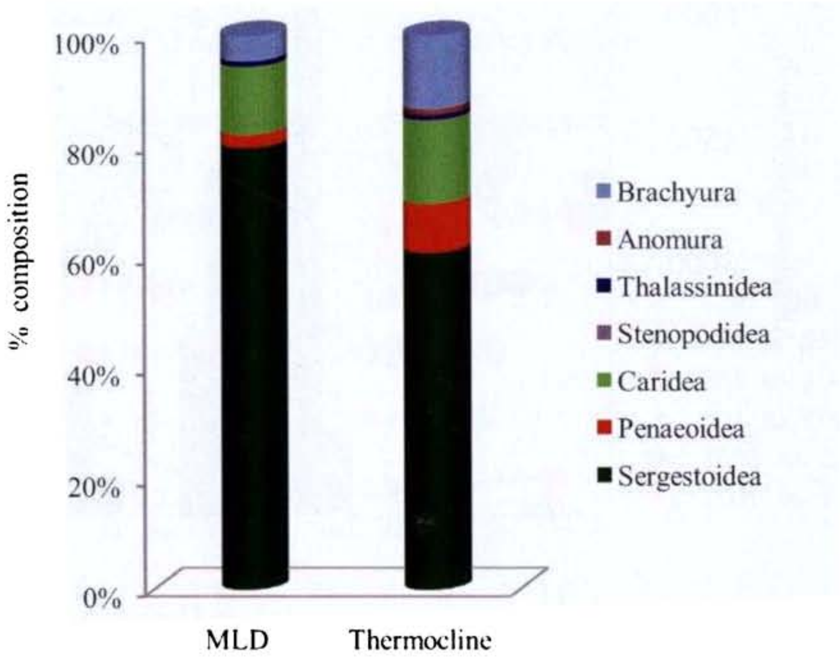

Fig. 23 Relative abundance of various groups of planktonic decapods in the mixed layer and thermocline layer during fall intermonsoon

Sergestids were sparsely distributed during this season, both in the mixed layer and thermocline layer (<30 no. $100m^{-3}$). Family Luciferidae was the major component under Sergestoidea and their abundance was concentrated more towards the northern transects (Fig. 24). The maximum abundance (1,681 no. $100m^{-3}$) of luciferids were reported from 19°N;89°E. Along 15°N transect, the coastal station sustained relatively more abundance (1,244 no. $100m^{-3}$) of luciferids as compared to the oceanic stations (160 no. $100m^{-3}$). Abundance in the thermocline layer was <50 no. $100m^{-3}$. Family luciferidae was represented by 7 species and the dominant species collected from the mixed layer were *Lucifer penicillifer* (33%) followed by *L. hanseni* (30%). Other species recorded from the mixed layer were *L. faxoni* (17%), *L. intermedius* (9%) *L. chacei* (7%) and *L. orientalis* (<1%). In the thermocline layer, the dominant species observed were *L. faxoni* (42%) followed by *L. penicillifer* (25%). Zoeal and mysis stages of *Lucifer* sp. were also present in the mixed layer and thermocline layer. Maximum abundance of *Lucifer* larvae was recorded at 13°N;83°E (584 no. $100m^{-3}$), followed by 15°N;82°E (442 no. $100m^{-3}$) in the mixed layer. Their occurrence was quite low in the thermocline layer (<30 no. $100m^{-3}$)

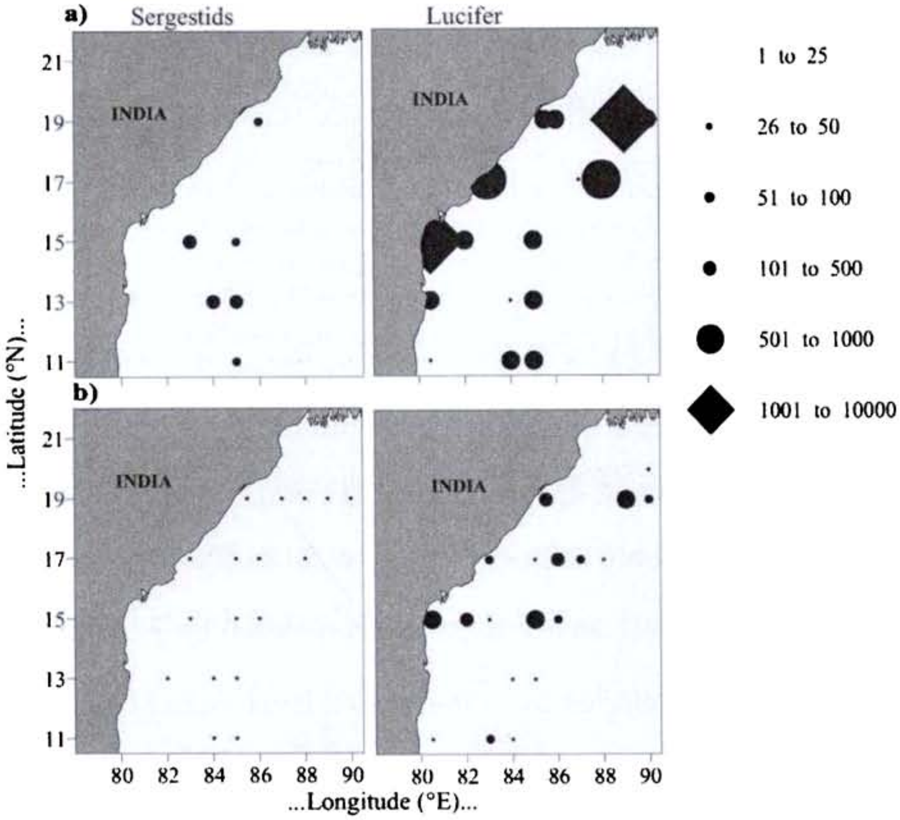

Fig. 24 Spatial distribution of Sergestids and *Lucifer* (no. $100m^{-3}$) in the a- mixed layer and b- thermocline layer during fall intermonsoon.

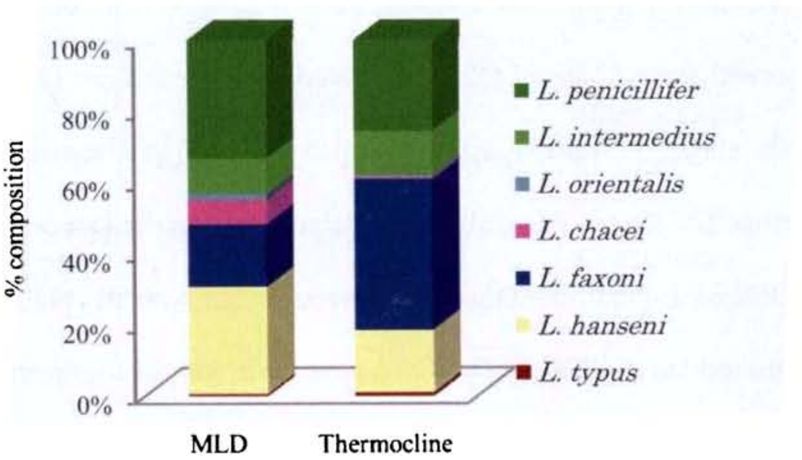

Fig. 25 Species composition of family Luciferidae in the mixed layer and thermocline layer during fall intermonsoon.

Penaeoideae contributed only 3% of the total planktonic decapod abundance and their distribution was scanty during this season. Benthesicymidae was recorded in the mixed layer at two stations and at 8 stations in thermocline and towards the deeper depths at few stations. The representatives under this family were the mysis stages of *Gennadas* sp. and adult specimens of *Gennadas sordidas* and *G.clavicarpus*. Larval stages were observed in the mixed layer (14 no. $100m^{-3}$, 17°N;85°E) and adult specimens in deeper strata. Maximum number (80 no. $100m^{-3}$) of adult specimens (*Gennadas* sp.) were recorded at 15°N;85°E station in the mixed layer. Family Penaeidae was poorly distributed in the mixed layer during this season. *Parapenaeus investigatoris* (44 no. $100m^{-3}$), *Parapenaeus* sp. (40 no. $100m^{-3}$) and *Atypopenaeus stenodacylus* (23 no. $100m^{-3}$) were observed in the mixed layer at 15°N;85°E, 19°N;86°E, and at 19°N;85.5°E respectively. In the thermocline, the density of Penaeidae was <10 no. $100m^{-3}$. The important species recorded in the thermocline layer were Mysis II of *Parapenaeus investigatoris* (7 no. $100m^{-3}$,19°N;87°E), post larvae of *Pelagopenaeus* sp. (6 no. $100m^{-3}$, 17°N;84°E) and post larva I *Metapenaeus barbata* (3 no. $100m^{-3}$, 11°N;80.5 °E). Towards the deeper waters the abundance of penaeids were <5 no. $100m^{-3}$.

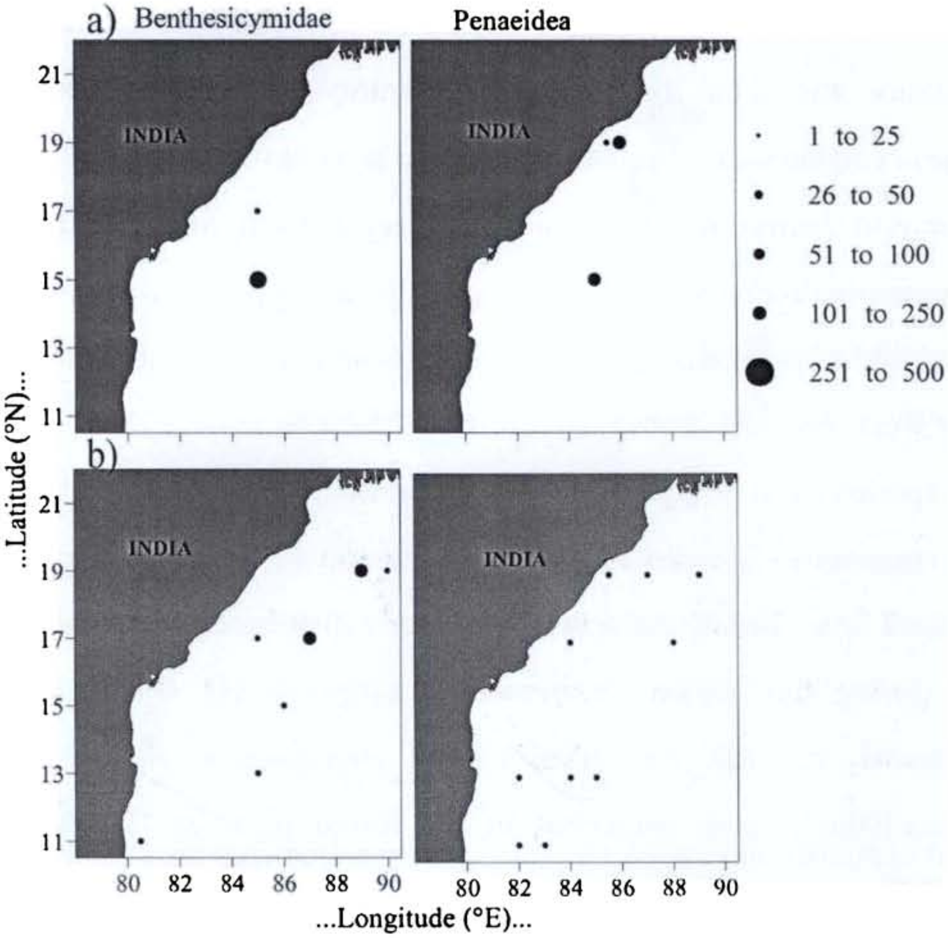

Fig. 26 Spatial distribution of Penaeoidea (no. 100m^{-3}) in the a- mixed layer and b- thermocline during fall intermonsoon.

Presence of Caridea during this season was relatively less compared to other seasons. The dominant family Thalassocaridae was encountered only at few stations with maximum abundance (450 no. 100m^{-3}) at 17°N;88° where the major component was zoea of *Thalassocaris* sp. (Fig. 27). *Thalassocaris crinata* (44 no. 100m^{-3}) and *T. lucida* (29 no. 100m^{-3}) were present in the mixed layer at two stations at

15°N;85°E and 13°N;85°E respectively. Mysis of *Periclimenes* sp. under the family Plalaemonidae (25 no. 100m^{-3}) was present at 11°N;83°E. Other important species reported under this family was *Periclimenes grandii* (25 no. 100m^{-3}) and unidentified Palemonid spp. (44 no. 100m^{-3}). Relatively higher abundance of *Hippolysmata* sp. (250 no. 100m^{-3}) and *Pasiphaea* sp. (164 no. 100m^{-3}) were present at 15°N;88°E and 19°N;85.5°E respectively.

