MICROPHYTOPLANKTON COMMUNITY STRUCTURE IN THE NORTH EASTERN ARABIAN SEA DURING WINTER MONSOON

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Microphytoplankton community structure in the North Eastern Arabian Sea during Winter Monsoon

Ph.D. Thesis under the Faculty of Marine Sciences

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CERTIFICATE

This is to certify that the thesis entitled "***Microphytoplankton community structure in the North Eastern Arabian Sea during Winter Monsoon***" is an authentic record of the research work carried out by Ms. Lathika Cicily Thomas, under my scientific supervision and guidance in the School of Marine Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the degree of Doctor of Philosophy of the Cochin University of Science and Technology and that no part thereof has been presented before for the award of any other degree, diploma or associateship in any University.

Dr. S. Bijoy Nandan

Kochi
February, 2015

DECLARATION

I hereby declare that the thesis entitled "***Microphytoplankton community structure in the North Eastern Arabian Sea during Winter Monsoon***" is an authentic record of research work done by me under the supervision of Dr. S. Bijoy Nandan, Associate Professor, School of Marine Sciences, Cochin University of Science and Technology and no part of this has been presented for any other degree or diploma earlier.

Kochi **Lathika Cicily Thomas**
February, 2015

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Lathika Cicily Thomas

Dedicated to
My Parents
For their love and endurance…

CONTENTS

Chapter 1

Introduction

"With every drop of water you drink, every breath you take, you're connected to the sea.
No matter where on Earth you live."

— Sylvia Earle, Oceanographer

Phytoplankton or microalgae are the microscopic plant like organisms that grow in the upper regions of the ocean where sunlight is available. They form the base of marine food web and contribute part or most of the organic carbon available to pelagic food webs (Reynolds 2006). The organic matter so produced ultimately determines the secondary and tertiary production among which fish, prawns, mussels etc. that we harvest. They are also known as the "grass of oceans" and are ubiquitous in distribution in marine ecosystems. Since marine environment occupy about 71% of the earth surface, these tiny creatures are responsible for about half of the photosynthetic activity on the total planet surface. Using carbon dioxide as the source of carbon for building of energy molecules they convert the physical energy available in the nature to utilizable form. These microscopic organisms play vital role in scavenging the much accountable green house gas, carbon dioxide by using it for photosynthesis and liberating oxygen. Some microalgae also contribute significantly to the climatic processes, providing nuclei for atmospheric water condensation (Aiken *et al.*, 1992).

Although their taxonomy is currently undergoing major revision and even the phylogenies are questioned, it is difficult to be categorical about the species representation and phyletic make-up of phytoplankton. About 5,000 species of phytoplankton have been described from oceans and coastal seas. They vary in size and some forms have siliceous cell wall, some with calcium carbonate shells and some without a hard shell with ability to swim in the water column. Phytoplankton communities comprise several algal groups, such as diatoms (Bacillariophyceae), dinoflagellates (Dinophyceae), green microalgae (Chlorophyceae), blue green algae (Cyanophyceae), phytoflagellates, silicoflagellates, coccolithophores and others.

The classification of plankton based on size spectrum by Sieburth *et al* (1978) has been widely used in nomenclature and ecological studies of phytoplankton (Figure 1). Accordingly the phytoplankton has size range

0.2µm - 2 µm → Picoplankton
2 µm - 20 µm → Nanoplankton
20 µm - 200 µm→ Microphytoplankton
0.2 mm - 20mm → Mesophytoplankton
>20mm → Macrophytoplankton

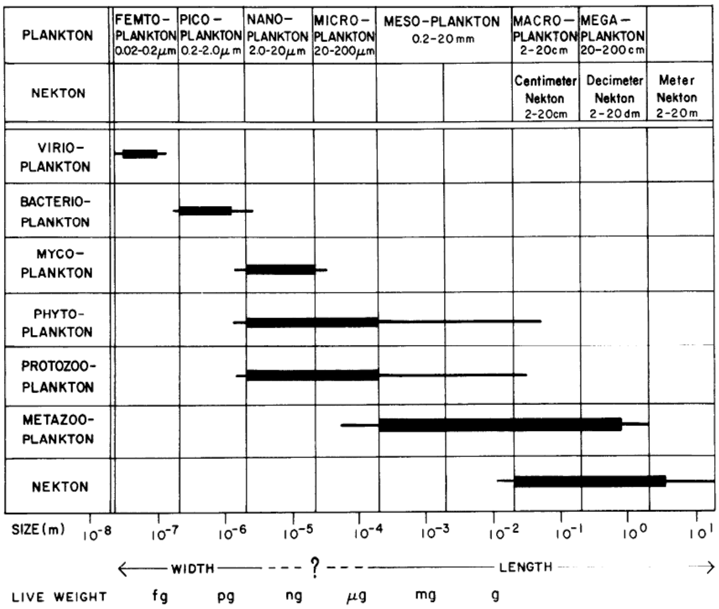


Figure 1. Distribution of different taxonomic- trophic compartments of plankton in a spectrum of size fractions, with a comparison of size range of nekton (Sieburth *et al.*, 1978)

Microphytoplankton sized cells are of more universal taxonomic distribution, although the largest species are found among Bacillariophyta (diatoms) and Dinophyta (dinoflagellates) (Lee, 1999). Picophytoplankton and nanophytoplankton are primarily consumed within the microbial loop (Sandergaad *et al.,* 1991) while the larger cells are grazed by herbivores within the classical food web. Among the phytoplankton, diatoms are the most diverse group (Armbrust 2009), and is estimated that diatoms can contribute up to 40% of the total oceanic primary production (Nelson *et al*., 1995) and thus contributing significantly to the biogeochemical cycle of carbon.

Based on the symmetry of the cells the diatoms can be classified as centric and pennate forms. Centric diatoms as the word indicates are generally having radial symmetry whereas pennate diatoms tend to appear bilaterally symmetrical (Annexure 1). Among these two forms, centric diatoms usually occupy the pelagic realm whereas pennate forms include both pelagic as well as benthic habitats with later being the prominent. Based on the presence or absence of raphe, pennate diatoms can further be classified into two sub-orders, the Fragilariineae which do not possess a raphe (araphid) and the Bacillariineae which posses a raphe (raphid). Further details regarding diatom classification and morphology is provided in annexure 1 of the thesis.

Dinoflagellates along with diatoms form an integral part in the phytoplankton community especially in the near shore as well as shelf waters. In 1885 Butschli proposed the name dinoflagellate (Greek *Dinos,* whirling). Differing from diatoms they have non-siliceous cell wall. The mode of nutrition also differs by having half of species as heterotrophic and the other half with autotrophy. Dinoflagellate classification undergoes time to time revisions and as per the homogenised classification adopted in standard identification keys mainly 5 subclasses were identified under class Dinophyceae that includes Dinophysiphycidae, Gymnodinophycidae, Noctilucophycidae, Peridiniphycidae and Prorocentrophycidae (Fensome *et al.*, 1993).

Cyanophyceae forms one among the ancestral part of phytoplankton community with substantial ecological importance especially in carbon as well as nitrogen cycle. Many of the cyanophycean members are capable of fixing atmospheric nitrogen thus providing a source of biologically available nitrogen to the environment (Postgate, 1987). Diatoms are generally non motile with fast growth rate having ability to withstand relatively turbulent waters and thrive well in cold nutrient rich waters. Dinoflagellates which are motile owing to the possession of flagella can regulate their position in the water column. This allows for their survival in the stratified waters (Margalef, 1978).

Phytoplankton must fulfil their ecological requirements for growth within the illuminated (euphotic) surface waters. The relative depth of the mixed layer and the euphotic zone are of obvious importance to suspend photoautotrophic cells. Mixing also served to replenish nutrients in the surface waters. The latter function especially pronounces along the western shores of some continents where wind and the effects of earth's rotation combine to move surface waters offshore. The nutrient rich upwelling water which replaces the surface waters contribute to the high productivity of these areas.

The structure of a phytoplankton community is influenced by various physico chemical factors. Factors like temperature (Goldman and Mann, 1980), illumination (Ryther, 1956), turbidity (Estrada and Berdalet, 1998) and nutrients (Sanders *et al.*, 1987) have significant affects on the distribution pattern of phytoplankton. In other word the different phytoplankton group co-occur according to the ecological demand on trophic (nutrients, food), physical (light, mixing and temperature) or biological factors (competition and predation) (Smayda, 1986). From the above said facts we can deduce that the phytoplankton standing crop in a particular geographical location is truly determined by the environmental, physico-chemical and biological attributes of the region.

Various physical processes recondition nutrients in the euphotic column through transport and mixing. In the absence of these processes nutrient supply towards the euphotic column ceases and biological production will be put on hold. Vertical supply mediated through large scale vertical advection, diffusion and convection replenishes the upper water column. Among these various mixing processes surface convection is highly significant especially during winter. This process primarily occurs throughout the ocean in response to surface buoyancy loss or wind stirring (Marshall and Schott, 1999). The coupling of solar irradiance and atmospheric forcings induces characteristics diurnal and seasonal cycles in the the mixed layer thickness. The winter cooling and associated convective mixing is of seasonal occurrence along the high latitude seas (sub polar and sub tropical waters). Over the North Atlantic, the surface buoyancy loss at high latitudes leads to a pronounced thickening of the mixed layer at the end of winter (Williams and Follows, 2003).

In the subpolar region, the winter mixed layer may be hundreds of meters thick and nutrients may be abundant. Photosynthesis is light limited during winter, so the bloom occurs in spring when the mixed layer shoals sufficiently to allow phytoplankton to remain within the sunlit region and enable net growth (Sverdrup, 1953). In the subtropical gyres, insolation and stratification are both strong, and winter mixed layers may be only 100 m or so thick. The system is nutrient limited and the bloom occurs in winter when the mixed layer deepening provides new nutrients (Menzel and Ryther, 1961). Here, enhanced convection during the bloom period leads to a strengthened bloom through the increase in nutrient supply.

Bermuda Atlantic Time Series Studies (BATS) as a part of United States- Joint Global Ocean Flux Studies (US JGOFS) brought out vast studies dealing with winter cooling and following spring blooms. Convective changes can alter biological production through the nutrient and trace metal supply to the euphotic zone, change the light experienced by phytoplankton, as well as impact on grazers and community structure. Eventhough enormous amount of nutrients are introduced into the euphotic column, limited solar irradiation acts as a major controlling force in the augmentation of biological production in the sub polar and subtropical waters (Sverdrup, 1953). Influence of winter convection on the biogeochemistry of North Atlantic has been studied towards the open ocean as well as adjoining seas (Michaels *et al.,* 1994; Williams *et al.*, 2006; Ferrari *et al.*, 2014; Grosse *et al.*, 2014).

Along the northern Indian Ocean, characteristic winter convective mixing has been identified along the north western region (Madhupratap *et al.*, 1996) and is initiated by the cool dry north east trade winds blow over the surface during north east monsoon season. The Indian Ocean, unlike the Pacific and Atlantic Oceans does not connect the two polar oceans and it is special in its geographic settings. Indian subcontinent divides the Northern Indian Ocean to Arabian Sea and Bay of Bengal, which forms the twin sea caressing the western and eastern boundaries of Indian peninsula. The North Western Indian Ocean (Arabian Sea) is a region of negative water balance where, evaporation far exceeds precipitation and runoff (Budyko, 1972). This region, known for its seasonally oscillating productivity associated with monsoon is one of the most productive areas of the world oceans. The area also experience extremes in the atmospheric forces, asymmetrically distributed, that bring about exceptionally large hydrographical changes and produce a wide variety of ecosystems or biogeochemical provinces. The land mass that limits the pole ward expanse of the Northern Indian Ocean to just about 25°N latitude profoundly influences physical process in Arabian Sea. The continental influence is best manifested by the monsoons, the seasonally reversing wind systems that is driven by a pair of low (high) and high (low) pressure zones over the sea and land, respectively during winter (summer). This eventually leads to annually occurring monsoons such as south west monsoon (*summer monsoon*) during June to September and North east monsoon (*winter monsoon*) during December to March. The period intervening the monsoon, April- May and October- November is referred to as spring monsoon and fall inter monsoon respectively.

It has been well documented from several works that Arabian Sea is a region of high biological production (Ryther *et al*., 1966; Qasim, 1977; 1982). Arabian Sea experiences four major seasons based on the reversing monsoon winds although there occur interannual variability. During winter (November-February), the cold, dry continental air brought by the prevailing north east trade winds from the atmosphere high pressure region situated between the Tibetan plateau blow across the northern Arabian Sea causes cooling, densification of surface waters and sinking (Wiggert *et al.,* 2002). This along with incoming solar radiations and high salinity drives convective mixing in northern Arabian Sea (Madhupratap *et al*., 1996).

According to Weller *et al* (1998) the characteristic features of this offshore flow during the season are moderate wind stress ($/\tau/$~ 0.071 Nm-2), air temperature around 1°C lower than sea surface temperature (SST) and a relative humidity (RH) of ~70%. This low relative humidity initiates evaporation (Tomczak and Godfrey, 1994) and elevated sea surface salinity (Weller *et al*., 2002). All these conditions promotes oceanic convective mixing which results in a cool, high saline surface water as the thermocline erodes and the mixed layer deepens. This deepening leads to pumping of nutrients into the surface layers generating higher production. Since light is not a limiting factor in these waters this mixing and flux of nutrients leads to elevated primary production (Prasannakumar *et al*., 2001). This increase was most apparent in north and waned towards south during the season (Madhupratap *et al*., 2001).

During the south west monsoon period (June- September), when the west coast is under the influence of south westerly winds the surface waters along the regions move away from the coast and get replaced by subsurface cold nutrient rich and comparatively oxygen depleted waters (Madhupratap *et al.,* 2001). This physical process triggers enhanced phytoplankton growth leading to blooms as well as increased primary production. An elevated primary production favours secondary producers which in turn stimulates the tertiary trophic levels. Concisely, Arabian Sea remains productive during both summer monsoon as well as winter monsoon seasons through upwelling during former and cooling and associated convective mixing during later. Further, there is a strong coupling between prevailing physical condition and biological process in the Arabian Sea (Banse, 1987).

The transition period from winter to summer (March- May) is referred to as spring intermonsoon period and the transition period from summer to winter (September- October) is called as Fall inter monsoon period. During these periods the entire Arabian Sea has on an average very low primary production and chlorophyll, with a Typical Tropical Structure (TTS) (Madhupratap *et al*., 2001). These periods have higher sea surface temperature (SST, about 28°C), shallow mixed layer depths (MLDs, around 20-30 m) and strong stratification. Nutrients mainly nitrates are at undetectable levels in the surface waters during this period. During the transition from winter monsoon to spring inter monsoon the surface wind stress and the outgoing latent heat flux decreases. This impedes the convective mixing process resulting in the shoaling of mixed layer and triggers the spring phytoplankton bloom.

Phytoplankton abundance and production is determined by the interplay between the euphotic zone and the mixed layer depth which in turn varies with the annually reversing monsoons (Rixen *et al*., 2002). Varying physical forcing and resultant hydrographical changes in the Arabian Sea give rise to widely differing phytoplankton assemblage and species diversity in both space and time. These organisms constitute an ideal window for the studies on the food web dynamics in an ecosystem. Short generation time and their tight coupling with environment permits to determine their response and recovery to the environmental changes easily than the higher organisms. Detailed analysis of the phytoplankton composition and its variability based on both space and time is still lacking along the north Eastern Arabian Sea ecosystem. Winter blooms along eastern Arabian Sea is a recurrent phenomenon during north east monsoon and is studied based on both *in situ* as well as satellite data since 2004 (Matondkar *et al.,* 2004). Even then a comprehensive workout regarding the microphytoplankton community structure and its variations is still vague. A valid checklist based on *in situ* observations is necessary to identify the major primary producers of the region. In this scenario the present study attempts to decipher the phytoplankton functional groups existing along NEAS during winter monsoons, with special reference to microphytoplankton.

A review on phytoplankton studies along Arabian Sea (North Western Indian Ocean)

Indian Ocean was the first to be used for trade but last to be scientifically explored in detail (Sengupta *et al*., 1992) The first organized maritime expedition in Indian Ocean sector was sent by Queen Hatchepsut of Egypt (1478 BC) to explore the southern Red sea and the Somali coast (Aleem, 1972*)*. In the medieval period (AD 800-1400) Arabs were the leading traders and mariners in the Indian Ocean and earliest reference of semi annual reversal of winds in the northern Indian Ocean pertain to them (Warren, 1966). Later during British period (AD 1757-1947) oceanography was established as science. Modern oceanography was born with Challenger Expedition (1872-76) by *HMS Challenger* who visited twice the Indian Ocean but the northern part was not covered. Even then it lightened up the further initiation of scientific marine expedition in Indian Ocean.

The surveys carried out through *John Murray Expedition* (September 1933-May 1934) brought out considerable information on oceanographic features of Indian Ocean. From 1947 onwards (post Independence period) considerable resources began to be diverted towards the study of Ocean with major objective to obtain more food from ocean. Even then Indian Ocean remained almost *mare incognitum* (*latin: unknown sea*) until International Indian Ocean Expedition. The IIOE (1959-1965) marked a turning point in the pursuit of knowledge of the Indian Ocean. Later the Indian Ocean Experiment (INDEX), investigations by the Netherlands (Netherlands Indian Ocean Program, 1992-1993), the United Kingdom (1994), Germany (German Joint Global Ocean Flux Studies; JGOFS, ARABESQUE-1995-1997), Pakistan (North Arabian Sea Environmental and Ecological Research; NASEER, 1992-1995), India (JGOFS-India, Arabian sea Process Study Data and Information, 1994-1997) and the United States (JGOFS-US, 1994-1996) have contributed much to the understanding of the Indian Ocean. The research programs funded by Government of India through five year plans (MLR-P) facilitated in gathering profound information on the seas around Indian sub continent. Bay of Bengal Process studies (BoBPs) 2000-2006 gathered quantifiable information regarding biogeochemistry of the bay including major phytoplankton components during different seasons.

Studies on the productivity patterns in the Arabian Sea as early as 1937 reveals that the phytoplankton production in the tropical upwelling region is far higher than that in any temperate sea and cannot be considered as a barren area as supposed to be (Gilson, 1937; Subrahmnayan, 1958). Since then several attempts have been made to quantify the phytoplankton along the east as well as west coast of India (Hornell and Nayudu, 1923; Menon, 1931; Aiyar *et al.,* 1936; George, 1953; Prasad, 1954; Ganapathy and Rao, 1953; Ganapathy and Murthy, 1955). These studies reveal a general account on the phytoplankton composition regionally and their peak periods of production.

Earlier studies as a part of International Indian Ocean Expedition (1960-1965) efforts were made to understand the physico-chemical factors and biological productivity in the Arabian Sea. The studies pointed out that higher primary productivity occurs along the continental margins of Somalia, Arabia and south west coast of India during the summer monsoon period (Smith and Codispoti, 1980). Bhattathiri *et al* (1996) as a part of Indian JGOFS programme has worked out the phytoplankton production and biomass during different seasons in Arabian Sea as well as its spatial variations. They recorded the high chlorophyll concentrations in the northern Arabian Sea during north east monsoon (winter) and along southern Arabian Sea during southwest monsoon (summer).

The important coastal upwelling systems in the North Western Indian Ocean include Somali, Oman, Pakistan coast and south west coast of India. Massive horizontal advection of Somali upwelled waters due to the strong Findlater’s jet transports nutrient rich water to the Central Arabia, and this along with the open ocean upwelling in the central areas defines the high production in this area. Because of this physical process the productivity of the southern Arabian Sea increases during the summer monsoon period causing summer phytoplankton blooms. Winter cooling resulting in surface cooling associated with convective mixing and sinking of surface waters, highly influence the nutrient level and thereby increasing the productivity in the Northern Arabian Sea during winter monsoon resulting in winter blooms. Thus, there is a strong coupling between prevailing physical condition and biological process in the Arabian Sea (Banse, 1987). Upward flux of nutrients due to the mixing process results in elevated primary production in Arabian Sea (Bhattathiri *et al.*, 1996). Varying physical forcing and resultant hydrographical changes in the Arabian Sea give rise to widely differing phytoplankton assemblage and species diversity in both space and time.

The phytoplankton biomass and photosynthetic production are higher in the northern Arabian Sea during both the monsoons (Marra *et al.*, 1998). Nutrient enrichment in euphotic zone resulting from the convective mixing during the northeast monsoon boost up the phytoplankton biomass over a large area in the northern Arabian Sea mainly north of 15ºN latitude. About 25% of the total photosynthetic production of the Arabian Sea occurs in northern regions in the winter (Sawant and Madhupratap, 1996). Average production rate in the region during the season covers more than 1 $gCm^{-2} D^{-1}$ (Wiggert *et al.,* 2000). However previous studies on primary production in the northern Arabian Sea have proven significant interannual variability (Banse, 1987; Bauer *et al*., 1991) in the phytoplankton biomass.

The nutrient enrichment as a result of convective mixing promotes massive algal blooms in the near shore as well as coastal waters (Banse and McClain, 1986; McCreary *et al*., 1996). Along the NEAS, blooms begin during early February and persist until March end (Sarangi *et al.,* 2001; Dwivedi *et al.,* 2006). Satellite imagery studies using Coastal Zone Colour Scanner (CZCS) supports the fact that maximum chlorophyll pigment concentrations were observed during February- March season mainly north of 20°N. These patches are observed to persist for 2-3 weeks (Banse and McClain, 1986). The classical explanation for bloom formation (Sarangi *et al*., 2001; McCreary *et al.,* 1996) in the north eastern Arabian Sea is that the nutrients build up prior to the onset of bloom is enormous. Along the north eastern Arabian Sea, the onset of bloom occurs towards the beginning of February. This is mainly due to the fact that the mixed layer detrains earlier in the region. Detrainment occurs when there is less turbulence as a result of weaker winds or due to surface heating. Detrainment results in thin mixed layer with intensified depth average light intensities favouring highly productive phytoplankton growth. These detrainment blooms tends to be short lived as there is no further injection of nutrients to the mixed layer and they exist until the initial nutrient supply is depleted. In addition to the nutrient limitation, grazing and self shading causes degradation of initial peak.

Goericke (2002) considers monsoonal regions of Arabian sea as High Nutrient Low Chlorophyll Regions (HNLC) but unlike other such areas these regions are not limited by inorganic nutrients (bottom up resources) including iron but it is in fact controlled by the grazing effects of micro and mesozooplankton (top down control) that approaches the rates of primary production. In the central Arabian Sea, diel variations in mixed layer depth in combination with grazing effect of zooplankton controls the full utilization of newly produced nitrogen as a result of convective mixing especially during early phase of winter convective mixing (December- January) (Landry *et al.*, 1998). This prevents from the establishing full bloom of phytoplankton during this early north east monsoon until late winter monsoon and early spring inter-monsoon (Wiggert *et al.*, 2002). The nutrient uptake experiments conducted during successive north east monsoons (McCarthy *et al.*, 1999) indicates that primary production was principally supported by the uptake of ammonium. The nitrate entrained into the water column by convective mixing resides for 1 to 3 months that slowly accumulates making it available for blooms in early spring inter monsoon.

The phytoplankton distribution along the eastern Arabian Sea has been analyzed as early as 1940's. But these studies are either close to the coast or more or less describing open ocean waters alone (US-JGOFS). Even then these efforts have brought some light to the basic composition of phytoplankton community along the west coast of India (Subrahmanyan, 1959; Subrahmanyan and Sarma, 1960; 1965). In recent times development of High Performance Liquid Chromatography (HPLC) has been proved to be a useful tool in easy determination of taxonomic groups in the phytoplankton community (Parab *et al.*, 2006; Latasa and Bidigare, 1998; Barlow *et al.*, 1999; Goericke, 2002; Brown *et al.*, 2002).

The preliminary studies on the growth rates of phytoplankton (Caron and Dennett, 1999) shows that the rates during winter monsoon were almost twice as that of spring inter monsoon in the northern Arabian Sea, whereas mortality (herbivorous grazing) were almost similar in both these season. This was supposed to account for much higher phytoplankton standing crop during winter monsoon season. Matondkar *et al* (2007) proposed that the species distribution of phytoplankton exhibit seasonality in the surface as well as column water in northern Arabian Sea. Earlier studies considered diatom as the major producers in the region during the winter monsoon (Sawant and Madhupratap, 1996; Latasa and Bridigare, 1998). But later the occurrence as well as spreading of *Noctiluca scintillans* gained scientific attention. The occurrence of *Noctiluca scintillans* in higher cell densities along Northern Arabian sea was reported as early as from the International Indian Ocean Expedition by *R.V Anton Brunn* 1963-1964 (Taylor, 1976). Later Devassy and Nair (1987) gave an account of the green tides of *Noctiluca* in the Malwan coast during February-April period. Saifullah and Chaghtai (1990) detailed on the *Noctiluca* bloom along Indus delta shelf during later part of north east monsoon. The extensive *Noctiluca* bloom occurrence during north east monsoon is considered as a peculiar feature of northern Arabian Sea.

Matondkar *et al* (2004) described large scale blooms of *Noctiluca scintillans* along northern Arabian Sea during winter monsoon. Even then detailed studies exclusively on the bloom expanse as well as duration were sparse. Comprehensive studies on various aspects of bloom gained momentum with routine monitoring surveys conducted by *FORV Sagar Sampada* under Marine Living Resources (MLR) program by Ministry of Earth Sciences, Government of India. Since then there were many studies both *in situ* as well as satellite based on the spatio temporal distributions of *Noctiluca scintillans* blooms (Sarangi *et al.,* 2005; Dwivedi *et al.*, 2006; Gomes *et al.*, 2008; Dwivedi *et al.*, 2008; Prakash *et al.*, 2008; Gomes *et al.*, 2009; Madhu *et al.*, 2012). Gomes *et al* (2008) suggests that high chlorophyll *a* concentrations in northern Arabian Sea during winter monsoon are mainly contributed by

Noctiluca scintillans blooms. The early spring inter monsoon studies in northern Arabian Sea during March 2000 (Madhu *et al.,* 2012) observed monospecific proliferation of *Noctiluca scintillans* in the bloom regions and the non bloom areas were dominated by diatoms. The preliminary studies on the ecological significance of these *Noctiluca scintillans* blooms has shown no adverse effect on the zooplankton as well as fish population in the northern Arabian Sea (Dwivedi *et al*., 2012).

Enormous efforts were made to study the bloom dynamics of *Noctiluca scintillans* based on *in situ* as well as satellite observations but most of them culminated in emphasizing their distribution rather than the dynamics of bloom and coexisting phytoplankton community structure. The intensified occurrence of *Noctiluca scintillans* blooms along the open ocean waters of Northern Eastern Arabian Sea deserves meticulous assessment. Northern Arabian Sea is approximately 25% of the total area of the Arabian Sea, but it supports nearly 50% of the total primary production (Naqvi *et al*., 1982). However a detailed study regarding the primary component of the biological production in the area is limited. Since the winter- spring intermonsoon production is considered as a significant component in the biogeography of the North Eastern Arabian Sea, assessment of the standing crop as well as community structure of the phytoplankton in the areas is significantly valuable.

Objectives of the study

The objectives of the present study can be stated as follows:

- To assess the physico- chemical characteristics *vis a vis* the production parameters and microphytoplankton community structure during winter monsoon in the NEAS
- To monitor inter annual variability and short term variability of micro phytoplankton community structure and their open ocean blooms during winter monsoon along NEAS

- To understand the variations in microphytoplankton community structure in concurrence to changes in the hydrography during the transition from winter monsoon to early spring inter monsoon in NEAS

Chapter 2

Materials and Methods

"The future is in the hands of those who explore... and from all the beauty they discover while crossing perpetually receding frontiers, they develop for nature and for humankind an infinite love."

— Jacques Yves Cousteau, Oceanographer

The data presented in this study has been obtained from the eight field based cruises carried out along the North Eastern Arabian Sea during 11th plan period (July 2008- March 2012) onboard research vessel *FORV Sagar Sampada* as a part of the Marine Living Resources Programmes (MLRP) "*Environment and Productivity patterns of Indian EEZ*" and "*Monitoring and Surveillance of Harmful Algal Blooms in the Indian EEZ*" funded by Ministry of Earth Sciences (MoES), New Delhi and implemented at the Centre for Marine Living Resources and Ecology (CMLRE), Kochi.

2.1 Study area and Data collection

North Eastern Arabian Sea (NEAS) was selected for the study. The region is known to be well influenced by the biannual reversal of monsoon winds that supports intense convective mixing of the surface waters during winter monsoon (WM) season and thereby increasing the biological productivity of the area. According to Asian monsoon calendar the period November to March is considered as the winter monsoon season (WM). But the intensity of winter cooling was found to be higher during February which extends to early and later weeks of March. Hence the sampling was conducted during the winter monsoon and early spring inter-monsoon periods. The study was conducted along the three latitudinal transects *viz* 22ºN, 21ºN and 18ºN (Figure 2) of NEAS for three years (2009-2012). Sampling was not carried out during the year 2010 due to unavailability of research vessel. Coastal and open ocean waters along 22ºN and 21ºN were sampled to study the influence of winter monsoon processes. A reference station was fixed along 18ºN offshore and sampled to understand the hydrobiology of the regions without the influence of winter convective mixing. Three consecutive cruises during winter monsoon of 2009, 2011 and two cruises during 2012, of which one was during late winter monsoon and another during early spring inter monsoon (SIM) were conducted. Each cruise is considered as different phases of winter monsoon depending on the physico-chemical and biological characteristics. February and March (2009, 2011) were selected for winter monsoon and April (2012) for early spring inter monsoon. Table 1 shows the sampling periods as well as their divisions chosen for data analysis and interpretations.

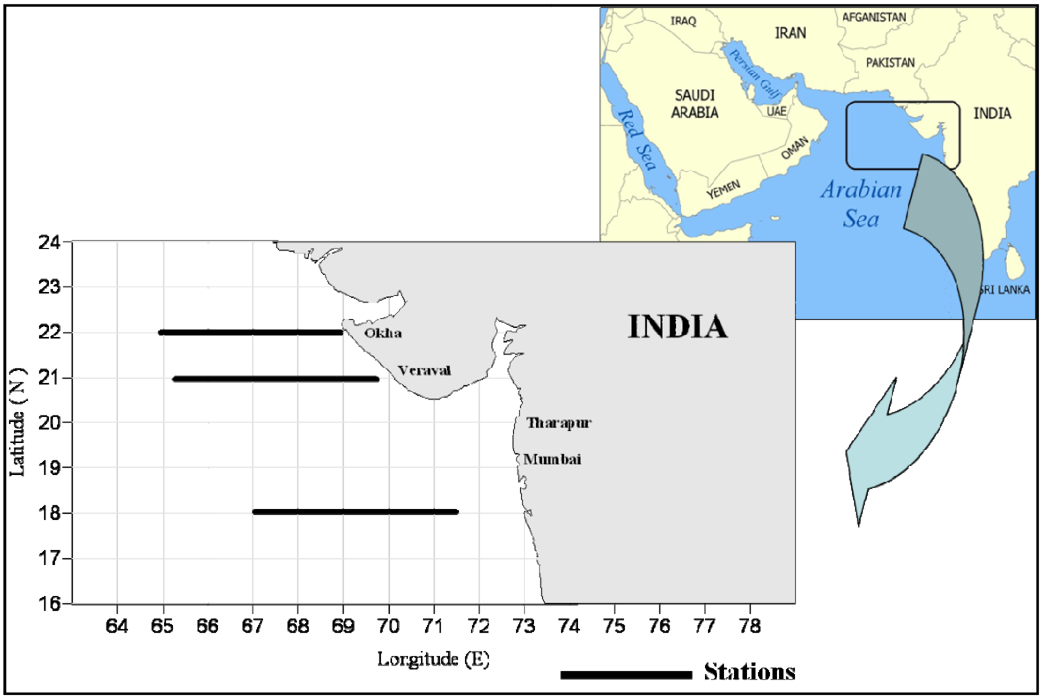


Figure 2. Study area NEAS

Year	Phase	Sample collection time	Season	FORV SS Cruise
2009	1	Early February	NEM	262
	2	Mid February- Early March	NEM	263
	3	Late March	NEM	264
2011	1	Early February	NEM	284
	2	Mid February- Early March	NEM	285
	3	Late March	NEM	286
2012	1	Late March	NEM	297
	2	Early April	SIM	298

Table 1. Details on sampling periods in the NEAS

2.2 Hydrographical parameters

2.2.1 Physical parameters

Meteorological parameters such as wind speed, wind direction and air temperature was obtained through Automated Weather Station (AWS) onboard FORV *Sagar Sampada*. Vertical profiling of parameters such as temperature, salinity and density was obtained using Conductivity- Temperature- Depth profiler (CTD, Sea Bird Electronics Model 911 series, Sea-Bird Inc) attached with sensors for understanding oceanic processes. Sea surface temperature was measured using a bucket thermometer. The values at 5m depth in the vertical profiling of the CTD were considered for the determination of Sea Surface Temperature (SST), Sea Surface Salinity (SSS) and Density (Sigma t). This depth is chosen to eliminate any possible bias in the profile data due to 'skin effects' at the ocean surface (Fairall *et al.,* 1996). Mixed Layer Depth (MLD), Isothermal Layer Depth (ILD) and barrier layer (BL) thickness were derived from the individual vertical profiles from CTD. Mixed layer depth (MLD) was determined using density criterion (Shetye *et al.,* 1996; Madhupratap *et al.,* 2003) where the density at the 5m depth rises by 0.2 units (0.2 kg/ m^{-3}). The isothermal layer depth (ILD) is defined as the depth at which temperature decreases by 1°C from the 5m depth (Sprintall and Tomczak, 1992; Kara *et al.,* 2000; Rao and Sivakumar, 2003).

2.2.2 Chemical Parameters

Water samples from standard depths via; surface, 10, 20, 30, 50, 75, 100 and 120m were collected using 10 liter Niskin bottles attached to the rosette sampler of CTD. The water samples were taken for chemical and biological analysis of various parameters.

2.2.2.1 Nutrients

Inorganic nutrients, nitrate-nitrogen (NO_3-N), nitrite- nitrogen (NO_2-N), phosphate- phosphorous (PO_4-P) and silicate- silicon (SiO_4-Si) were analyzed, using a segmented flow Auto Analyzer (SKALAR) onboard the vessel by following UNESCO- JGOFS protocol 1994. Nitrate in the water sample was reduced to nitrite using amalgamated cadmium granules. Nitrite was estimated by reacting (diazotization) with sulphanilamide in acid solution which was then coupled with N- (1-Naphthyl) ethylene diamine dihydrochloride resulting in an azo dye and its absorbance was measured spectrophotometrically at 543 nm (Grasshoff, 1983). Phosphate was determined by reducing with an acid solution containing molybdic acid, ascorbic acid and trivalent antimony and the absorbance was measured at 882 nm (Grasshoff, 1983). Silicate was determined by treating the water sample with molybdic solution and the absorbance of resultant molybdenum blue complex was obtained at 810 nm (Grasshoff, 1983).

2.3 Biological Parameters

2.3.1 Chlorophyll *a*

Chlorophyll *a* is taken as the index of phytoplankton biomass during the present study. Acetone extraction method was used for the chlorophyll estimation (Parsons *et al.*, 1984). One litre of water samples free of zooplankton were filtered through Whatman GF/F filter paper of porosity 0.7 μm. For the extraction of pigments the filter paper with filtrate was placed in a stoppered test tube containing 10 ml of 90% aqueous acetone. To accelerate the extraction of pigments, the filtrate was gently ground with a homogenizer or glass rod and the test tube was then stoppered. This operation must be carried out in a semi-darkened area. The test tube with the solution was subsequently transferred to a dark colored cloth bag, and placed in a refrigerator for 24 hours in order to facilitate the complete extraction of pigments. After the extraction period the extract was transferred to a graduated centrifuge tube and the volume made up to 10ml by adding fresh 90% acetone. The solution was centrifuged for about 20 minutes at 5000 rpm and the supernatant solution was used for determination of optical density using *Perkin Elmer (Lambda 25)* UV/VIS Spectrophotometer. The supernatant solution was then transferred to 1 cm (path length) cuvette of the spectrophotometer for the determination of optical densities at different wavelengths, viz. 750, 664, 647 and 630 nm, the maximum absorption wave length of the pigments. All the extinction values were corrected for a small turbidity blank by subtracting the optical density of 750nm from the 665, 645 and 630nm absorptions. The following equation was used to calculate the chlorophyll *a* concentration (Strickland and Parsons, 1965).

$$\text{Chlorophyll } a \text{ (C)} = 11.85\, E665 - 1.54\, E645 - 0.08\, E630$$

Where 'E' is the absorbance at different wavelengths in the respective wavelengths.

$$\text{Chlorophyll } a\ \mu\text{g/ litre} = \frac{C \times v}{V \times 1}$$

Where 'v' is volume of acetone (ml), 'V' is volume of water (litre) filtered and 'I' is the path length (cm) of cuvette.