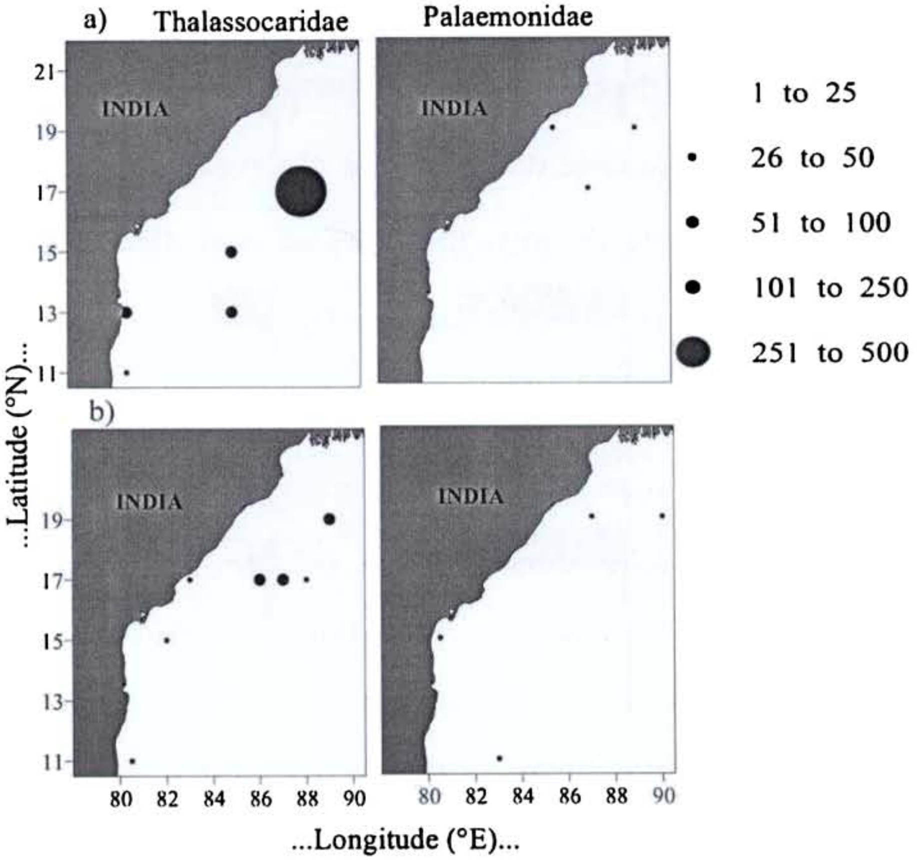

Fig. 27 Spatial distribution of Thalassocaridae and Palaemonidae (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during fall intermonsoon.

Thalassinidea, Anomura and Brachyura together contributed 5% of the total planktonic decapoda during this season. Brachyuran zoeae and megalopae were the dominant forms under the Brachyura and *Axius* sp. (Family Axidae) under Thalassinidea. Maximum abundance of Brachyura (100 no. 100m^{-3}) was observed at 11°N;84°E. Other groups were relatively less in abundance.

The diurnal variation during FIM was very prominent in the oceanic stations than in the coastal stations especially northern transects. The abundance of planktonic decapods was observed more in night hauls. Along 17 and 19°N, the night hauls yielded more decapods than day in the mixed layer at the oceanic stations (Fig. 28).

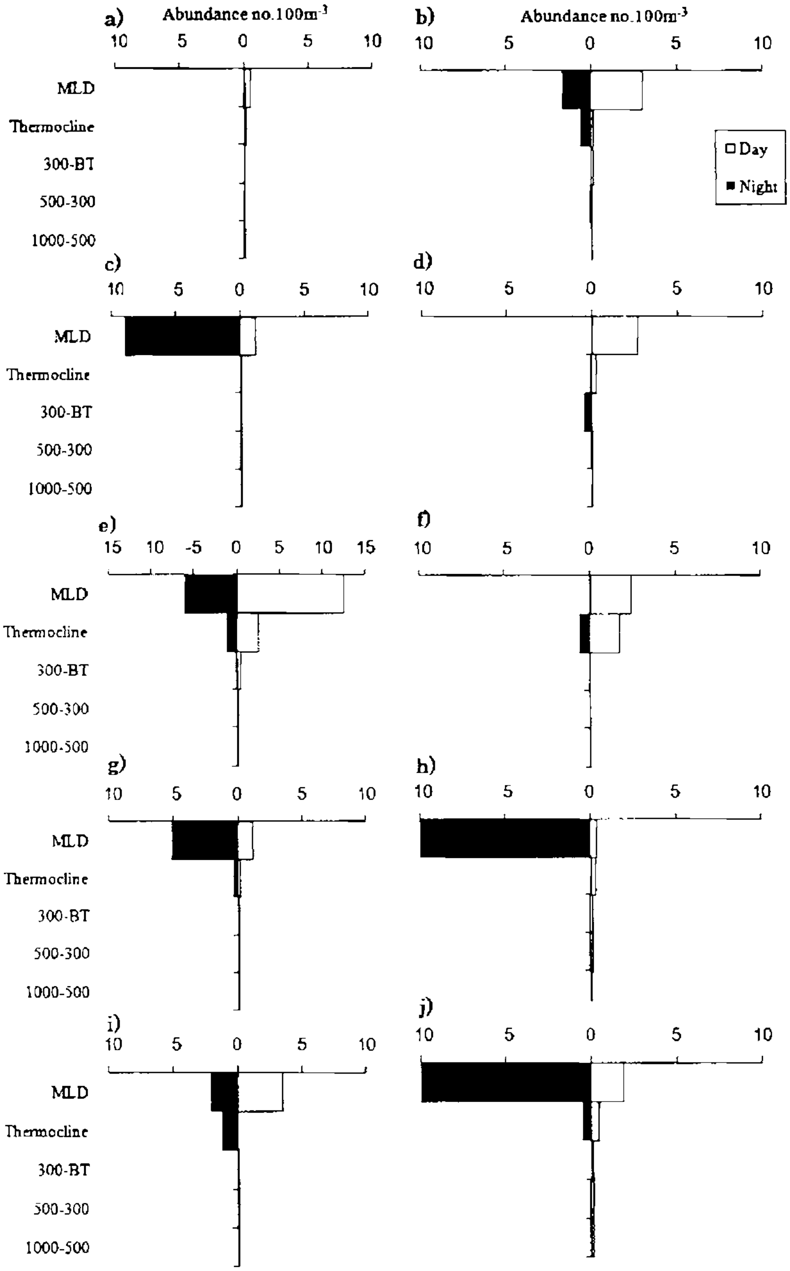

Fig. 28 Diurnal variation of abundance of planktonic decapods during fall intermonsoon in the coastal and oceanic station along 11°N (a&b); 13°N (c&d); 15°N (e&f) ; 17°N (g&h) and 19°N (i&j) transects (note: scales are not the same and the value are in hundreds).

The diversity of planktonic decapods in the thermocline layer was relatively greater than in other layers (Table VI). There is a significant difference in the in the abundance of planktonic decapods between depth strata and various diversity indices ($P<0.01$) (Table VI). Thermocline has significantly high diversity indices compared to other layers. Significant difference was observed between diversity indices ($P<0.01$). Fisher's diversity index (α) is significantly higher than all other indices

Table VI Diversity indices recorded during fall intermonsoon in the different sampling strata; d= Margalef's richness index, J' = Pilous evenness, α= Fisher's diversity, H'= Shannon weiner's species diversity index.

Sampling strata	**d**	**J'**	**Fisher's α**	**H'(log10)**
Mixed layer	0.420	0.700	0.571	0.383
Thermocline	0.869	0.895	1.371	0.475
300 m-BT	0.316	0.442	0.911	0.352
500 m-300 m	0.316	0.442	0.911	0.153
1000 m-500 m	0.549	0.342	0.981	0.161

Table VII ANOVA table between different diversity indices on the sampling layers during fall intermonsoon.

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F critic***
Strata	0.624	4	0.156	7.427	0.001397	3.006917
Diversity index	1.277	4	0.319	15.205	2.6E-05	3.006917
Error	0.336	16	0.021			
Total	2.237	24				

The analysis of variability in the qualitative abundance of planktonic decapods between the coastal and oceanic stations by cluster analysis is shown in Fig. 29. The southern transects formed separate cluster but with low level similarity.

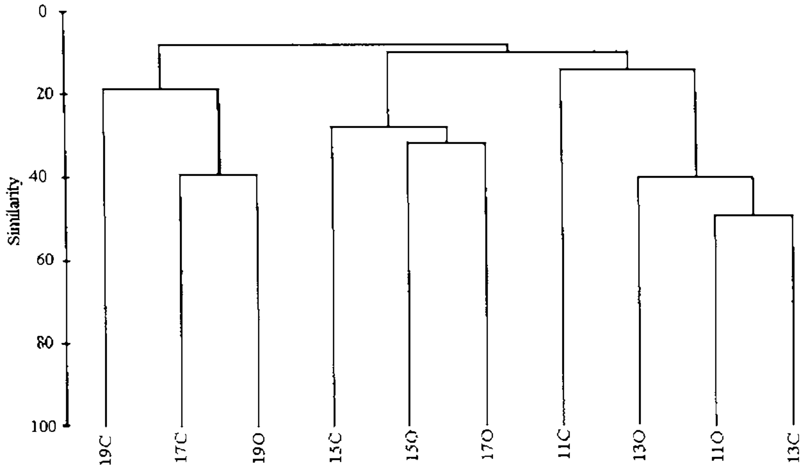

Fig. 29 Dendrogram for grouping the coastal (C) and oceanic (O) stations based on the qualitative abundance of decapods during fall intermonsoon.

Table VIII Composition of planktonic decapods identified during the fall intermonsoon ('+' - <50; '++' - 50-100; '+++' - >100 no. 100m^{-3} and '-' - not present.

Name of the species	**Sampling Depth strata**				
	MLD	**Thermocline**	**300 m-BT**	**500-300 m**	**1000-500 m**
Solenocera sp. *(larvae)*	+	+ +	-	+	+
Gennadas clavicarpus	-	-		+	-
Gennadas sp.	+ +	+	+	-	+
Gennadas sp. *(Zoea &Mysis)*	+	+ +	+	+	+
Sergestes sp. *(adult)*	-	+	+		+
Sergestes sp. *(Elaphocaris)*	+ +	+	-		-
Sergestes sp. *(Acanthosoma)*	+ + +	+ +	+		-
Sergestes sp. *(Mastigopus)*	+ + +	+	-	-	+
Acetes sp.	+	+	+	+	-
Acetes sp. (Acanthosoma)	+ +	+	-	+	-
Lucifer typus	+	+	-	+	+
L. hanseni	+ + +	+ + +	+		+
L. faxoni	+ + +	+ + +	+		+
L. chacei	+ + +	+			-

Table VIII Cont................

L. orientalis	+ + +	+	-	+	-
L. intermedius	+ + +	+ + +	+	-	-
L. penicillifer	+ + +	+ + +	+		+
Lucifer sp. (larval stages)	+ + +	+ + +	-		-
Funchalia balboae	-	-	+		-
Funchalia	-	-	+		+
Atypopenaeus stenodactylus	+		+		-
Penaeus sp.	-		-		+
Metapenaeus sp.			+		-
Metapenaeopsis barbata	-	+			-
Parapenaeus investigatoris	+	+		-	-
Parapenaeus sp.	+	-		-	-
Penaeopsis sp.	-			+	-
Penaeid protozoeae		+	-		-
Pelagopenaeus sp.		+	+		+
Acanthyphyra sp.		+	-		+
Pasiphaea sp.	+ +	+ +	+		+
Pasiphaea longitaenia	-	+	+		-
Leptochela robusta		+		-	..
Leptochela robusta (zoea & Mysis)		+		+	-
Alpheus sp.	+	+			-
Synalpheus sp.	+				-
Athanas sp. *(dimorphus?)*	+				-
Thalassocaris lucida	+	+			-
Thalassocaris lucida (Zoea & Mysis)	-	+			-
Thalassocaris obscura	-	+			-
Thalassocaris crinata	+	+			-
T. sp (Zoea & Mysis)	+ + +	+	-		-
Procletes biangulatus	-	-	+		-
*P.*sp.	-	-	-	+	
Hippolysmata	+ + +	-	+		-
Processa sp. (edulis)	-	+	-	-	-
Palaemonid	+	+	-	+	-
Periclimenes grandii	+	-	+	-	-
P. sp.	+	+	-	-	-
Stenopus sp.	-	+	-		-
Axiids	+ + +	-	-		-
Axius sp.	-	+	+		-
Callianassa sp.		+	+		-
Upogebia sp.			+	-	-
Pagurid megalopa		-	+	-	-
Hippa sp.		+	-	+	-
Clibanarius sp.	-	-	-	+	-
Crab zoea	+ + +	+ + +	+	-	-
Crab megalopa	+ + +	+ + +	+	-	-
Stomatopoda	+ +	+	+	+	-

2.4 Winter Monsoon (WM)

Variability in the abundance of planktonic decapoda in the mixed layer and thermocline layer during this season was more prominent. The abundance in the mixed layer was relatively more than in the thermocline layer, with more concentration towards the southern region. The maximum number (8581 no. 100m^{-3}) of planktonic decapods was recorded in the mixed layer at 11°N;83°E, followed by 17°N;83.5E (1920 no. 100m^{-3}). Towards the northern transect (19 and 20.5°N), the dispersal was scanty (<300 no. 100m^{-3} in the mixed layer and thermocline). Along the 19°N transect, the maximum abundance was observed at the coastal station (384 no. 100m^{-3}). In the thermocline layer, the abundance was <300 no. 100m^{-3}, both along the northern and southern transects (Fig. 30). The higher number of specimens (284 no. 100m^{-3}) in the thermocline layer observed at 15°N;80.5°E followed by 19°N;85°E (274 no. 100m^{-3}). Towards the deeper levels, planktonic decapod abundance was very low.