2.3.2 Phytoplankton analysis

Phytoplankton samples for quantitative and qualitative analyses were collected by filtering ~50 litres of surface water through 20µ bolting silk and the filtrate preserved in 1-3% neutralized formaldehyde/ Lugol's iodine solution. Prior to the preservation the live sample was analysed and microphotographs were taken. Quantitative analysis involved calculation of the number of cells of each species of phytoplankton in one liter of sea water. Quantitative estimation of phytoplankton was done by employing Sedgewick-Rafter counting cell. The total number of microphytoplankton cells present was calculated per litre using the formula (Santhanam *et al.*, 1989)

$$N = \frac{n \times v}{V}$$

Where,

N = Total number of microphytoplankton cells present per litre
n = Number of microphytoplankton cells in one ml
v = volume of plankton sample preserved in ml
V = Total volume of water filtered in litre

For studying the vertical distribution of phytoplankton 250 ml of water samples from standard depths (0, 10, 20, 30, 50, 75, 100 and 120m) were collected using the Niskin bottles attached to CTD and preserved with formalin/Lugol's iodine solution. Species identification was done employing Nikon Eclipse E200 light microscope using standard identification keys (Allen and Cupp, 1935; Venkataraman, 1939; Cupp, 1943; Desikachary, 1959; Hendey, 1964; Desikachary *et al.*, 1987; Subrahmanyan, 1946, 1959a, 1959b, 1968, 1971; Subrahmanyan and Sharma, 1960; Hallegraeff *et al.*, 1995; Tomas, 1997; Karlson *et al.*, 2010). For Scanning Electron Microscope (SEM) analysis diatoms cells were cleaned (Hasle and Fryxell, 1970) and microphotographed using JEOL Model JSM 6390 LV SEM at an accelerating voltage of 20kV.

2.4 Statistical analysis

PRIMER V.6 was used for univariate and multivariate statistical analysis and plotting of data. The bivariate correlation of environmental parameters with the biological parameters and phytoplankton density was carried out and Pearson correlation coefficient was found in both the cases using SPSS (7.5) software. GRAPHER 8, SURFER 11 and ORIGIN 7 were used for suitable graphical representations

2.4.1 Univariate analysis

Shannon – Wiener index

For measuring the variation in phytoplankton species diversity of the region diversity index (H') was calculated using the Shannon- Wiener's formula (1949)

$$H' = -\sum_{i=1}^{S} Pi \log 2\ Pi \ldots\ldots \qquad ..$$

which can be rewritten as

$$H' = \frac{3.3219\ (N \log N - \sum ni - \log ni}{N}$$

where, H'= species diversity in bits of information per individual

ni = proportion of the samples belonging to the ith species (number of individuals of the ith species)

N = total number of individuals in the collection and

$\sum$ = sum.

Simpson index (λ')

Simpson index assigns to the measure of dominance in a community

λ' = Sum(Ni*(Ni-1)/N*(N-1))

N is the number of individuals in each sample

Margalef's species richness (d)

Margalef's species richness is a measure of the number of species present, making some allowance for the number of individuals belonging to each species. It was calculated according to the formula,

Species richness (Margalef): d = (S-1)/ log (N)

Where, S= Number of species,

N= Number of individuals

Pielou’s evenness index (J’)

The equitability (J’) was computed using the following formula of Pielou (1966):

$$J' = \frac{H'}{\log_2 S} \text{ or } \frac{H'}{\ln S}$$

where, J' = evenness,

H' = species diversity in bits of information per individual and S = total number of species

Species-Abundance distributions

Dominance plot

Dominance plot are used for abundance, biomass, %cover or other biotic measure representing quantity of each taxon (Clarke and Warwick, 2001).

The k-dominance plot

k-dominance plot shows the cumulative percentage (the percentage of the k-th most dominant plus all more dominant species) in relation to species (k) rank or log species (k) rank. The cumulative curve is used for comparing the biodiversity. When k-dominance curve is used for comparing the biodiversity between many habitats, it is called as multiple k-dominance curves.

2.4.2 Multivariate methods

Multivariate methods of classification and ordination were used to compare communities on the basis of the identity of the component species as well as their relative importance in terms of abundance or biomass.

Cluster analysis:

Cluster analysis was done to find out similarities in the abundance and distribution of microphytoplankton between years and between phases within the years. SIMPER analysis (analysis of similarity percentages) was then performed to identify the species/ groups which contributed to this clustering (Clarke, 1993). Seasonal abundance data were fourth root transformed and a triangular matrix of similarities between samples was derived using the Bray-Curtis similarity coefficient. The similarity matrix was then subjected to cluster analysis. Bray- Curtis coefficient (Bray and Curtis, 1957) was calculated by the following formula:

$$S_{jk} = 100 \left\{ 1 - \frac{\sum_{i=1}^{p} \left| y_{ij} - y_{ik} \right|}{\sum_{i=1}^{p} (y_{ij} + y_{ik})} \right\}$$

$$= 100 \; \frac{\sum_{i=1}^{p} 2 \min(y_{ij}, y_{ik})}{\sum_{i=1}^{p} (y_{ij} + y_{ik})}$$

where, y_{ij} represents the entry in the i th row and j th column of the data matrix i.e.

the abundance or biomass for the i th species in the j th sample;
y_{ik} is the count for the i th species in the k th sample;
l … l represents the absolute value of the difference;
‘min’ stands for, the minimum of the two counts and
∑ represents the overall rows in the matrix.

In the resulting dendrogram, the seasons in the same cluster have more similar species/ group composition than seasons in different clusters. All these analysis were performed using PRIMER v6 software (Clarke and Warwick, 1994).

Chapter 3

Microphytoplankton community structure during winter monsoon 2009

"Nothing in the sea falls haphazard; if we cannot predict, it is because we do not know the cause, or how the cause works..."
-Henry Bryant Bigelow, Oceanographer

Introduction

Primary producers form the base of marine trophic level. The structure of phytoplankton community, the major primary producers is directly or indirectly influenced by the ambient environmental conditions. North Eastern Arabian Sea (NEAS) experienced a moderate level of winter convection during the year 2009 with lower sea surface temperatures, deeper mixed layers and thereby eutrophication of water column. These convective mixing supported flourishing of microphytoplankton along the open ocean waters of NEAS. A three phase analysis of the winter monsoon responses along the region with emphasis on the community structure of microphytoplankton and their short term variations are detailed in this chapter.

3.1. Phase- 1 (Early February 2009)

3.1.1. Physico- chemical characteristics

During the study period, northeasterly winds (ave.5.5 m/s) prevailed in the region. The weather condition (cold, dry, strong north easterly winds and clear sky) in the transect 21°N and 22°N latitudes represented the general characteristic feature of the winter monsoon (NE monsoon). The atmospheric pressure was normal and varied between 1005.6 mb to 1014.6 mb and air temperature was ~24ºC. Sea surface temperatures (SST) in the open ocean waters were ~24.6ºC along 22ºN and were slightly lower towards coastal waters ~24.3ºC. SST increased towards south that reached to ~25ºC along 21ºN and 27ºC at 18ºN (ref station) (Figure 3). Sea Surface Salinity (SSS) increased towards north (36.5) and reached ~35.7 along southern extent (Figure 4). Vertical distribution of temperature and salinity showed well mixed waters with a deep mixed layer depth (MLD) of 91m along the offshore waters of 22ºN latitude (Figure 5). Surface distribution of nutrients was maximum along the offshore regions of 22ºN latitude. Inorganic nitrate (NO_3-N) concentrations were ~1.8 µmol L^{-1} along the open waters of 22ºN and were negligible towards the coastal waters. Nitrate distribution was almost uniform upto 50m and beyond which nitracline was observed (Figure 6). Nitrate value decrease southward and was 0.2 µmol L^{-1} at 21° N open ocean region and <0.1 µmol L^{-1} towards south (ref. station).

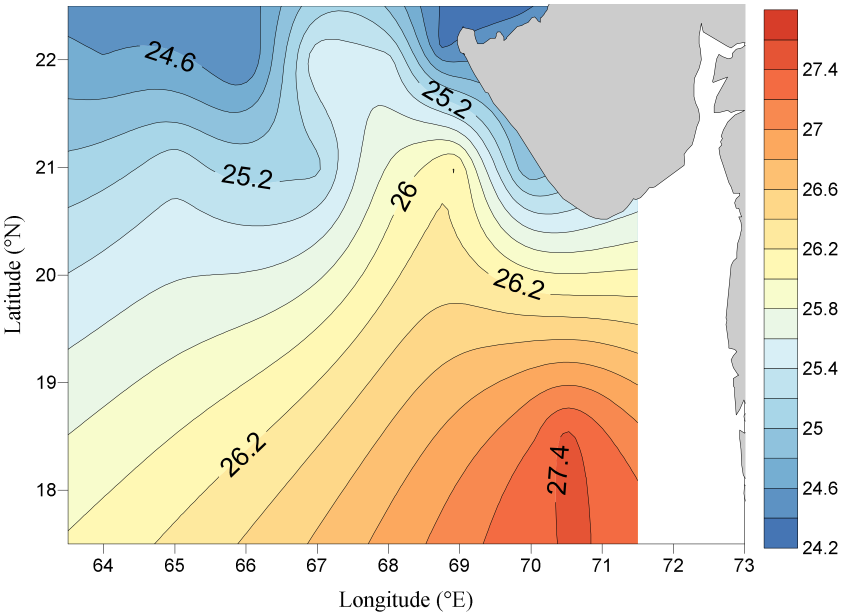


Figure 3. Distribution of SST (ºC) along the NEAS during Phase-1 of winter monsoon 2009

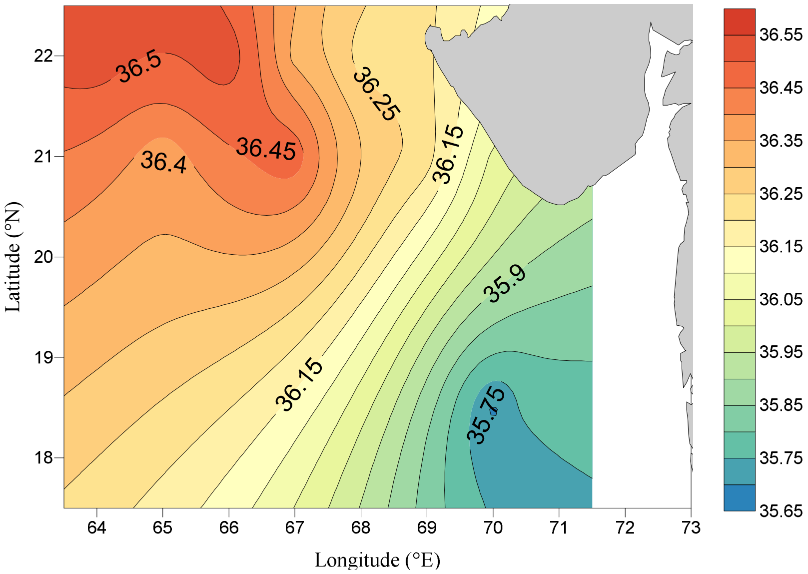
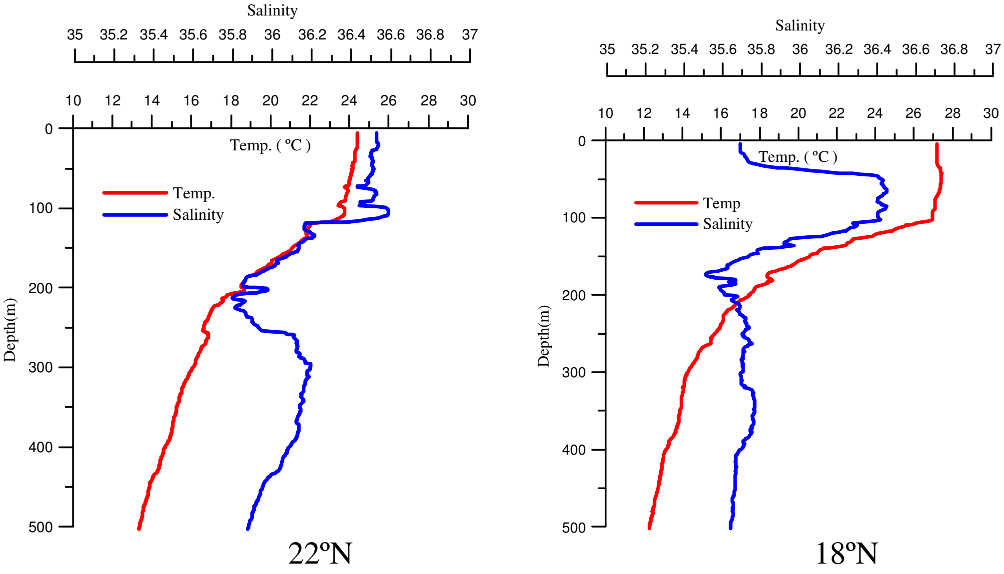


Figure 4. Distribution of Sea Surface Salinity along the NEAS during Phase-1 of winter monsoon 2009



22ºN

18ºN

Figure 5. Vertical profiles of Temp (ºC) and Salinity in the regions of intense convective mixing along NEAS (22ºN) and reference station without mixing (18ºN)

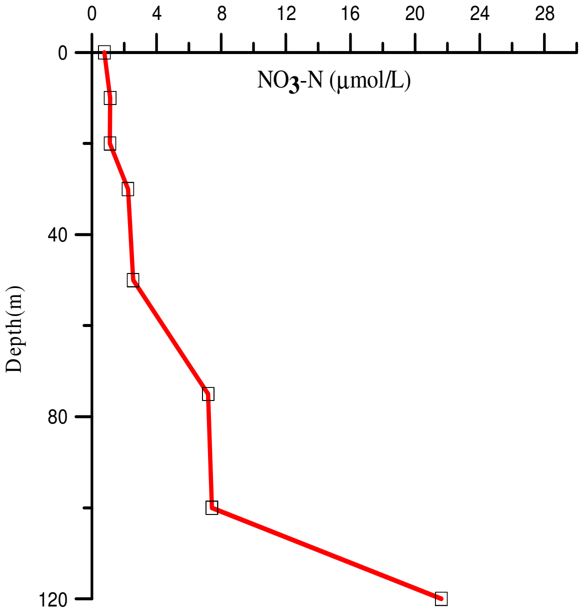


Figure 6. Vertical profiles of Nitrate (NO_3-N) in the regions of intense convective mixing along NEAS

3.1.2. Chlorophyll *a*- Phytoplankton biomass

The average surface chlorophyll *a* along NEAS during Phase-1 was 1.04 ± 0.55 mg m^{-3}. Open ocean waters of northern latitudes (22ºN and 21ºN) observed comparatively higher surface chlorophyll *a* (1.48 ± 0.3 mg m^{-3}). Towards the coastal waters, average chlorophyll *a* concentrations were 1.04 ± 0.02 mg m^{-3}. Regionally, surface chlorophyll *a* concentrations were high along the open ocean waters (Figure 7) of 22ºN latitude (2.9 mg m^{-3}) and the coastal chlorophyll *a* values reached to 1.3 mg m^{-3}. The values decreased towards south, with 1.26 mg m^{-3} along the offshore waters and 1.06 mg m^{-3} in the coastal regions of 21ºN latitude. A subsurface chlorophyll maxima (SCM) was not observed throughout the NEAS during the study period. In region along 18ºN latitude (ref station) the surface chlorophyll *a* concentrations were 0.17 mg m^{-3}, showing a decreasing trend towards south.

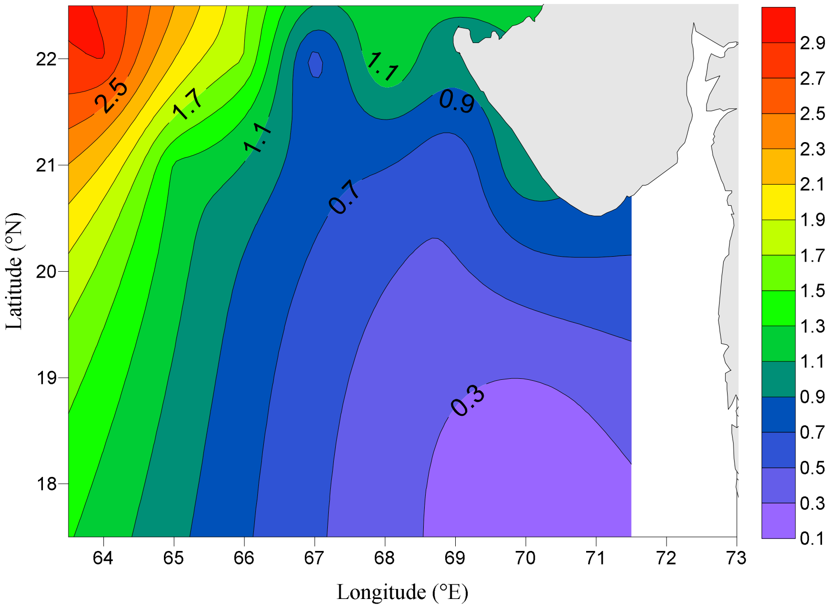


Figure 7. Distribution of surface chlorophyll *a* (mg m^{-3}) along the NEAS during Phase-1 of winter monsoon 2009

3.1.3. Phytoplankton cell density- numerical abundance and diversity

Open ocean waters of NEAS observed fairly higher total phytoplankton cell density (TCD) and were represented mainly by diatoms (93%). Maximum phytoplankton abundance was observed along the offshore regions of 22ºN latitude (1.2x 10^4 cells L^{-1}) and diatoms dominated (97%) the phytoplankton community (Figure 8). Along the open ocean waters of 21ºN latitude the total cell density were reaching up to 1.1x 10^4 cells L^{-1} with a diatom cell density of 10.1x 10^3 cells L^{-1}. Dinoflagellate cell density was recorded to be maximum along the coastal regions of 21ºN (6% of total cell density). Towards south, the TCD was lesser both inshore (0.4x 10^3 cells L^{-1}) as well as offshore (1x 10^3 cells L^{-1}) in comparison to northern latitudes. Around 53 species of microphytoplankton were identified during the phase.

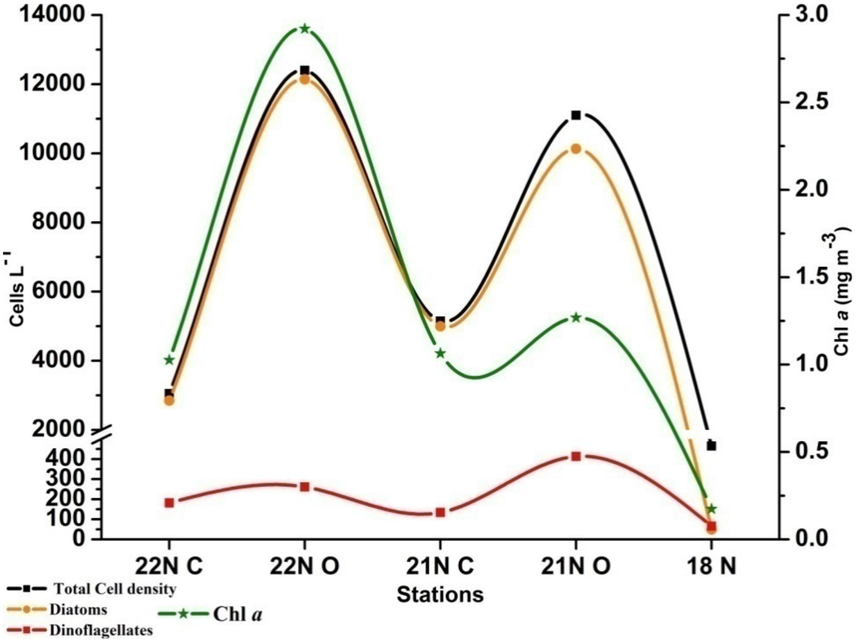


Figure 8. Variations in phytoplankton cell densities and Chlorophyll *a* along the NEAS during Phase- 1 of winter monsoon 2009

The diversity indices obtained for different stations during 3 phases were given in Table 2. The diversity of phytoplankton was found to be maximum towards the coastal waters (H’ 3.5) with lesser dominance index (λ’ 0.13) and having comparatively even distribution (j’ 0.7). However along the offshore areas comparatively lesser diversity was observed with the least along the offshore waters of 22ºN (H’ 2.3). The region was also characterised by higher dominance (λ’ 0.3). Along the southern region 18ºN with few phytoplankton density the diversity was low (H’=1.57) with an increased dominance (D=0.57)

Phase	Area	Shannon-Weiner Diversity (H’)	Simpsons Dominance Index (λ’)	Margalef’s species richness (d)	Pielous's evenness (j’)
1	22° N coast	3.612358	0.137	3.863152	0.722472
	22° N offshore	2.342562	0.313	2.015784	0.542018
	21° N coast	3.411503	0.154	3.625629	0.682301
	21° N offshore	3.28699	0.199	3.886259	0.630966
	Ref Stn.(18°N)	1.573902	0.573	1.628124	0.45496
2	22° N coast	2.299958	0.308	1.215944	0.725556
	22° N offshore	0.726483	0.840	1.722371	0.177734
	21° N coast	3.276276	0.23	3.119024	0.697015
	21° N offshore	1.654845	0.387	1.198951	0.434644
	Ref Stn.(18°N)	2.313525	0.436	2.844603	0.526721
3	22° N coast	3.855978	0.12	3.011143	0.83034
	22° N offshore	1.799153	0.38	1.34359	0.501861
	21° N coast	3.360308	0.186	2.623968	0.714892
	21° N offshore	1.125481	0.690	1.127575	0.338804
	Ref Stn.(18°N)	1.302693	0.652	1.31589	0.39215

Table 2. Diversity indices of phytoplankton community during winter monsoon 2009

3.1.4. Phytoplankton community assemblage

Diatom dominated the phytoplankton community (97%) and was composed of mainly centric forms (Subclass- Coscinodiscophycidae). They consisted about 72% of the total diatom assemblage (Figure 9a). *Rhizosolenia hebetata, Chaetoceros lorenzianus, Guinardia striata* were the major centrales present throughout the area. Another class of diatoms, raphid pennates (Subclass- Bacillariophycidae) were observed in significant cell densities (25%) and was the dominant class in certain regions. Raphid pennates were mainly contributed by *Nitzschia longissima*, *Navicula* sp., *Pseudo-nitzschia* spp., Araphid pennate diatoms (Subclass- Fragilariophycidae) were also present in a smaller proportion (3%) in the diatom community represented mainly by *Thalassiothrix longissima*. Dinoflagellate population was generally dominated by armoured dinoflagellates (Subclass- Peridiniphycidae) (Figure 9b) composed mainly of Order Gonyaulacales (*Gonyaulax polygramma* and *Ceratium* spp.) and Peridiniales (*Protoperidinium* spp.)

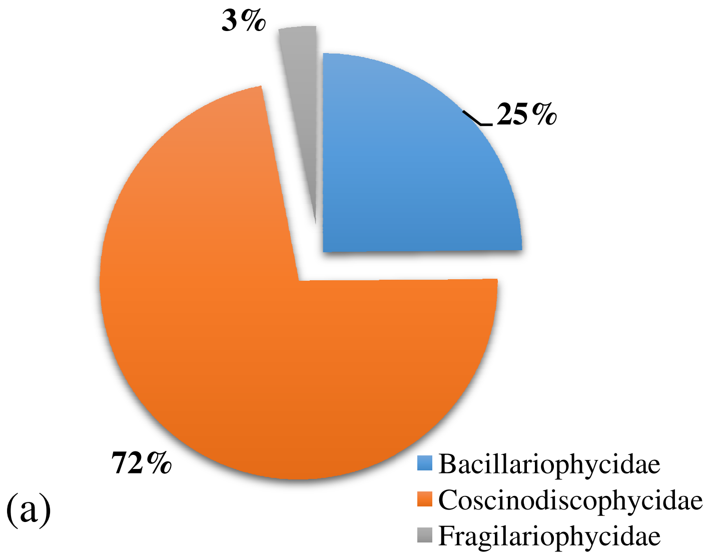


Figure 9a. Percentage composition of major subclass of diatoms along the NEAS during Phase 1 of winter monsoon 2009

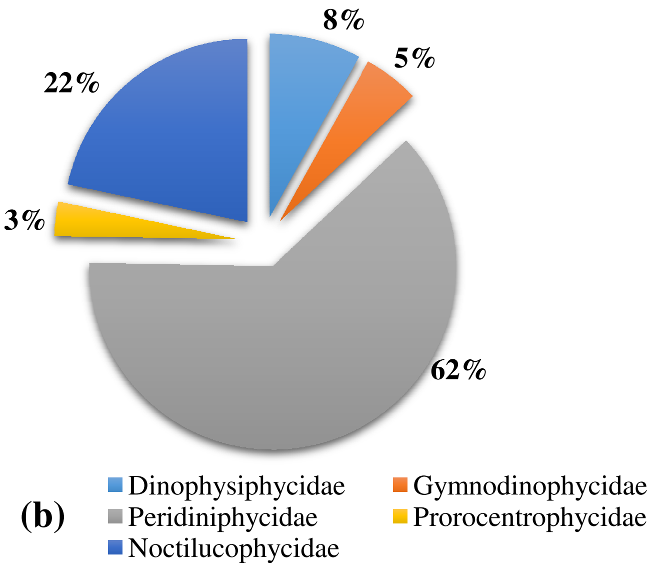


Figure 9b. Percentage composition of major subclass of dinoflagellates along the NEAS during Phase 1 of winter monsoon 2009

Along the offshore waters of 22ºN latitude where the highest cell densities were observed, the diatom *R. hebetata* was abundant (74 %) (Figure 10) with cell density 6.3x 10^3 cells L^{-1}. These cells were observed as extensive assemblage resembling mates and hence called "*Rhizosolenia* mats" (Plate 1). The dinoflagellate *Noctiluca scintillans* was also present in the region with cell density 173 cells L^{-1}. Microscopic investigation of the cells revealed that the *N. scintillans* cells were in an active dividing stage and can be considered as a phase before the formation of an intense bloom. Coastal waters of 21ºN and 22ºN latitudes as well as the reference station along 18ºN latitude were devoid of *N. scintillans*. Other diatoms present along with *R. hebetata* were *Nitzschia longissima* (2.1x 10^3 cells L^{-1}), *Navicula* sp (4.4x 10^2 cells L^{-1}), *Chaetoceros lorenzianus* (1.6x 10^3 cells L^{-1}), *Haslea* spp. etc. Dinoflagellate *Gonyaulax polygramma* was observed along the offshore region in association with *Noctiluca scintillans* (Figure 11). The toxic diatom *Pseudo-nitzschia seriata* was also present with a fewer cell densities (~700 cells L^{-1}) throughout the study area. Along the coastal waters of 22ºN latitude the diatoms dominated the phytoplankton community and was mainly represented by *Guinardia striata* (800 cells L^{-1}) *Chaetoceros lorenzianus* (420 cells L^{-1}), *Navicula directa* (262 cells L^{-1}), *R. hebetata* (552 cells L^{-1}) etc. Dinoflagellates present in the region were few cells of *Protoperidinium* sp., *Protoperidinium oceanicum, Ceratium furca* and *C. fusus*.

Along the coastal waters of 21ºN latitude diatoms dominated the phytoplankton community with *Pseudo-nitzschia seriata* (1.6x 10^3 cells L^{-1}) as the major species present. *Chaetoceros lorenzianus* (850 cells L^{-1}), *Guinardia striata* (541 cells L^{-1}), *Nitzschia longissima* (317 cells L^{-1}), *Rhizosolenia hebetata* (586 cells L^{-1}) were the other diatoms present. Along the offshore waters the diatoms present in the order of abundance were *R. hebetata* (2.7x 10^3 cells L^{-1}), *C. lorenzianus* (850 cells L^{-1}), *P. seriata* (600 cells L^{-1}) etc. Dinoflagellates present in the coastal waters were composed mainly of

Protoperidinium sp. but was a more diverse community along the offshore waters. *Protoperidinium oceanicum* (100 cells L^{-1}), *Noctiluca scintillans* ~50 cells L^{-1}, *Gonyaulax polygramma* and *Ceratium* spp. were the major dinoflagellates present.

Phytoplankton abundance decreased (~500 cells L^{-1}) in the southern part of the study area (18ºN). *Trichodesmium erythraeum* (Class- Cyanophyceae) was dominant and contributed significantly (70%) of the phytoplankton population of this region. Both diatom as well as dinoflagellate cell densities were lesser. Diatom community consisted of few cells of *Chaetoceros lorenzianus Nitzschia longissima, R. hebetata* and *Thalassiosira* sp. along the offshore regions. Dinoflagellate community consisted of *Protoperidinium* sp., *Gonyaulax polygramma*, *Ceratium* spp. and *Prorocentrum lima*.

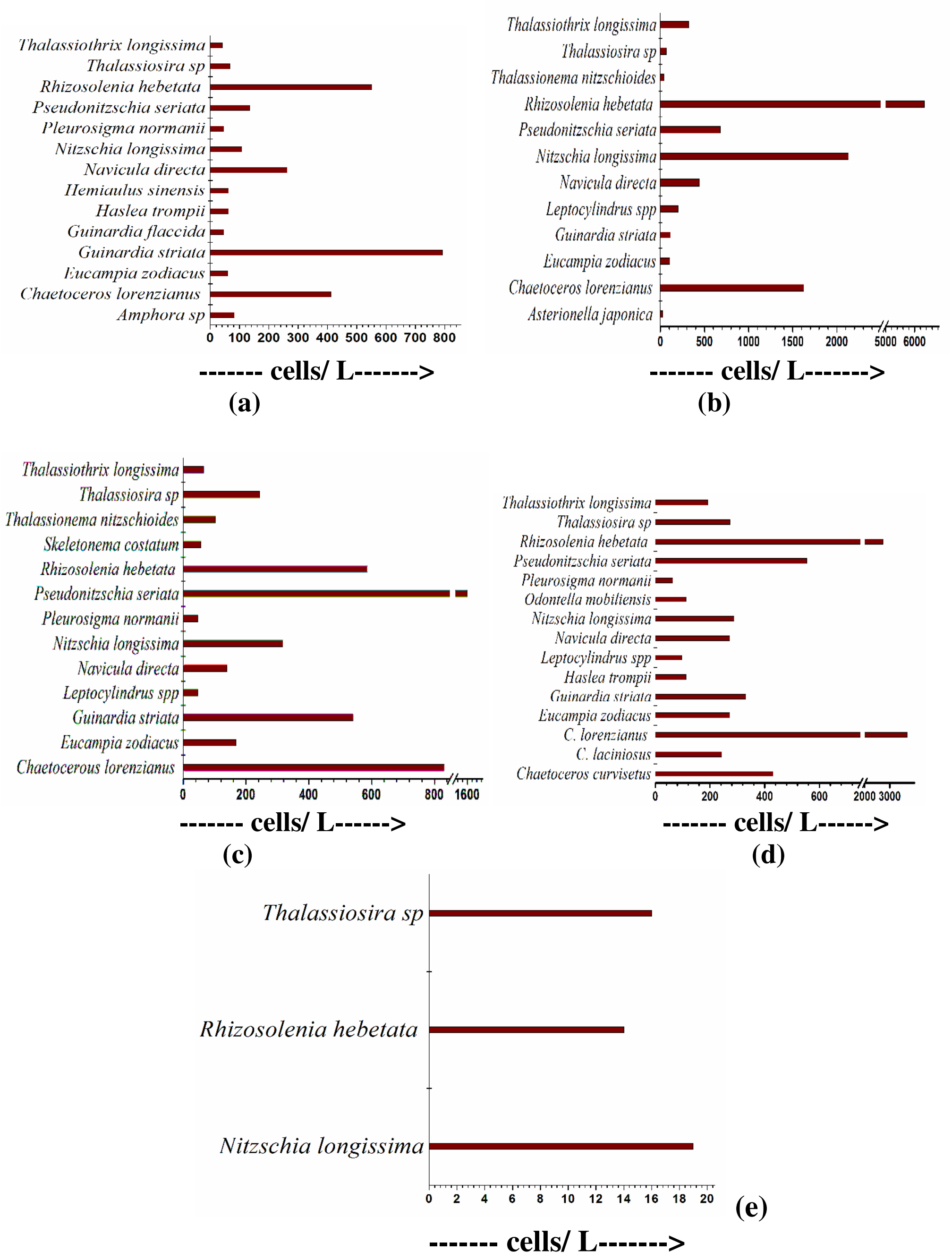


Figure 10. Community composition of diatoms along different stations during Phase 1 of winter monsoon 2009, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

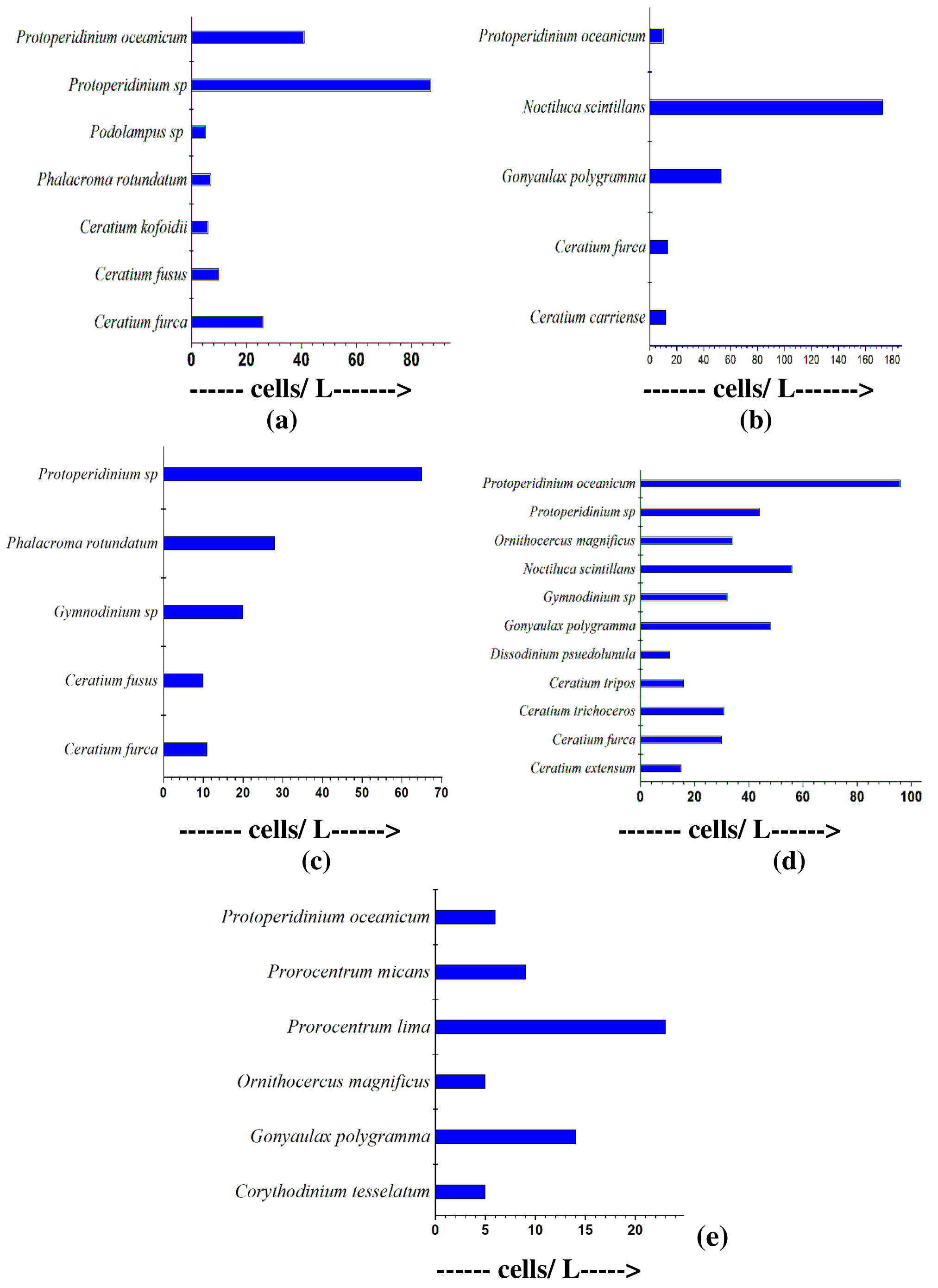


Figure 11. Community composition of dinoflagellates along different stations during Phase 1 of winter monsoon 2009, **(a)** 22°N Coastal **(b)** 22°N Offshore **(c)** 21°N Coastal **(d)** 21°N Offshore **(e)** 18°N reference

3.2. Phase- 2 (Mid February- early March 2009)

3.2.1. Physico-chemical characteristics

During the study period no consistency was observed in the wind pattern; however it was north to north-westerly with an average speed of 5.1 m/s. Atmospheric pressure varied between 1009 to 1012 mb and the wind observed was cold and dry (Average humidity was 74.3% and low air temperature). The air temperature varied from 24.4 to 25.7°C along the northern offshore regions (22°N) and southward, 18°N (27°C). SST followed a similar pattern as that of the previous period with northern regions having lower SST (~25ºC) which increased towards south (27ºC) (Figure 12). Signatures of convective mixing were still evident along the northern regions with lower SST and high saline surface waters. SSS in the offshore regions reached to 36.5 whereas towards coastal waters surface salinity ranged from 36.1 to 36.2 (Figure 13). Along the southern region (18ºN) low saline surface waters (~ 35.65) were observed. The vertical profiles of SST and SSS showed that the depth of mixed layer (MLD) shoaled to ~ 45m during the period along the open ocean waters of NEAS (Figure 14). Towards the south (18ºN) sea surface temperature increased along with which salinity decreased and MLD shoaled up (20 m). Surface distribution of nitrate varied from 0.4 to 0.05 µmol L^{-1} from north to south.