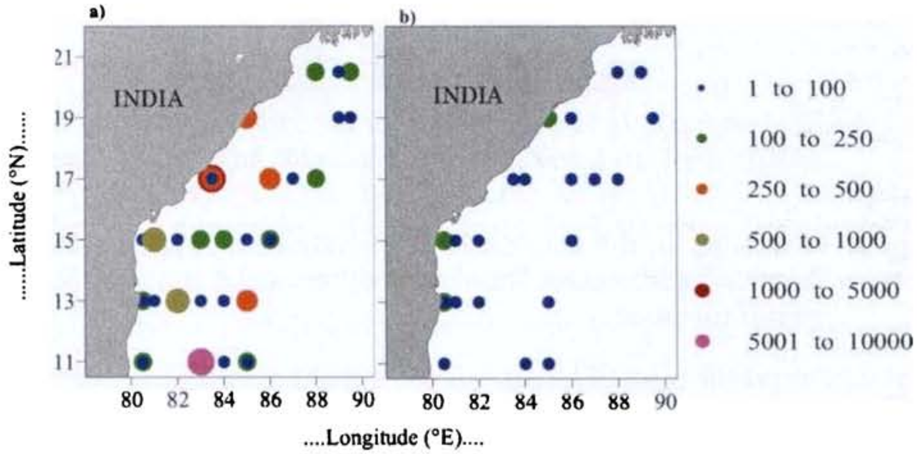

Fig. 30 Spatial distribution of planktonic decapods (no. 100m^{-3}) in the a- mixed layer and b- thermocline layer during winter monsoon.

The variability in the abundance of planktonic decapod between coastal and oceanic stations during this season was negligible. The abundance recorded in the mixed layer and thermocline layer was <300 no. 100m^{-3}, except at two stations (Fig.31). Maximum abundance at the coastal stations (1,920 no. 100m^{-3}) was recorded along 17°N transect and at oceanic station along 11°N transect (8,581 no. 100m^{-3}).

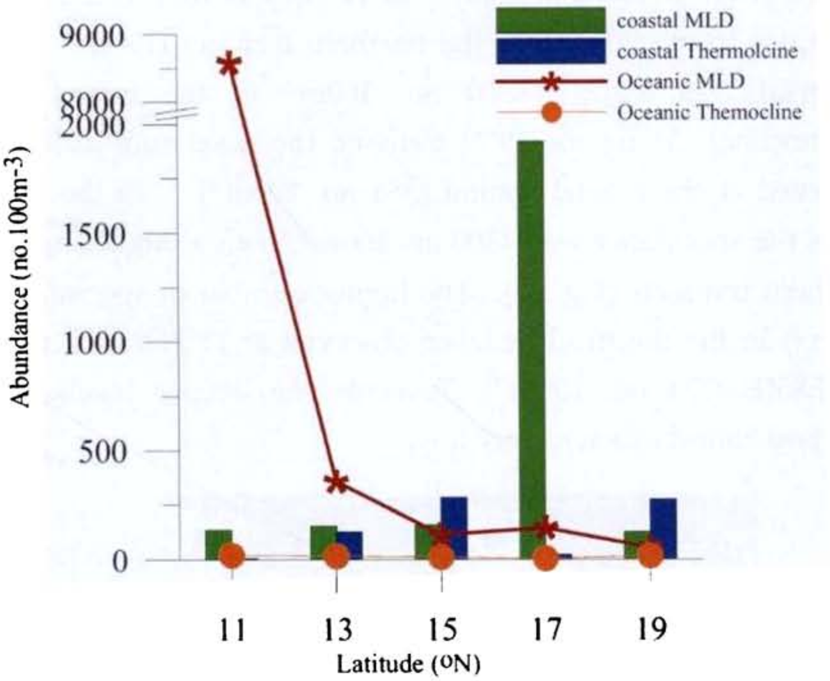

Fig. 31 Variability in the abundance of planktonic decapods in the coastal (bar plot) and oceanic (line plot) regions along the transects during winter monsoon.

Composition of decapods in the plankton samples did not show much variation between the mixed layer and thermocline layer. Sergestoidea was the dominating group in both the layers (58% in the mixed layer and 63% in the thermocline layer). The next abundant group was Caridea that contributed 17% in the mixed layer and 65% in the thermocline layer. Penaeoidea, Thalassinidea, and Brachyura contributed

11, 7 and 4% respectively in the mixed layer. In the thermocline layer, the percentage contribution of Penaeidae was 4% and Brachyura was 5% (Fig. 32).

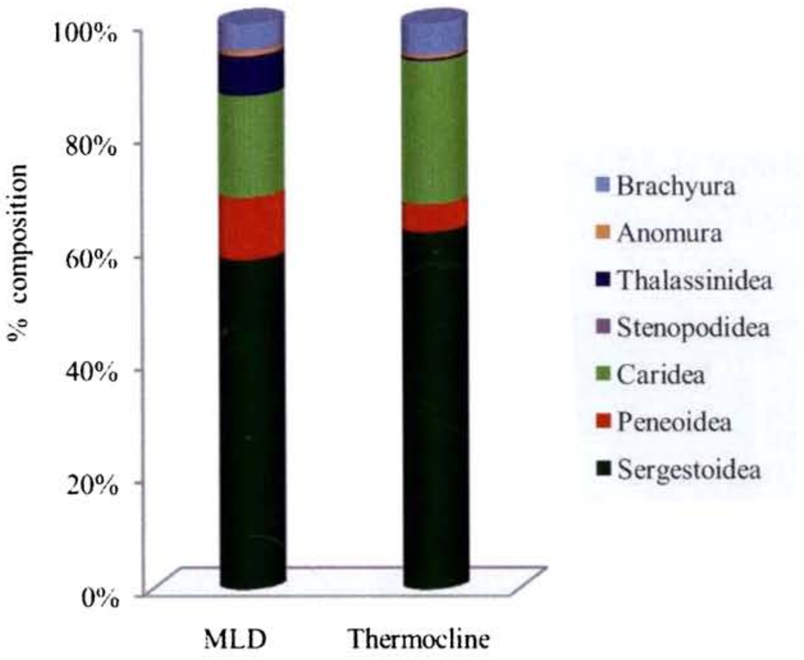

Fig. 32 Relative abundance of various groups of planktonic decapods in the mixed layer and thermocline layer during winter monsoon.

Under Sergestoidea, the dominant families were Sergestidae and Luciferidae. Sergestidae represented larval stages (*Elaphocaris, Acanthosoma and Mastigopus*) and adult specimens of *Sergestes* sp. The highest number of Sergestoidea observed was from the mixed layer at 11°N;83°E (*Sergestes* sp. : 36 no. $100m^{-3}$; *Acanthosoma* stage : 409 no. $100m^{-3}$; *Mastigopus* stage : 109 no. $100m^{-3}$). Maximum abundance (483 no. $100m^{-3}$) of Elaphocaris stage was recorded at 17°N;87°E in the mixed layer. In thermocline layer, the sergestids were sparsely recorded (<25 no. $100m^{-3}$). Dispersal of Luciferidae in the mixed layer was relatively more than the thermocline layer. The highest abundance of Luciferidae in the mixed layer (1681 no. 100m^{-3}) and thermocline layer (198 no. 100m^{-3}) was observed at 19°N;89°N (Fig. 33). The dominant species under family Luciferidae was *Lucifer faxoni* in the mixed layer (40%) and thermocline layer (39%). The second dominant species was *L. typus* (39%) in the mixed layer and *L. hanseni* (35%) in the thermocline layer. *L. chacei* was not recorded during this season (Fig. 34). The percentage composition of other species in the mixed layer was *L. hanseni* (5%), *L. orientalis* (9%) and *L. intermedius and L. penicillifer* (3% each).

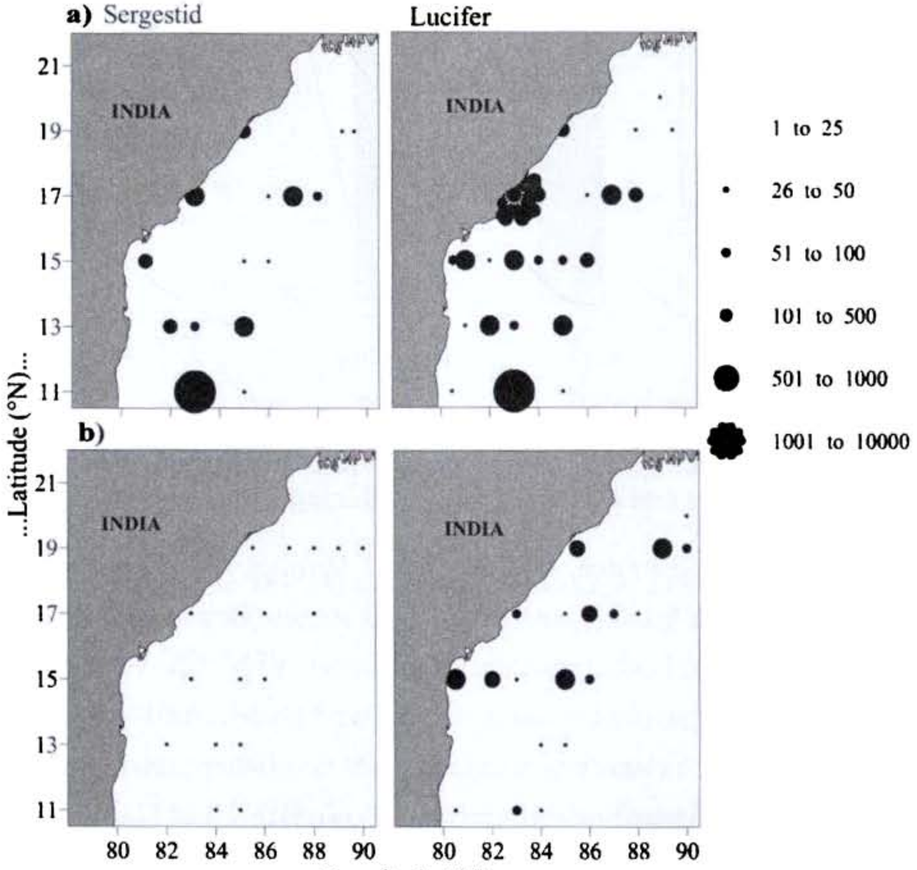

Fig. 33 Spatial distribution of Sergestids and Luciferidae in the a- mixed layer and b- thermocline layer during winter monsoon.