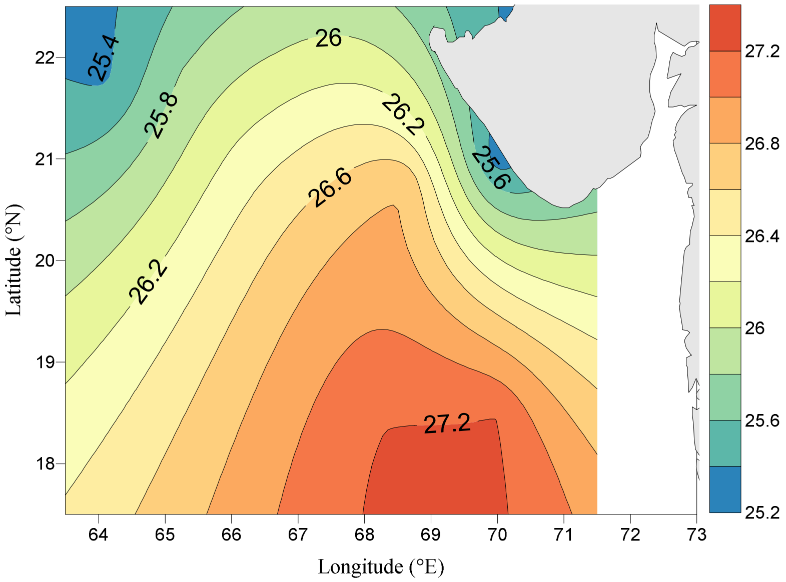


Figure 12. Distribution of SST (ºC) along the NEAS during Phase- 2 of winter monsoon 2009

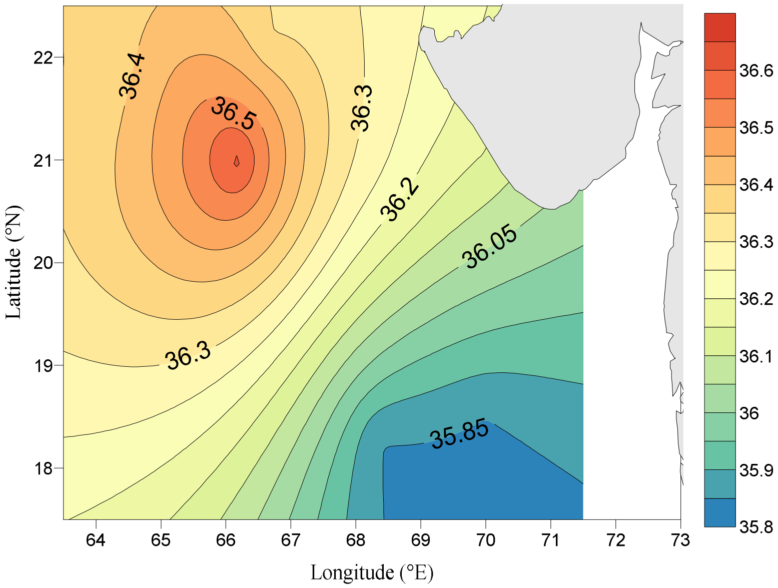


Figure 13. Distribution of Sea Surface Salinity (SSS) along the NEAS during Phase- 2 of winter monsoon 2009

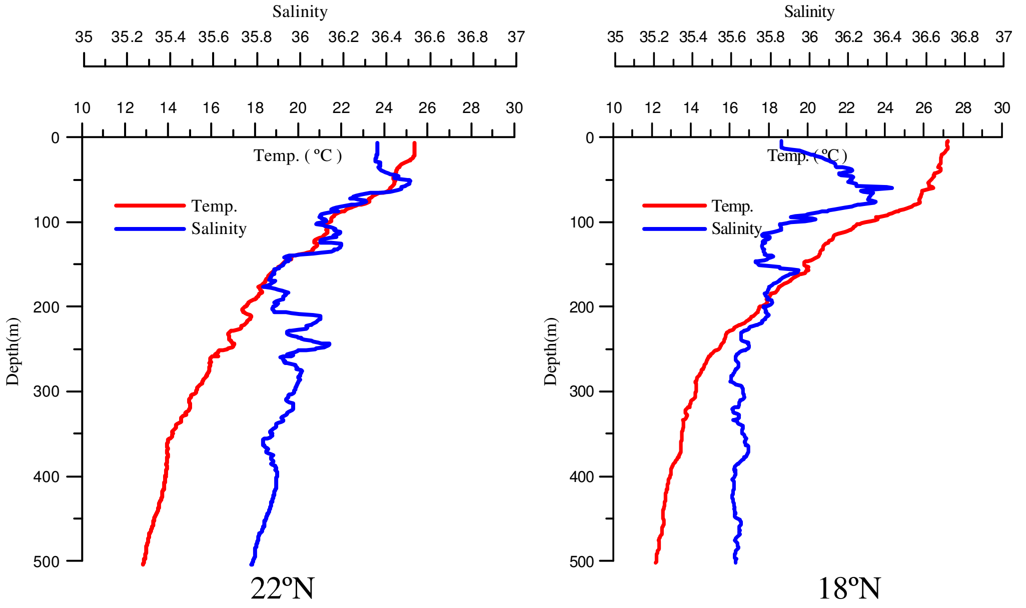


Figure 14. Vertical profiles of Temp (°C) and Salinity in the regions of intense convective mixing along NEAS (22°N) and reference station without mixing (18°N)

3.2.2. Chlorophyll *a*- Phytoplankton biomass

The average surface chlorophyll *a* concentrations along NEAS during the phase was 0.68 ± 0.4 mg m^{-3}. The open ocean waters observed an average chlorophyll *a* of 0.88± 0.2 mg m^{-3} and coastal waters were having 0.59 ± 0.8 mg m^{-3}. Maximum Surface chlorophyll *a* concentrations were observed along 21°N open ocean waters (1.6 mg m^{-3}). However the offshore areas of 22°N sustained low chlorophyll *a* (0.68 mg m^{-3}) (Figure 15). The coastal waters of 21°N observed higher surface chlorophyll *a* (1.6 mg m^{-3}). The surface chlorophyll *a* concentration decreased towards south 18°N (0.45 mg m^{-3}).

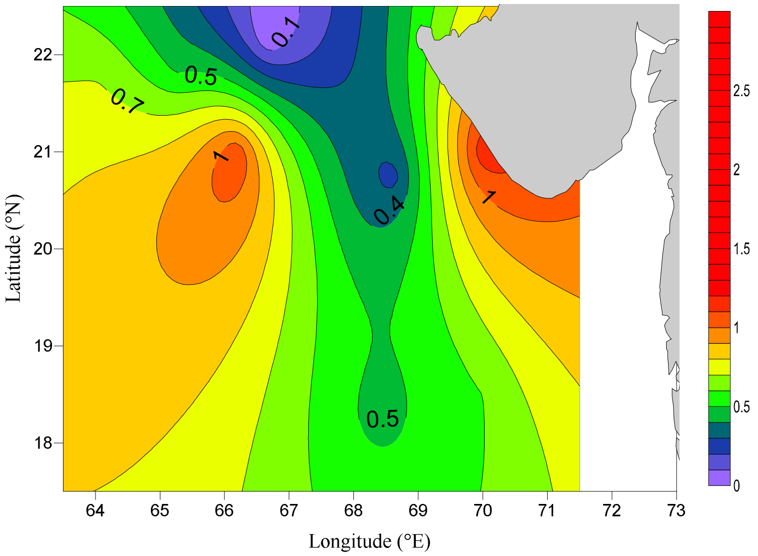


Figure 15. Distribution of surface Chlorophyll *a* (mg m^{-3}) along the NEAS during Phase- 2 of winter monsoon 2009

3.2.3. Phytoplankton cell density- numerical abundance and diversity

Phytoplankton assemblage was dominated by diatoms (60%) along NEAS. Offshore waters of 22°N and 21°N observed considerably high density of phytoplankton. Maximum cell densities were observed along the offshore waters of 21°N (5.1x 10^4 cells L^{-1}) (Figure 16). The region was characterised by the abundance of both diatoms (53%, 2.6x 10^4 cells L^{-1}) and dinoflagellates (47%, 2.4x 10^4 cells L^{-1}). Coastal waters of 21°N observed a total cell density of 3x 10^3 cells L^{-1} contributed mainly by diatoms (89%). Total cell densities, diatom cell densities (96%) and dinoflagellate cell densities (4%) along the offshore regions of 22°N were 1x 10^4 cells L^{-1}, 1x 10^4 cells L^{-1} and 1.6x 10^3 cells L^{-1} respectively. Cell densities were decreased towards 18°N latitude (1x 10^3 cells L^{-1}), there observed few filaments of blue green alga *Trichodesmium erythraeum* (740 filaments L^{-1}). A total of 44 species were observed.

The community of phytoplankton observed a diverse species assemblage with increased evenness towards the coastal. Maximum diversity was observed along the coastal waters of 21°N (H’ 3.27) with significant evenness (j’ 0.69). However towards the offshore waters diversity decreased and dominance increased. This variation was significant along the offshore areas of 22ºN with diversity (H') 0.72 and dominance (λ') 0.8.

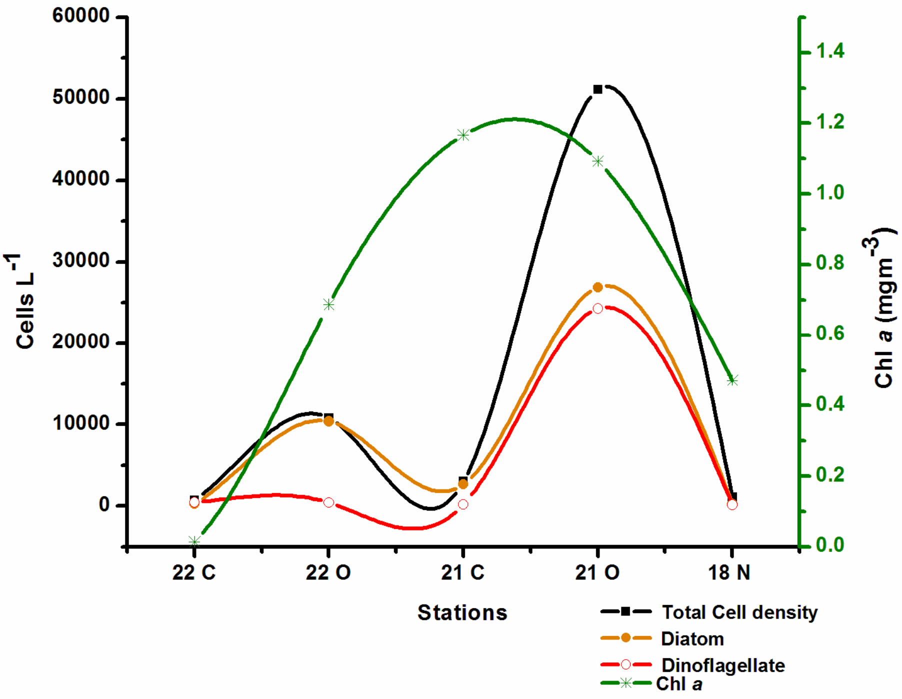


Figure 16. Variation in phytoplankton cell densities and Chlorophyll *a* along the NEAS during Phase- 2 of winter monsoon 2009

3.2.4. Phytoplankton community assemblage

During Phase-2, the dominance of diatoms (~60%) decreased along NEAS when compared to that of Phase-1 (97%), and the numerical abundance of dinoflagellates increased. This increase in dinoflagellate proportion was mainly due to the bloom of *Noctiluca scintillans* towards the offshore waters. Among the diatom class, the percentage contribution of raphid pennates (Subclass- Bacillariophycidae) increased and contributed nearly 54% of the phytoplankton community in the study area. The contributions of centric forms (Subclass- Coscinodiscophycidae) were ~45% and that of araphid pennates (Subclass- Fragilariophycidae) were ~1% (Figure 17a). Among the dinoflagellate community *Noctiluca scintillans* (Subclass- Noctilucophycidae) dominated by nearly 96% of the total dinoflagellates followed by armoured dinoflagellate (Subclass Peridiniphycidae) by ~ 3% (Figure 17b).

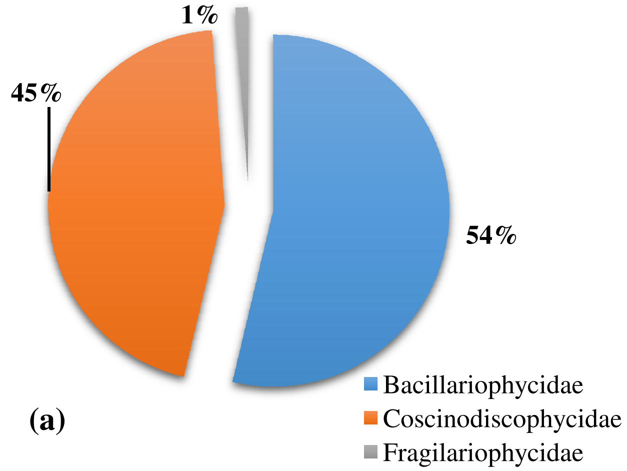


Figure 17a. Percentage compositon of major subclass of diatoms along the NEAS during Phase- 2 of winter monsoon 2009

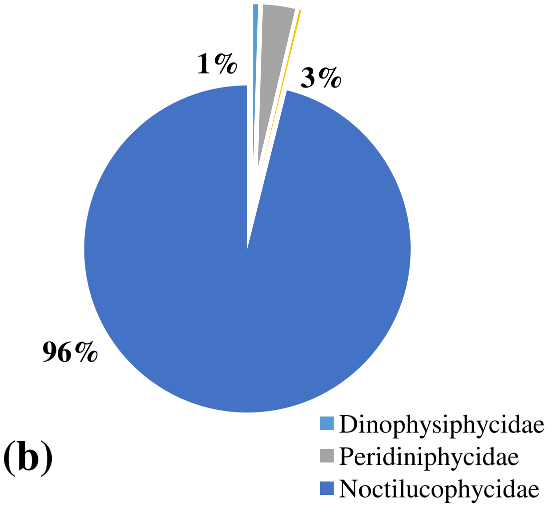


Figure 17b. Percentage compositon of major subclass of dinoflagellates along the NEAS during Phase- 2 of winter monsoon 2009

Dinoflagellate *Noctiluca scintillans* cells were present in bloom cell density (2.4x 10^4 cells L^{-1}) along the offshore regions of 21°N latitude. The region was also characterized by mucilaginous aggregations of pennate diatom *Navicula directa* (2x 10^4 cells L^{-1}) in along with *N. scintillans*. Centric diatoms

Rhizosolenia hebetata (3.6x 10^3cells L^{-1}) and *Thalassiosira* sp. (1.9x 10^3 cells L^{-1}) were also present in fairly high cell densities in the region. Community composition of diatoms along different regions of NEAS is shown in Figure 18. Along with *N. scintillans* other dinoflagellates present were *Gonyaulax polygramma* (140 cells L^{-1}), *Ceratium furca* (60 cells L^{-1}), *C. trichoceros* (Figure 19). Unlike that of 21ºN offshore areas, towards the offshore regions of 22ºN latitude, *R. hebetata* dominated (9x 10^3 cells L^{-1}, 97%) with a smaller proportion of *Chaetoceros lorenzianus* (100 cells L^{-1}). Dinoflagellates present in the region were mainly *N. scintillans* (143 cells L^{-1}), *Gonyaulax polygramma* (289 cells L^{-1}), *Ceratium extensum*, *C. trichoceros*, *C. declinatum* and *Oxytoxum tessellatum*.

Phytoplankton community along the coastal waters of northern region (22ºN) was dominated by dinoflagellate *N. scintillans* (375 cells L^{-1}). A few cells of centrales, *R. hebetata, R. hyalina* etc. were also present along with *N. scintillans*. Varying from that of north, 21ºN coastal water was dominated by diatoms mainly *Guinardia flaccida* (1x 10^3 cells L^{-1}) and a few cell densities of dinoflagellates, *Ceratium furca*, *Dinophysis hastata, Pyrodinium* sp. and *Gonyaulax polygramma. Trichodesmium erythraeum* filaments were also present at density of 124 filaments L^{-1}. Towards further south (18ºN) the dominant phytoplankton group was blue green algae *Trichodesmium erythraeum* (740 filaments L^{-1}). Other phytoplankton present in the region were *Grammatophora* sp., *Nitzschia longissima*, *Rhizosolenia hebetata*. Dinoflagellate community consisted of *Ceratium* spp., *Protoperidinium* sp. and *Gonyaulax* sp.

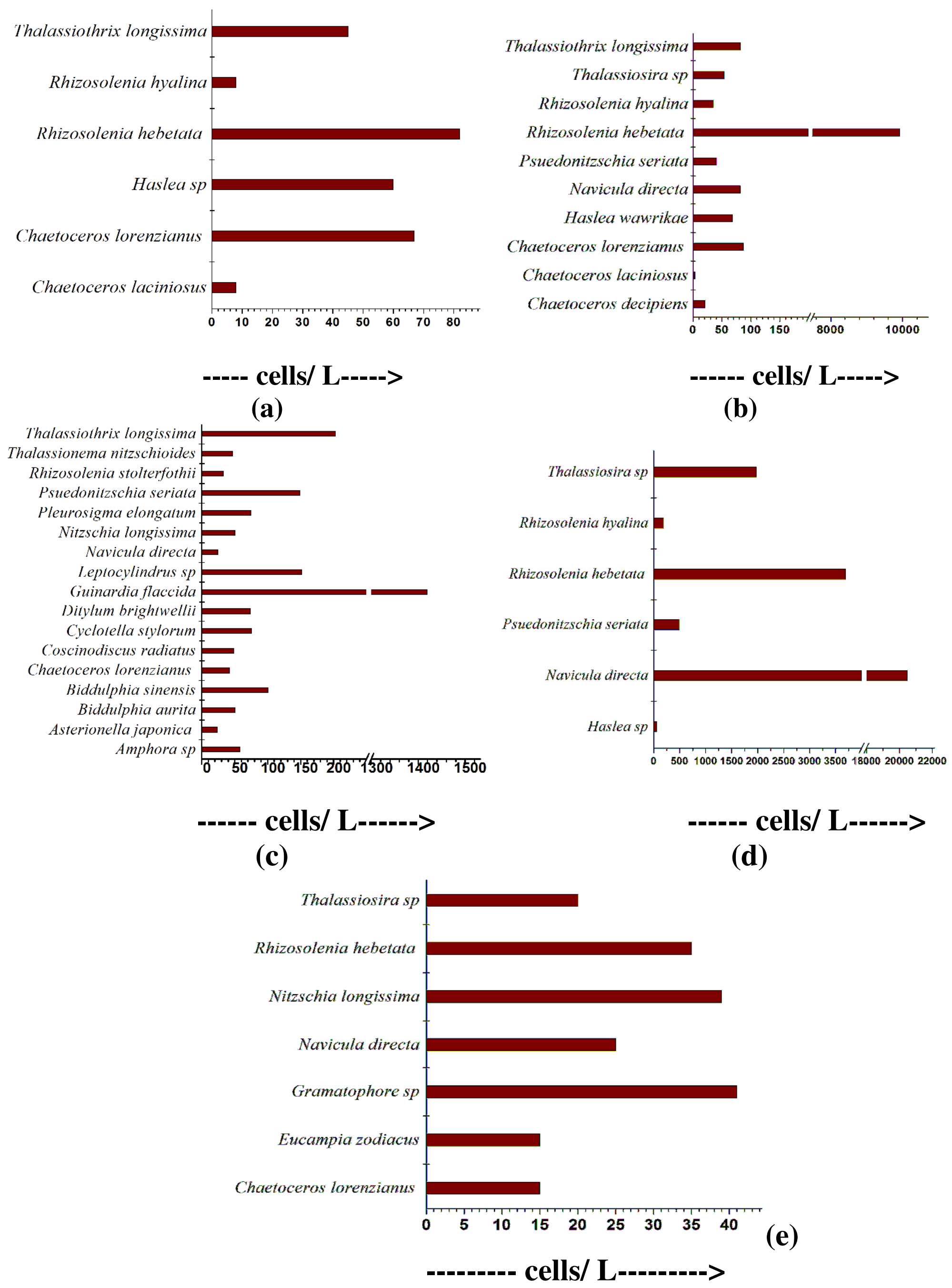


Figure 18. Community composition of diatoms along different stations during Phase- 2 of winter monsoon 2009, **(a)** 22°N Coastal **(b)** 22°N Offshore **(c)** 21°N Coastal **(d)** 21°N Offshore **(e)** 18°N reference

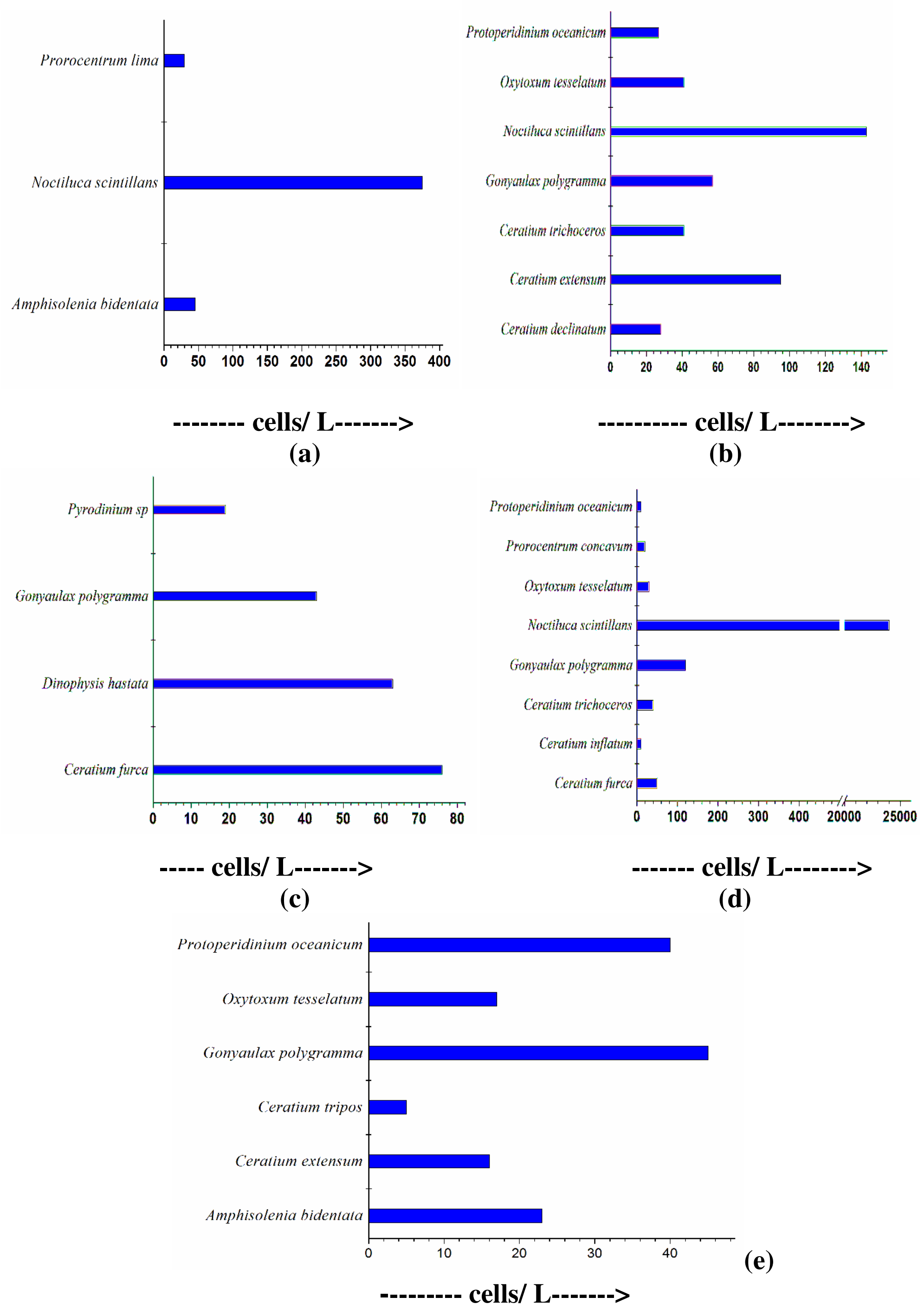


Figure 19. Community composition of dinoflagellates along different stations during Phase- 2 of winter monsoon 2009, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

3.3. Phase- 3 (Late March 2009)

3.3.1. Physico- chemical characteristics

Wind speed during the period of observation was ~3.5 m/s with an increased air temperature (~27ºC). Lower coastal SST (25.7ºC) prevailed along the northern most regions (22ºN) and towards the offshore it slightly increased (26.8ºC) (Figure 20). Vertical profiles also showed an up sloping of isotherms towards the coastal waters. Moving southwards along 21ºN there was not much variation in SST between the coastal (26.5ºC) and offshore (26.8ºC) water. Towards 18ºN latitude the sea surface temperature increased to 27.4ºC. High saline surface waters were observed along the offshore waters of 22ºN (36.5) and 21ºN (36.4) (Figure 21). Towards the south surface salinity decreased (35.8). The vertical profile of temperatures and salinity (Figure 22) observed shallow mixed layer (~28m) along the offshore regions of north. Surface nutrient distribution showed a nitrate concentration of 0.19 µmol L^{-1} along the northern offshore waters and 0.11 to 0.14 µmol L^{-1} along the coastal waters. The surface waters along the southern region (18ºN) were having nitrate concentrations of 0.05 µmol L^{-1}. The physico-chemical characters of the region show waning of winter characters and stabilisation of the water column.

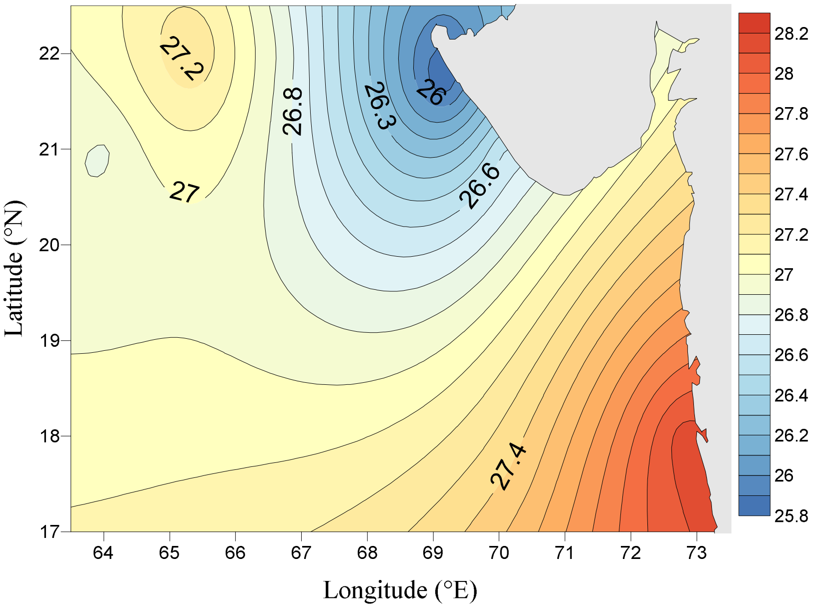


Figure 20. Distribution of SST (ºC) along the NEAS during Phase- 3 of winter monsoon 2009

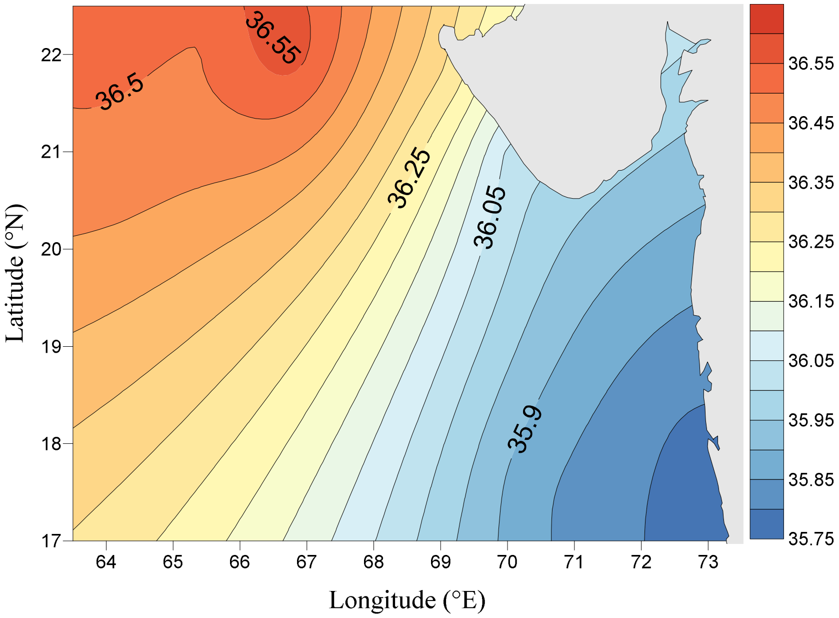


Figure 21. Distribution of sea surface salinity along the NEAS during Phase- 3 of winter monsoon 2009

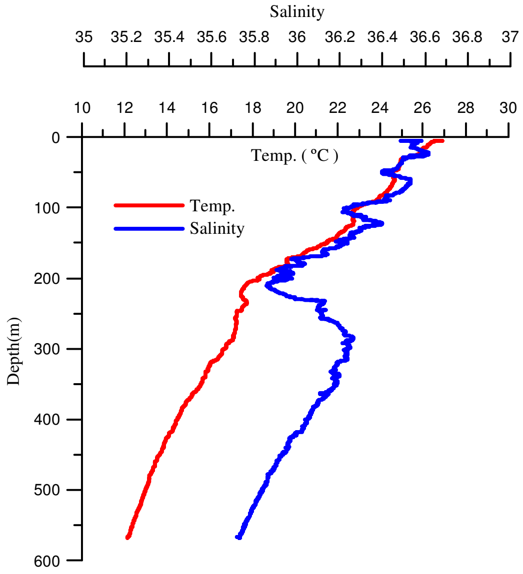


Figure 22. Vertical profiles of Temp. (°C) and Salinity along the open ocean waters off 22°N during Phase- 3

3.3.2. Chlorophyll *a*- Phytoplankton biomass

The average chlorophyll *a* along NEAS during Phase-3 was 1.14 ± 1.02 mg m^{-3}. Comparatively higher chlorophyll *a* was observed along the offshore areas 1.35 ± 0.8 mg m^{-3} but towards coast average chlorophyll *a* was 1.4 ± 1.5 mg m^{-3}. Chlorophyll *a* distribution showed an increasing trend during Phase-3 than Phase-2. Surface chlorophyll *a* along the offshore regions of 22°N and 21°N were 1.9 mg m^{-3} and 0.7 mg m^{-3} and decreased towards the coastal regions to 0.3 mg m^{-3} and 2.49 mg m^{-3} respectively (Figure 23). The surface chlorophyll *a* observed a further decrease along 18°N (0.22 mg m^{-3}).

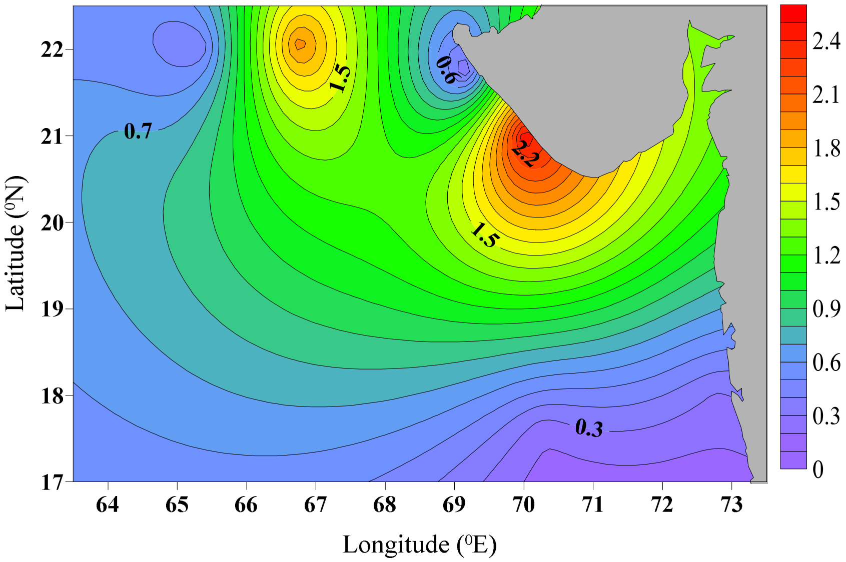


Figure 23. Distribution of surface Chlorophyll *a* (mg m^{-3}) along the NEAS during Phase-3 of winter monsoon 2009

3.3.3. Phytoplankton cell density- numerical abundance and diversity

Phytoplankton abundance decreased during Phase- 3 especially along the offshore waters. However coastal waters sustained high numerical abundance due to the presence of small diatoms. Diatoms contributed ~87% of the total phytoplankton community in the NEAS. Maximum abundance were observed towards the coastal regions of 21ºN latitude (13x 10^{3} cells L^{-1}) with diatom density 12x 10^{3} cells L^{-1} (Figure 24). Along the coastal waters of 22ºN latitude with total cell density 2.88x 10^{3} cells L^{-1}, diatoms were observed in a density of 2.83x 10^{3} cells L^{-1}. Towards the open ocean waters of NEAS, bloom of dinoflagellate *Noctiluca scintillans* was observed along the offshore areas of 22ºN with a density of 1.4x 10^{3} cells L^{-1}. Total cell density in the region was observed to be 3x 10^{3} cells L^{-1} with diatom cell density 1.9x 10^{3} cells L^{-1}. Along the coastal waters of 21ºN latitude filaments of blue green algae *Trichodesmium erythraeum* were observed (500 filaments L^{-1}), and were also present along the southern extend of the NEAS (18ºN). Phytoplankton cell densities were lower towards the south (18ºN) with total cell density of 9x 10^{2} cell L^{-1} in which diatoms dominated (8x 10^{2} cell L^{-1}) followed by dinoflagellates (1x 10^2 cell L^{-1}) and blue green algae (11 filaments L^{-1}). During the phase 46 species were identified. Microphytoplankton community was more diverse towards coastal waters (~3.5) than the offshore areas (~1.5) (Table 2).

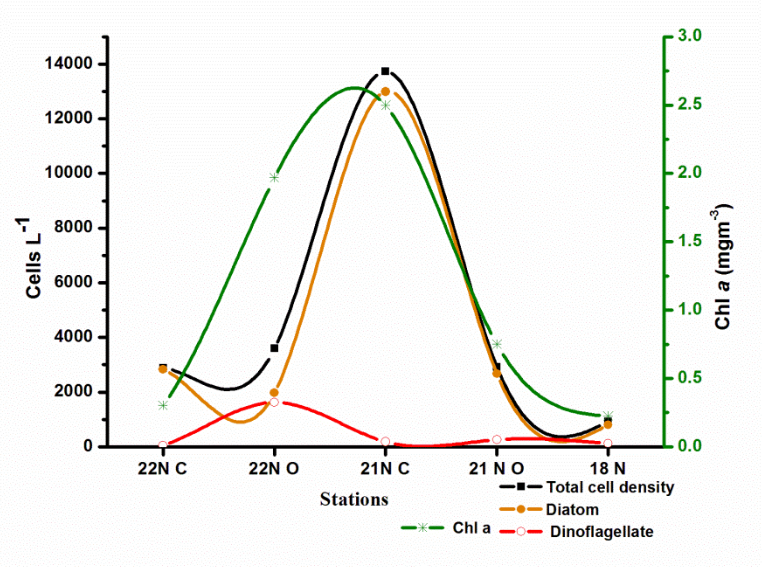


Figure 24. Variations in phytoplankton cell densities and Chlorophyll *a* along the NEAS during Phase- 3 of winter monsoon

3.3.4. Phytoplankton community assemblage

Diatoms formed the major class of phytoplankton during Phase-3 (87%). Among the diatom subclass, centric diatoms (Subclass- Coscinodiscophycidae) formed the predominant group of the community (52%). However raphid pennates (Subclass- Bacillariophycidae), 34% and araphid pennates (Subclass- Fragilariophycidae), 14% were also present in significant proportions (Figure 25a). Centrale *R. hebetata* was the major diatom species observed prominently towards the offshore waters whereas along the coastal regions the community was more evenly distributed with a highly diverse diatom community.

Among the dinoflagellates, *Noctiluca scintillans* (Subclass- Noctilucophycidae) was the major species present and was limited towards the offshore areas. Dinoflagellate contribution towards the TCD of NEAS was nearly 9%. The population of dinoflagellates excepting the offshore *Noctiluca* bloom were generally dominated by subclass Peridiniphycidae (Figure 25b) including *Gonyaulax polygramma*, *Ceratium* spp. and *Protoperidinium* spp.

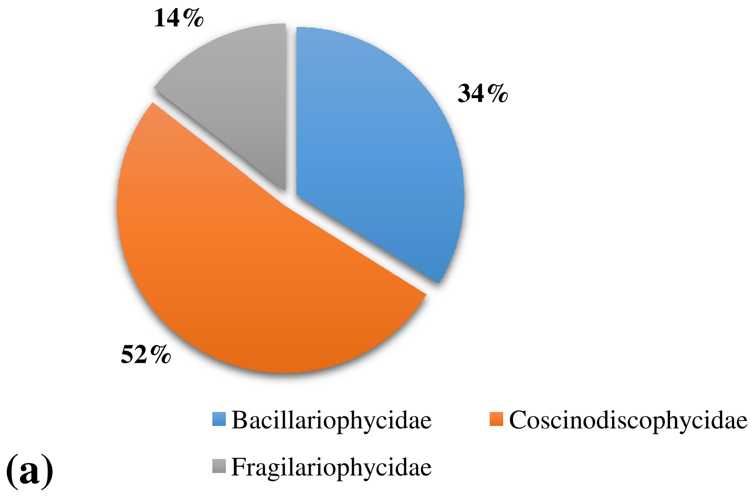


Figure 25a. Percentage composition of major subclass of diatoms along the NEAS during Phase- 3 of winter monsoon 2009

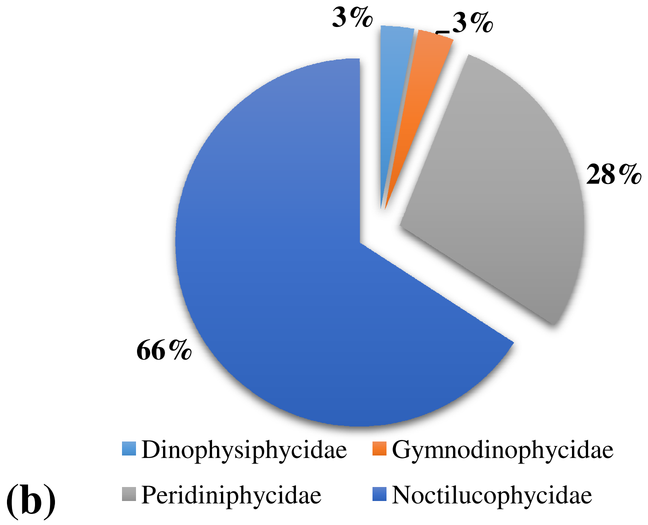


Figure 25b. Percentage composition of major subclass of dinoflagellates along the NEAS during Phase- 3 of winter monsoon 2009

Phytoplankton composition along the offshore region of 22ºN latitude was dominated by diatoms mainly *Rhizosolenia hebetata* (1.6x 10^3 cells L^{-1}) and a fewer cell densities of *Thalassiothrix longissima* (126 cells L^{-1}), *Navicula directa*, *Nitzschia longissima* and dinoflagellate community consisted of mainly *Noctiluca scintillans* (1465 cells L^{-1}), *Pyrophacus steinii* (81 cells L^{-1}), *Gonyaulax polygramma* (76 cells L^{-1}), *Ceratium furca* and *Protoperidinium oceanicum*. The coastal phytoplankton community in the region was supported by a diverse community of diatoms like *Guinardia flaccida* (347 cells L^{-1}), *Thalassiothrix longissima* (528 cells L^{-1}), *Leptocylindrus danicus* (330 cells L^{-1}), *Rhizosolenia hebetata* (343 cells L^{-1}) and *Pseudo-nitzschia* sp. (264 cells L^{-1}). The dinoflagellate community in the region was meagre with few cells of *Ceratium furca*, *Gonyaulax polygramma* and *Protoperidinium oceanicum*.

The phytoplankton community along the offshore region of 21ºN latitude was dominated by diatom *Rhizosolenia hebetata* (2.4x 10^3 cells L^{-1}). The community composition of diatoms along different regions of NEAS is shown in Figure 26. Dinoflagellates present in the region were very few consisting of *Ceratium furca* and *Gonyaulax polygramma* (Figure 27). The coastal phytoplankton community was abundant and diverse dominated by diatoms mainly *Pseudo-nitzschia seriata* (5x 10^3 cells L^{-1}), *Thalassiothrix longissima* (1.6x 10^3 cells L^{-1}), *Guinardia flaccida* (1x 10^3 cells L^{-1}) *Chaetoceros curvisetus* (910 cells L^{-1}) and dinoflagellates present were *Protoperidinium oceanicum* (125 cells L^{-1}), *Amphisolenia bidentata.* A few filaments of blue green algae *Trichodesmium erythraeum* (500 filaments L^{-1}) were also observed in the coastal waters. Towards the south (18ºN) diatoms dominated the phytoplankton community with *R. hebetata* (752 cells L^{-1}), *R. hyalina*, *R. alata* and dinoflagellates mainly *Ceratium furca*, *Ceratium fusus*, *Gonyaulax* sp. *Scrippsiella trochoidea*.

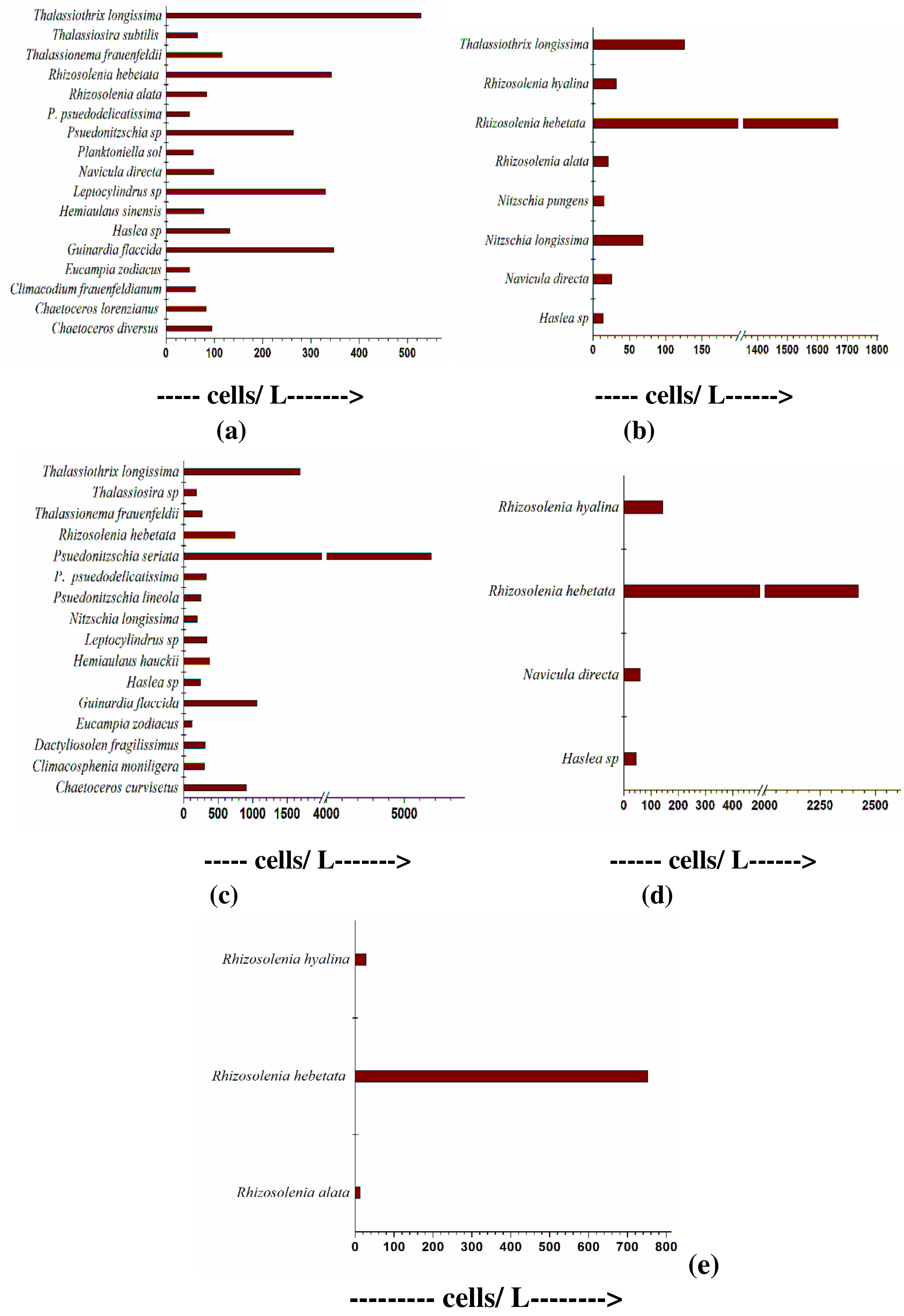


Figure 26. Community composition of diatoms along different stations during Phase 3 of winter monsoon 2009, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

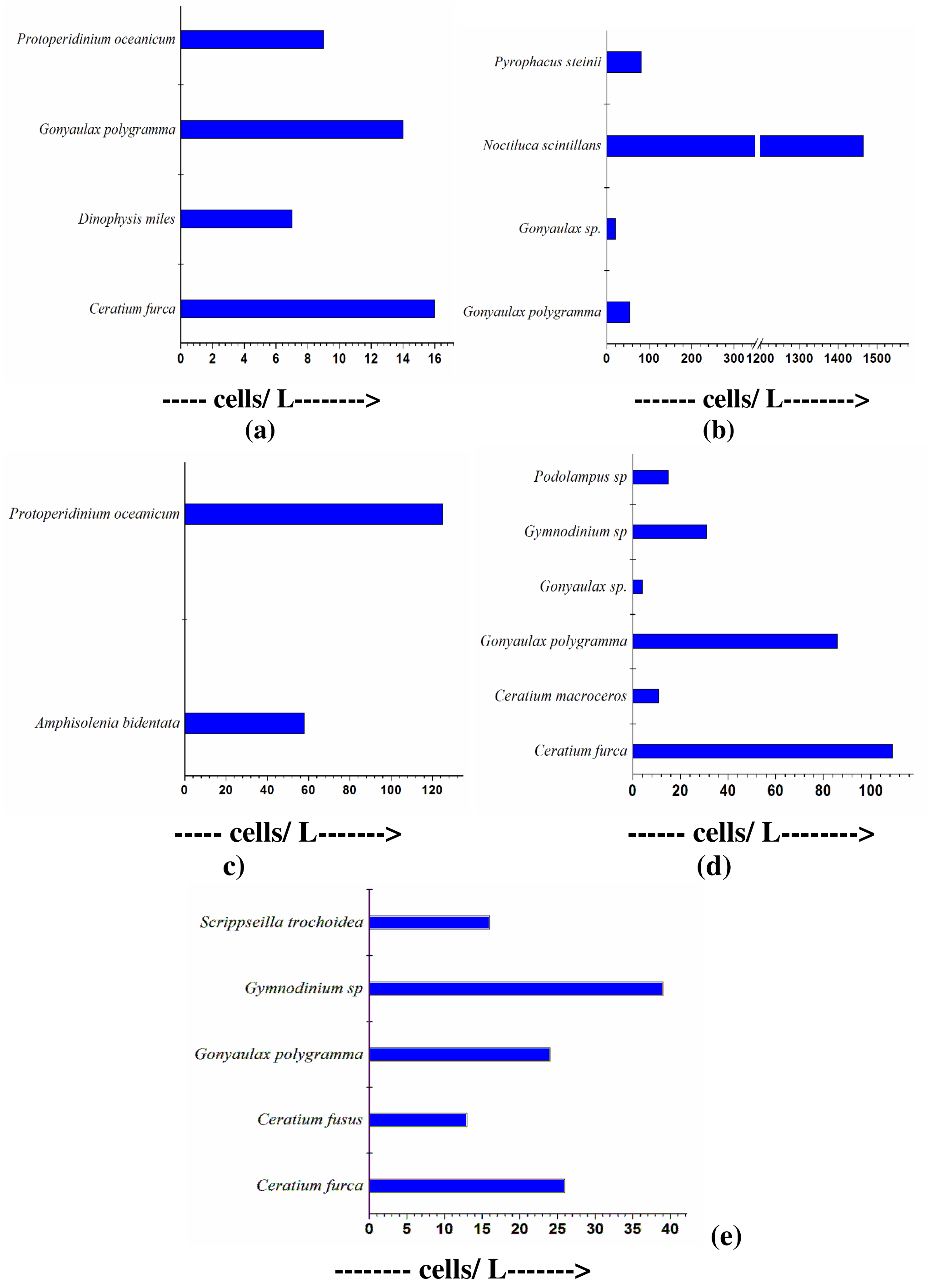


Figure 27. Community composition of dinoflagellates along different stations during Phase 3 of winter monsoon 2009, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

3.4. Variability in the microphytoplankton community during winter monsoon 2009- *a spatio-temporal analysis*

The surface hydrography of NEAS during winter monsoon of 2009 observed signals of convective mixing throughout the northern regions and diminished towards south. In addition the intensity of convective mixing decreased with progression of phases and significantly high level of convective mixing was observed during Phase-1. The environmental signatures of convective mixing like low sea surface temperatures, high salinity, deep MLD was more evident along the offshore regions of 22ºN latitude followed by 21ºN. In accordance with this the surface chlorophyll *a* was comparatively high in these regions throughout the three phases of study. The signals of convective overturning were more prominent during Phase-1 and were observed to decrease with phases. The increase in SST and decrease in SSS along with shoaling of mixed layer suggests that intensity of convective mixing declined with phases (Figure 28, 29).

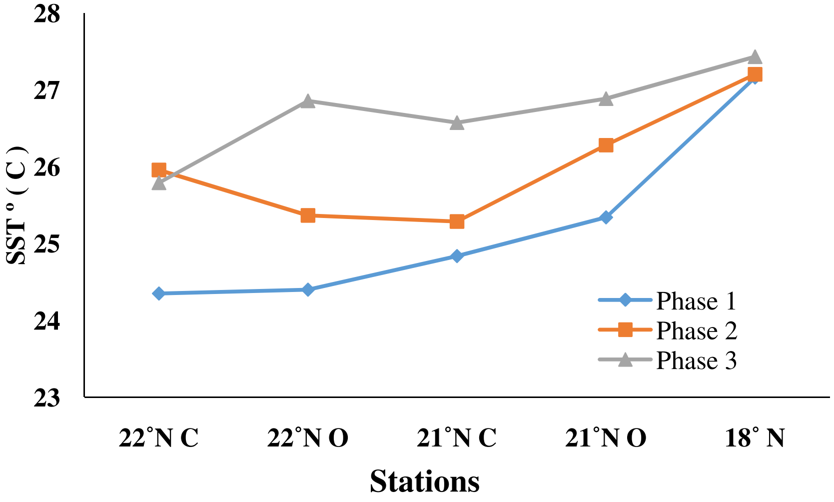


Figure 28. Variation in SST during different phases of winter monsoon 2009

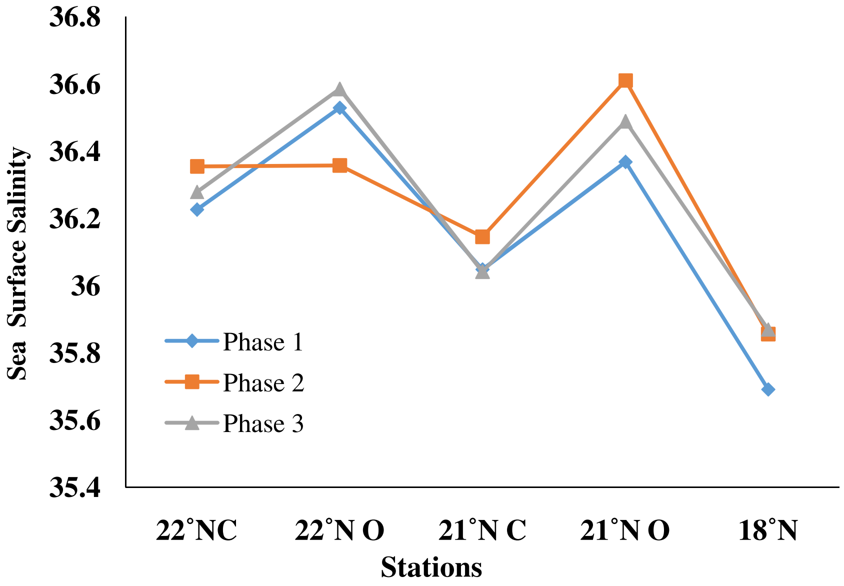


Figure 29. Variation in SSS during different phases of winter monsoon 2009

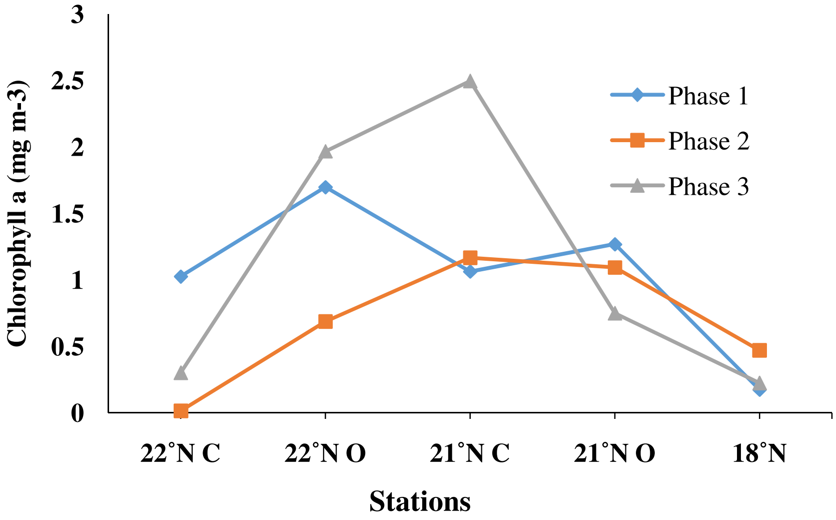


Figure 30. Variation in surface chlorophyll *a* (mg m^{-3}) during different phases of winter monsoon 2009

Surface chlorophyll *a* distribution showed variability between phases as well as between different areas of NEAS (Figure 30). However the offshore chlorophyll *a* correlated very well with that of the *Noctiluca scintillans* blooms. The bloom region maintained comparatively high chlorophyll *a* concentration irrespective of the phase. This might be due to the increased chlorophyll pigments inside each *Noctiluca* cells so that even with few active cells high chlorophyll values are obtained. Towards the coastal water the region along 21ºN observed markedly high chlorophyll *a* values throughout the three phases.

Phase	Shannon-Weiner Diversity (H')	Simpsons Dominance Index (λ')	Margalef's species richness (d)	Pielous's evenness (j')
1	2.845463	0.27	3.00379	0.606543
2	2.054218	0.44	2.020179	0.512334
3	2.288723	0.40	1.884433	0.555609

Table 3. Mean values of diversity indices of the phytoplankton community of NEAS for each phase of winter monsoon 2009

Temporal analysis of the phytoplankton community observed maximum mean diversity (H') during Phase-1 (2.84) and decreased with phases. Subsequently the dominance of the community by one or two species increased during Phase-2 and 3 attributing comparatively high dominance index (λ') during these phases (0.4). Phase-2 was characterized by the occurrence of diatom as well as dinoflagellate blooms in the coastal as well as offshore areas of NEAS and the mean diversity (H') and evenness (j') decreased during the period.

The k- Dominance plots (Figure 31) generated for the phase wise pooled data confirms increased dominance during Phase- 2 characterised by *Noctiluca scintillans* as well as monospecific (single species) diatom blooms. The inference from diversity indices suggests comparatively diverse and species rich community during Phase-1 and 3, but a less diverse and more dominant community during Phase-2 can clearly be interpreted using the k-dominance plot.

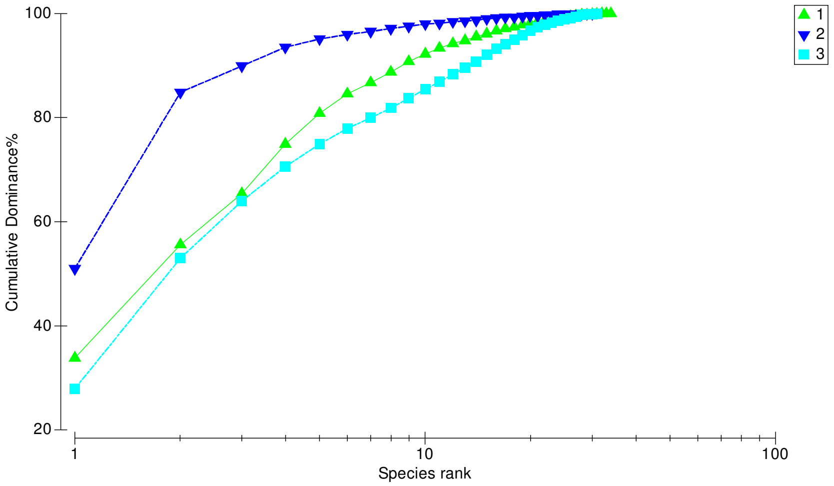


Figure 31. Phase wise k- dominance plot for microphytoplankton during winter monsoon of 2009

Regionally, along the coastal waters there was lesser species dominance and was supported by more species rich phytoplankton community. Hence, the coastal waters were having more diversity (H’) with maximum along 21ºN (3.122874) with lesser dominance index (λ’ 0.19). The mean of diversity indices for each station during three phases are shown in Table 4. The region along 18ºN latitude (ref station) was having a lower number of species as well as numerical abundance than the northern regions. This withstands that the area was least influence by the convective mixing process with higher SST and lower SSS and shallow MLD.

Area	**Shannon-Weiner Diversity (H’)**	**Simpsons Dominance Index (λ’)**	**Margalef’s species richness (d)**	**Pielous's evenness (j’)**
22°N coast	3.256098	0.178	2.696746	0.759456
22°N offshore	1.622732	0.487	1.693915	0.407204
21°N coast	3.349363	0.1925	3.122874	0.698069
21°N offshore	2.022439	0.4254	2.070928	0.468138
18°N (Ref stn)	2.2441	0.439	1.9850	0.55

Table 4. Mean value of diversity indices in the stations during 2009

Interpreting the k- dominance plots (Figure 32) for regionally pooled data, cumulative dominance was observed to be higher in the offshore waters where nearly 1 to 2 species contributed to ~80% of the community. Along the coastal waters cumulative dominance curve obtained a gradual rise than the offshore waters. Here 10- 12 species contributed to ~80% of the community.

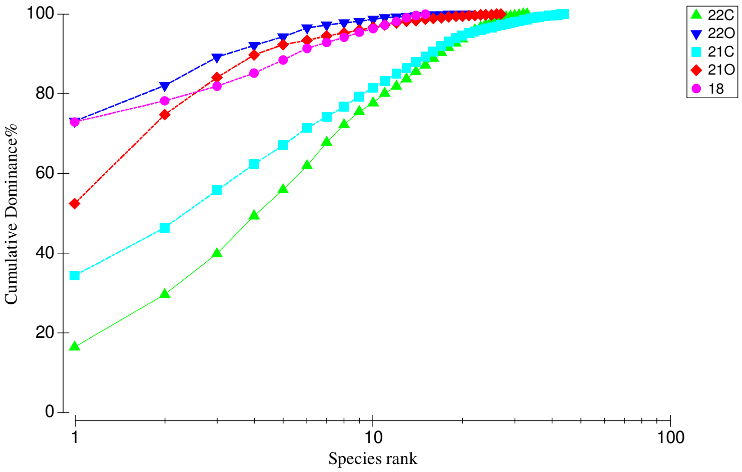


Figure 32. Area wise k- dominance plot for microphytoplankton during winter monsoon of 2009

To interpret the similarity in the abundance of phytoplankton between stations during different phases Bray- Curtis similarity dendrogram was plotted (Figure 33). The northern transects 21ºN and 22ºN formed a single cluster during Phase-1 at nearly 60% similarity. There was a similarity of more than 70% between the offshore stations as well as between the coastal stations. Another cluster with >40% similarity was observed with the offshore stations during Phase-2 and 3. The reference station along 18ºN latitude stands as a separate cluster at nearly 60% similarity during Phase-1 and 2, but Phase-3 showed a slight similarity towards the offshore regions of north during the phase.

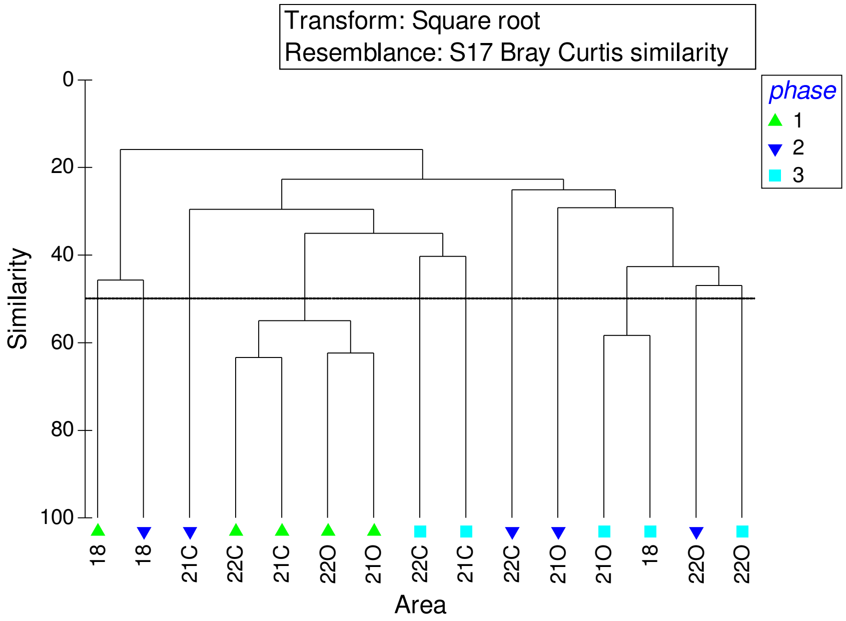


Figure 33. Dendrogram using Bray Curtis similarity of phytoplankton abundance along the NEAS during winter monsoon 2009

3.4.1 Phytoplankton community structure

Along the North eastern Arabian Sea during winter monsoon of 2009, diatoms dominated the phytoplankton community with an exception along the bloom regions of *Noctiluca scintillans.* Among the diatoms, subclass Coscinodiscophycidae (centric diatoms) and Bacillariophycidae (raphid pennate) were the dominant groups present with a fewer representation from subclass Fragilariophycidae (araphid pennate).

An inter comparison of the phytoplankton community during the three phases clearly showed that centric diatoms mainly *R. hebetata* and *Chaetoceros lorenzianus* dominated the phytoplankton community during Phase-1. *Guinardia striata* was another centrale present especially along the coastal waters. Towards Phase-2 even though centric diatoms were present in dominating cell densities, raphid pennates such as *Navicula directa*, *Nitzschia longissima*, *Pseudo-nitzschia* spp., were found to increase. Araphid pennate were found to increase during Phase-3 with *Thalassiothrix longissima* as the dominant species followed by *Thalassionema frauenfeldii*, *Thalassionema nitzschioides* etc. *Rhizosolenia hebetata* constituted a major species in the northern Arabian Sea during the winter monsoon 2009. The abundance and distribution of *R. hebetata* correlated at 5% significance level to the sea surface salinity, contributing to the fact that their intensity was found to increase towards the offshore waters. *R. hyalina* and *R. alata* were the other two species representatives from the genus in smaller cell densities.

Chaetoceros spp., mainly *Chaetoceros lorenzianus* was observed in higher cell densities during Phase-1 but was decreased or absent during the successive phases. *C. laciniosus*, *C. decipiens* and *C. curvisetus* were the other representatives from the genus. The cell densities of *Chaetoceros* genus including *C. lorenzianus* decreased with increasing Sea Surface Temperature as well as with progression of phases (p= -0.67, 1% significance).

Guinardia striata and *G. flaccida* were the two major species observed under the genus. *G. striata* was observed mainly during Phase-1 in both coastal as well as offshore areas (correlating positively with the occurrence of *C. lorenzianus*, p= 0.71, and negatively with SST, p= -0.716) and *G. flaccida* was observed mainly during Phase-2 and 3 (correlated with the occurrence of *T. longissima*).

The raphid pennate well known to be associated with toxin production, *Pseudo-nitzschia seriata* was observed in the study area mainly towards the coastal waters of 21ºN latitude. The abundance of *Pseudo-nitzschia* sp. was mainly observed during Phase-1 and 3 with a lower occurrence during Phase-2. *Pseudo-nitzschia pseudodelicatissima* was another species of the genus observed in significant cell densities mainly towards Phase-3 along coastal waters.

The abundance of the pennate diatom *Nitzschia longissima* was more during Phase-1 which decreased in the succeeding phases was very well correlated with that of the distribution of *C. lorenzianus* (p= 0.699). The species was also found to have an affinity towards the nitrate rich areas (p= 0.724) and was negatively correlated with temperature (p= -0.56). *Navicula directa*, pennate diatom was present throughout the study region but was in higher cell densities and was found to coexist with the intense bloom of *Noctiluca scintillans* during Phase-2.

Thalassiothrix longissima (araphid pennate) was present in the phytoplankton assemblage throughout the three phases in both coastal as well as offshore areas but the abundance increased in the coastal waters during Phase- 3, more significantly along 21ºN latitude.

Among the dinoflagellates *Noctiluca scintillans* (Subclass- Noctilucophycidae, order Noctilucales) was observed to be an important species associated with the physicochemical effects of the winter monsoon seasons. The species was found in bloom cell densities especially in the offshore waters of northern regions and was more intense during Phase-2. Excepting the bloom regions, the armoured dinoflagellates (subclass- Peridiniphycidae) dominate the dinoflagellate population. *Gonyaulax polygramma* (Order Gonyaulacales) was another dinoflagellate observed throughout the study area and mainly towards offshore areas and the intensity of occurrence increased with phases. *Ceratium* spp., *Protoperidinium* spp. (Order- Peridiniales) were also present in the offshore as well as coastal waters along with *Gonyaulax* sp. The abundance of subclass Peridiniphycidae was inversely related to the occurrence of Dinophysiphycidae. Prorocentrophycidae and Gymnodinophycidae were the other subclass present.

Functional groups of phytoplankton

From the analysis of the phytoplankton composition during the winter monsoon of 2009 using SIMPER as well as using NMDS it was clear that there exist a particular group of phytoplankton that was dominated mainly by diatoms throughout the stations (Table 5). The variations were somewhat significant in coast and offshore areas. The cluster analysis showed a considerable similarity between the stations during Phase-1 (similarity at ~60%) with slight variation with Phase-2 and 3 whose stations were having near similar compositions with varying cell densities.

The major contributing factor towards the dissimilarities (%) between Phase-1 and 2 (87%) is by *Rhizosolenia hebetata* (25%) (Av. abundance 2749 cells L^{-1}), *Noctiluca scintillans* (12%, av. Abundance 2930 cells L^{-1}) and *Navicula directa* (10%) which was more abundant during Phase-2 and *Chaetoceros lorenzianus* (11%) and *Pseudo-nitzschia seriata* (6%) which was more abundant during Phase-1. *Guinardia* spp. varied with *Guinardia striata* being more abundant in Phase-1 (av. abundance 355 cells L^{-1}) and *G. flaccida* (av. Abundance 283 cells L^{-1}).

The variability between the stations as well as phases was mainly due to the variations in the phytoplankton abundance. More clearly the phytoplankton composition did not varied much with respect to the composition in between the phases unless their cell density varied creating variations in the dominant species groups.