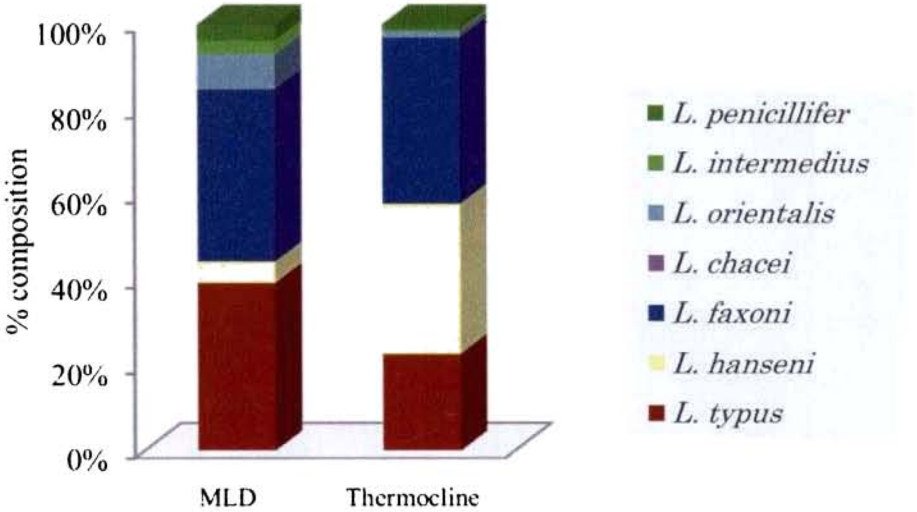

Fig. 34 Species composition of Family Luciferidae in the mixed layer and thermocline layer during winter monsoon.

Distribution of Penaeoidea during winter monsoon was very scanty (Fig. 35). Members of family Solenoceridae and Penaeidae were present along the coastal stations and Benthesicymidae along the oceanic stations in the mixed layer. The maximum abundance (64 no. 100m^{-3}) of Solenoceridae was recorded at 19°N;85°E and was represented by protozoeae of *Solenocera* sp. Family Benthesicymidae was represented by the mysis stage of *Gennadas* sp. (60 no. 100m-3) at 17°N;87°E and adult specimens of *Gennadas sordidas* (32 no. 100m^{-3}) at 19°N;85°E in the mixed layer. In the thermocline layer, the number of organisms were <25 no. 100m^{-3}. Family Penaeidae were reported from two stations in the mixed layer with a maximum number of 73 no. 100m^{-3} recorded at the coastal stations along 17°N transect. Mysis stages of *Parapenaeus investigatoris* were the major component of Penaeidae at both the stations.

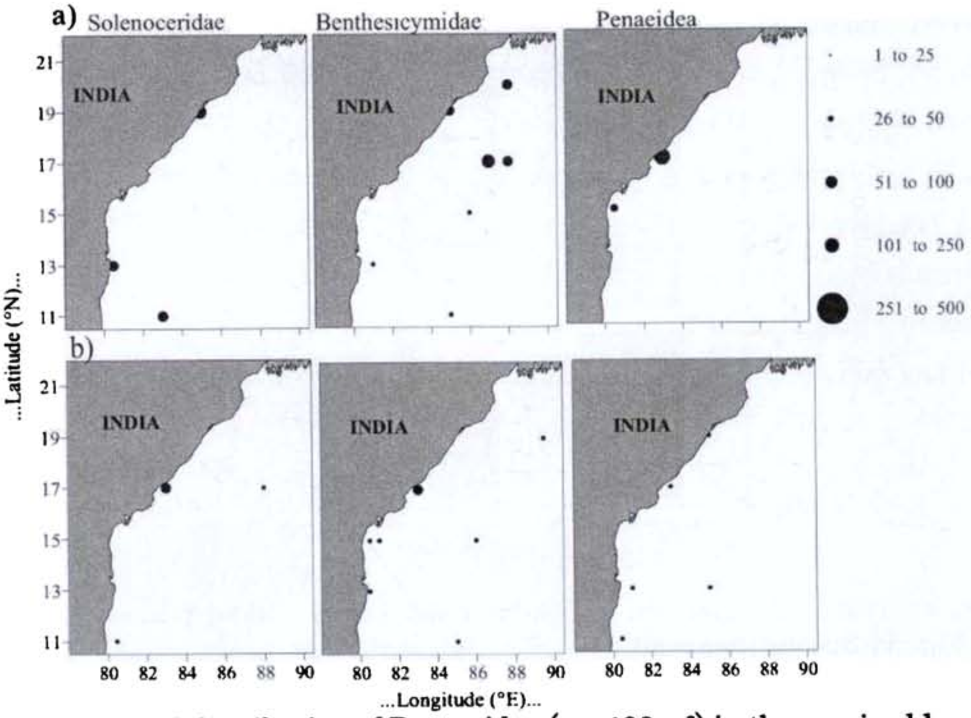

Fig. 35 Spatial distribution of Penaeoidea (no. 100m^{-3}) in the a- mixed layer b- thermocline layer during winter monsoon.

Thalassocaridae was the dominant family under caridea with maximum abundance (1,163 no. 100m^{-3}) observed at 11°N;82°E. Larvae of (zoea and mysis) *Thalassocaris* sp. were common in caridean samples (Fig. 36). Larval stages of *Thalassocaris* sp., *T. obscura,* and adults of *T.* sp., *T. obcura* and *T. cirnata* were observed in the mixed layer during this season. The highest number larvae (345 no. 100m^{-3}) of *T. obscura* was noticed at 13°N;85°E. Other genus encountered during this period under caridea were *Acanthephyra* sp., *Hippplysmata* sp., *Periclimenes* sp., *Pontocaris* sp. *etc.* in the mixed layer.

Brachyuran larvae were found in large numbers towards the coastal region during this season (<400 no. 100m^{-3}). The maximum number of Brachyura (160 no. 100m^{-3}) was recorded at the coastal station (81°E) along 15°N transect in the mixed layer (Fig. 37). In thermocline strata, the concentration was <50 no. 100m-3. Anomura, Thalassinoidea were represented < 60 no. 100m-3 from very few stations.

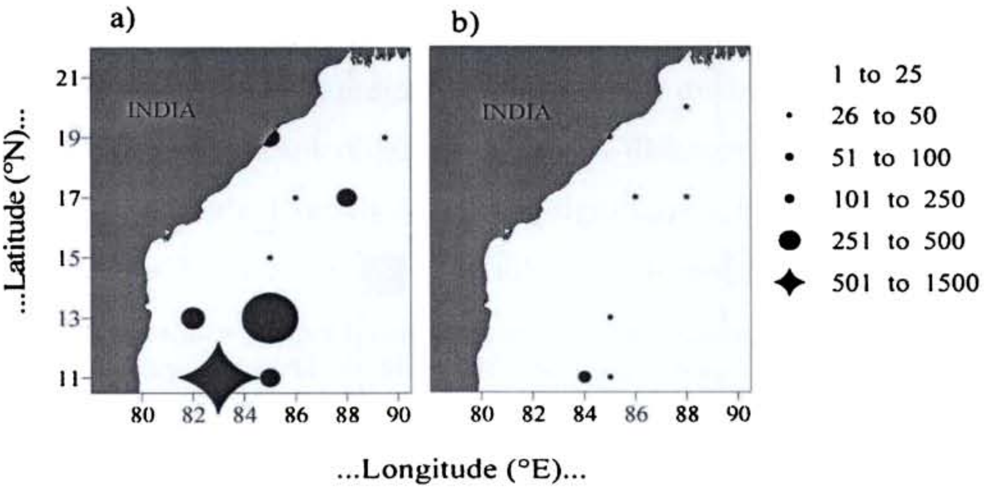

Fig. 36 Spatial distribution of Thalassocaridae (no. $100m^{-3}$) in the mixed layer and thermocline layer during winter monsoon.

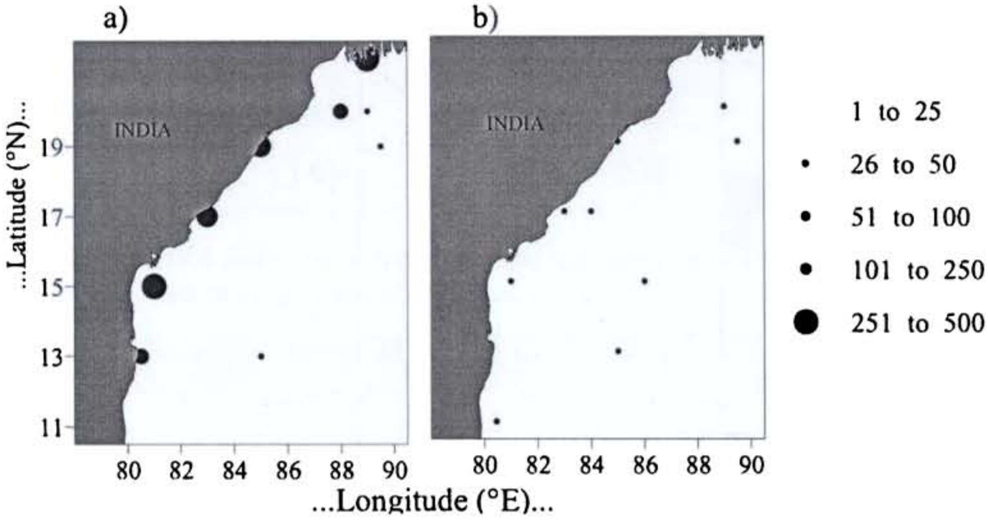

Fig. 37 Spatial distribution of Brachyura (no. $100m^{-3}$) in the a- mixed layer and b- thermocline layer during winter intermonsoon.

Diurnal variability during this season was not prominent. Coastal stations of 17 and 19°N and oceanic station of 11, 13 and 15°N transects sustained a relatively greater abundance during the night time in the mixed layer (Fig. 38).

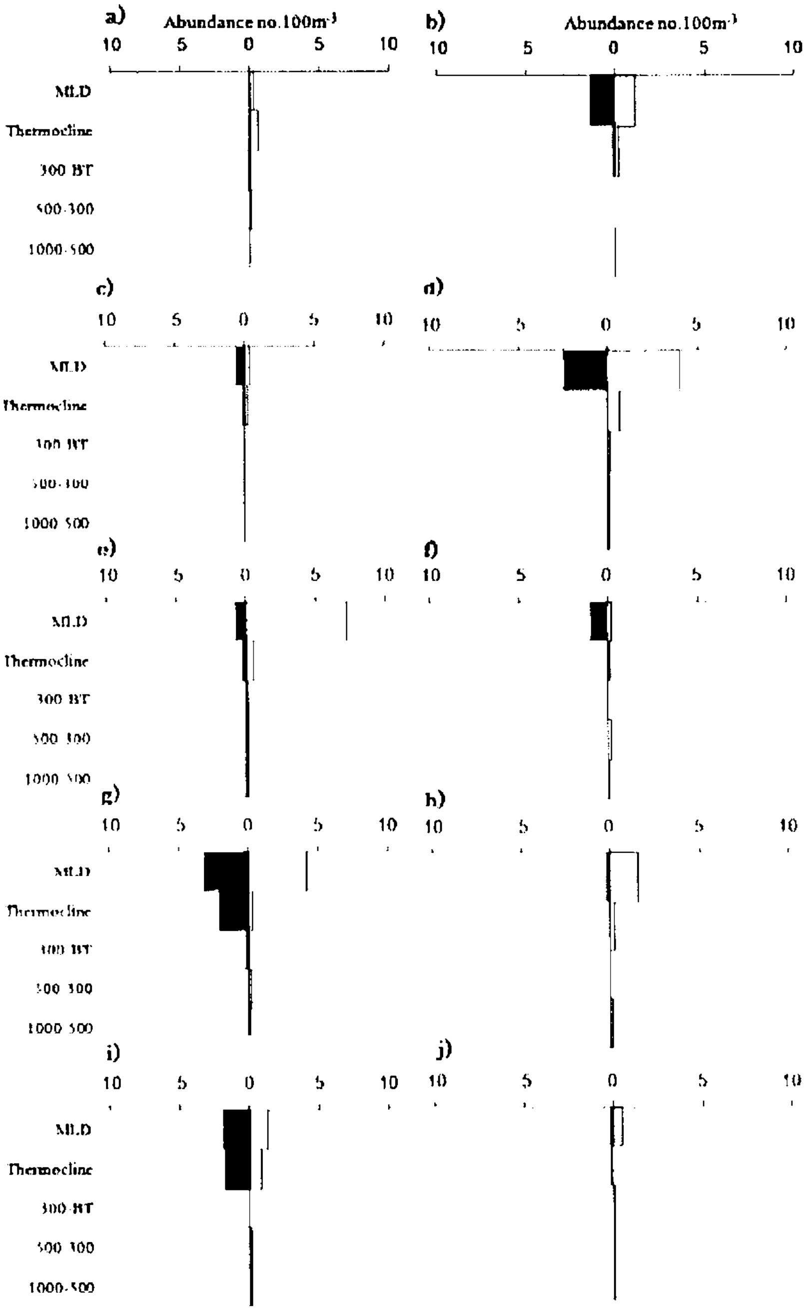

Fig. 38 Diurnal variability in the abundance of planktonic decapods during winter monsoon in the coastal and oceanic station along 11°N (a&b); 13°N (c&d); 15°N (e&f); 17°N (g&h) and 19°N (i&j) transects (note: values are in hundreds).

The diversity indices in the different depth strata showed that the values in the thermocline layer was relatively more than in the other layers (Table IX), but the variations were not significant. The comparison of diversity indices between layers during winter showed that there is significant difference between different diversity indices (P< 0.001). Fisher's diversity index was significantly higher than all the other indices. There is no significant difference between layers (Table X)

Table IX Diversity indices recorded during winter monsoon in the different sampling strata; d= Margalef's richness index, J' = Pilous evenness, α= Fisher's diversity, H'= Shannon weiner's species diversity index

sampling strata	**d**	**J'**	**α**	**H'(log10)**
Mixed layer	0.420	0.684	0.622	0.343
Thermocline	0.669	0.751	1.136	0.381
300-BT	0.601	0.750	1.047	0.330
500-300	0.375	0.469	0.992	0.185
1000-500	1.089	0.639	2.147	0.192

Table X ANOVA table between different diversity indices on the sampling layers during winter monsoon.

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Depth strata	0.62415	4	0.156038	7.427925	0.001397	3.006917
Diversity index	1.277665	4	0.319416	15.20531	2.6E-05	3.006917
Error	0.33611	16	0.021007			
Total	2.237926	24				

The cluster analysis based on the qualitative abundance of planktonic decapods between the coastal and oceanic stations showed that the oceanic stations along northern regions clustered together but the similarity was <60% (Fig. 39)

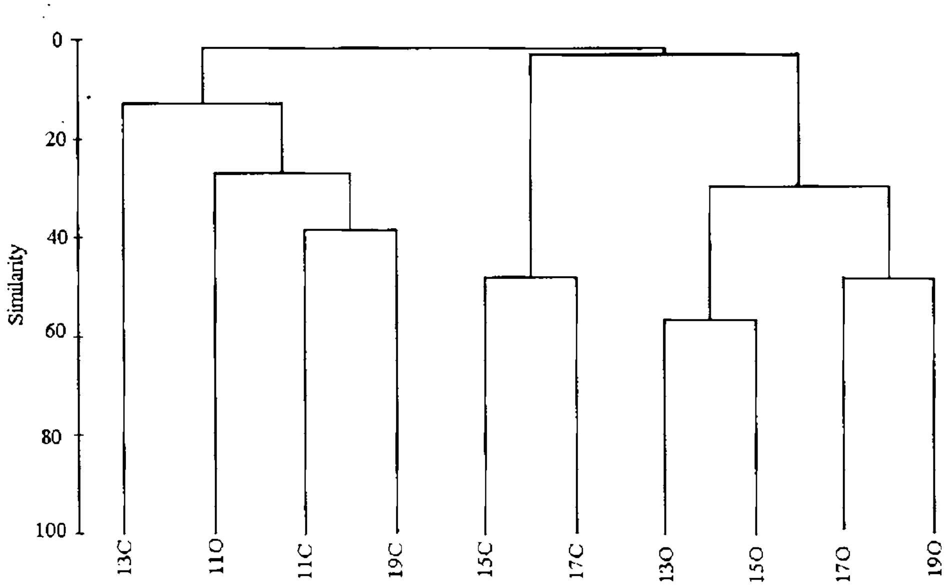

Fig. 39 Dendrogram for grouping the coastal (C) and oceanic (O) stations based on the qualitative abundance of decapods during winter monsoon.

Table XI Composition of planktonic decapods identified during the winter monsoon ('+'- <50 ; '++' - 50-100; '+++' - >100 no.100m^{-3} and '-' - not present.

	Sampling Depth strata				
Name of the species	MLD	Thermocline	300 m-BT	500-300 m	1000-500 m
Solenocera sp.	-	+	-	-	-
Solenocera sp.	+++	+		+	-
Gennadas sordidas	+	+	+	+	+
Gennadas clavicarpus				+	-
Gennadas sp.	+	+	+	++	+
Gennadas sp. (Zoea &Mysis)	+++	+	+	+	+
Sergestes sp. (adult)	+++	++	+	+	+
Sergestes sp. (*Elaphocaris*)	+++	+		+	-

Table XI Conti...........

Sergestes sp. *(Acanthosoma)*	+++	+		+	+
Sergestes sp. *(Mastigopus)*	+++	+++	+	+	
Acetes sp.	++			+	-
Lucifer typus	+++	+++		+	+
Lucifer hanseni	+++	+++	+	-	-
Lucifer faxoni	+++	+++	+	+	-
Lucifer orientalis	+++	+			-
Lucifer intermedius	+++	+			-
Lucifer penicillifer	+++	+			-
Lucifer sp. *(larval stages).*	+++	+	+	+	-
Funchalia balboae					-
Atypopenaeus stenodactylus	++				-
Penaeus monodon		+		+	-
Metapenaeus sp. (Mysis)		+			-
Parapenaeus investigatoris	+++	+	+		
Oplophorus sp.	++				-
Acanthyphyra sp.	+	+			-
Pasiphaea sp.		+		+	-
Pasiphaea longitaenia			+		+
Eupasiphaea sp.					+
Leptochela robusta		+			-
Heterocarpus sp.					+
Alpheus sp.	+	+			-
Synalpheus sp.	+	+	+		-
Athanas sp. *(dimorphus?)*		+			-
Thalassocaris lucida	+				-
Thalassocaris obscura	+++	+	+		-

Table XI Conti...........

Thalassocaris obscura (Zoea & Mysis)	+++	+	-	+	-
Thalassocaris crinata	+++	+		+	-
T. sp. (Zoea & Mysis)	+++		+	-	-
Hippolysmata	+	-	-	-	-
Exhippolysmata sp.	+		-	-	-
Processa sp. *(edulis?)*		+		-	-
Palaemonid	++	+		-	+
Pontoninae	+		-	-	-
P. sp.	+	+		-	-
Crangon sp.	-				-
Axius sp.	+	+		-	-
Callianassa sp.	+	+		-	-
Pagurid megalopa		+	+		-
Albunea sp.	++			-	-
Crab zoea	+++	+	-	-	+
Crab megalopa	+++	++	+	+	+

A comparison of the seasonal abundance of various components of planktonic decapods showed that the Sergestoidea was the major taxa during all the seasons. The maximum abundance was noticed during the summer monsoon followed by fall intermonsoon, winter monsoon and spring intermonsooon. The second important taxon was Caridea during all seasons, except spring intermonsoon when the second dominant group was Brachyura in the mixed layer. In the thermocline layer, Sergestoidea dominated during winter monsoon and fall intermonsoon whereas Caridea and Brachyura outnumbered Sergestoidea during summer and spring intermonsoon respectively (Fig. 40)

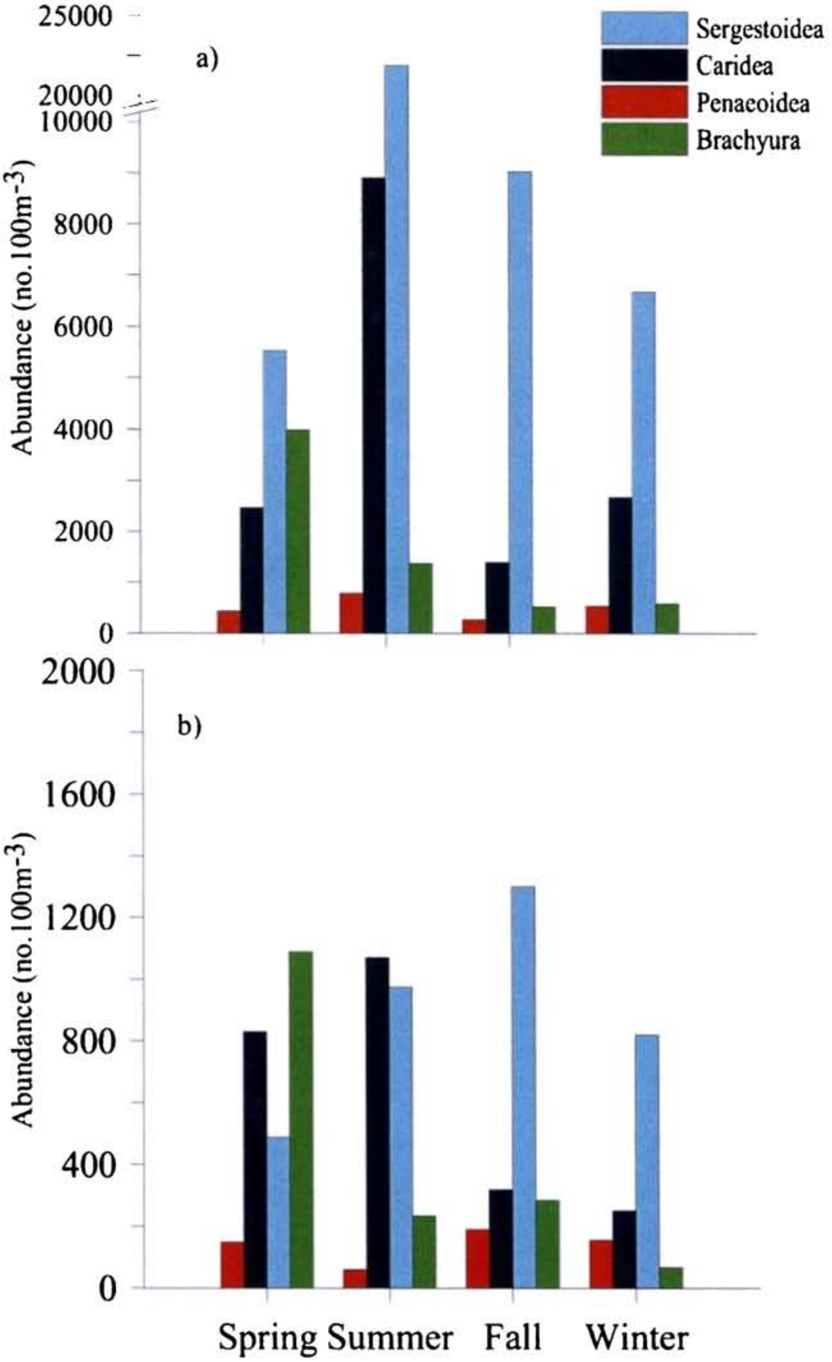

Fig. 40 Abundance of planktonic decapods in the a- mixed layer and b- thermocline layer during different seasons.

The dominance plot is used for comparing diversity between seasons. Steep curves lying over the others, showed that the diversity of planktonic decapods during summer monsoon was quite different from other seasons. All other seasons have sigma-shaped curves with more or less similar condition.

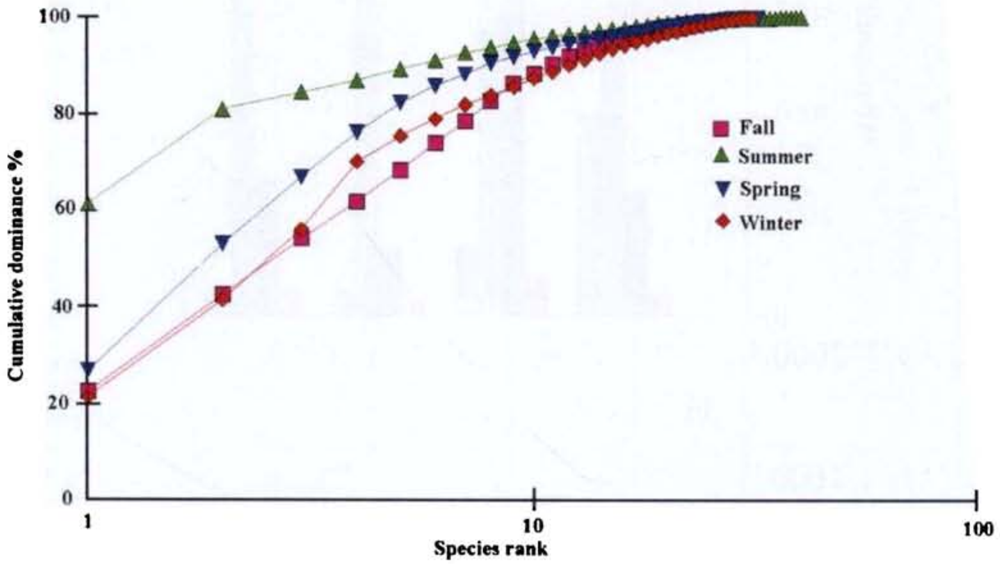

Fig. 41 Dominance plot showing the diversity of planktonic decapods during different season.