Region	**C/ O**	**Functional Diatom Groups**	**Functional Dinoflagellate group**
22°N	C	*Guinardia striata, Rhizosolenia hebetata, Thalassiothrix longissima*	*Ceratium* spp., *Protoperidinium, Noctiluca scintillans* (only during Phase- 2)
22°N	O	*R. hebetata, C. lorenzianus, Nitzschia longissima*	*Noctiluca scintillans, Gonyaulax* sp., *Ceratium* spp.
21°N	C	*Rhizosolenia hebetata, Pseudonitzschia seriata, Thalassiothrix longissima, Guinardia flaccida*	*Ceratium* spp., *Gonyaulax, Protoperidinium* sp.
21°N	O	*Rhizosolenia hebetata, Pseudonitzschia seriata, Chaetoceros lorenzianus, Navicula directa,*	*Noctiluca scintillans, Ceratium* spp., *Gonyaulax* sp., *Protoperidinium* sp.
18°N	Ref	*R. hebetata*, *Thalassiosira* sp.	*Gonyaulax* sp., *Protoperidinium* sp., *Trichodesmium erythraeum* filaments consistently present throughout

Table 5. Functional group of phytoplankton during winter monsoon 2009

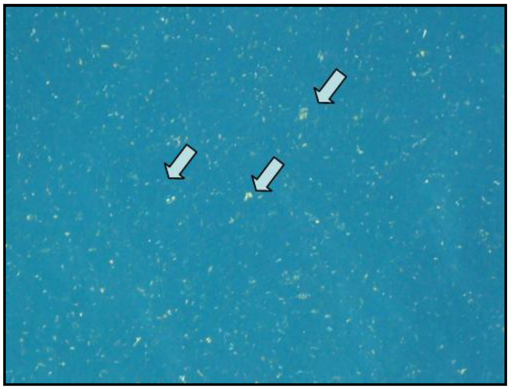
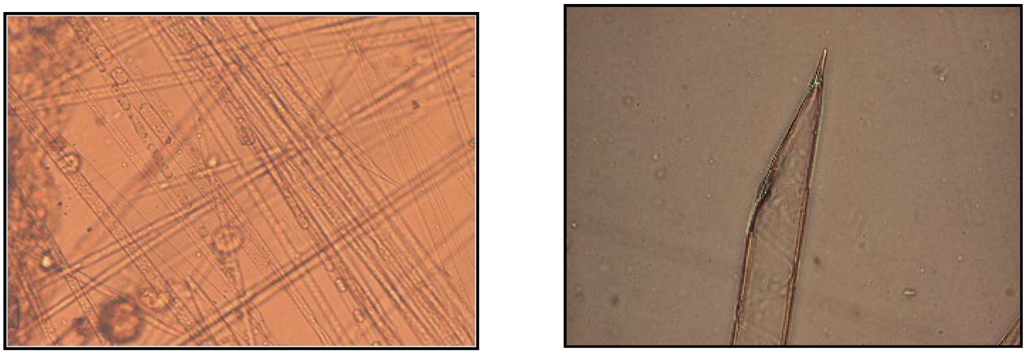
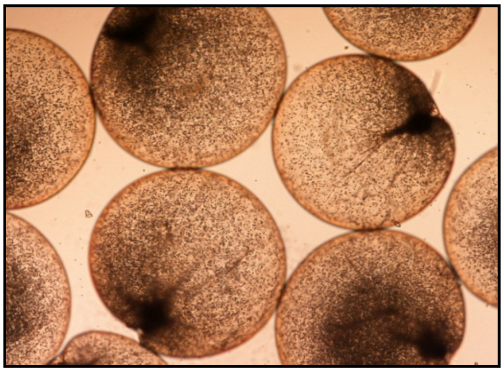


Plate 1.a



Rhizosolenia mat x200

Rhizosolenia hebetata x400



Noctiluca scintillans x40

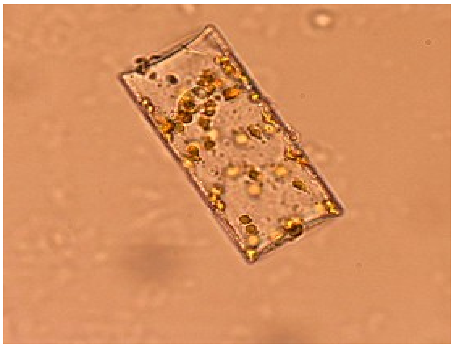
Plate 1.b

Plate 1: Major microphytoplankton observed during winter monsoon 2009 along NEAS; (a). Sea surface view of *Rhizosolenia* mat (b). Microphotographs of major microphytoplankton

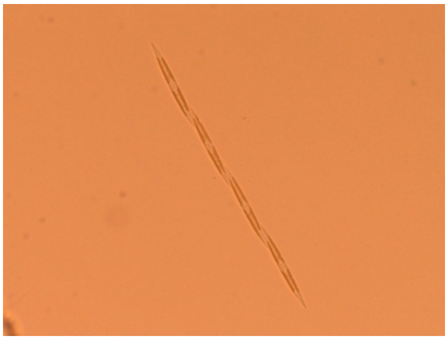
Chaetoceros lorenzianus x 400

Navicula sp. x 200

Guinardia striata x400

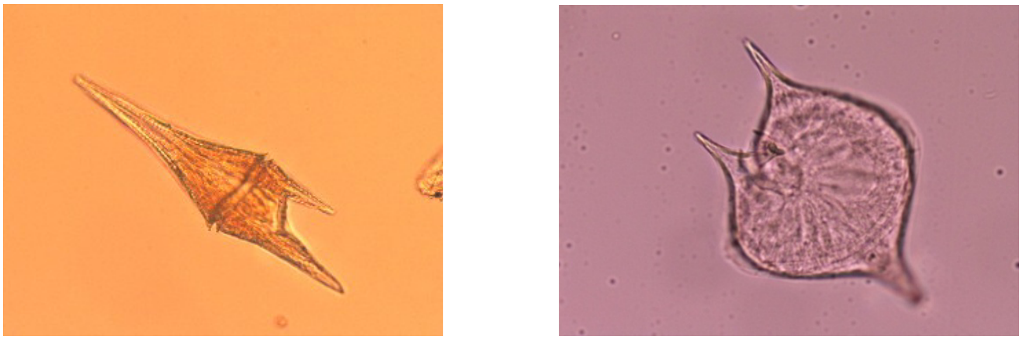


Guinardia flaccida x 400



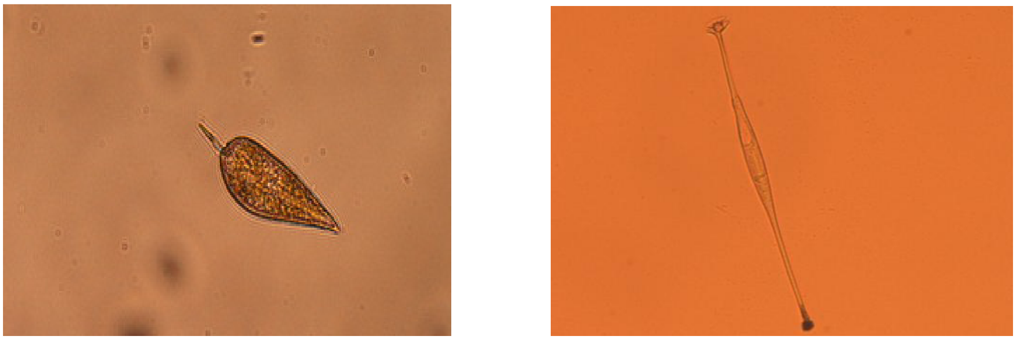
Pseudo-nitzschia seriata x200

Plate 2: Microphotographs of major diatoms observed during winter monsoon 2009



Ceratium furca x 400

Protoperidinium sp. x400



Prorocentrum lima x400

Amphisolenia bidentata x200

Plate 3: Microphotographs of major dinoflagellates observed during winter monsoon 2009

Chapter 4

Microphytoplankton community structure during winter monsoon 2011

"The world's finest wilderness lies beneath the waves ... "
— Wyland, Marine Life Artist

Introduction

Extensive open ocean blooms of microalgae are a recurrent phenomenon associated with winter cooling in North Eastern Arabian Sea. Convective mixing and associated eutrophication pave way for these proliferations. The influences of winter cooling are prominent along the northern latitude which decreases southward. These variations directly or indirectly influence the community composition of phytoplankton resulting in distinct population structure. During the year 2011, winter mixing along NEAS was intense with low sea surface temperatures and deeper mixed layers. Extensive and intense blooms of microphytoplankton were observed along NEAS during the season. The community assemblage of phytoplankton, their spatial variations and associations are addressed through a three phase analysis in this chapter.

4.1. Phase - 1 (Early February 2011)

4.1.1. Physico-chemical characteristics

During the period of observation the winds were predominantly northerly with an average speed of 5 m/ s. Cold dry winds prevailed over the area with air temperature varying between 22.9°C to 25.4°C and humidity <80%. The atmospheric pressure varied from 1010 to 1016mb. Air temperature showed a gradual increase along the offshore waters from north (22°N) to the southern latitudes (18°N). The average air temperature along the open ocean waters of 22°N latitude was 23.7°C and along the 21°N latitude the value increased to an av. 24.2°C which further increased to 25.4°C along 18°N. Sea surface temperatures along the 22ºN latitude were ~23.8ºC and increased to 24.4ºC towards the 21ºN (Figure 34). SSTs of coastal waters were further low and reached to ~23ºC along 22ºN as well as 21ºN latitudes. SST increased southwards and reached to ~26.2ºC towards 18ºN latitude. Surface waters were saltier towards the offshore waters (~36 psu) (Figure 35) and were less saline towards the coast (~35.3). Vertical profile of temperature and salinity (Figure 36) clearly distinguished the presence of deep MLD (~90 m) along the offshore regions of 22ºN and 21ºN. Surface nitrate (NO_3-N) was ~1.2 µmol L^{-1} in the offshore areas and decreased towards the coast (~0.3 µmol L^{-1}). In the region of intense convective mixing nitrate was uniformly distributed up to ~50m and beyond which nitracline was observed (Figure 37). Along the southern boundary (18ºN) with higher surface temperatures and shallow MLDs nitrate concentration further decreased to ~0.1 µmol L^{-1}. Deep MLD with low SST and increased nutrient (nitrate) concentrations supports the existence of winter convective mixing in the northern regions and was more or less absent in the south.

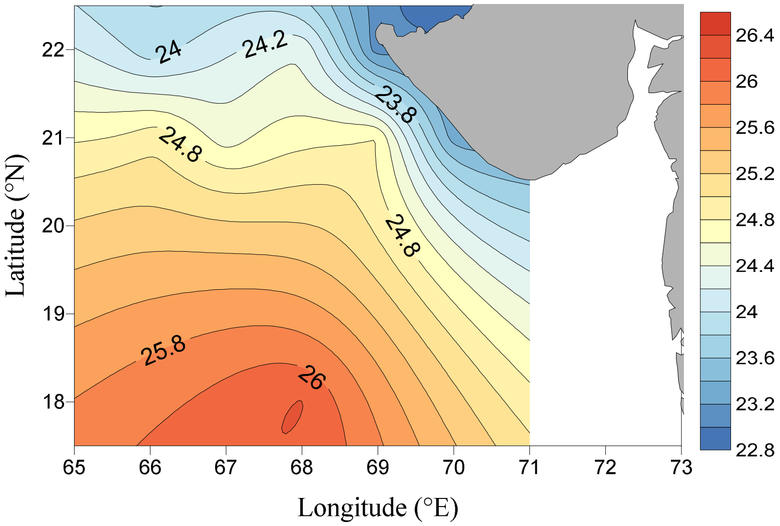


Figure 34. Variation in SST (ºC) along the NEAS during Phase-1 of winter monsoon 2011

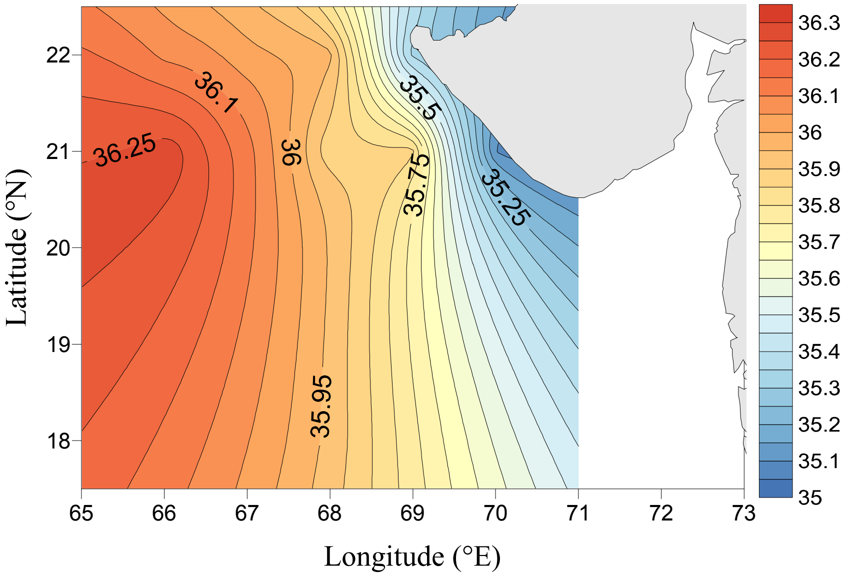
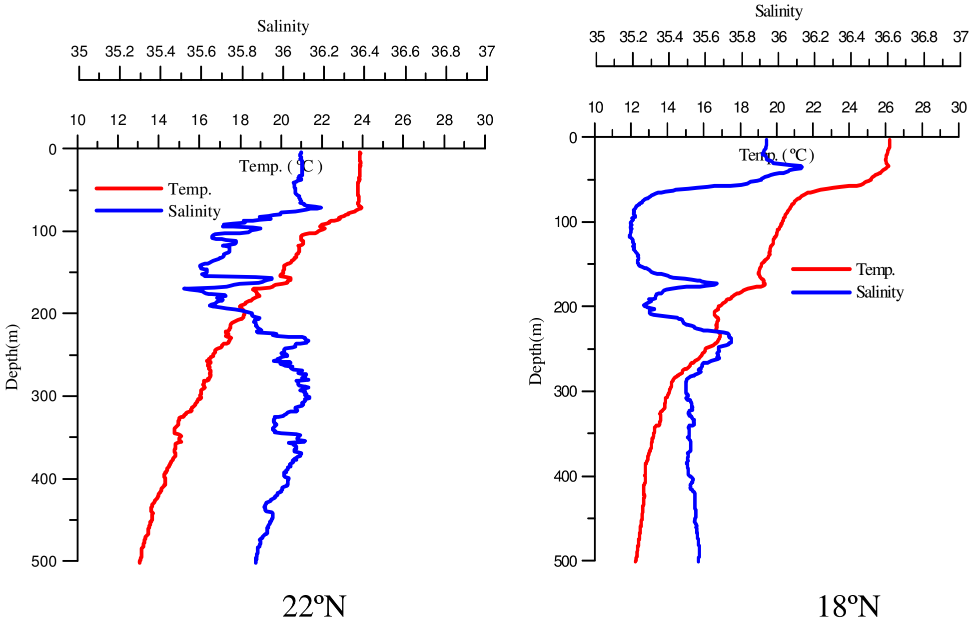


Figure 35. Variation in Sea surface salinity along the NEAS during Phase-1 of winter monsoon 2011



22ºN

18ºN

Figure 36. Vertical profiles of Temp (ºC) and Salinity in the regions of intense convective mixing along NEAS (22ºN) and reference station (18ºN)

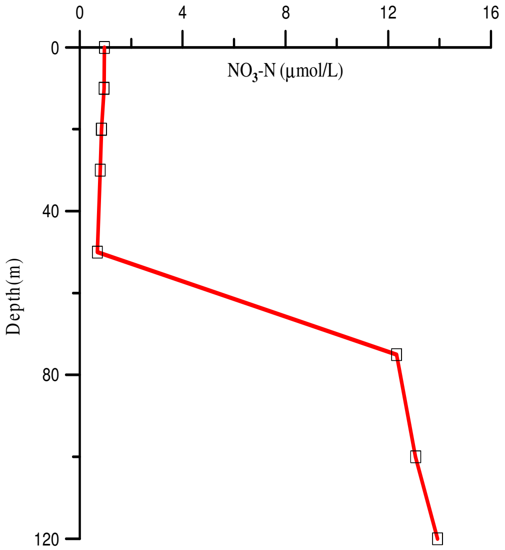


Figure 37. Vertical profile of nitrate (NO_3-N) along the region of intense convective mixing

4.1.2. Chlorophyll *a*- Phytoplankton biomass

The surface chlorophyll *a* along NEAS during Phase-1 was 1.34 ± 1.2 mg m^{-3}. The open ocean waters of northern regions were having average chlorophyll *a* 0.9 ± 0.8 mgm^{-3} whereas coastal waters observed 2.2 ±1.4 mgm^{-3}. Regionally surface chlorophyll *a* distribution was observed to be maximum along the coastal waters of 21ºN latitude (3.2 mg m^{-3}) but decreased towards offshore waters (0.9 mg m^{-3}) (Figure 38). The region along the 22ºN latitude had almost comparable chlorophyll *a* concentrations both along the coastal as well as offshore waters (~1.5 mg m^{-3}). Towards the south of the study area (18ºN) the chlorophyll *a* concentrations decreased to ~0.3 mg m^{-3}.

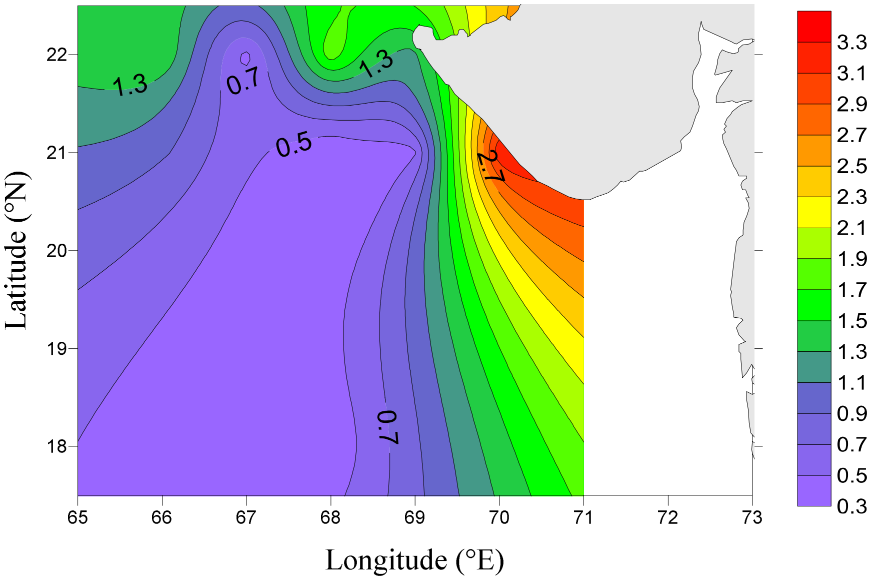


Figure 38. Variation in surface chlorophyll *a* (mg m^{-3}) along the NEAS during Phase- 1 of winter monsoon 2011

4.1.3. Phytoplankton cell density- numerical abundance and diversity

Diatom dominated the phytoplankton community during Phase-1 by nearly 92%. Numerical abundance of microphytoplankton was observed to be maximum along the coastal waters (Figure 39). However open ocean waters of 22ºN observed considerable abundance of phytoplankton (2.4x 10^{3} cells L^{-1}), dominated by diatoms (90%) , which decreased towards south (0.2x 10^{3} cells L^{-1} along 21ºN and 21 cells L^{-1} along 18ºN latitudes).

Along the coastal waters with high cell densities, dinoflagellates dominated (96%) along the 22ºN region (total cell density 2x 10^{3} cells L^{-1}) and diatoms (77%) along 21ºN (total cell density 34x 10^{3} cells L^{-1}). Diatoms along the offshore regions were with cell densities of 2.1x 10^{3} cells L^{-1} along 22ºN latitude, which decreased to 1.8x 10^{2} cells L^{-1} towards 21ºN which further decreased to 14 cells L^{-1} along 18ºN latitude. The dinoflagellate cell density along the offshore waters varied from 213 cells L^{-1} along 22ºN to nearly 53 cells L^{-1} along the offshore region of 21ºN latitude

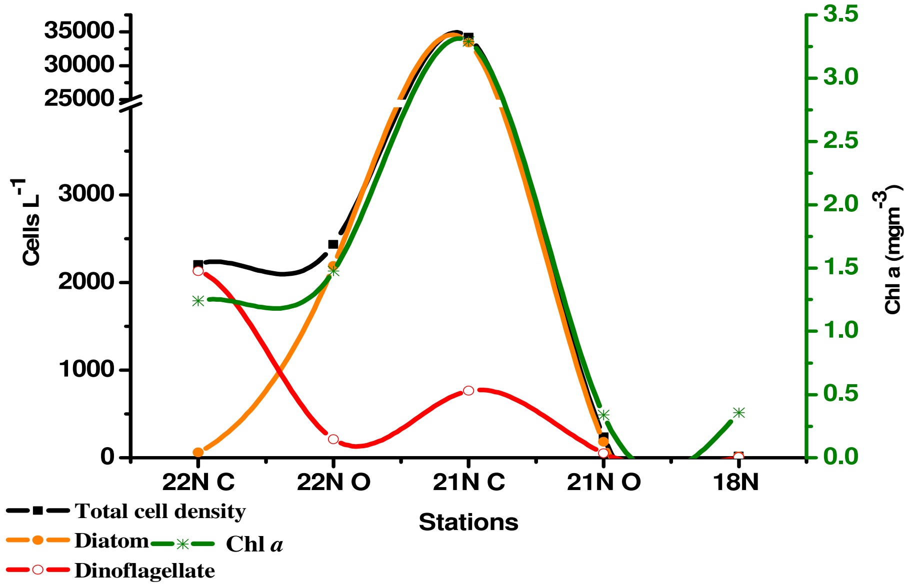


Figure 39. Variations in phytoplankton cell densities and chlorophyll *a* along the NEAS during Phase-1 of winter monsoon 2011

Around 67 species of microphytoplankton were recorded during the phase. The diversity indices obtained for different stations during three phases are given in Table 6. Maximum diversity was observed along the offshore regions of 22ºN (H'= 4) with lower dominance (D=0.09), higher species richness (d=3.97) and evenness (j'=0.8). The offshore region of 21ºN latitude was also having a higher diversity as well as species richness but was with a lower numerical abundance. The coastal waters along 21ºN also showed the similar pattern, but the region along 22ºN stayed different with a higher dominance (0.6) and very less diversity values (H'= 1.2).

Phase	Area	Shannon-Weiner Diversity (H')	Simpsons Dominance Index (D)	Margalef's species richness (d)	Pielous's evenness (j')
1	22ºN coast	1.217194	0.69	1.688644	0.319696
	22ºN offshore	4.042133	0.096	3.976788	0.808427
	21ºN coast	3.047554	0.163	3.16104	0.599032
	21 ºN offshore	3.794223	0.11	4.005053	0.838769
	Ref stn. (18ºN)	1.584963	0.3	0.656917	1
2	22ºN coast	3.555703	0.113	2.435504	0.852702
	22ºN offshore	0.520086	0.872	1.555423	0.130021
	21ºN coast	3.897837	0.117	4.149179	0.79436
	21ºN offshore	0.516765	0.879	1.332297	0.13965
	Ref stn. (18ºN)	2.467885	0.185	1.076567	0.954708
3	22ºN coast	1.48069	0.482	1.654804	0.355088
	22ºN offshore	0.062399	0.988	1.501937	0.014438
	21ºN coast	2.678815	0.22	2.043251	0.600708
	21ºN offshore	1.433005	0.65	1.599594	0.358251
	Ref stn. (18ºN)	1.202292	0.44	0.621335	0.758562

Table 6. Diversity indices of phytoplankton community during winter monsoon 2011

4.1.4. Phytoplankton community assemblage

Diatoms dominated the phytoplankton community and were mainly contributed by subclass Coscinodiscophycidae (centric, 49%) followed by Fragilariophycidae (araphid pennate, 27%) and Bacillariophycidae (raphid pennate, 24%) (Figure 40a, b). The subclass of Coscinodiscophycidae was composed of diverse groups including various species of *Chaetoceros* sp., *Rhizosolenia* sp., *Thalassiosira* sp. and *Detonula* sp. Fragilariophycidae was represented by *Thalassionema nitzschioides, T. frauenfeldii, Thalassiothrix* sp. and *Lioloma* sp. Bacillariophycidae was represented by *Pseudo-nitzschia* sp., *Navicula* sp., *Cylindrotheca closterium* and *Haslea* spp. Dinoflagellate community during Phase-1 was mainly supported by subclass Dinophysiphycidae (*Ornithocercus* spp. mainly *Ornithocercus magnificus*) followed by Peridiniphycidae (*Protoperidinium* spp., *Ceratium* spp.). These groups dominated especially along the coastal waters and offshore waters that were having fewer dinoflagellate populations.

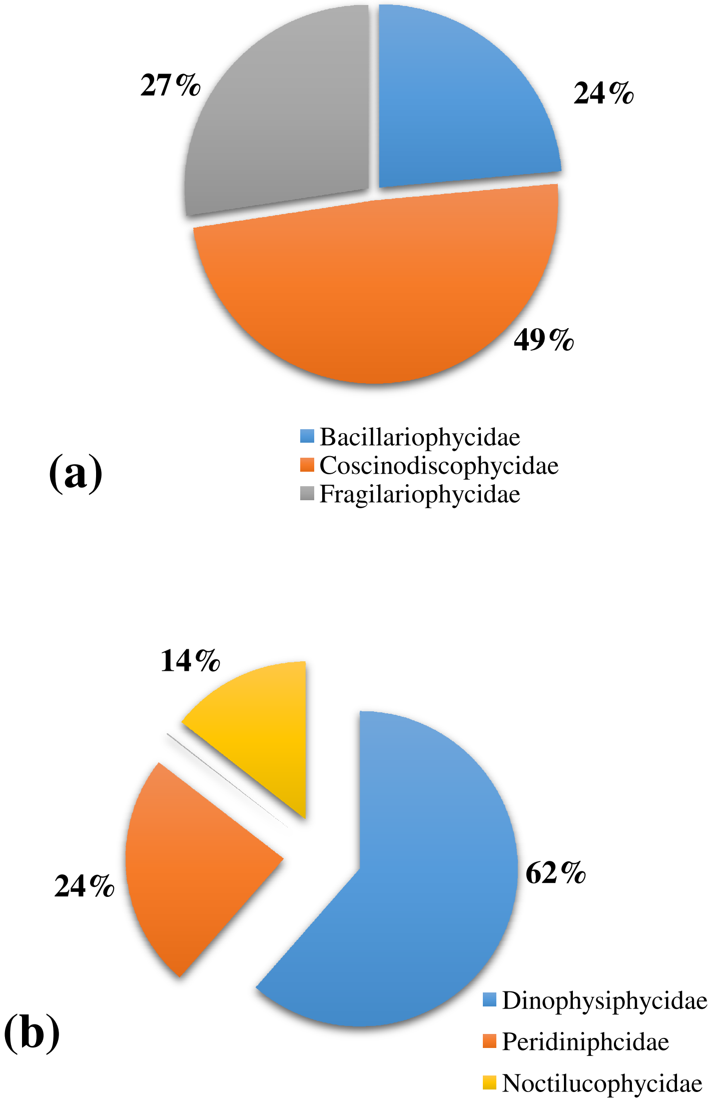


Figure 40. Percentage composition of major subclass of diatoms **(a)** and dinoflagellates **(b)** along the NEAS during Phase-1 of winter monsoon 2011

The regional analysis of phytoplankton community showed diverse composition in each regimes. The coastal water of 22ºN latitude was with bloom of dinoflagellate *Ornithocercus magnificus* (2x 10^3 cells L^{-1}) with a few diatom cells (Figure 41, 42). But towards the offshore diatoms dominated and was mainly represented by centric forms like *Chaetoceros lorenzianus* (4x 10^2 cells L^{-1}), *C. affinis* (2.1x 10^2 cells L^{-1}), *C. laciniosus* (2.3x 10^2 cells L^{-1}) , *Rhizosolenia alata* (137 cells L^{-1}), *R. hebetata* (213 cells L^{-1}) and *Thalassiosira* sp. etc. Raphid pennates present were *Pseudo-nitzschia* sp., *Navicula* sp. and few cells of *Haslea* spp. and araphid pennates were *Thalassionema* sp., *Thalassiothrix* sp. and *Lioloma* sp. The offshore waters of 21ºN region observed very low abundance of phytoplankton but was diverse consisting of mainly centrales like *Thalassiosira* spp., *Rhizosolenia* spp., *Detonula pumila* with a few raphid pennates (*Navicula* sp. and *Pseudo-nitzschia* sp.) and araphid pennates (*Thalassionema nitzschioides*). The coastal region of 21ºN latitude was having mixed diatom assemblage with contribution from all the three classes and among these, centric forms predominated. *Thalassiosira* sp. was observed in mucilaginous colonial assemblage (5.7x 10^3 cells L^{-1}) along with *Cerataulina pelagica* (2.2x 10^3 cells L^{-1}). *Thalassionema nitzschioides* (9.3x 10^3 cells L^{-1}) was also present in significantly higher cell densities followed by *Cylindrotheca closterium* (4.5x 10^3 cells L^{-1}) and *Pseudo-nitzschia* sp (3.4x 10^3 cells L^{-1}). Southern most region of NEAS (18ºN) was having a less abundant phytoplankton community composed of a few cells of *Thalassiosira* sp. and dinoflagellate *Pyrocystis fusiformis*.

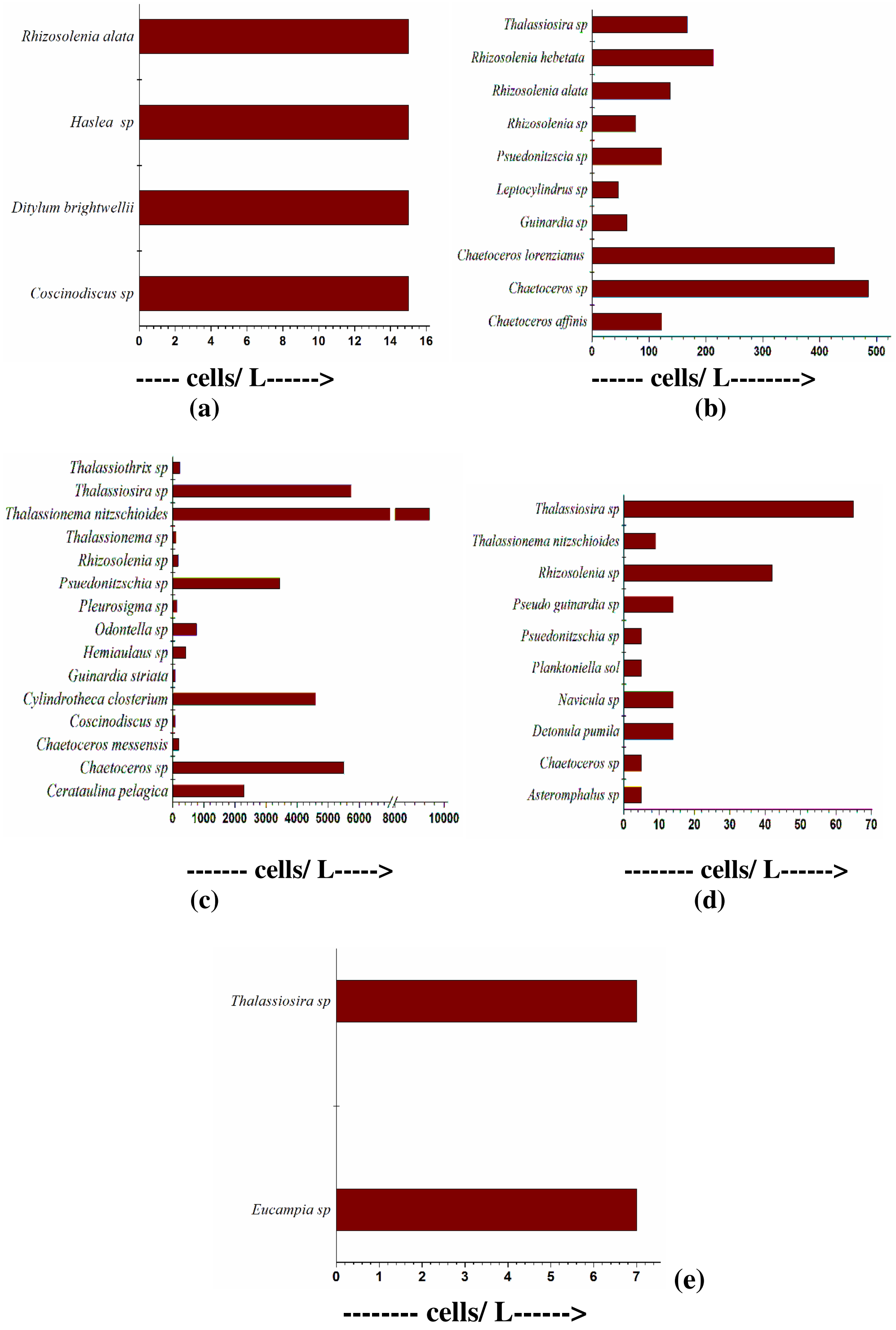


Figure 41. Community composition of diatoms along different stations during Phase 1 of winter monsoon 2011, **(a)** 22°N Coastal **(b)** 22°N Offshore **(c)** 21°N Coastal **(d)** 21°N Offshore **(e)** 18°N reference

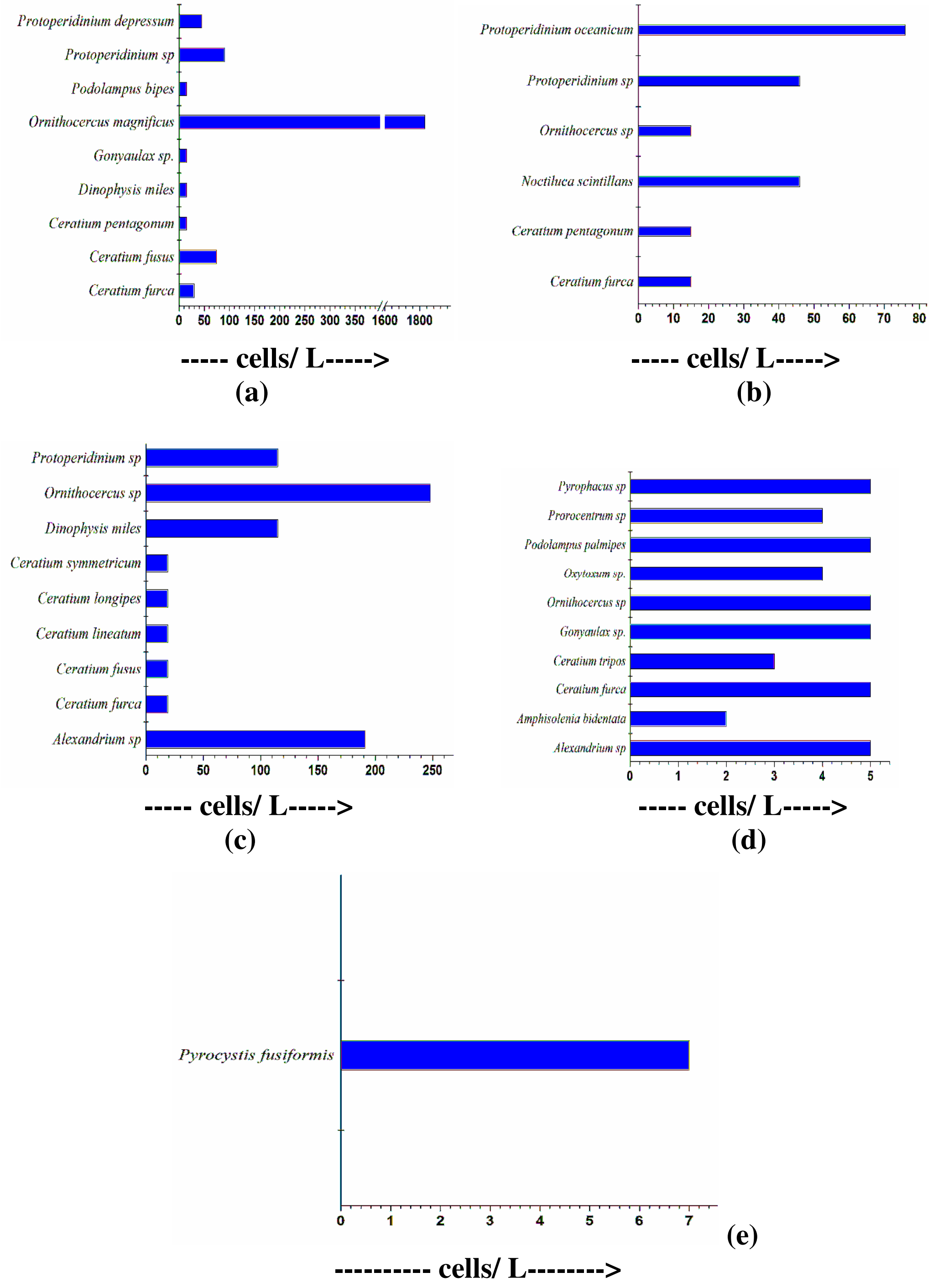


Figure 42. Community composition of dinoflagellates along different stations during Phase 1 of winter monsoon 2011, **(a)** 22°N Coastal **(b)** 22°N Offshore **(c)** 21°N Coastal **(d)** 21°N Offshore **(e)** 18°N reference

4.2. Phase- 2 (Mid February- early March 2011)

4.2.1. Physico-chemical characteristics

Weak winds, predominantly northerly prevailed in the region (2.2 to 4 m/s) with lesser humidity (50 to 83%). Air temperature in the northern region was ~24°C that gradually increased southward (25°C). The sea surface temperature along the northern offshore region was ~24ºC (Figure 43) and decreased towards coastal areas (23.2ºC). The SST increased towards south and reached to ~26.5ºC along the 18ºN latitude. In accordance with the low SST, the offshore areas were having high saline surface waters, which reached to nearly 36.3 (Figure 44). The offshore waters during Phase-2 observed convective mixing of greater intensity with mixed layers (MLD) deepening up to ~140m as evident from the temperature and density profiles (Figure 45) along 22ºN offshore waters which shoaled to ~60m along 21ºN and further decreased towards south. Towards south as well as coastal waters salinity was less, ~35.21 to 35.7. The distribution of surface nitrate concentrations was maximum along the offshore regions of 22ºN latitude (1.14 µmol L^{-1}). The nitrate was almost uniformly distributed in the water column up to ~75m and beyond which nitracline was observed (Figure 46). The surface nitrate concentrations decreased towards south (<0.2 µmol L^{-1}).

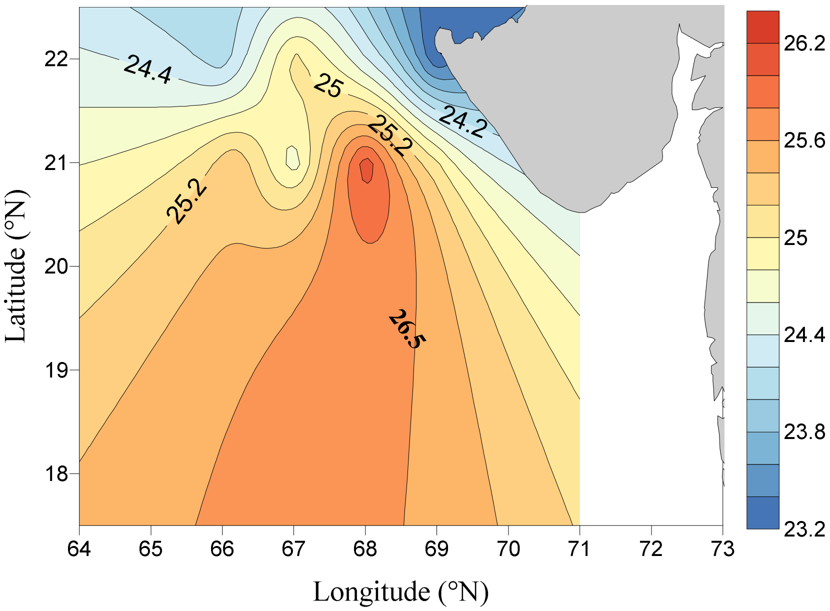


Figure 43. Variations in SST (ºC) along the NEAS during Phase-2 winter monsoon of 2011

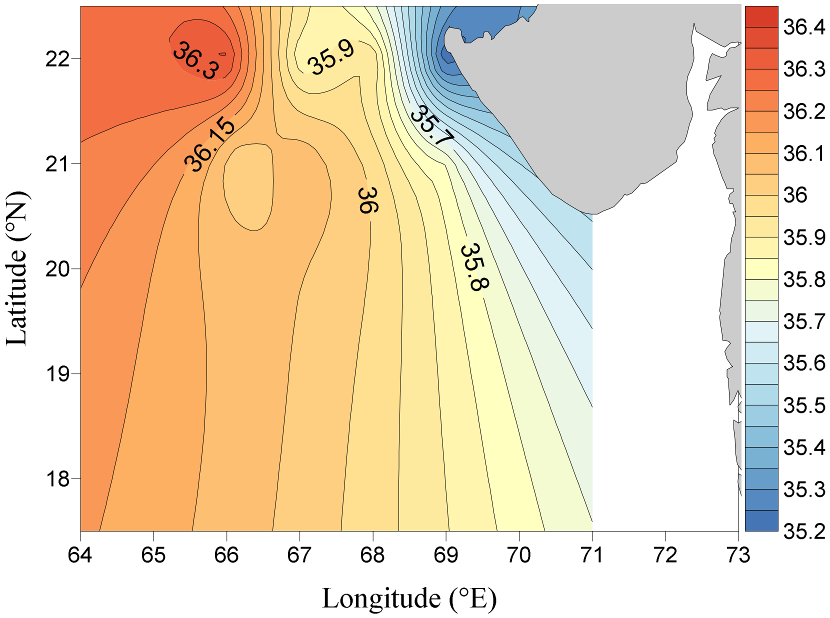


Figure 44. Variations in sea surface salinity along the NEAS during Phase-2 of winter monsoon 2011

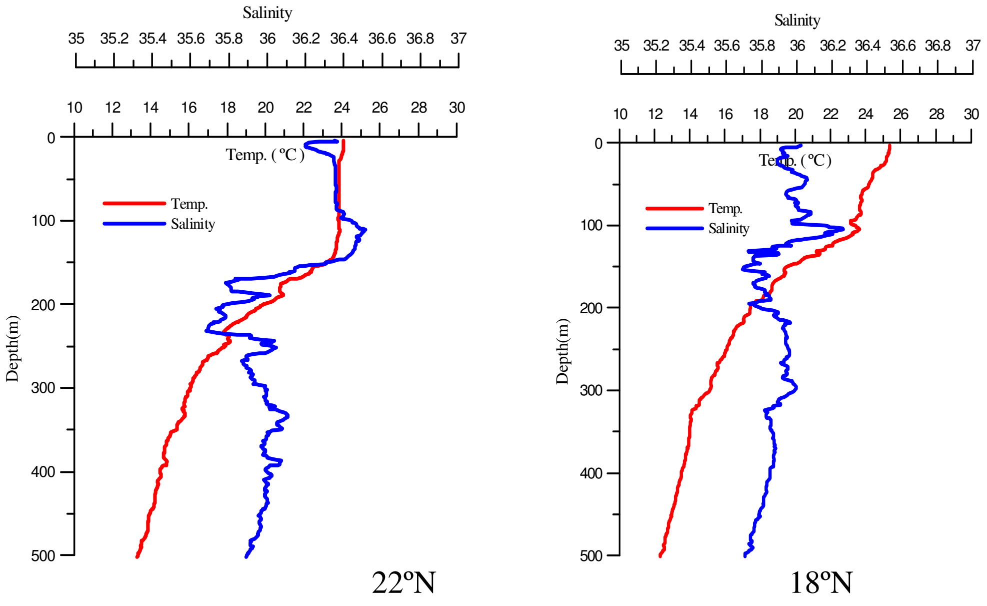


Figure 45. Vertical profiles of Temp. (°C) and Salinity in the regions of intense convective mixing along NEAS (22°N) and reference station (18°N)

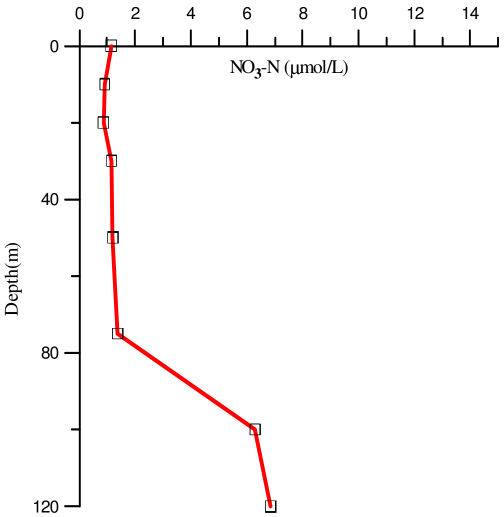


Figure 46. Vertical profiles of Nitrate (NO_3-N) in the regions of intense convective mixing (22°N) along NEAS

4.2.2. Chlorophyll *a*- Phytoplankton biomass

The average surface chlorophyll *a* concentration during Phase-2 was 1.2 ± 0.95 mg m^{-3}. Open ocean waters observed an average surface chlorophyll *a* of 1.4 ± 1.1 mg m^{-3} and coastal waters with 1.36 ± 1.28 mg m^{-3}. The distribution of surface chlorophyll *a* showed markedly high concentrations along the coastal (2.27 mg m^{-3}) as well as offshore waters (2.24 mg m^{-3}) of 22ºN (Figure 47), where there was intense mixing with low SST and deep MLDs. The chlorophyll *a* was found to decrease towards 21ºN (0.4 mg $m^{-3}$and 0.6 mg m^{-3} along the coastal and offshore waters respectively). The concentration further decreased towards south along the 18°N latitude (0.4 mg m^{-3}) characterised by comparatively higher SSTs and shallow MLDs.

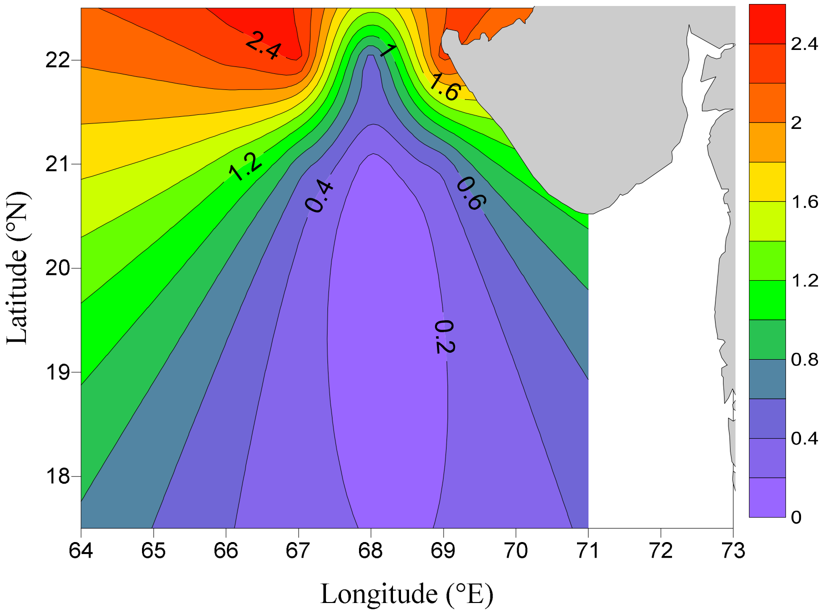


Figure 47. Variations in surface chlorophyll *a* along the NEAS during Phase- 2 of winter monsoon 2011

4.2.3. Phytoplankton cell density- numerical abundance and diversity

During Phase-2, markedly higher phytoplankton abundance was observed along the open ocean waters of 22ºN and 21ºN. Dinoflagellates dominated the phytoplankton community (~95%) along the offshore waters (Figure 48). Maximum cell densities were observed along the northern extend of NEAS (22ºN) and the region observed a total cell density of 1.5x 10^4 cells L^{-1}. Dinoflagellate cell density along the 22ºN offshore waters was 14x 10^3 cells L^{-1} and towards the offshore areas of 21ºN it was 7.9x 10^3 cells L^{-1} where the total cell density was ~8x 10^3 cells L^{-1}. Diatom cell density was significantly lower in the northern area that reached up to 0.5x 10^3 cells L^{-1} along the open ocean waters of 22ºN and 0.32x 10^3 cells L^{-1} along the open ocean waters of 21ºN. Along the coastal waters abundance of phytoplankton was lesser (TCD, 1x 10^3 cells L^{-1}) dominated by diatoms (~850 cells L^{-1}). The cell densities of phytoplankton decreased towards 18ºN (~100 cells L^{-1}) and were represented mainly by diatoms (81%). A total of 50 species were recorded during the phase.

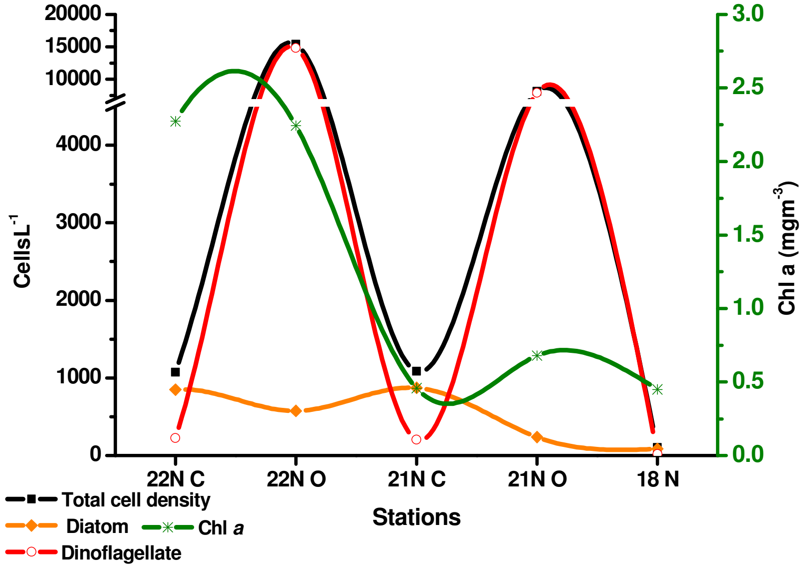


Figure 48. Variations in phytoplankton cell densities and chlorophyll *a* along the NEAS during Phase-2 of winter monsoon 2011

The phytoplankton community along NEAS during Phase-2 observed maximum diversity along the coastal waters. The diversity of community (H') along 21ºN coastal region was 3.89 with least dominance index (λ' 0.1) and high species richness (d 4). The coastal waters along 22ºN also recorded similar diversity trend. The offshore water with the bloom of dinoflagellate was having a lower diversity (H' 0.52) and higher dominance (λ' 0.8) sustaining a less even community (j' 0.1).

4.2.4. Phytoplankton community assemblage

Phytoplankton community along the open ocean waters were dominated by dinoflagellate *Noctiluca scintillans* (Subclass- Noctilucophycidae) with nearly 95%, whereas the coastal waters were dominated by diatoms. The contributions towards the diatom community by the classes were in the order Coscinodiscophycidae (42%, consisting of mainly *Rhizosolenia* spp., *Chaetoceros* spp., *Thalassiosira* sp.) Bacillariophycidae (42%, *Nitzschia* sp., *Haslea* sp., *Navicula* sp.) and Fragilariophycidae (16%, *Thalassionema nitzschioides*) (Figure 49 a,b).

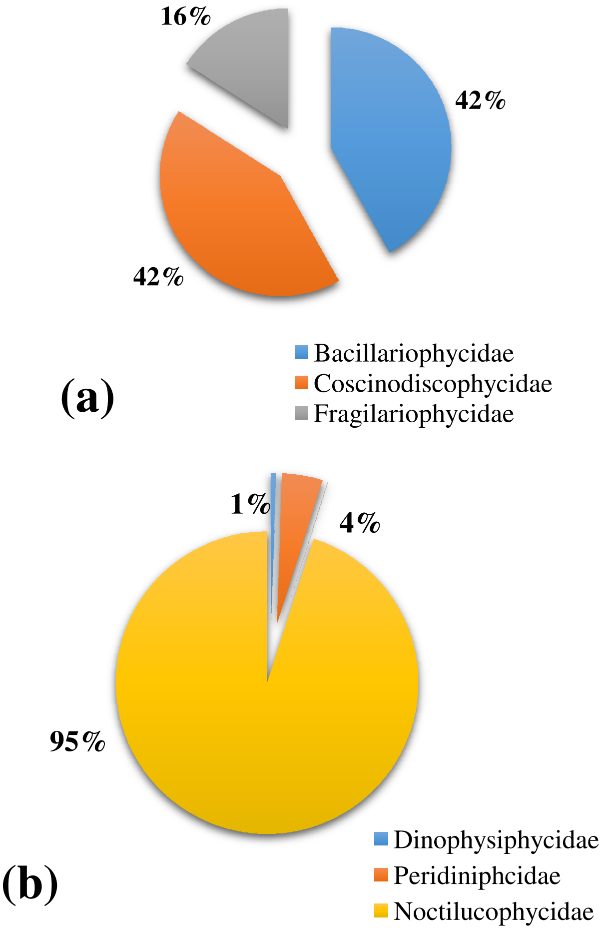


Figure 49. Percentage composition of major subclass of **(a)** diatoms and **(b)** dinoflagellates along the NEAS during Phase-2 of winter monsoon 2011

The bloom of *Noctiluca scintillans* (14x 10^3 cells L^{-1}) along the offshore waters of 22ºN latitude was accompanied by raphid pennates *Haslea* spp. (~400 cells L^{-1}) and a few cells of centrales, *Rhizosolenia hebetata* and those along 21ºN (7.9x 10^3 cells L^{-1}) that coexisted with raphid pennate *Navicula* spp. (153 cells L^{-1}) and a very few centrales (Figure 50). Dinoflagellates present along with the bloom species (*N. scintillans*) was mainly subclass Peridiniphycidae belonging to order Gonyaulacales such as *Gonyaulax polygramma*, *Ceratium furca*, *Ceratium fusus*, *Corythodinium tessellatum* (Figure 51).

Towards the coastal waters nearly 80% of the phytoplankton community was dominated by diatoms. Along the coastal waters of 22ºN latitude, the araphid pennate of the genus *Thalassionema* (mainly *T. nitzschioides,* 236 cells L^{-1}) dominated the phytoplankton community. The centric forms present were more diverse in assemblage and consisting of *Rhizosolenia* spp. mainly *Rhizosolenia stolterfothii* (85 cells L^{-1}), *Leptocylindrus* sp. and *Lauderia* sp. Dinoflagellates present in these coastal waters were mainly Dinophycids like *Dinophysis miles*, *D. acuminata*, *Ornithocercus* sp. and Peridiniphycids like various species of *Ceratium* sp. and *Protoperidinium* sp.

Unlike the coastal waters of 22ºN latitude, the coastal waters of 21ºN were dominated by centric diatoms belonging to genus *Chaetoceros* (~300 cells L^{-1}) and *Rhizosolenia* (~200 cells L^{-1}) with a highly diverse species composition. The major ones were *Chaetoceros lorenzianus*, *C. coarctatus*, *Rhizosolenia hebetata, R. bergonii,* and *R. alata,* accompanied with raphid pennate *Nitzschia* sp. (~ 200 cells L^{-1}). Dinoflagellate composition was more varied with several species of *Ceratium* and *Protoperidinium*. Along the 18ºN latitude with very low phytoplankton cell density, it was composed of a few cells of *Thalassiosira* sp. and *Rhizosolenia* sp.

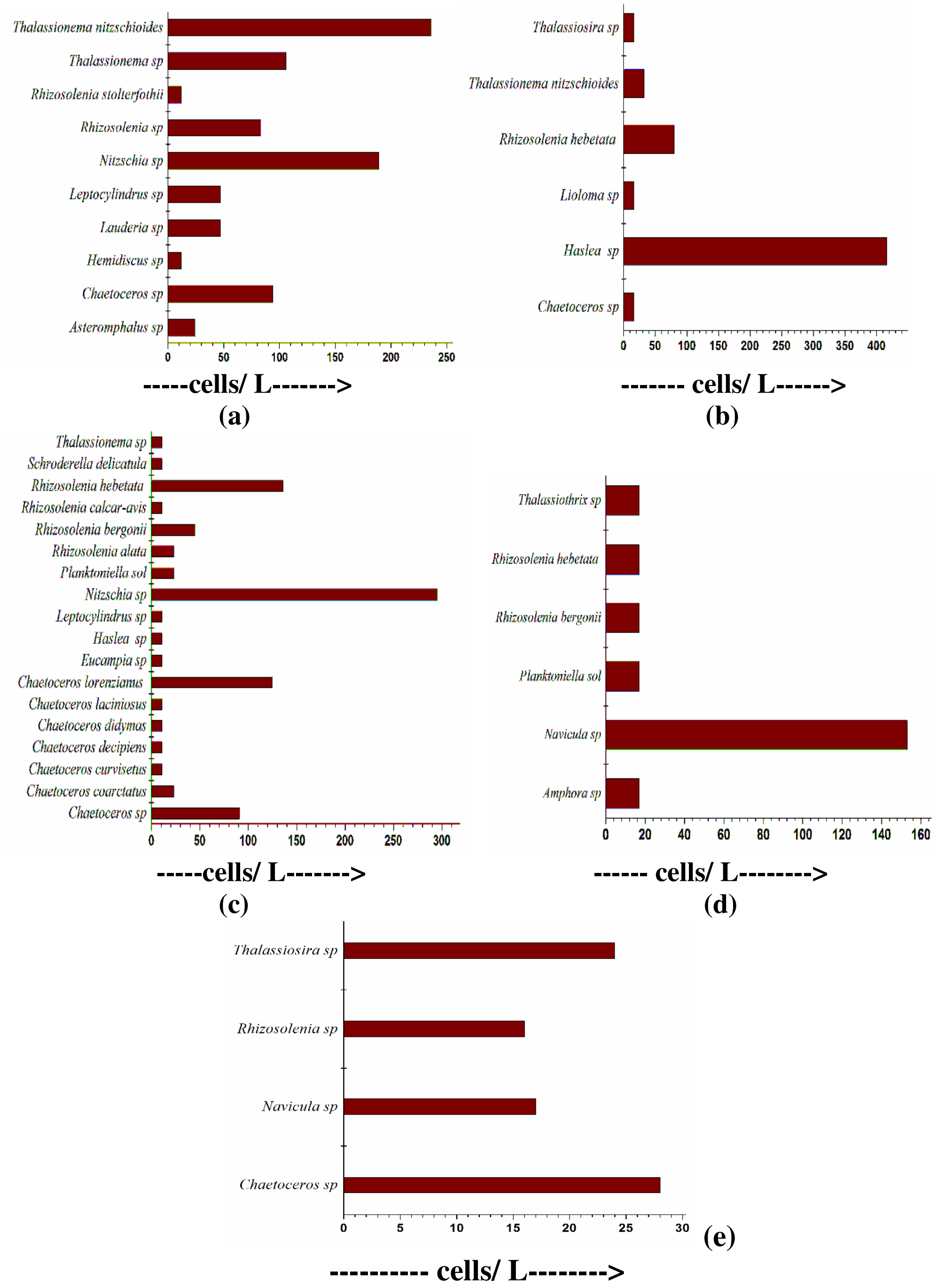


Figure 50. Community composition of diatoms along different stations during Phase 2 of winter monsoon 2011, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

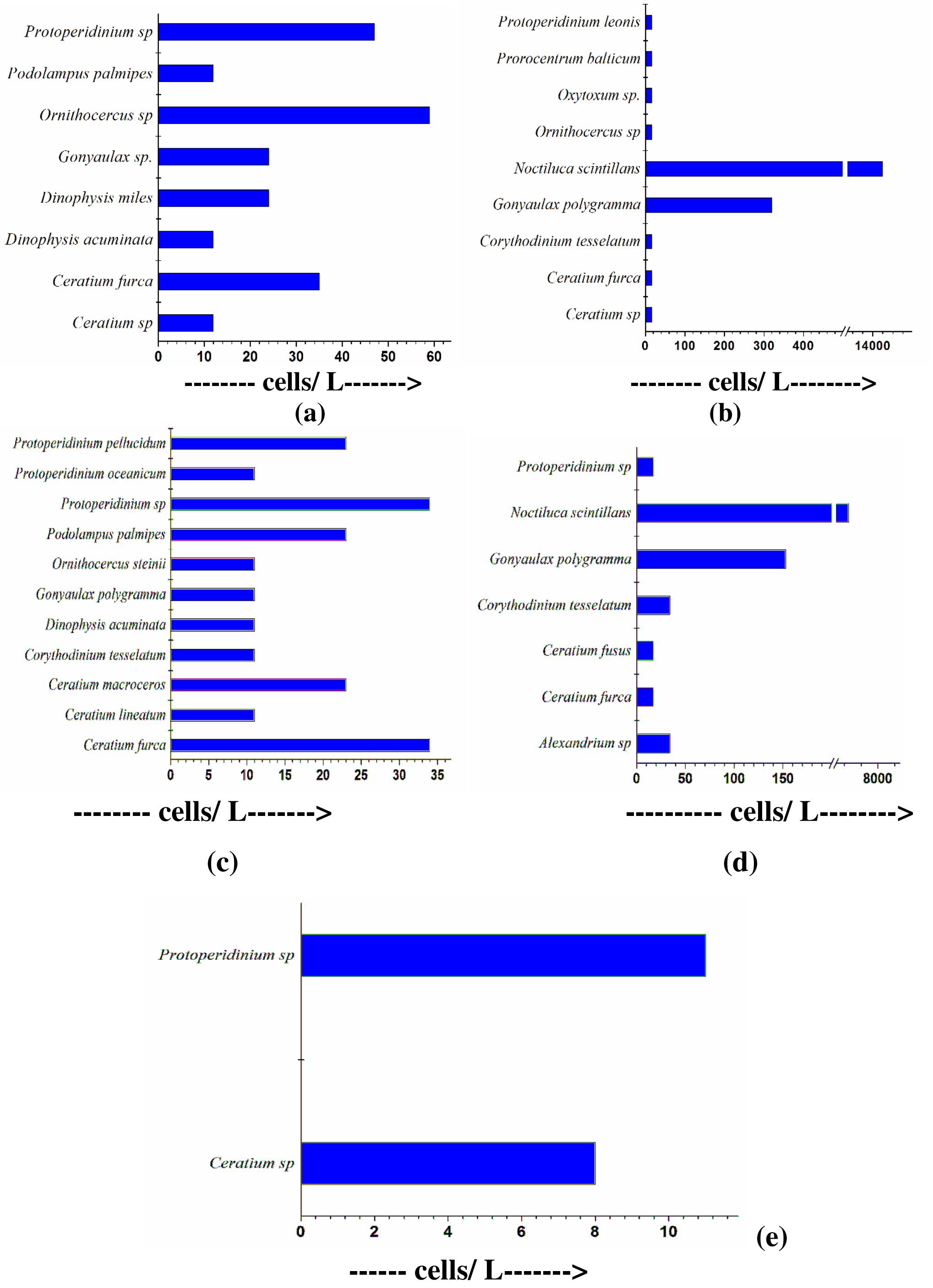


Figure 51. Community composition of dinoflagellates along different stations during Phase 2 of winter monsoon 2011, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

4.3. Phase- 3 (Late March 2011)

4.3.1. Physico-chemical characteristics

During the period of observation weak winds prevailed in the region predominantly northerly in direction. Humidity along the region increased in comparison with that of the previous observation during Phase-2 and ranged between 75-85% with an air temperature of ~24.6 ºC. Humidity as well as air temperature increased towards south of the North Eastern Arabian Sea and was ~86% and 28.3ºC respectively. Atmospheric pressure varied between minimum of 1005 and maximum of 1017 mb along the study area. The SST increased during Phase-3 when comparing with previous two phases. Along the offshore waters SST increased to 25.2ºC to 25.6ºC in the northern region whereas towards the south, SST was nearly 26.8ºC (Figure 52). Surface salinity decreased to 36 along the offshore areas (Figure 53). Towards the near shore regions still low saline waters (35.3) were present. The temperature and salinity profiles (Figure 54) revealed that the process of convective mixing has subsided and the water column was moving to a stable condition, with shallow mixed layer < 30 m. The surface nitrate concentration decreased that reached to ~0.32 μmol L^{-1} along 22ºN and 0.08 μmol L^{-1} along the 21°N offshore areas. The coastal waters of 22ºN latitude sustained significantly higher nitrate concentration (3.6 μmol L^{-1}) which subsequently decreased towards 21ºN.

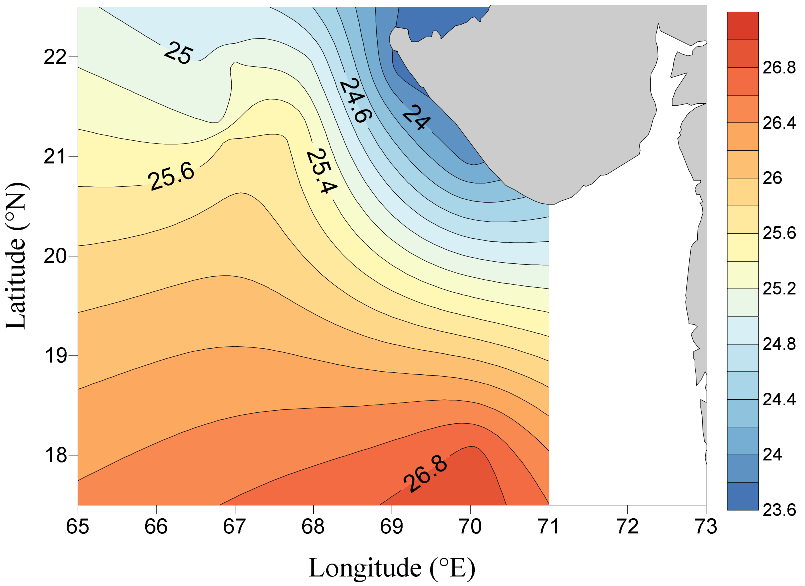


Figure 52. Variations in SST (ºC) along the NEAS during Phase-3 of winter monsoon 2011

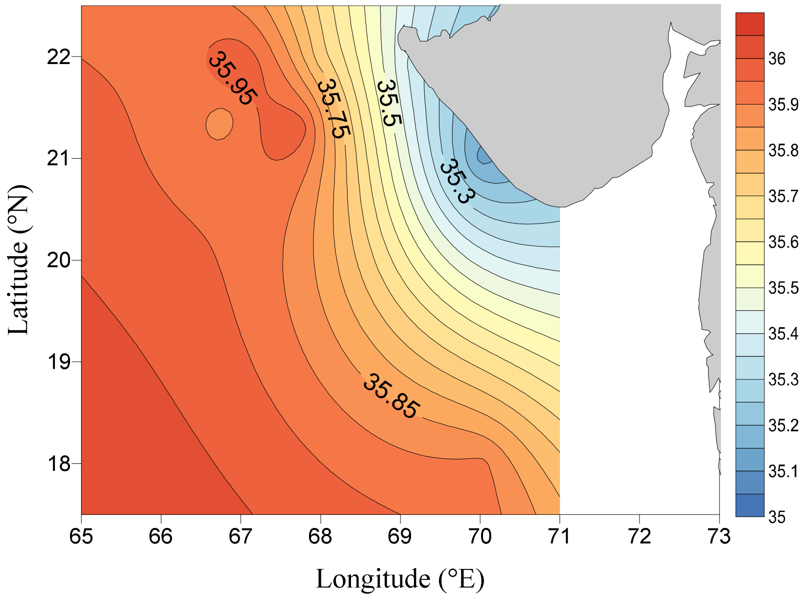


Figure 53. Variations in sea surface salinity along the NEAS during Phase-3 of winter monsoon 2011

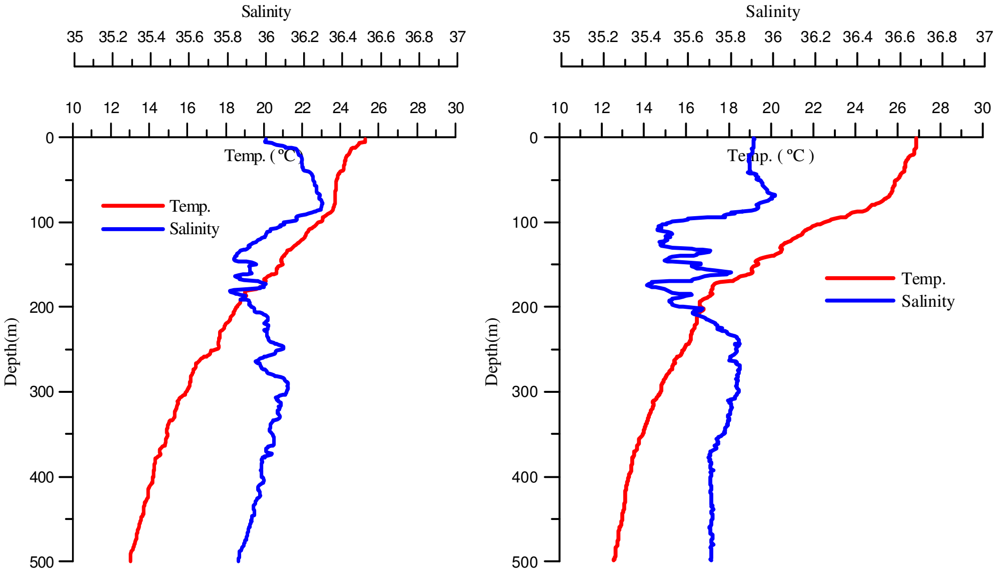


Figure 54. Vertical profiles of Temp. (°C) and Salinity along 22°N offshore and 18°N (reference station)

4.3.2. Chlorophyll *a*- Phytoplankton biomass

The average surface chlorophyll *a* during Phase-3 was 2.13 ± 1.85 mg m^{-3}. Surface chlorophyll *a* concentration shows significant variations between the offshore areas of 22°N and 21°N latitudes (Figure 55). Open ocean waters observed an average chlorophyll *a* of 1.4 ± 1.7 mg m^{-3} and coastal waters with 3.8 ± 0.22 mg m^{-3}. Higher chlorophyll *a* concentration (2.6 mg m^{-3}) was observed along the offshore waters of 22°N latitude which decreased to 0.2 µg L^{-1} along 21°N. But the coastal waters of 22°N and 21°N maintained fairly higher surface chlorophyll *a* (~3.6 mg m^{-3}). Thus during the period of observation surface chlorophyll *a* distribution observed maximum towards the coastal waters and decreased towards the open ocean areas. Towards southern extend of northern Arabian sea (along 18°N) the chlorophyll *a* decreased to nearly 0.1 mg m^{-3}.

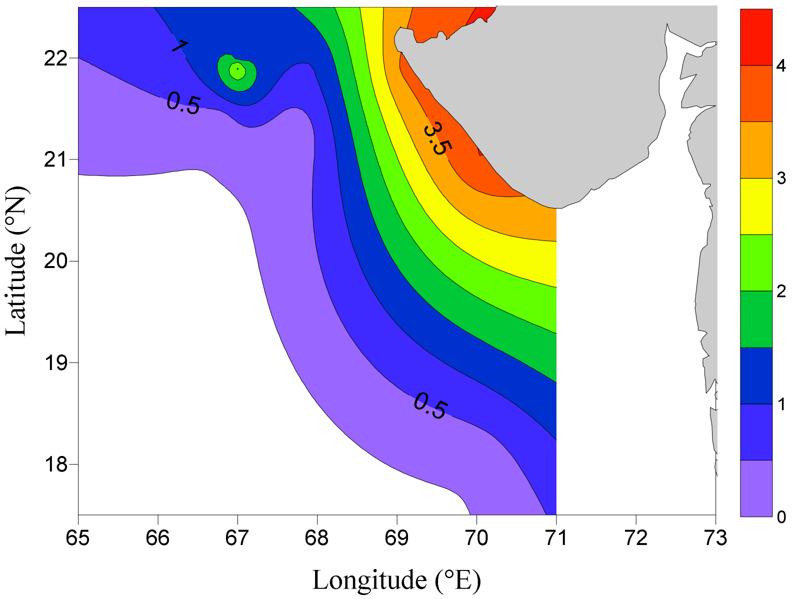


Figure 55. Variations in surface chlorophyll *a* (mg m^{-3}) along the NEAS during Phase- 3 of winter monsoon 2011

4.3.3. Phytoplankton cell density- numerical abundance and diversity

Phytoplankton abundance (TCD) was maximum (31.1x 10^{4} cells L^{-1}) along the offshore waters of 22ºN latitude and towards the offshore regions of 21ºN phytoplankton abundance decreased (11.8x 10^{3} cells L^{-1}). Phytoplankton cell densities were almost numerically similar along the coastal regions of 22ºN and 21ºN (2.9x 10^{4} cells L^{-1}). Diatoms dominated in cell densities (> 95%) along NEAS during the period. Along the offshore waters of 22 ºN, maximum abundance of diatoms was observed (3.1x 10^{5} cells L^{-1}) (Figure 56). Dinoflagellates were also observed in significant densities in the region (1.6x 10^{3} cells L^{-1}). Along the offshore regions of 21ºN phytoplankton abundance decreased (11.8x 10^{3} cells L^{-1}) and was composed of mainly diatoms (10x 10^{3} cells L^{-1}) followed by dinoflagellates (1.3x 10^{3} cells L^{-1}). TCD was very less along the 18ºN latitude. Along the 22ºN latitude the blue green algal filaments were present in a cell density of 187 filaments L^{-1} along the offshore waters and 36 filaments L^{-1} in the coastal region. Total number of species observed during the phase was 54.