The diversity parameters indicate that Fisher's α scored high values during summer monsoon when the Margalef's richness index and Pilou's evenness index were with more or less same value. The richness index was minimum during the spring intermonsoon period (Fig. 42).

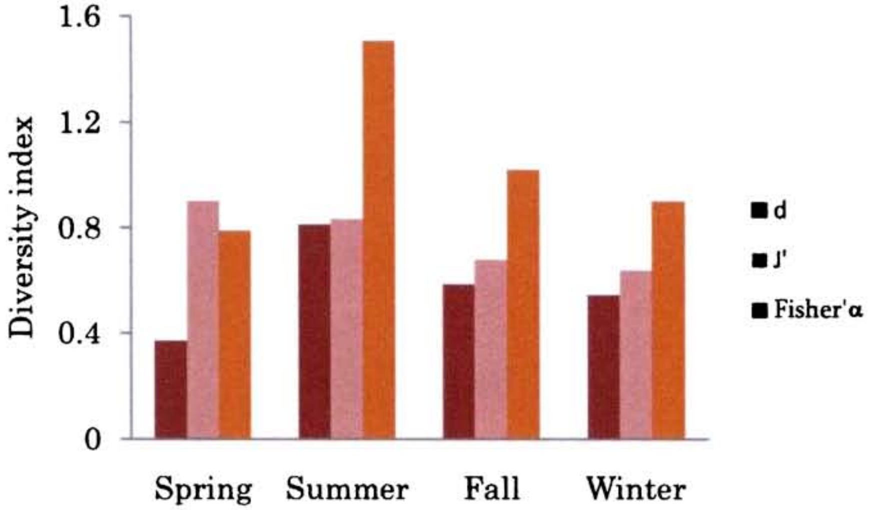

Fig. 42 Variability of diversity indices during different season

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Chapter 3

DISCUSSION

Spatio-temporal variations of qualitative and quantitative abundance of planktonic decapoda in the Bay of Bengal is very prominent. On quantitative assessment, the planktonic decapods showed maximum abundance during summer monsoon followed by the fall intermonsoon, winter monsoon and spring intermonsoon. During summer monsoon, they have a wider distribution and high density especially towards the southern coastal region. According to Paulinose (1979b), spawning of some of the commercially important species of decapods takes place all along the Indian coast during summer. The increased spawning activity results in the release of a large quantity of larval population to the coastal waters. The larval forms together with the holoplanktonic group (Luciferidae) support the high density of planktonic decapods along the coastal waters during SM. Coastal station along 13°N transect was characterised with signatures of upwelling which enhances the biological production through nutrient input from the subsurface waters. The zooplankton population including the planktonic decapods get attracted towards the upwelling region and form aggregations. Paulinose (1979b) reported the affinity of decapod larvae to the upwelling region. But this was found to be antagonistic to the findings of Panikkar and Rao (1973); in their opinion, the decapod larvae come late in the sequence of production commencing from phytoplankton, and they would therefore get located at places away from the actual upwelling areas. The effectiveness of upwelling in larval transport, however, depends on the position of larvae in the water column, a position that is governed mainly by turbulent mixing and larval behaviour, i.e. vertical migration (Blanton *et al.*, 1995). During FIM (October) and WM (November to February) the abundance was comparatively lower than in SM. According to Menon and Paulinose (1973), during the period from October to November the BoB sustains less density of planktonic decapods. They postulate that during June to October, BoB appears to be very calm and it supports more larval forms in the zooplankton and subsequent reduction in the winter due to high turbulence. During WM, the waters around the southern peninsula had a good representation of decapod larvae, whereas most of the east coast of India, mainly north of Madras, had low concentration (Paulinose, 1979a). The total abundance of planktonic decapoda during SIM was relatively low, and whatever available was concentrated towards the southern region. Spring is a period of increased solar radiation and surface heating. This season is generally considered low-productive oligotrophic period, especially, towards the southern transects. According to Jyothibabu *et al.*, (2006), BoB experiences strong oligotrophic condition during SIM. 'Microbial food web loop' is more active during this period. The small phytoplankton cells available are grazed by the ciliates, and it becomes the prey for other zooplankton and thus enters into the classical food chain. The increased abundance of planktonic decapods could be related to this condition. Gowswami (1983) reported high incidence of decapods in the zooplankton samples during abnormally high SST. Qualitative analysis of the samples reveals that the dominant taxon was Luciferidae, which is a holoplanktonic form; it can sustain in the warm waters.

Fall intermonsoon was characterised by the prevalence of low saline surface water along the northern region due to the persistent river discharge right through the SM. The nutrient-rich water might support the phytoplankton production and thus in turn support the abundance of zooplankton population. Coastal stations especially to the north of 15°N transect, experienced low saline surface water due to the river discharge. This increased nutrient flux sometimes possibly enhance the phytoplankton standing stock, either in the surface waters or subsurface waters, rather than strong stratification. The high density to planktonic decapods may be associated either with the food availability or with the transportations through water currents. Certain larval forms were found to adhere to the continental shelf area associated with the river run off. In some cases, the low saline water makes an estuarine situation which is more preferable for certain decapods for their breeding and feeding.

The coastal waters of northern and middle transects during SM and WM were characterised by relatively higher density of decapods than oceanic waters. The coastal waters of India are known to be comparatively rich in decapod larvae. From IIOE samples, Menon and Paulinose (1973) observed that midcentral region of southeast coast and coastal waters of Gangetic delta have fairly high abundance of planktonic decapods, especially larval forms.

Besides upwelling, various other physical processes were identified during the course of the present study period. The response of planktonic decapods to physical processes was quite interesting. During spring intermonsoon, summer monsoon and fall intermonsoon, cyclonic eddies were observed at the oceanic stations, along 19°N, 17.5°N and 19°N transects respectively. The detailed hydrographical features which prevailed in the corresponding transect is given in Part 1, Chapter 3. According to PrasannaKumar *et al.*, (2004a), cold core eddies are seasonal phenomena in the BoB and are identified as a mechanism of nutrient injection in the oceanic waters and associated high biological production. During winter monsoon, along 13°N transects at 82°E, a cyclonic gyre was observed. As in an eddy, cold gyre also enhances the biological production through the circular movement of the current which brings the nutrient rich subsurface water to the photic zone. In the regions where these physical processes were active, the number of planktonic decapods remained relatively large. The aggregation of decapods in these regions may be because of two reasons: firstly, the increased phytoplankton due to the nutrient enrichment might enhance the zooplankton population, including planktonic decapoda for forage; secondly, it may be due to the retention of planktonic form, especially the larval forms of decapoda by their increased buoyancy. According to Mc William and Philips (1983); Griffiths and Brandt (1983), eddies and gyres play an important role in the oceanic circulation, which can influence distribution as well as retention of larvae of mesopelagic crustaceans.

Marked diurnal variation was observed with increased abundance of decapods at night time during summer monsoon and spring intermonsoon, compared to other seasons, especially along the coastal stations. During summer, 17°N transect experienced freshwater discharge and the 13 and 15°N transects showed signatures of upwelling along the coastal waters. This particular environmental condition during the summer monsoon may attract the planktonic decapod population towards surface waters during night time for feeding. High zooplankton biomass and high decapod density at night were also observed by Nair *et al.,* (1977). Generally, zooplankton collections in the BoB and adjacent areas are rich in decapod larvae during night (Paulinose 1979b). During winter, along the southern transects, less abundance of planktonic decapods was observed and hence no pronounced diurnal variation.

Regarding the relative abundance, the samples were dominated by members of Sergestoidea followed by Caridea and Brachyura. The seasonal variation in the abundance of Sergestoidea showed that, during summer monsoon, the number increased enormously followed by fall intermonsoon, winter monsoon and spring intermonsoon. Sergestidae and Luciferidae are the two families which contributed mainly to the abundance of Sergestoidea along the basin. Luciferidae, the holoplanktonic epipelagic shrimp family, with its larvae and adults contributed appreciably to a large percentage of mesozooplankton along the coastal waters around India. Genus Lucifer is successful and widely distributed in the tropical and subtropical waters (Hashizume and Omori, 1998; Naomi *et al.*, 2006). Their distribution is patchy in nature in the Indian waters, more towards the coastal belt, however, their percentage contribution and species composition may vary according to the seasonal pattern. According to Rajagopalan *et al.*, (1992), *Lucifer* was abundant in the plankton throughout the year exhibiting peak dominance during the southwest monsoon and immediate post-monsoon months. This is supported with the present result of increased abundance during the summer monsoon (May to September) followed by fall intermonsoon (October). Towards the oceanic region, the abundance was decreasing irrespective of seasons, except in some stations along 19°N transect. Of the total population of Luciferid shrimp in the Indian waters around 12% are from the area between 100 to 200m and 8% from the oceanic waters beyond 200m (Naomi *et al.*, 2006). Antony *et al.*, (1989) depicted the distribution pattern of *Lucifer* spp. in the Arabian Sea and Bay of Bengal and found that the coastal regions of BoB were richer in abundance >10,000 no1000m^{-3}. Patterns of seasonal variation in spatial distribution of lucifers were prominent during the study period. The maximum abundance of lucifers was noticed along the coastal stations irrespective of seasons. During summer and winter monsoon, the coastal as well as oceanic stations of northern region were found to experience low saline, cold waters due to the fresh water influx which resulted in enhanced phytoplankton production. This may be the reason for the increased abundance of lucifers in the region. As compared to the other groups of planktonic decapods, *lucifer* enjoy the whole of their life as plankton, and thus they may have a wide range of tolerance of various environmental conditions, compared to the other meroplanktonic forms. Recent research conducted in the East China Sea, suggests that species like *Lucifer hanseni* and *Lucifer intermedius* are useful indicators for the effect of long term climate change on aquatic ecosystems (Ma Z *et al.*, 2009)

Family Sergestidae are often represented with the larval stages of *Sergestes* sp and *Acetes* sp. Sergestids are major component in the micornekton community, which constitutes an important link between the zooplankton and higher trophic levels in the pelagic ecosystem. Their larval stages were very common in the zooplankton samples all the year round. George (1968) reported that year-round breeding of certain species of decapoda suggest the fair presence of meroplankton throughout the year. According to Achuthankutty and Selvakumar (1979) *Acetes* shrimps are very common in Indian waters along the coastal region and inshore areas (Achuthankutty *et al.*, 1973) within the continental shelf. Along the north western coast of India *Acetes indicus* appear in big shoals in the inshore and coastal waters almost throughout the year and contribute about 20% of the estimated annual crustacean landings. The seasonal distribution of the larvae showed that they occur abundantly during October to January Pillai (1973). The percentage contribution of *Acetes* was quite lower than of the *Sergestes* species in the present study. This may be due to the present samplings which are mostly beyond 50m of the continental shelf area or, in other words, the larval stages of *Acetes* may not get transported to the oceanic regions because mostly they prefer the more productive coastal waters. The increased abundance of Sergestid larval forms, especially, *Acanthosoma* and *Mastigopus* (later stages) in the offshore area of the continental shelf may be because of their aggregation and transportation of the larval population to the area of parent population. *Elaphocaris* (early stages) were concentrated more towards the coastal region, which might be due to the proximity of the parental populations for breeding purpose. The occurrence of adult Sergestid shrimp in the zooplankton sample quite often might be related with its feeding habits. Sergestids are zooplankton feeders and their food includes copepods, chaetognaths, ostracods, molluscs, euphausiids, detritus and organic debris.

Caridea was the second dominant taxon after Sergestoidea during all seasons except spring intermonsoon. The increased abundance of decapods in the plankton samples was due to the highest abundance of Caridea along the southern region. The supporting species were *Thalassocaris* sp., *T. obscura* (larval stages; zoea and mysis). Gopalamenon and Williamson (1971) described the distribution of *Thalassocaris* in the Indian Ocean and found that the *T. Lucida* is more abundant in the vast stretches of the BoB. While the coastal species *T. crinata* is more restricted towards the eastern part of the BoB. Zoea and mysis stages of *T.obscura* were found to contribute equally along with the larval stages of *T.* sp. at the 15, 13 and 11°N transects. Earlier studies (Gopalamenon and Williamson, 1971) reported smaller number of *T. obscura* and their larval stages from the BoB. Other species of Caridea were rarely distributed in the study region.