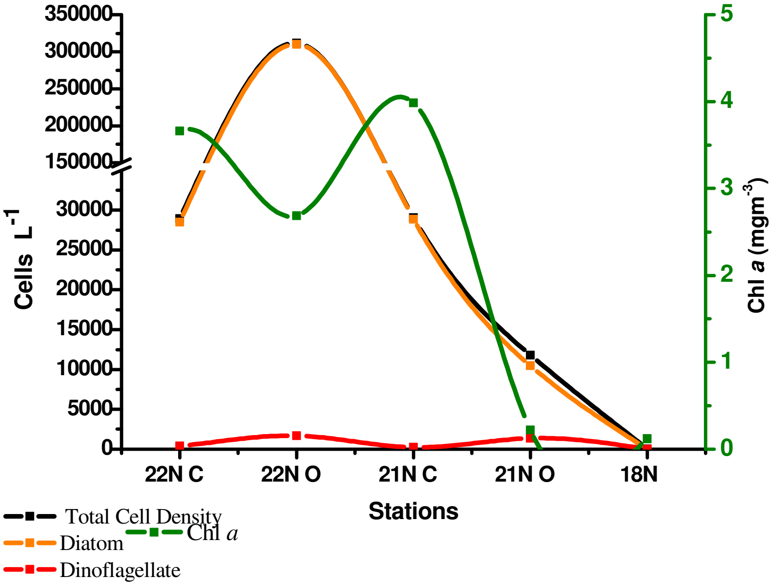


Figure 56. Variations in phytoplankton cell densities and chlorophyll *a* along the NEAS during Phase-3 of winter monsoon 2011

The microphytoplankton community observed a decrease in diversity during the Phase-3 in comparison with the previous two phases (Table 6). Maximum species diversity was observed along the coastal waters of 21ºN (H' 2.6) where there was increased richness (d 2.04) with lower dominance (λ' 0.22). Owing to the bloom formation the diversity along offshore waters were found to decrease (~1) with increased dominance (0.6-0.9).

4.3.4. Phytoplankton community assemblage

Diatoms dominated the phytoplankton community and were contributed by subclass Bacillariophycidae (85%, mainly *Haslea* spp., *Pseudo-nitzschia pungens*, *Meuniera membranacea, Pleurosigma* sp. followed by Coscinodiscophycidae (13%, *Rhizosolenia* spp., *Chaetoceros* spp., *Leptocylindrus mediterraneus*, *Skeletonema costatum*) and Fragilariophycidae (2%, *Thalassionema nitzschioides*, *Tabellaria fenestra*). Class Dinophyceae was represented by largely Peridiniphycidae (*Ceratium* sp.*, Protoperidinium* sp., *Gonyaulax polygramma*) followed by Dinophysiphycidae (*Ornithocercus* *magnificus, Ornithocercus steinii*) and Prorocentrophycidae (*Prorocentrum* sp.) other than *Noctiluca scintillans* (subclass Noctilucophycidae) (Figure 57a, b).

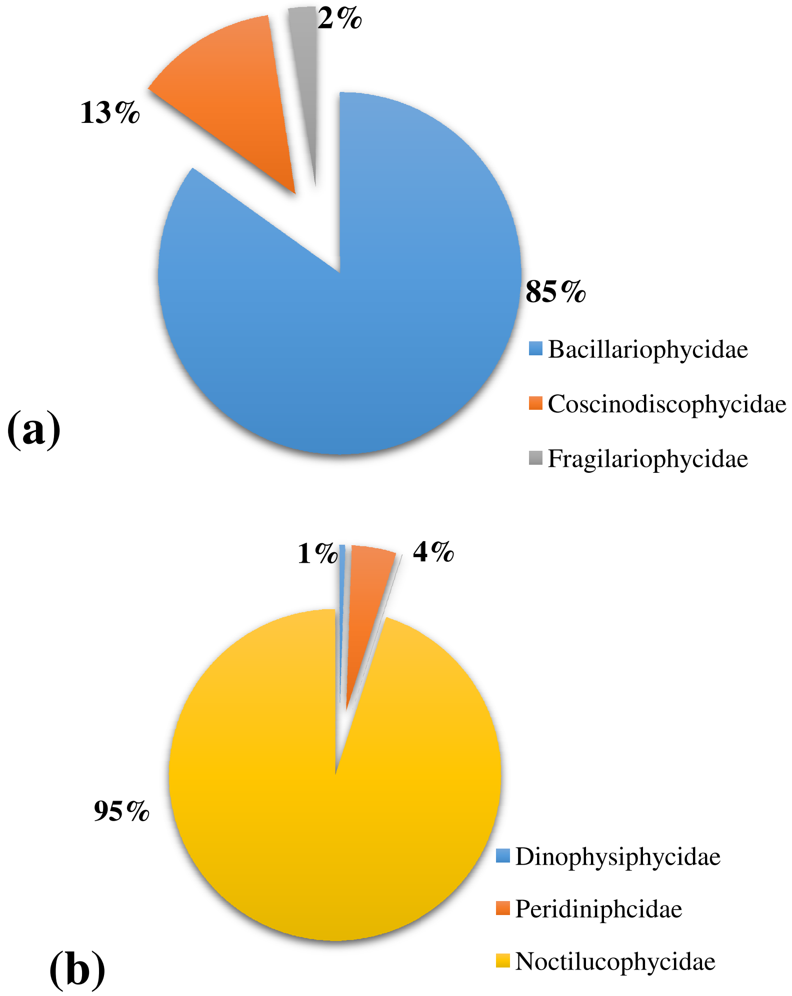


Figure 57. Percentage contribution of major subclass of **(a)** diatoms and **(a)** dinoflagellates along the NEAS during Phase-3 of winter monsoon 2011

The pennate diatom *Haslea* sp. dominated the phytoplankton community along the offshore waters of 22ºN latitude (Figure 58). The species was observed in mucilaginous aggregation (3.1x 10^5 cells L^{-1}) along with bloom patch of *Noctiluca scintillans* (1.4x 10^4 cells L^{-1}). Detailed analysis of the *Haslea* spp., aggregation observed two species viz *Haslea gretharum* and

Haslea gigantea. Proboscia alata was another diatom sustained along with the aggregation in a few numbers (90 cells L^{-1}). Dinoflagellates other than *Noctiluca scintillans* were very few in number represented by *Ceratium furca*, *Ceratium fusus*, *Ceratium symmetricum*, *Protoperidinium* spp. (Figure 59). Along the offshore waters of 21ºN latitude, the TCD decreased in comparison with northern area and was dominated by diatom *Leptocylindrus mediterraneus* (9x 10^{3} cells L^{-1}) which was found in a symbiotic association with stramenopile protist *Solenicola setigera*. Other major diatoms present were *Leptocylindrus danicus* (173 cells L^{-1})*, Haslea* sp (~90 cells L^{-1}) and *Proboscia alata* (225 cells L^{-1}). Dinoflagellates were present in a higher cell density with a diverse community composed of *Ornithocercus magnificus* (303 cells L^{-1}), *Prorocentrum* sp. (228 cells L^{-1}), *Protoperidinium* sp. (250 cells L^{-1}), *Ornithocercus steinii* (147 cells L^{-1}), *Gonyaulax polygramma* (225 cells L^{-1}), *Ceratium lineatum* (147 cells L^{-1}) and *Ceratocorys* sp.

The coastal waters of 22ºN and 21ºN latitudes with a higher surface chlorophyll *a* concentrations were supported mainly by diatoms. Along the coastal waters of 22°N the diatoms were mainly represented by *Chaetoceros* spp., (18x 10^{3} cells L^{-1}), *Thalassionema nitzschioides* (8.6x 10^{3} cells L^{-1}), *Odontella* sp. (~320 cells L^{-1}), *Tabellaria fenestrata* (360 cells L^{-1}), *Eucampia* sp., *Rhizosolenia setigera*, *Thalassiosira* sp. Along the coastal waters of 21ºN latitudes the diatoms were represented by *Pseudo-nitzschia pungens* (1.1x 10^{4} cells L^{-1}), *Chaetoceros socialis* (1x 10^{4} cells L^{-1}), *Chaetoceros* spp. (5x 10^{3} cells L^{-1}), *Chaetoceros lorenzianus* (4x 10^{3} cells L^{-1}), *Skeletonema costatum.* Dinoflagellates along the coastal waters were mainly represented by *Protoperidinium* sp. (~200 cells L^{-1}), *Gonyaulax polygramma*, *Ornithocercus steinii* and *Pyrophacus steinii*. *Rhizosolenia* sp. and *Protoperidinium* sp. were the phytoplankton present along 18ºN area.

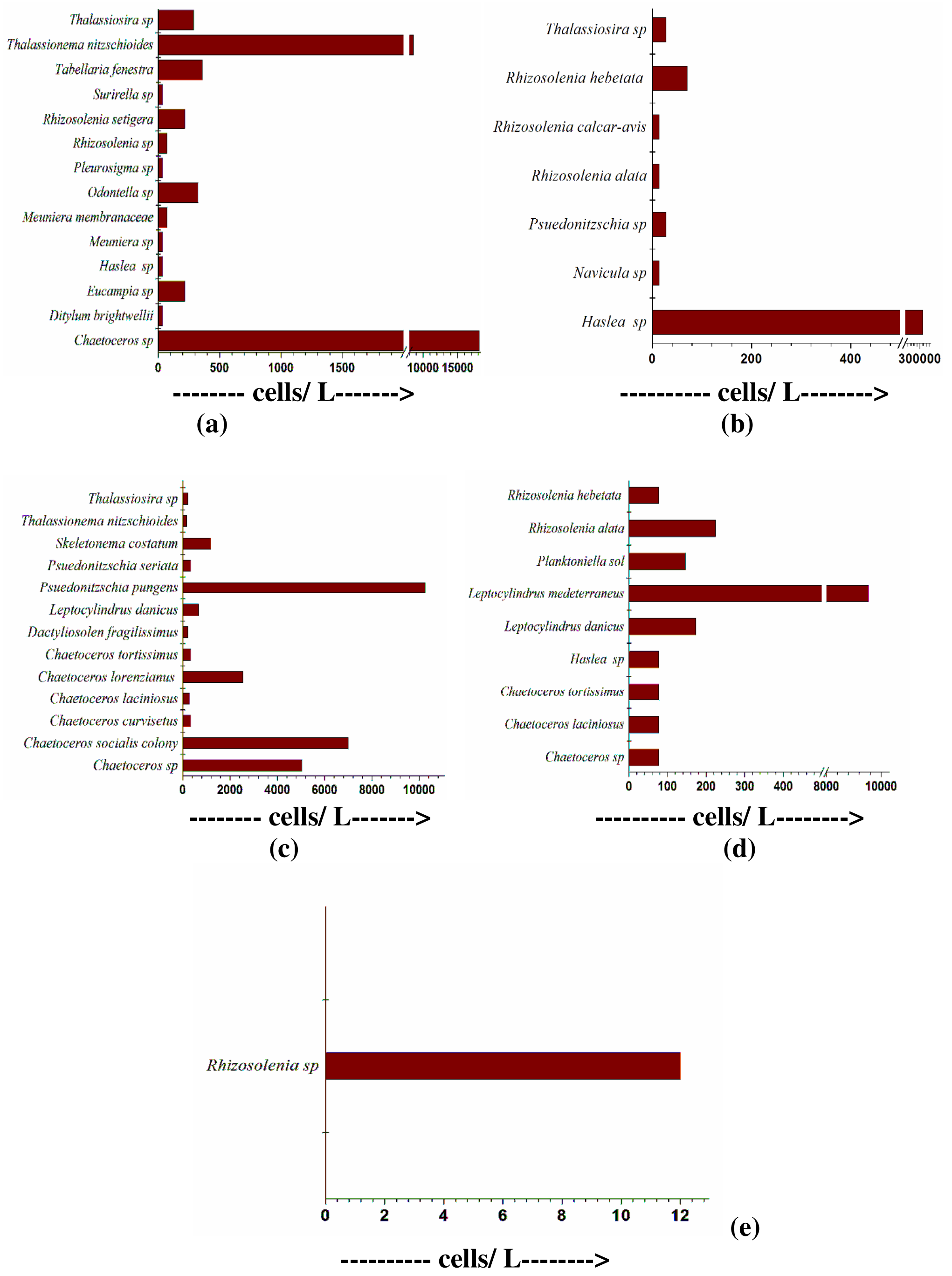


Figure 58. Community composition of diatoms along different stations during Phase 3 of winter monsoon 2011, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

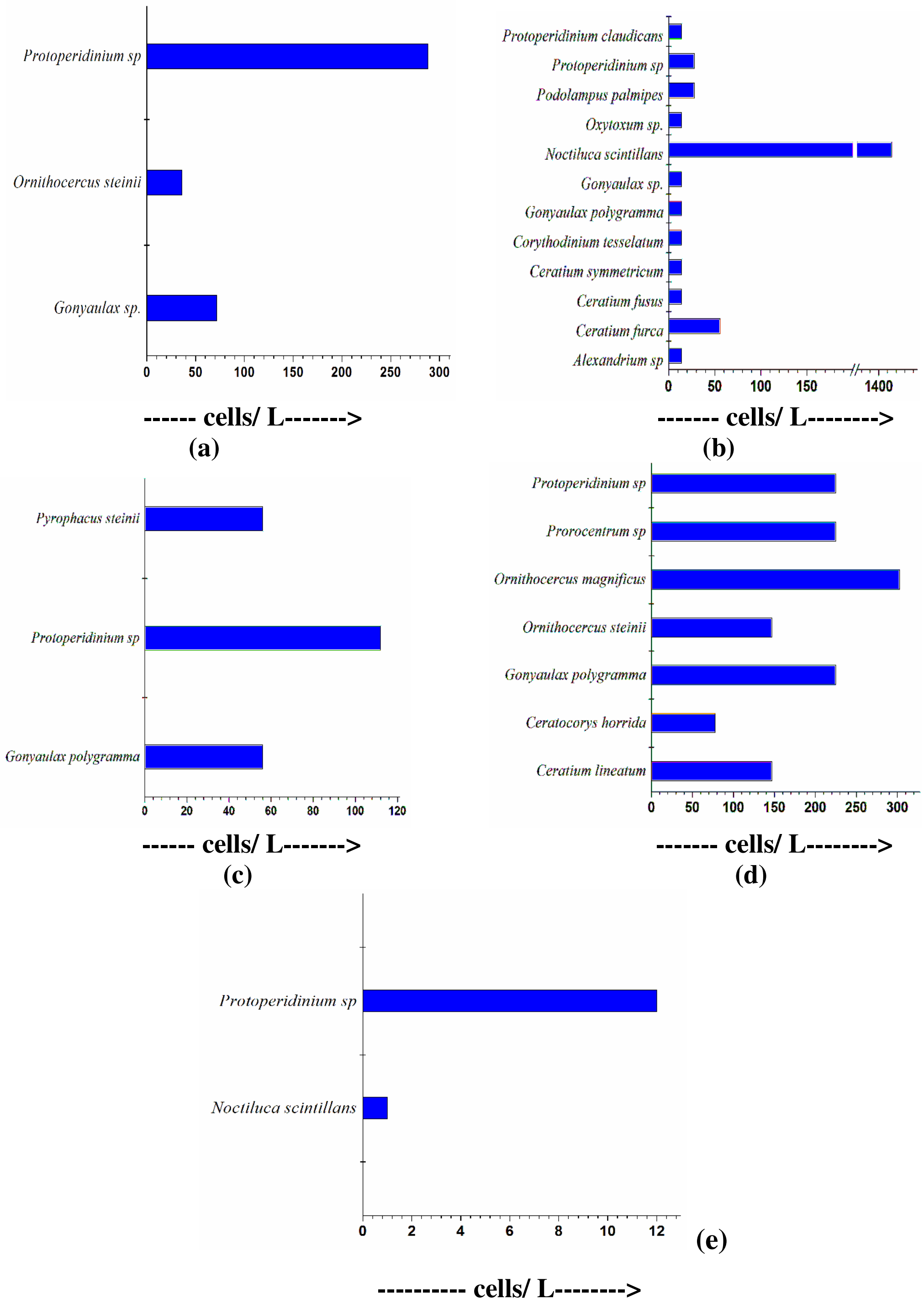


Figure 59. Community composition of dinoflagellates along different stations during Phase 3 of winter monsoon 2011, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 18ºN reference

4.4. Variability in the microphytoplankton community during winter monsoon 2011- *a spatio-temporal analysis*

North Eastern Arabian Sea during winter monsoon 2011 experienced comparatively intense convective mixing than 2009. The surface waters of the northern Arabian Sea during winter monsoon of 2011 were observed to be cooler than that of 2009. The average SST during Phase-1 was 24.24 ± 1.26 ºC that increased in the subsequent phases (Figure 60). Surface salinity was maximum along the offshore waters of 22ºN latitude. The region was also having low SST throughout the season. Deepest MLD was observed along the offshore water during Phase-2 with maximum along 22ºN latitude and shoaled up during Phase- 3.

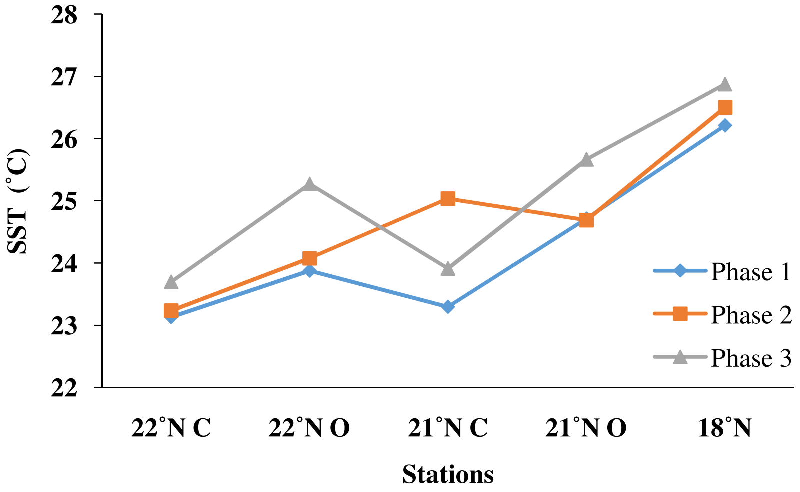


Figure 60. Variation in SST during different phases of winter monsoon of 2011

Coastal waters of 21ºN latitude observed higher chlorophyll *a* during the Phase-1 as well as Phase-3 but were less productive during Phase-2. Conversely the offshore waters of 21ºN stayed to be less productive during both Phase-1 and 3 with a slight increase in chlorophyll *a* and phytoplankton cell densities during Phase-2. Towards south 18ºN was having higher SST and low surface chlorophyll *a*, remaining less productive throughout the phases.

The cell density of phytoplankton was lesser during Phase-2 in comparison with that of Phase-1 and 3.

Microphytoplankton community was characterised by diverse species assemblage during phase 1 (H' av. 2.73) with lesser dominance (λ' 0.27) and high species richness (d av. 1.48) (Table 7).

Phases	Shannon-Weiner Diversity (H')	Simpsons Dominance Index (D)	Margalef's species richness (d)	Pielous's evenness (j')
Phase 1	2.737213	0.273635	2.697689	0.713185
Phase 2	2.191655	0.433735	2.109794	0.574288
Phase 3	1.37144	0.557428	1.484184	0.417409

Table 7. Average of diversity indices for three phases during winter monsoon 2011

The k-dominance plot for the species wise abundance of microphytoplankton for three phases of winter monsoon 2011, clearly depicted the increased dominance in the community during Phase-2 and 3. The open ocean blooms that were dominated by dinoflagellate *Noctiluca scintillans* during Phase-2 and by diatom during Phase-3 caused more or less straight line for the k-dominance plot rather than a sigmoid curve. Phase-1 was having more diverse with lesser dominant community assemblage along NEAS (Figure 61). Nearly six species contributed to ~80% of the total community. The phytoplankton community during Phase-2 and 3 expressed increased dominance where a single species contributed to ~80% of the total community.

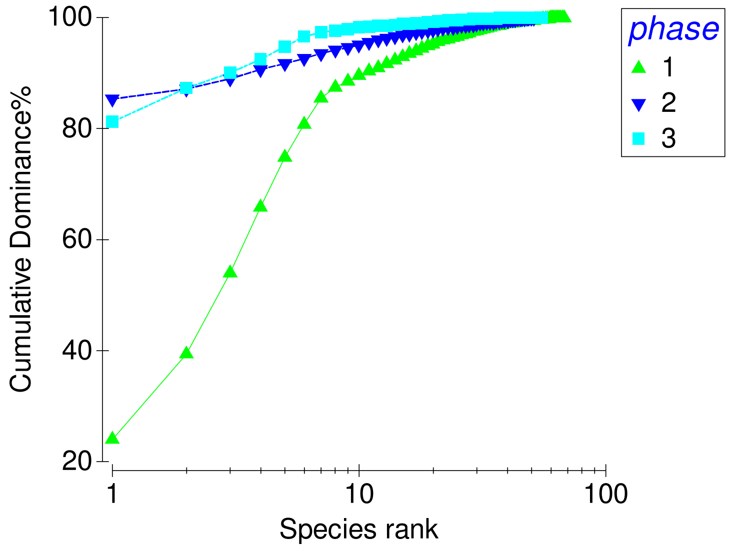


Figure 61. Phase wise k- dominance plot for microphytoplankton during winter monsoon of 2011

Regionally coastal waters were more diverse, considerably the coastal regions of 21ºN (H'= av. 3.2) with a higher species richness (d= av. 3.1). The offshore areas were having higher dominance (D =0.5) with lesser diversity (H'=1.9) (Table.8).

Region	Shannon-Weiner Diversity (H')	Simpsons Dominance Index (D)	Margalef's species richness (d)	Pielous's evenness (j')
22°N coast	2.084529	0.429565	1.926317	0.509162
22°N offshore	1.541539	0.652426	2.344716	0.317629
21°N coast	3.208069	0.167646	3.117823	0.6647
21°N offshore	1.914664	0.549894	2.312315	0.445557
18°N (Ref stn.)	1.751713	0.308467	0.78494	0.904423

Table 8. Average of diversity indices for the area during winter monsoon of 2011

The k- dominance plot for the regions showed more diverse and even community along the coastal waters of 21°N latitude. Along the region 6-7 species contributed to ~80% of the community. Similar observation occurred along the reference station along 18°N latitude, having comparatively more diverse and even community than the northern offshore areas (Figure 62).

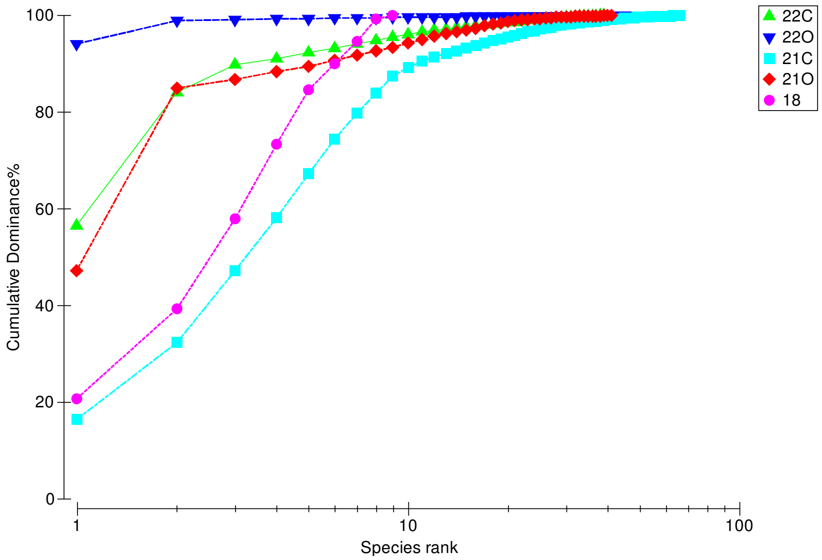


Figure 62. Station wise k- dominance plot for microphytoplankton during winter monsoon of 2011

4.4.1 Phytoplankton community structure

General distribution of phytoplankton along NEAS during the winter monsoon of 2011 showed that the community was mainly composed of centric diatoms (mainly Coscinodiscophyceae) with maximum abundance towards the coastal waters. Towards the offshore waters, the abundance of raphid pennates (Bacillariophyceae) increased. Araphid pennates (Fragilariophyceae) were present mainly along the coastal waters and their abundance was more during Phase-1 and Phase-3. Dinoflagellates markedly increased during Phase-2 (90%) with extensive *Noctiluca scintillans* bloom along the offshore waters. There was a significant decrease in the diatom cell density mainly along the offshore waters. Abundance of raphid pennates peaked during Phase-3 with the dominance of *Haslea* spp., which outnumbered other groups along the offshore waters. The abundance of *Pseudo-nitzschia* spp. increased along the coastal waters.

The major centric diatoms observed during the study period were *Chaetoceros* spp., *Thalassiosira* sp., *Rhizosolenia* spp., *Eucampia zodiacus* and *Leptocylindrus mediterraneus*. Among this *Chaetoceros* spp., formed the major phytoplankton present among the community. Abundance was more during Phase-1 and 3. Even though their abundance increased towards the coastal waters, they were also present in the offshore areas. In general *Chaetoceros* spp. was found to have slight negative correlation with that of the salinity (p - 0.57) and was showing an affinity towards nitrate concentration (p 0.67). *Chaetoceros* genus was mainly supported by *C. lorenzianus* followed by *C. curvisetus, C. affinis, C. tortissimus, C. socialis* and *C. laciniosus*. *Thalassiosira* sp. was observed mainly during Phase-1 and 3 usually in mucilaginous aggregations along the coastal waters.

Rhizosolenia spp. was ubiquitously distributed throughout the 21ºN and 22ºN latitudes both in coastal as well as offshore waters but was comparatively much lesser towards the southern extend of the study area (18ºN latitude). Among the genus *Rhizosolenia*, *R. hebetata* was the dominant species present followed by *Rhizosolenia (=Proboscia) alata, R. bergonii, R. imbricata, R. setigera* and *R. stolterfothii*.

Even though the cell densities of raphid pennates peaked during Phase-3 than that of Phase-1 and 2 it was more or less uneven community with higher dominance supported by high cell density of one or two species. The class of raphid pennates was mainly constituted by *Haslea* sp., *Navicula* sp., *Nitzschia* sp. and *Pseudo-nitzschia* sp. *Haslea* sp. was observed along the offshore waters throughout the three phases. The species was present in smaller cell density during Phase-1 which increased during Phase-2 and formed intense bloom during Phase-3 succeeding the *Noctiluca scintillans* bloom. *Nitzschia* sp. represented mainly by *Nitzschia longissima* was observed abundantly along the coastal waters during Phase-2. *Navicula* sp. was present throughout the three phases but maximum during Phase-2 along the offshore areas. The presence of

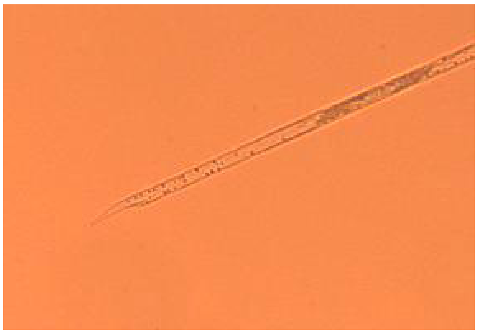
Pseudo-nitzschia spp. was less intense when comparing with that of winter monsoon of 2009. *Pseudo-nitzschia seriata*, *Pseudo-nitzschia pungens* were the major species present and the later present mainly during Phase-3. Araphid pennate was represented by the genus *Thalassionema* and was mainly represented by two species, *T. nitzschioides* along the coastal waters during Phase-1 and 3 and *T. frauenfeldii* along the offshore waters during Phase-1.

Dinoflagellate community was dominated by subclass Dinophysiphycidae during Phase-1, composed of *Ornithocercus* spp., *Ornithocercus magnificus* and *Dinophysis miles*. Their abundance was significant along the coastal waters whereas, during Phase-2 the bloom of *Noctiluca scintillans* spread all over the offshore areas (>90%). The species was present along the offshore waters of 22ºN throughout the three phases. It was observed as an intense bloom along the offshore waters during Phase-2 extending to the Phase-3, but slackened along the 22ºN region. The abundance of subclass Peridiniphycidae increased during Phase-2 and 3, and was mainly contributed by Peridiniales like *Protoperidinium* sp., *Ceratium* spp. and *Alexandrium* sp. during Phase-1 and was replaced by Gonyaulacales mainly *Gonyaulax polygramma* along the offshore waters during Phase-2 and 3. *Ceratium* spp. was distributed throughout the region with higher cell densities along the coastal waters and was supported by a varied species and groups. The genus was contributed by *C. furca*, *C. fusus*, *C. pentagonum*, *C. lineatum*, *C. symmetricum*, *C. longipes*, *C. macroceros*. Among this *C. furca* was dominant and present throughout the three phases followed by *C. fusus*.

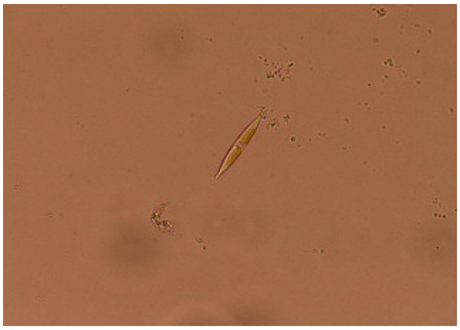
The phytoplankton community structure was analysed for identification of functional groups along the different regions of North Eastern Arabian Sea. Major species that occupied regionally along the NEAS based on the pooled data of 3 phases are listed in the Table 9.

Region	C/ O	Functional Diatom Groups	Functional Dinoflagellate group
22°N	C	*Thalassionema nitzschioides*, *Chaetoceros* spp.,	*Ornithocercus magnificus*, *Ceratium furca*., *C. fusus*, *Protoperidinium* spp.,
22°N	O	*Haslea* spp., *R. hebetata*, *C. lorenzianus*	*Noctiluca scintillans*, *Gonyaulax* sp.
21°N	C	*Thalassionema nitzschioides*, *Chaetoceros* spp., *Pseudo-nitzschia spp.*, *Thalassiosira* sp.	*Ceratium* spp., *Protoperidinium* sp., *Ornithocercus* sp.
21°N	O	*Rhizosolenia alata*, *Leptocylindrus* sp., *Navicula directa*,	*Noctiluca scintillans*, *Gonyaulax* sp., *Prorocentrum* sp.
18°N	Ref	*R. hebetata*, *Thalassiosira* sp, *Chaetoceros* sp	*Protoperidinium* sp, *Ceratium* spp.,

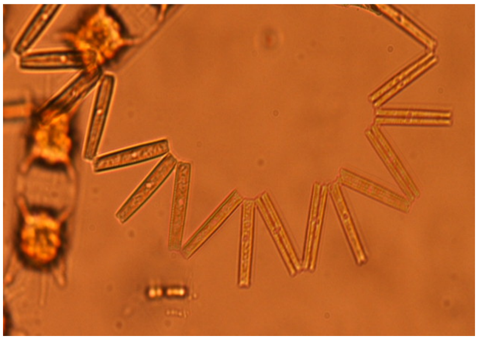
Table 9. Phytoplankton functional groups recorded during winter monsoon of 2011



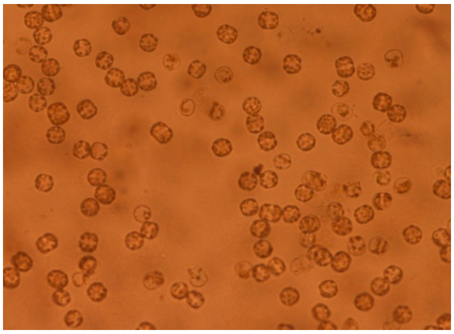
Proboscia alata x 400



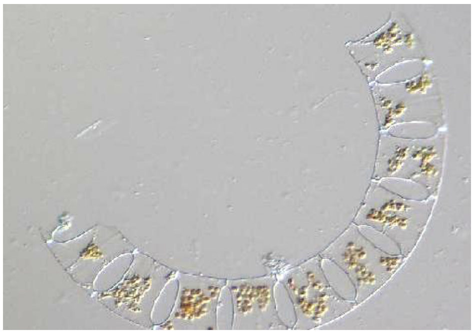
Nitzschia sp. x 400



Thalassionema nitzschioides x400



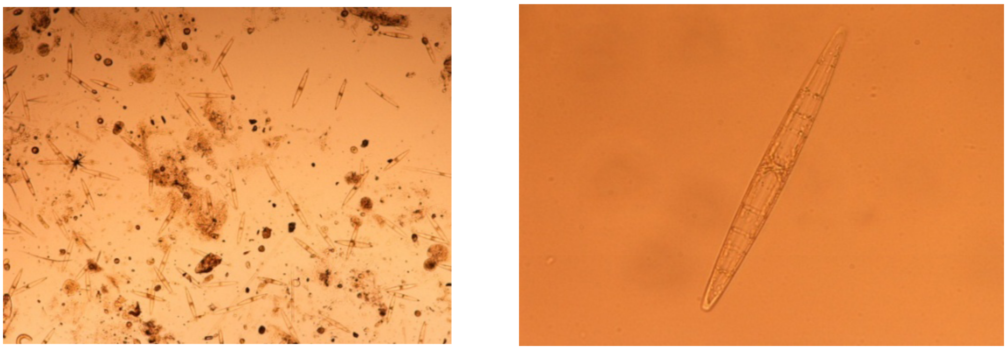
Thalassiosira sp (mucilage) x200



Eucampia zodiacus x 400

Cylindrotheca closterium x400

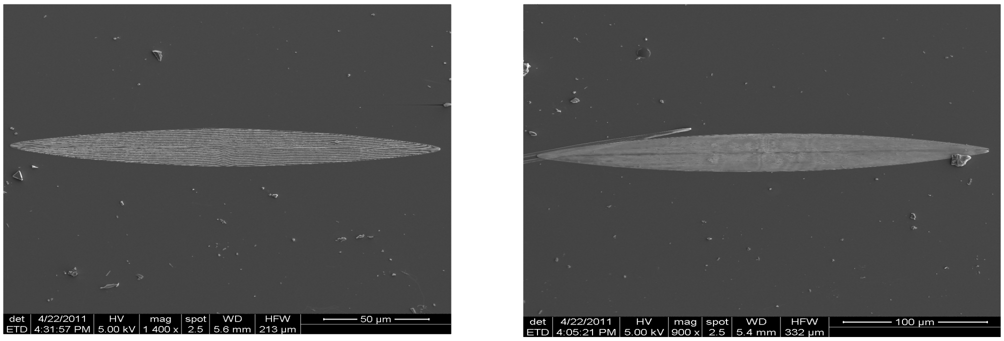
Plate 4: Microphotographs of major diatoms observed during winter monsoon 2011



Haslea sp. x40 (aggregation)

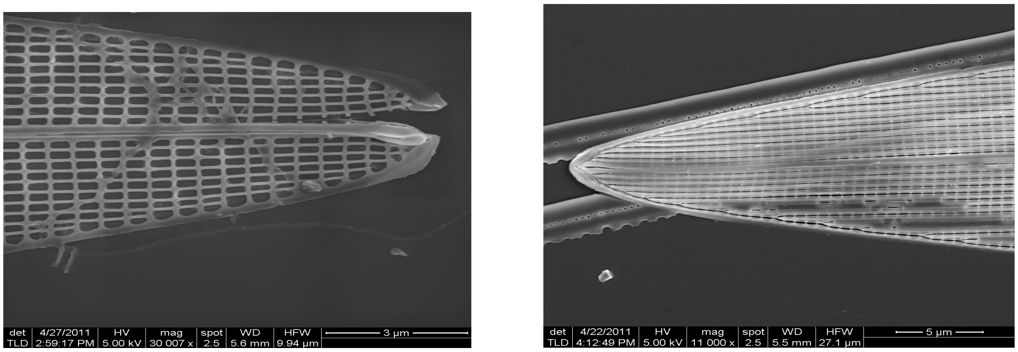
Haslea sp x200

Plate 5: Microphotographs of diatom *Haslea* spp



Haslea gretharum
External view of valve (SEM)

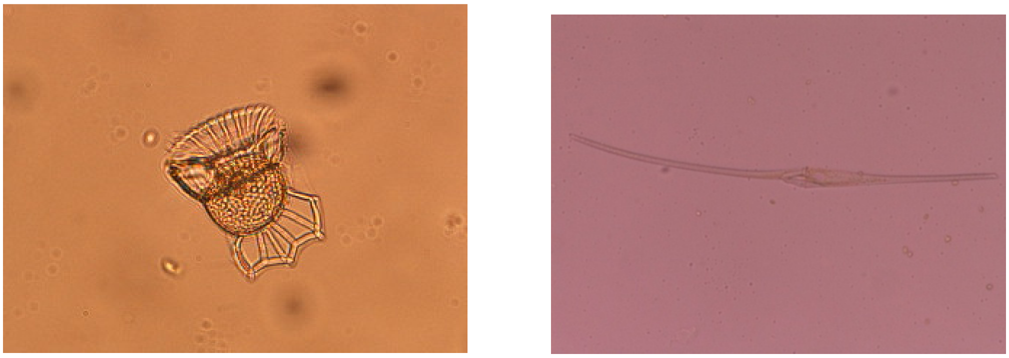
Haslea gigantea
External view of valve (SEM)



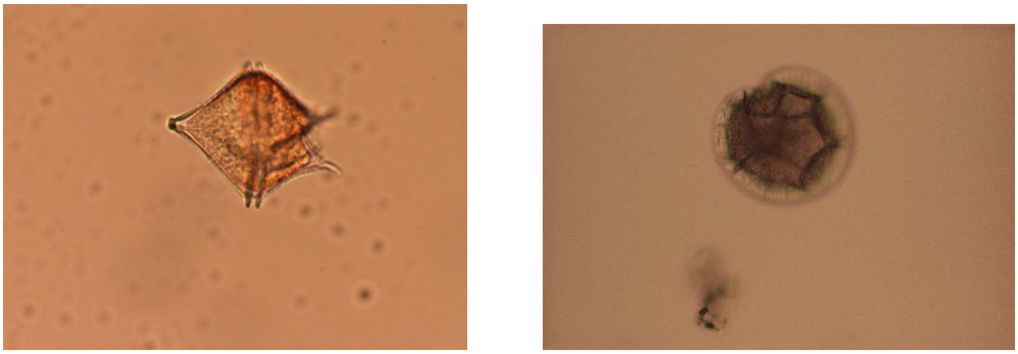
Haslea gretharum
Internal view of valve (SEM)

Haslea gigantea
External view of valve (SEM)

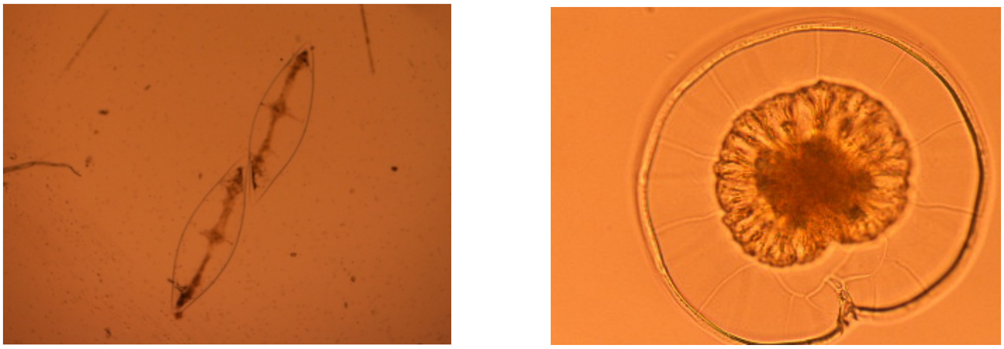
Plate 6: SEM pictures of *Haslea gretharum* and *Haslea gigantea* observed during winter monsoon 2011



Ornithocercus magnificus x400 *Ceratium fusus* x200



Protoperidinium depressum x 200 *Alexandrium* sp. x200



Pyrocystis fusiformis x40 *Pyrophacus steinii* x400

Plate 7: Microphotographs of major dinoflagellates observed during winter monsoon 2011

Chapter 5

Microphytoplankton community structure during late winter and early spring inter monsoon 2012

"There's nothing wrong with enjoying looking at the surface of the ocean itself, except that when you finally see what goes on underwater, you realize that you've been missing the whole point of the ocean. "

— Dave Barry, Author

Introduction

Arabian Sea, one among the productive seas of world ocean is regulated by the biannually reversing monsoon winds. North east monsoon or winter monsoon (November- March) and South west monsoon or summer monsoon (June- September) are the dynamic periods of Arabian Sea with respect to the biological production. The intermediate period between these productive phases are springs inter monsoon (April- May) and fall Inter monsoon (October). These inter monsoon periods are characterized by oligotrophic conditions of euphotic column with lower primary production. The responses of phytoplankton community on transition from a highly productive period to less productive more or less oligotrophic conditions appear to be heedful in biological oceanographic studies. In this chapter such an attempt is made to understand the variations in microphytoplankton community both qualitatively and quantitatively during the transition from productive winter monsoon to less productive or oligotrophic spring inter monsoon season.