Among Penaeoidea, the dominant families present during the course of this study period were Solenoceridae, Benthesicymidae and Penaeidae. But in all the seasons studied, the concentrations of larvae of penaeoids were comparatively lower than the larvae of Sergestoidea and Caridea. Family Solenoceridae which was present during summer and winter monsoon months had very low density (<10 no $100m^{-3}$) and during intermonsoon months their density was very thin or nil. Though, the members of the family Solenoceridae support the commercial fishery along the coast, the breeding and larval development of this species is still unknown. Similarly members of the family Solenoceridae, Benthesicymidae and Penaeidae also had only scattered distribution at a few stations, mostly of the mysis stage. The adults of *Gennadas sp* under the Benthesicymidae and mysis and postlarval stages of *Metapenaeus affinis, Metapenaeus barbata, Atypopenaeus, Trachypenaeopsis, Penaeopsis rectacuta, Parapenaeopsis invetigaoris* etc under family Penaeidae were often noticed. Larvae were more concentrated in the upper water column (MLD) and the adult animals in the lower strata. Karuppasaamy *et al.,* (2006) observed the presence of pelagic shrimps of the genus *Gennadas* from the deep scattering layer of Eastern Arabian Sea. The abundance of mysis stages of *Gennadas* sp. was more during summer monsoon than in the other seasons. However, it is possible to make an inference regarding the presence of more of mysis stages during summer monsoon which might be due to the coincidence of breeding habits during this season and migration of post larval and juvenile stages to the oceanic waters carried by prevailing currents. Low number of larval forms in the samples especially of family Penaeidae, may be due to the sampling, mostly beyond 50m depth. Inshore species of family Penaeidae are known to spawn in the areas of lesser depths (<50m) and deep water species spawn mostly in deeper waters. In the case of commercially important penaeids, the larval forms perform shoreward movement and there are no reports of coast to coast movement or one region to another. Therefore, the occurrence of larvae would reasonably indicate the presence of a spawning population of adults in the neighbourhood areas (Paulinose and George, 1976). Paulinose and George (1976) had made an attempt to correlate the occurrences and abundance of penaeid larvae with its fishery in the Arabian Sea and BoB, and found that a maximum number of larval forms were obtained from the BoB, with two outstanding areas: 1) along the coast off Madras, and 2) off the Nicobar islands. According to their observation, the Indian Ocean region was very poorly represented with the species of deep water and oceanic penaeids. Information on the oceanic species penaeids in the Indian waters is very meagre and hence wide scope for future research is open.

Presence of brachyuran larvae in the planktonic samples was quite frequent during the study period, with maximum abundance during the spring intermonsoon and falls intermonsoon. Generally, during spring intermonsoon the concentration was more towards the coastal stations of southern transects.

From an observation made during these studies covering over a wide area, it is clear that the distribution patterns of planktonic decapods vary considerably with seasons. The hydrographic features play a vital role in the occurrence and abundance of decapod larvae in the plankton community. Incidence of several seasonal features, such as river water influx, localized coastal upwelling, eddies (either warm core or cold core) *etc.* would affect directly or indirectly in distribution and abundance of planktonic decapods. In general, the Bay of Bengal was found to be more productive in summer season and holds high decapod density, than in winter. More intensive studies may be planned so as to assess and validate the quantitative and qualitative diversity of planktonic community, especially the commercially important species of decapod larvae and allied groups, with a view to formulating an index of commercial fishery potential and its maximum sustainable exploitation.

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SUMMARY AND CONCLUSION

Zooplankton, the secondary producers in marine environment, is the connecting link between the primary and tertiary trophic levels. It transfers the energy produced by unicellular organisms to next higher trophic level, such as pelagic fish stock, and hence acts as a controlling factor for the year class strength of a large number of fish stocks. Apart from this, zooplankton grazing determines the composition and amount of vertical particle flux. The efficiency of mesozooplankton to convert and transfer the energy to successive trophic levels, ultimately determines the biomass of primary and tertiary production. Thus, the assessment and study of secondary producers provides a valuable tool to assess the status of fish production and estimation of exploitable resources.

Understanding the ecological and biological features of the EEZ will provide baseline information for the effective management and sustainable development of marine resources of the country. The Indian EEZ has an area of 2.02 million km^2 including the island ecosystems. The Arabian Sea and Bay of Bengal basins are separated by the Indian peninsula and at the north are bounded by the Asian continent. The Bay of Bengal is considered as an oligotrophic basin and supports less than half of the biological production compared to the Arabian Sea. The enormous fresh water runoff to the BoB, particularly during the monsoon months, dilutes the marine to a semi estuarine condition. According to the marine fish landing statistics for the year 2006-2007, the east coast contributed 35% of the total marine landings of the country (CMFRI, 2008). Hence a proper understanding of the BoB, especially the seasonal variability and associated biological production is important for the future prospective. The present study deals with the biological production and associated hydrography of Bay of Bengal, with special emphasis on mesozooplankton and planktonic decapods.

This thesis is organised in two parts. Part 1 deals with the secondary production and associated hydrography of the Bay of Bengal. Influence of semi annual wind reversal on the circulation and hydrography of Bay of Bengal is pronounced during the period of this study. During Spring Intermonsoon (SIM), the variations of hydrographical features between northern and southern regions were found to be prominent. Along the northern region, the surface waters were characterised with relatively low SST (25.7°C), SSS (29.7) and shallow MLD (~8 m), which indicates the presence of river discharge into the region. While, the southern regions were relatively more salty (33.9) and warm (29.7°C) waters with deep MLD (~90 m). This spatial heterogeneity in the hydrography was reflected in the biological parameters. The distribution of chlorophyll *a* (av. 0.19 ± 0.11 mg m^{-3}) concentration and mesozooplankton (av. 0.3. ± 049 ml m^{-3}) biovolume during this season was relatively lower than other three seasons. Southern and central regions sustained low volumes of mesozooplankton standing stock compared to the northern region. The diurnal variability in the mesozooplankton standing stock was not prominent, except along the oceanic station of the 17°N transect. Moreover, because the sampling was done during the early months of SIM, the transition from WM to SIM could be traced out. The influence of fresh water influx during the active winter may presumably persist up to the early months of SIM, which gradually spreads cool, less saline water to the south and central BoB and finally makes the region more stratified during the months of April - May. Relatively high surface chl. *a* values along the northern regions may be linked with the availability of nutrient rich water, through riverine influx. The increased column chl. *a* concentration, especially in the coastal waters of 15 and 17°N transect may be due to the subsurface chlorophyll maxima observed at 50m. The prevalence of salinity stratification in the upper water column might be a supporting feature for the subsurface increase of phytoplankton standing stock (chl. *a*). In the present study the abundance of microzooplankton community was relatively lower during SIM, compared to other seasons. This may be either the enhanced production due to some localized features along the northern regions (fresh water discharge, eddy circulation), or the transition between the more productive winter to the oligotrophic spring. The low volume of mesozooplankton standing stock during this season may similarly be due to the strong stratification which prevents the nutrient injection to the surface and resulting low biological production. From these observations, it is possible to suggest that SIM is a settling phase after the strong winter monsoonal activities of winds and currents which churn up the entire bay.

Summer monsoon is the period of maximum fresh water influx from the perennial rivers to the BoB. During this season, along the coastal waters especially on southern transects (11.5, 13.5 and 15.5°N), coastal upwelling was noticed which resulted in the spreading of relatively high saline (33.9), cold (27.5°C), and less oxygenated ($<198\ \mu M\ l^{-1}$) waters. This supports relatively higher chl. *a* concentration ($0.15\ mg\ m^{-3}$), mesozooplankton standing stock ($2.7\ ml\ m^{-3}$) and abundance ($5{,}559\ no.\ m^{-3}$) in the region. Dominance of fish eggs in the mesozooplankton composition at the upwelling stations indirectly supports high phytoplankton production. Spawning activities of many fishes are associated with the seasonal phenomenon like upwelling, which provides a favourable environment to gravid females for feeding and breeding; the availability of small phytoplankton cells which form the food for the first feeding larval stages may also enhance the survival rate.

Along 17.5°N, the upheaval of temperature and salinity contours from the subsurface to the surface, indicates the presence of a cold core eddy, with its core at 84°E. This station sustained relatively higher biovolume of mesozooplankton than other stations along the transect. Diurnal variability of mesozooplankton standing stock was more prominent along the coastal stations when compared to oceanic stations.

Coastal processes like upwelling can moreover effectively augment the biological production due to the expansion of classical food chain than the oceanic processes like eddy.

Fall intermonsoon, the transitional period between the two monsoon (summer and winter) seasons, is characterized by the interim heating of the basin resulting in high SST (>28°C). A marked variation in the hydrography between the northern and southern region was observed during the study. In the northern transects, large amount of fresh water (<30.3) were found as compared to the southern regions. Chlorophyll *a* concentration and the mesozooplankton standing stock (biovolume) showed an increasing trend towards the north. The average chl. *a* concentration during this season was >0.2 mg m^{-3}, with relatively higher values in the coastal region. This may be due to the availability of nutrients either as a result of weak upwelling during the season or the remains of strong upwelling experienced during the preceded summer monsoon. The peak of river discharge in the Bay is seasonal and is more evident during the latter half of the summer monsoon. Higher abundance of microzooplankton was observed along 11°N, in both coastal and oceanic stations. Coastal station along 17°N sustained relatively more mesozooplankton biovolume (2.4 ml m^{-3}) and abundance during this season. Diurnal variability in the mesozooplankton biovolume was remarkable in the coastal stations compared to the oceanic stations. This may be due to the availability of preferred food in the subsurface layers during day and grazing of phytoplankton cells in the surface waters during night. Dominance of chaetognaths and copelates among the non copepod members in the MLD meanwhile reflects the presence of small prey organisms for active predators like chaetognatha and filter feeders like copelates.

During winter monsoon, when cold weather prevailed over the entire Bay, the northern region (20.5 and 19°N) was relatively cooler (25.2°C) and with less salinity (31.5) in the surface waters, indicates the presence of freshwater influx. Along 20.5°N transect, signatures of thermal inversion was observed in the subsurface waters. The average SST and SSS during this season was 26.6 ± 0.54°C and 32.8 ± 1.05 respectively. Unlike the northern region, southern areas contained high salinity (34.08) in the surface waters, especially towards the oceanic region. Along 13°N transect, prevalence of a cold gyre a cold gyre with relatively cold, high saline and nutrient rich waters was observed with its core at 82°E. The average chl. *a* concentration during this season was 0.22 ± 0.13 mg m^{-2}. The variation in the distribution of chl. *a* between the coastal and oceanic stations along the northern region was relatively less noticeable than that in the southern region. The microzooplankton community was more concentrated towards the oceanic areas when compared to coastal regions. The mesozooplankton biovolume was comparatively less along the northern transects than southern transects. During WM, the average mesozooplankton biovolume recorded in the MLD was 0.59 ± 0.35 ml m^{-3}. Maximum biovolume (1.92 ml m^{-3}) was observed at the coastal station along 15°N transect. This increase of mesozooplankton biovolume may be ascribed to the combined effects of cyclonic gyre circulation which favours the appearance of cold deeper waters to the surface (upwelling) and fresh water runoff or oceanic precipitation. Coastal stations sustained more mesozooplankton biovolume compared to oceanic stations. River run off is one of the major source of nutrient supply in the coastal waters, which enhances the biological production, whereas in the open ocean dilution effect, strong stratification or rapid vertical sinking or its combined effect might address the low biological production. The dominant non-copepod taxa of mesozoopankton were Chaetoganatha, Copelata and Ostracoda.

A seasonal comaprison of the hydrographic features showed strong variability. The monsoon months expereinced more turbulance than the intermonsoon months. In the the northern transects, the fresh water discharge from the major perennial rivers which peaked during winter and summer monsoon months which resulted in the strong stratification of the area. During intermonsoon periods, the biological production, both primary and secondary showed an increasing trend towards the northern transects and during the monsoon months the condition was reverse. Prevelance of subsurface chlorophyll maxima was observed during spring intermonsoon period. The distribution of mean mesozoplankton biovolume during different seasons showed that winter monsoon (0.66 ml m-^{3}) sustained more biovolume, followed by fall intermonsoon (0.62 ml m^{-3}), summer monsoon (0.52 ml m^{-3}) and spring intermonsoon (0.35 ml m^{-3}). The variation in the mean mesozooplankton biovolume between the winter monsoon and fall intermonsoon was marginal. From statstical analysis, it was observed that the seasonal variation of mesozooplankton abundance in the thermocline layer was siginficant during the intermosnoon months ($P > 0.05$). The physical processes observed during summer monsoon months sustained more mesozooplankton standing stock compared to other seasons. The coastal upwelling observed during summer monsoon had more influence on the biological production, especially mesozooplankton (2.4 ml m^{-3}), than physical processes obseved during other seasons. During winter monsoon the presence of cold gyre along the southern transect greatly influenced the overall biological production during the season. Localised effects of various physical processes were observed in the biological production, such as subsurface chl. *a* maxima and increased mesozooplankton biovolume. The combined effect of freshwater discharge and cold gyre make the region more productive during winter monsoon.

Part 2 of this thesis deals with the quantitative and qualitative analysis of planktonic decapods in the Bay of Bengal. Variability of spatio-temporal distribution, abundance and composition of planktonic decapods are the major aspects considered in this section.

The quantitative and qualitative studies reveal a prominent seasonal and spatial distribution of decapods in the plankton sample. During spring intermonsoon the average abundance in the MLD and thermocline layer was 459 ± 417 and 106 ± 181 no. 100m^{-3} respectively. Southern transects sustained more concentration of decapods compared to northern transects during this period. Of the total abundance of decapods, the dominant taxa in the MLD was Sergestoidea (49%) followed by Brachyura (31%). The relative abundance of other taxa were Caridea 19.52%, and

Penaeidea 3%. Thalassinoidea and Anomura contributed <1%. In the thermocline layer, the Brachyura contributed 40% as the dominant taxa followed by Caridea (31%) and Sergestoidea (18%). Under Sergestoidea, larval stages such as acanthosoma and mastigopus of family Sergestidae and adults of family Luciferidae were identified. *Lucifer typus* was the dominant species under family Luciferidae. Caridea was dominated by the members of family Thalassocaridae. Larval stages of *Thalassocaris obscura, Thalassocaris lucida* and *Thalassocaris crinata* were identified in the sample. Mysis stages of *Gennadas* sp, *Metapennaeopsis barbata, Metapennaeus* sp, and *Metapennaeus affinis* represented the family Penaeidae. The diurnal variability in the dispersal of planktonic decapods was observed more clearly along the coastal stations than along the oceanic stations. The total abundance of planktonic decapods during spring intermonsoon was relatively low, and those available were concentrated towards the southern region. The qualitative analysis, the sample reveals that the dominant taxon was Luciferidae, which is holoplanktonic form and can sustain well in the warm waters.

During summer monsoon the planktonic decapods have a wider distribution and high density especially towards the southern coastal region. The average abundance in the MLD was 1,011 ± 1,033 and in the thermocline layer it was 130 ± 215 no. 100m^{-3}. Members of the Sergesteiodea dominated both in MLD (65%) and thermocline layer (38%). The second dominant group was Caridea which contributed about 26% in the MLD and 42% in the thermocline layer. Relatively higher density of decapods were observed along the coastal regions. Along 17°N transect the number of individuals were more in all stations irrespective of coastal and oceanic stations. Sergestoidea was the dominant taxon composed of meroplanktonic (Elaphocaris, Acanthosoma and Mastigopus of sergestids and Acetes) and holoplanktonic forms (Lucifer). *Lucifer penicillifer* (40%) was found to be dominant in the MLD, followed by *Lucifer hanseni* (33%), and representation of other species were only >10%. Penaeoidea was represented by the larval forms of *Gennadas* sp, *Solenocera* sp, *Metapenaeus monoceros, Metapenaues sp. Metapenaeus affinis, Atypopenaeus stenodactylus, Trchaypenaues curvirostris, Penaeus monodon,* and *Parapenaeus investigatoris.* Under Caridea, the dominant species identified were Mysis III and IV of *Leptochela robusta,* Zoea III and IV of *Thalassocaris obscura,* adults of *Thalassocaris lucida* and *Thalassocaris* sp in the MLD. The increased spawning activity results in the release of large quantity of larval population in the coastal waters. The larval form together with holoplanktonic group (Luciferidae) supports high density of planktonic decapods along the coastal waters during summer monsoon. Diurnal variability in the total abundance of planktonic decapods were more pronounced along the ocastal stations than along the oceanic stations.

During fall intermonsoon the dispersal of planktonic decapods in the study regions was relatively higher when compared to other seasons. Northern region sustained an abundance of decapods in the plankton samples which gradually decreased towards south. This can be substantiated either with the food availability or with the transportation of certain larval forms to the continental shelf area through the river discharge. The low saline water makes an estuarine situation which is more preferable for the breeding and feeding of certain decapods. The dominant component was Sergestoidea (79% and 67%) followed by Caridea (12% and 15%) in the MLD and thermocline layer respectively. The relative abundance of Penaeoidaea in the MLD was 2%, and in thermocline layer it was 8%. The diurnal variation during FIM was more prominent at the oceanic stations than in coastal stations especially in the northern transects.

During winter monsoon, the abundance of planktonic decapods in the MLD was relatively more than the thermocline layer with more concentration towards the southern regions. The coastal and oceanic variability in the abundance of planktonic decapod was meagre during this season. Sergestoidea was the dominant group in both the layers (58% in the MLD and 63% in the thermocline layer). The next abundant group, Caridea contributed 17% in the MLD and 65% in the thermocline layer. Penaeoidaea, Thalassinoidea, and Brachyura contributed 11,7 and 4% respectively in the MLD. In the thermocline layer, the percentage contribution of Penaeidae was 4% and Brachyura was 5%.

The seasonal comparison in the abundance of various groups of planktonic decapods showed that the Sergestoidea was the dominant taxa during all the seasons. The maximum abundance was noticed during the summer monsoon, followed by fall intermonsoon, winter monsoon and spring intermonsooon. The second leading taxa was Caridea during all seasons except spring intermonsoon when the second dominant group was Brachyura in the MLD. In the thermocline layer, Sergestoidea dominated during winter monsoon and fall intermonsoon whereas Caridea and Brachyura outnumbered Sergestoidea during summer and spring intermonsoon respectively. An abundance of planktonic decapods was observed during night time hauls.

Regions where the physical processes like upwelling, eddy or gyre were active, relatively greater numbers of planktonic decapods congregated. The aggregation of planktonic decapods to these regions may be because of two reasons: a) the presence of phytoplankton in large quantities due to the nutrient enrichment which may attract the zooplankton population including planktonic decapoda for foraging; or b) due to the retention of planktonic form, especially the larval forms of decapods, by their increased buoyancy.

From the study it is clear that the distribution pattern of planktonic decapods varied considerably with seasons. The hydrographic parameters play an important role in the abundance of decapods in the plankton community. Incidence of seasonal features such as river water influx, localized coastal upwelling, eddies (either warm core or cold core) *etc.* would directly as well as indirectly influences the distribution and abundance of planktonic decapods. In general the Bay of Bengal was found to be more productive and holds high decapod density in summer than in winter monsoon. Further, studies are needed to be undertaken both quantitatively and qualitatively on plankton diversity, especially the commercially important forms such as decapod larvae which seems as an index of commercial fishery for sustainable resource exploitation and management.

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List of acronyms and abbreviations

ANOVA	Analysis of variance
AS	Arabian Sea
av.	Average
BoB	Bay of Bengal
BoBMEX	Bay of Bengal Monsoon Experiment
BoBPS	Bay of Bengal Process Studies
BT	Bottom of thermocline
chl. *a*	Chlorophyll *a*
CMFRI	Central Marine Fisheries Research Institute
CMLRE	Centre for Marine Living Resources and Ecology
CTD	Conductivity- Temperature- Depth
DO	Dissolved oxygen
E	East
e.g.	exempli gratia (Latin word meaning ‘for the sake of example’)
EEZ	Exclusive Economic Zone
EICC	East India Coastal Current
et al.	et alii (Latin word meaning ‘and others’)
etc.	et cetera (Latin word meaning ‘and other similar things; and so on)

Fig.	Figure
FIM	Fall intermonsoon
FORV	Fisheries and Oceanographic Research Vessel
GF/F	Glass Fibre/Filter
HDF	Heterotrophic dinoflaellates
IAPSO	International Association for Physical Sciences of the Ocean
IIOE	International Indian Ocean Expedition
INDEX	Indian Ocean Experiment
IOBC	Indian Ocean Biological Centre
JGOFS	Joint Global Ocean Flux Studies
km	kilometer
m	meter
mg	milligram
ml	milli litre
MLD	Mixed Layer Depth
MPN	Multiple Plankton Net
MR-LR	Marine Research Living Resources
N	North
NE	Northeast
NIO	National Institute of Oceanography
NO_2	Nitrite
NO_3	Nitrate
ORV	Oceanographic Research Vessel
P-E	Precipitation-Evaporation
PRIMER	Plymouth Routines In Multivariate Ecological Research
SeaDAS	SeaWiFS Data Acquisition System
SeaWiFS	Sea Viewing Wide Field -of- view Sensor
SIM	Spring intermonsoon

SM	Summer monsoon
sp.	species
SSS	Sea surface salinity
SST	Sea surface Temperature
SW	South West
TT	Top of the thermocline
UNCLOS	United Nations Convention of Law of Sea
UNESCO	United Nations Education, Scientific and Cultural Organisation
viz	videlicet (Latin word meaning 'namely')
WICC	West India Coastal Current
WM	Winter Monsoon
μM	micro moles

Research papers published/under review/Communicated

1. Redtide of *Noctiluca miliaris* off south of Thiruvananthapuram subsequent to the "stench event" at the southern Kerala coast Satish sahayak, R. Jyothibabu, K. J. Jayalakshmi, H. Habeebrehman, P. Sabu, M. P. Prabhakaran, P. Jasmine, P. Shaiju, G. Rejomon, J. Thressiamma, and K. K. C Nair Published: Current Science, 89 (9) 2005.
2. Variability in the biological responses influenced by upwelling events during summer monsoon in the eastern Arabian Sea. Habeebrehman. H., Prbhakaaran. M. P., Josia Jacob., Sabu, P., Jayalakshmi, K. J., Achuthankutty, C. T and Ravichandran, C. Accepted: Journal of Maine Systems,74 (1-2),545-560, 2008.
3. Seasonal abundance, ecology, reproductive biology and Biochemical composition of Mesopodopsis orientalis W.M Tattersall (Mysidacea) from a tropical estuary (Cochin Back waters) in India. A. Biju, R. Gireesh, K.J. Jayalakshmi, C.K. Haridevi and S.U. Panampunnayil. *Crustaceana*, 82(8), 981-996 2009.
4. Swarm of *Euphausia sibone* in the upwelled waters of the southwest coast of India. **Jayalakshmi, K. J.,** Muraleedharan, K. R., Jasmine, P., Habeebrehman, H., Prabhakaran , M. P., Josia Jacob, and. Achuthankutty C.T. Under review: *Journal of Marine Biological Association, U.K.*
5. Seasonal variations and trophic ecology of microzooplankton in the south eastern Arabian sea. C.R. Asha Devi, R. Jyothibabu,

P. Sabu, Josia Jacob, Habeebrahman, P. Prabhakaran, K.J. Jayalakshmi and C.T Achuthankutty. Continental shelf Research, *under review*.

6. Mesozooplankton composition and community structure of Copepods in the cold core eddy off northern bay of Bengal during summer and winter monsoons **Jayalakshmi. K.J,** Jasmine P, Muraleedharan, K.R, Rosamma Stephen and C.T.Achuthankutty. 7th Asia Pacific Marine biotechnology Conference. 2nd to 5th November 2006.
7. Copepod community structure in the upwelling regions of Arabian Sea and Bay of Bengal during summer monsoon Jasmine, P., **Jayalakshmi, K.J.,** Jayalekshmy, K.V., Honey. U.K.Pillai, Muraleedharan, K.R., Achuthankutty, C.T. 7th Asia Pacific Marine biotechnology Conference. 2nd to 5th November 2006.
8. Tsunami 2004 and the biological oceanography of Bay of Bengal. Rosamma Stephen, **Jayalakshmi, K.J,** Habeebrehman, Karuppasaamy, P.K., and Nair, K.K.C. Proceedings of the National commemorative Conference of Tsunami, Madurai, 26-29 December 2005
9. Status of coral reefs in Mahatma Gandhi Marine National Park at Wandoor (South Andaman, India. T. Shanmugaraj, S. Sundaramoorthy,Tune Usha, K.J. Jayalakshmi, M.P. Divya, K.B. Padmakumar, C.L. Fanimol, S. Meera, Dhanya Sethunarayanan, V.N. Sanjeevan, and B.R. Subramanian. National Conference on Coral Reef Ecosystem. 18-19 September 2008 , Thoohtukudi

Seminars and Symposia

- National Seminar on Aquaculture in the Changing Environmental Perspectives, 25 to 27 March 1998, conducted by Department of Aquatic Biology and Fisheries, University of Kerala,Trivandrum
- 7th Asia Pacific Marine Biotechnology conference, Kochi 2nd to 5th November 2006. Organised by National Institute of Oceanography, Goa, India
- National Conference on Coral Reef Ecosystem (NACCRE 2008) 18-19th September 2008, at Fisheries College and Research Institute Tuticorin.

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