5.1. Phase- 1. Late winter monsoon (Late March 2012)

5.1.1. Physico-chemical characteristics

During the period of observation relatively weaker winds (av. 4.4 m/s) prevailed in the region predominantly north westerly in direction. Atmospheric pressure varied between 1003 to 1014 mb and humidity from 80 to 98%. Air temperature was on an av. 25°C showing an increasing trend towards the south (~27°C). Surface hydrography of NEAS during late winter monsoon of 2012 recorded a sea surface temperature (SST) of ~24.5ºC along the offshore waters which further decreased to ~24ºC in the nearshore coastal areas (Figure 63). Along the southern extend of NEAS at 18ºN, SST was comparatively higher (~25.6ºC). High saline surface waters persisted along the northern offshore regions (36.4) and along the coastal regions surface salinity was comparatively lower (36.1). Towards 18°N latitude the salinity further decreased reaching to 35.7 (Figure 64). Mixed layer (MLD) was observed up to a depth of 25 m along the offshore waters of 22ºN latitude that shoaled up to 13 m along the 21ºN latitude (Figure 65). Along the offshore areas with low SST and high salinity, surface nitrate (NO_3-N) concentration was high that varied from 1.18-1.3 µmol L^{-1} (Figure 66). Nitrate concentrations were found to decrease towards the coastal waters as well as towards southern extend (0.1 to 0.2 µmol L^{-1}).

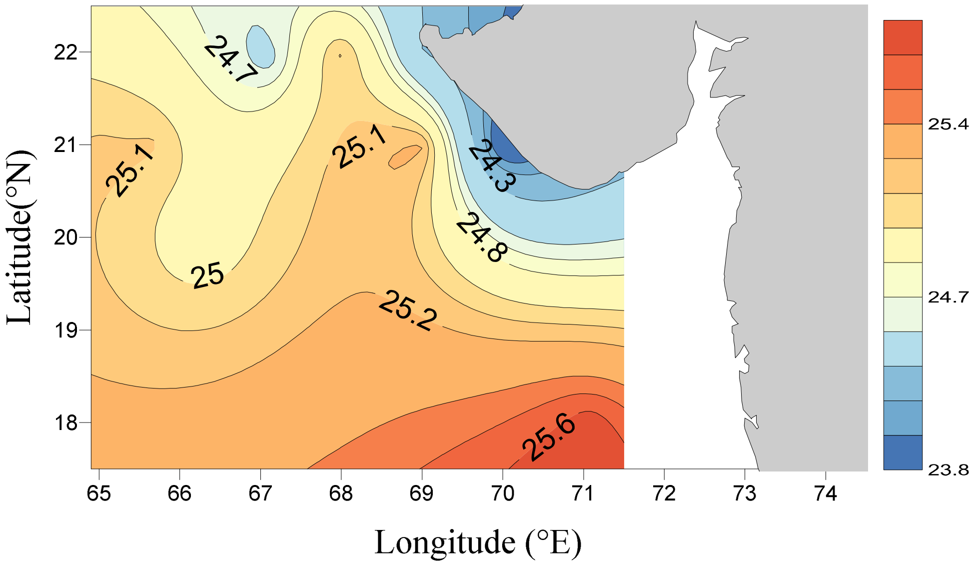


Figure 63. Variations in SST (ºC) along the NEAS during Phase-1, late winter monsoon of 2012

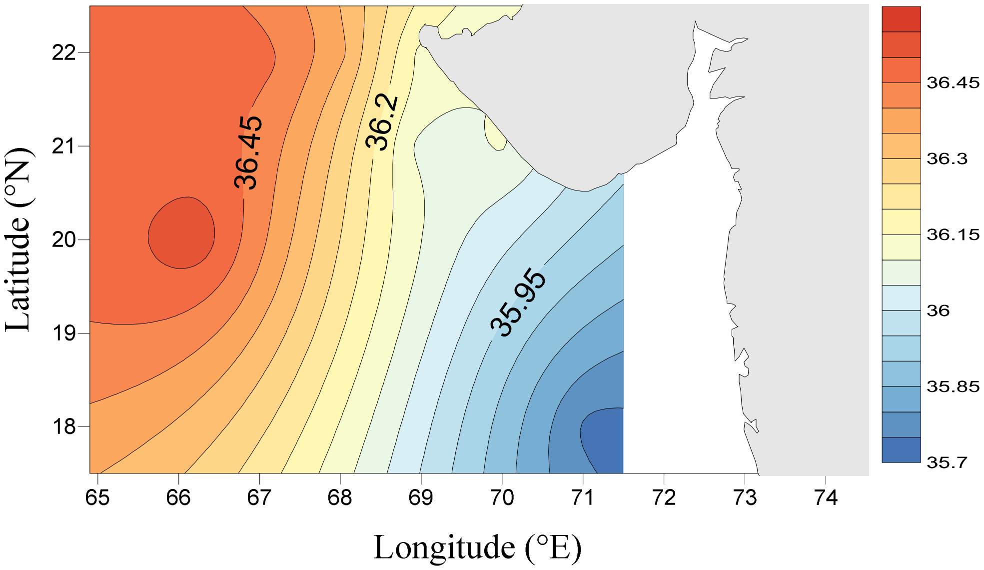


Figure 64. Variations in Sea Surface Salinity along the NEAS during Phase- 1, late winter monsoon of 2012

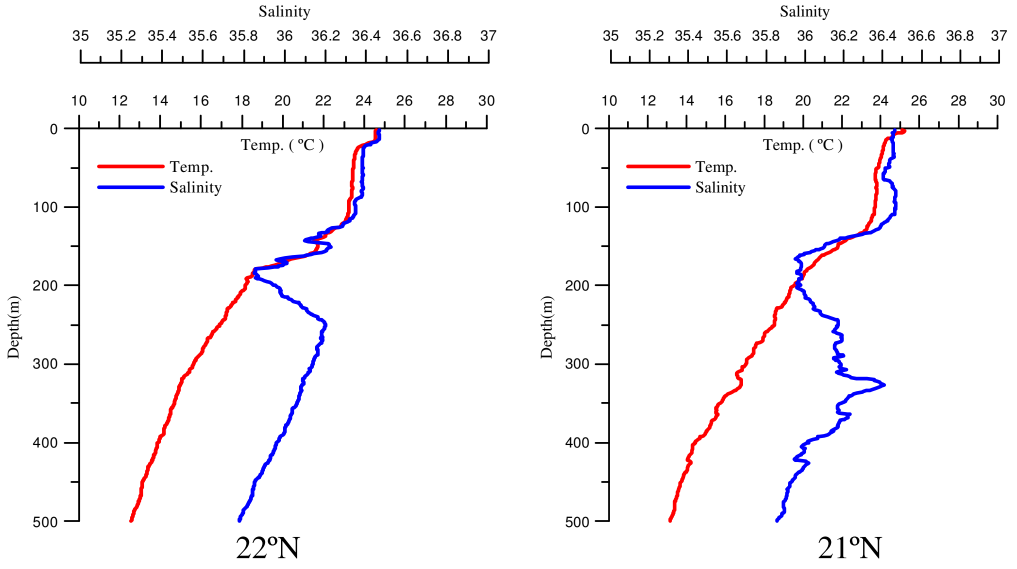


Figure 65. Vertical profiles of Temp. (ºC) and Salinity along 22ºN and 21ºN offshore waters along NEAS

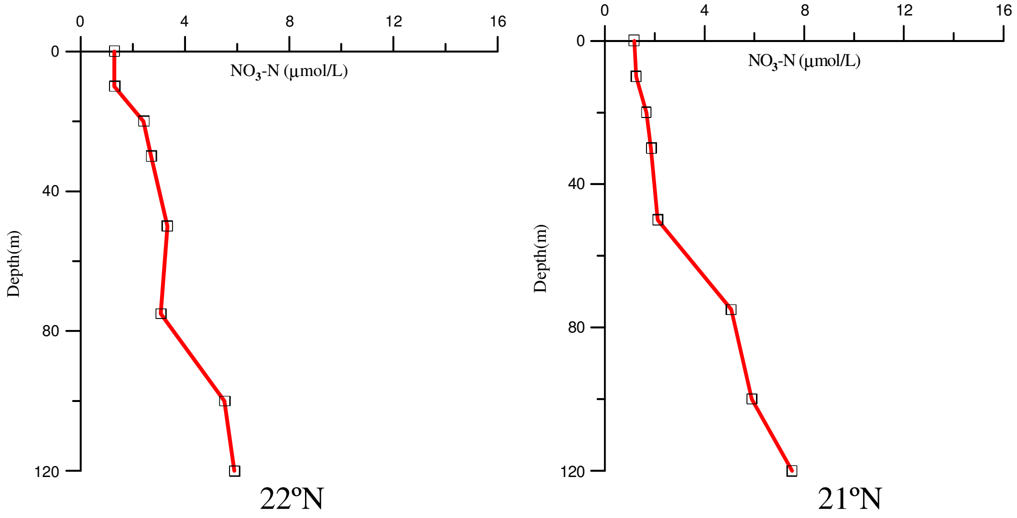


Figure 66. Vertical profiles of nitrate (NO$_3$-N) along 22ºN and 21ºN offshore waters along NEAS

5.1.2. Chlorophyll *a*- Phytoplankton biomass

Surface distribution of chlorophyll *a* showed wide variations from 0.56 mg m^{-3} in the non bloom open oceans to 59.2 mg m^{-3} in the intense phytoplankton bloom regions along the NEAS (Figure 67). Extremely high surface chlorophyll *a* concentrations were observed during intense bloom of *Noctiluca scintillans* along 21ºN latitude. Along the 22ºN offshore the surface chlorophyll *a* concentration was on av. 0.9 mg m^{-3}. Coastal waters were having a moderate surface chlorophyll *a* concentrations varying from 1.8 mg m^{-3} and 0.6 mg m^{-3} along 21ºN and 22ºN latitude respectively. Chlorophyll *a* decreased towards south (< 0.31 mg m^{-3}) of the NEAS.

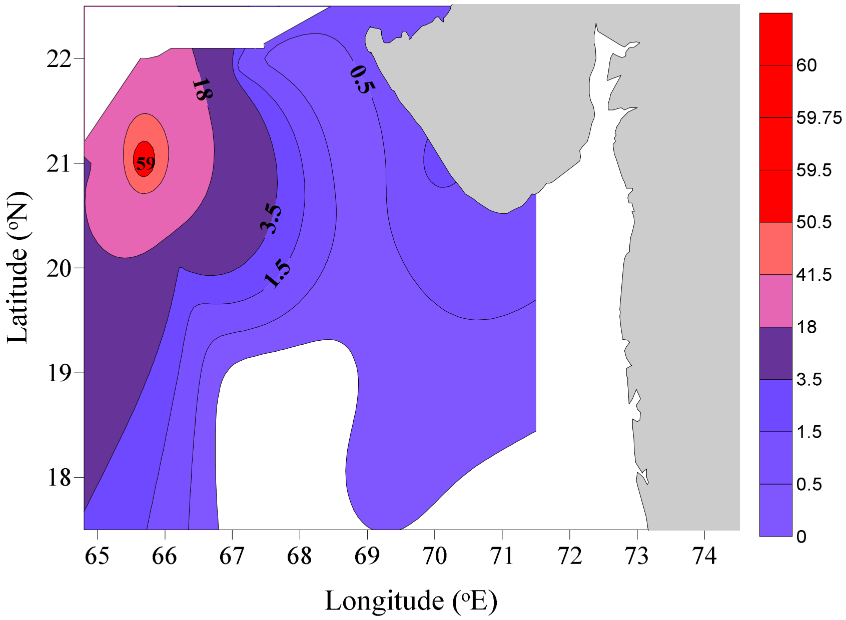


Figure 67. Variations in surface chlorophyll *a* (mg m^{-3}) along the NEAS during Phase- 1, late winter monsoon of 2012

5.1.3. Phytoplankton cell density- numerical abundance and diversity

During the period of observation the phytoplankton community was proportionally contributed by diatoms (45%) and dinoflagellates (54%) along the NEAS. Surface phytoplankton cell density reached maximum along the bloom region (21ºN, >2500 m sonic depth) of *Noctiluca scintillans* along with aggregation of diatoms *Haslea* sp. and *Nitzschia* sp. Total cell density of the area reached to (6.6x 10^{6} cells L^{-1}) which was composed of a mixed assemblage of dinoflagellate (3.7x10^{6} cells L^{-1}) and diatoms (2.9x 10^{6} cells L^{-1})

(Figure 68). The phytoplankton abundance decreased towards the coastal waters with total cell density of 3.4x 10^3 cells L^{-1} mainly contributed by diatoms (3.3x 10^3 cells L^{-1}) and dinoflagellates (105 cells L^{-1}). Along the offshore waters of 22ºN latitude the phytoplankton cell density were lower (3x 10^2 cells L^{-1}) but increased towards the coastal waters (4.1x 10^4 cells L^{-1}). Dinoflagellates dominated the coastal phytoplankton community along 22ºN (4x 10^4 cells L^{-1}). A total of 50 species were observed. The diversity indices obtained for different stations during the two phases (late winter monsoon and early spring inter monsoon) are given in Table 10. The diversity of phytoplankton community along the offshore regions varied from H' ~1.8-1.05 along the offshore regions of 22ºN and 21ºN latitudes. The offshore areas along 21ºN were characterised by high abundance of microphytoplankton with increased dominance (λ' 0.5) and decreased species richness (d 0.38). Maximum diversity of microphytoplankton during the phase was observed along the coastal waters of 21ºN (H' 2.29) with lesser dominance index (λ'0.31) and increased species richness (d 2.3).

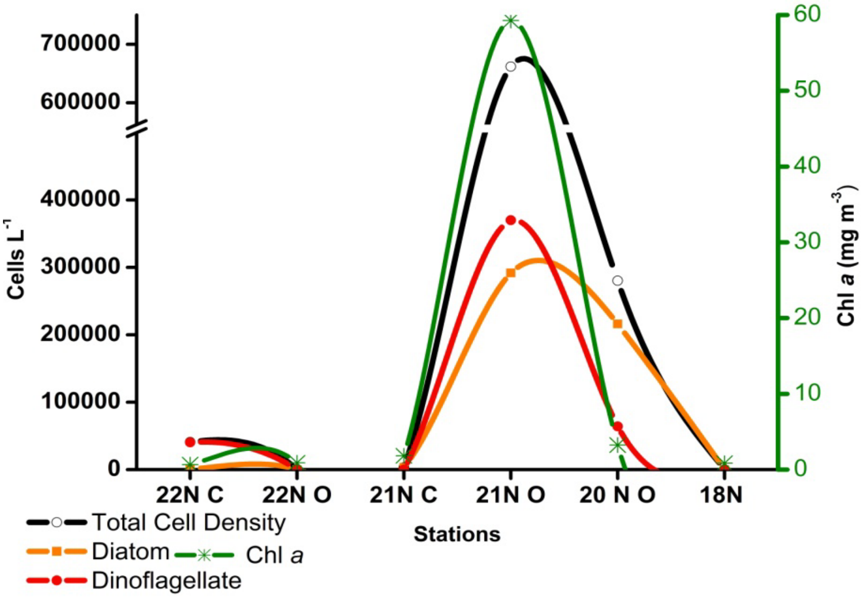


Figure 68. Variations in phytoplankton cell densities and chlorophyll *a* along the NEAS during Phase- 1, late winter monsoon of 2012

Phase	Area	Shannon-Weiner Diversity (H’)	Simpsons Dominance Index (D)	Margalef’s species richness (d)	Pielous's evenness (j’)
1	22ºN coast	0.299665	0.93589	1.412211	0.074916
	22ºN offshore	1.84147	0.351602	0.87014	0.712378
	21ºN coast	2.299185	0.316354	2.32992	0.531981
	21ºN offshore	1.014747	0.504536	0.382035	0.36146
	20ºN offshore	0.790321	0.64586	0.717492	0.23791
	Ref.Stn. (18ºN)	1.4278226	0.3958149	0.4199763	0.9008558
2	22ºN coast	3.257733	0.105919	1.677234	0.980675
	22ºN offshore	2.584963	0.155844	1.147655	1
	21ºN coast	3.213967	0.180973	2.768842	0.661585
	21ºN offshore	2.03162	0.357836	1.068293	0.677207
	20ºN offshore	0.100721	0.976666	0.366683	0.043378
	Ref. Stn. (18ºN)	1.584963	0.315789	0.545917	1

Table 10. Diversity indices of phytoplankton community during the late winter (Phase 1) and early spring inter monsoon (Phase 2) of 2012

5.1.4. Phytoplankton community assemblage

The microphytoplankton community during the period of observation was characterised by blooms of *Noctiluca scintillans* along with diatom assemblages towards the offshore waters. The intensity of bloom was maximum towards the offshore waters of 21ºN with an extension towards south (20ºN). The diatoms observed along with *Noctiluca scintillans* were mainly *Cylindrotheca closterium* and *Haslea* spp. Among diatom subclass Bacillariophycidae (raphid pennates) dominated by contributing nearly 87% of the total diatom population. *Cylindrotheca closterium*, *Haslea* spp. and *Nitzschia* sp. were the major raphid pennates present in the bloom region whereas towards coastal waters *Pseudo-nitzschia* sp. was the major raphid pennate present. Subclass Coscinodiscophycidae (centric diatom) contributed nearly 13% and was supported mainly by *Chaetoceros* sp. (Figure 69 a,b).

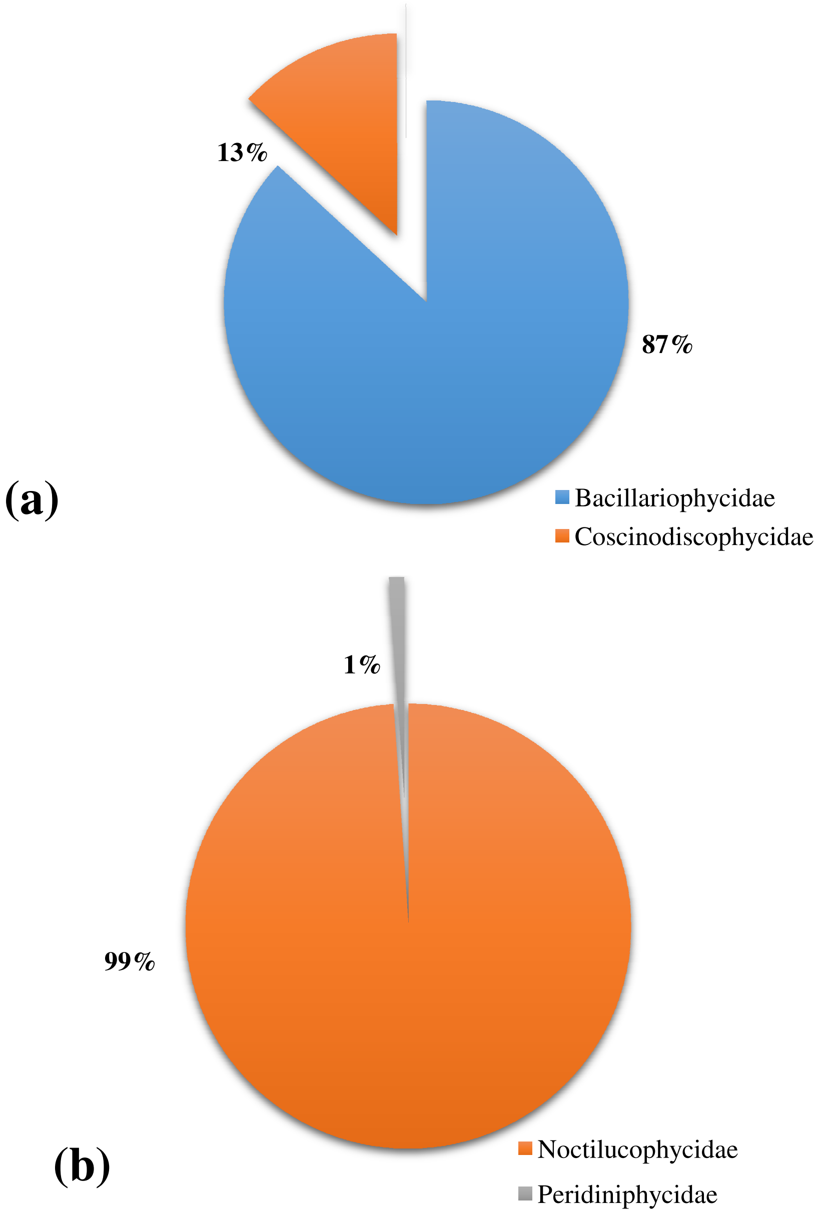


Figure 69. Percentage contribution of major subclass of diatoms **(a)** and dinoflagellates **(b)** along the NEAS during Phase-1, late winter monsoon of 2012

Intense bloom of *Noctiluca scintillans* (3.7x 10^6 cells L^{-1}) along with mucilaginous aggregation of diatoms mainly *Cylindrotheca closterium* (2.8x 10^6 cells L^{-1}) and *Haslea* spp. (1.8x 10^4 cells L^{-1}) were observed along the offshore region off 21ºN latitude (Figure 70). Other diatoms present in this region were *Thalassionema frauenfeldii*, *Thalassiothrix longissima*, *Leptocylindrus danicus* and dinoflagellate community consisted of mainly *Protoperidinium* sp. Along the coastal region of 21ºN latitude the phytoplankton community exhibited variations in composition with diatoms *Chaetoceros* sp. (1.7x 10^3 cells L^{-1}), *Pseudo-nitzschia* sp. (8x 10^2 cells L^{-1}), and *Thalassionema nitzschioides* (4x 10^2 cells L^{-1}). Dinoflagellates were present in a few numbers and consisted of *Protoperidinium* sp., *Prorocentrum gracile*, *Ceratium* spp. (Figure 71).

Towards the offshore regions of 22ºN, *Noctiluca scintillans* cells were observed in a few cell densities (108 cells L^{-1}). The offshore phytoplankton composition consisted of mainly *Thalassiothrix longissima* (149 cells L^{-1}). *Ceratium furca* was the other dinoflagellate present in smaller cell density. Towards the coast, there was a higher cell density of dinoflagellate due to the presence of *Scrippsiella* sp. (3.9x 10^4 L^{-1}). *Thalassionema nitzschioides* (218 cells L^{-1}) and *Chaetoceros* sp. (116 cells L^{-1}) were the major diatoms present in these coastal waters

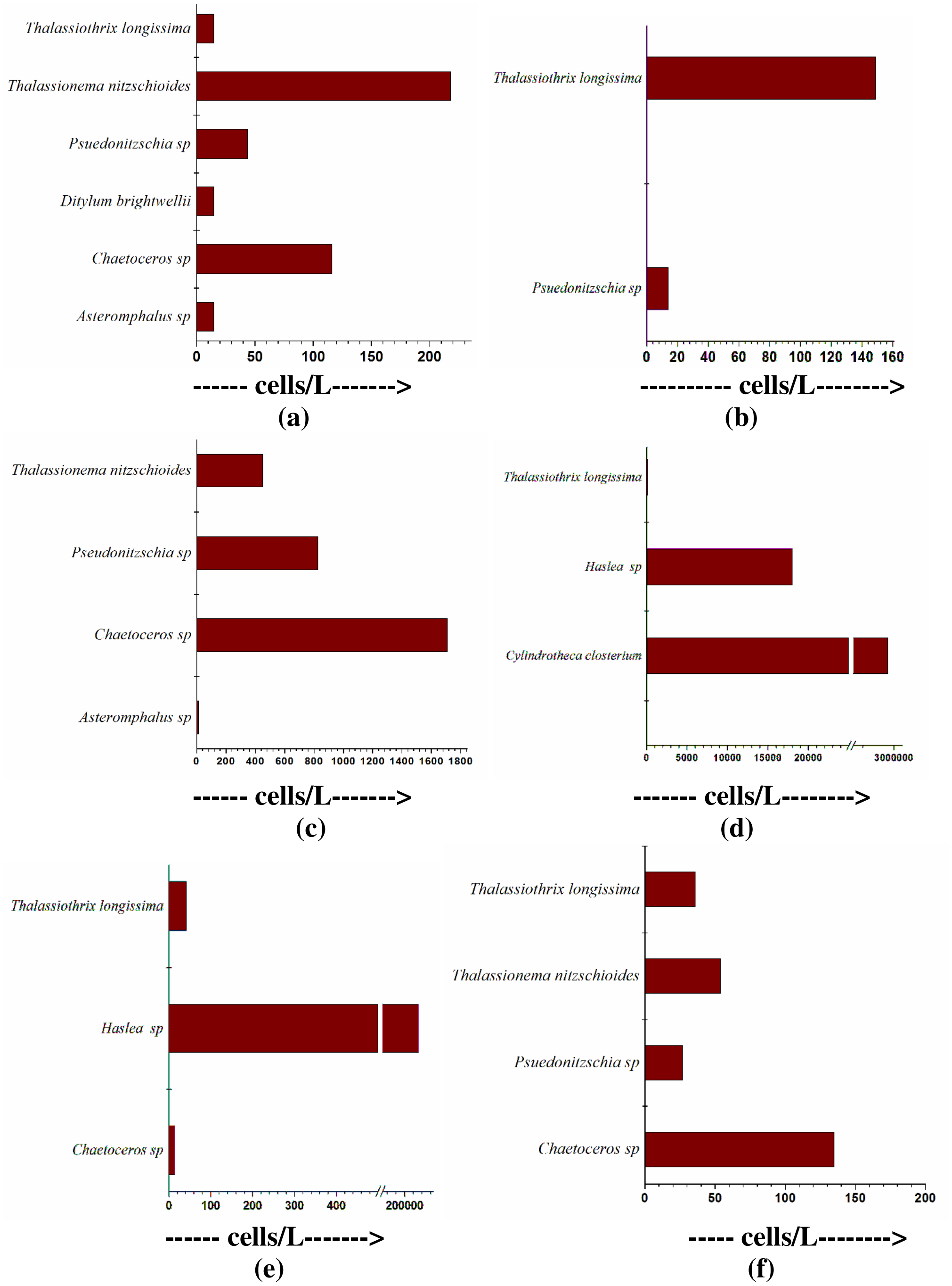


Figure 70. Community composition of diatoms along different stations during Phase 1 of winter monsoon 2012, **(a)** 22ºN Coastal **(b)** 22ºN Offshore **(c)** 21ºN Coastal **(d)** 21ºN Offshore **(e)** 20ºN and 18 ºN reference

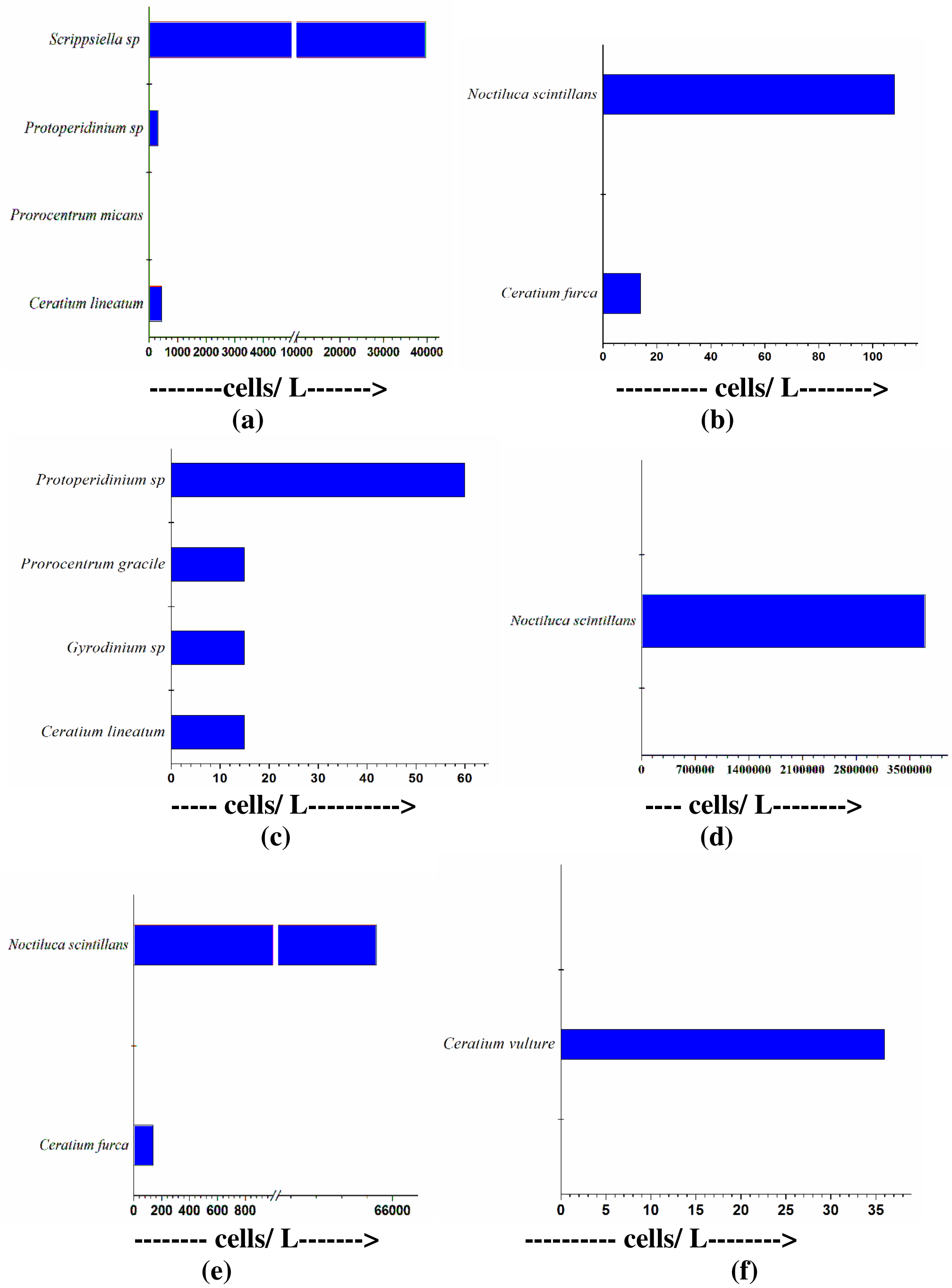


Figure 71. Community composition of dinoflagellates along different stations during Phase 1 of winter monsoon 2012, **(a)** 22°N Coastal **(b)** 22°N Offshore **(c)** 21°N Coastal, **(d)** 21°N Offshore, **(e)** 20°N and **(f)**18°N reference

5.2. Phase- 2. Early spring inter monsoon (Early April 2012)

5.2.1. Physico-chemical characteristics

Winds were weaker (`3.5m/sec) and north westerly with increased air temperature (25.5ºC) and humidity (> 90 %). Air temperature further increased southward (27ºC). Surface waters along the northern Arabian Sea started warming up during the phase. Sea surface temperature (SST) reached to ~26°C along the offshore waters of NEAS (Figure 72). Maximum SST was observed along the surface waters off 18ºN (27.8ºC). Sea Surface Salinity was ~36.5 along the offshore areas of 22ºN, which decreased towards coast (~36.1) as well as south (35.8) (Figure 73). Mixed layer reached to ~36m along the northern regions (22ºN) that shoaled up to 18 m along 21ºN (Figure 74). Surface distribution of nitrate ranged from 0.05 µmol L^{-1} in the offshore waters to 0.2 µmol L^{-1} in the coastal regions. Nitracline was observed at a depth of >35m (Figure 75).

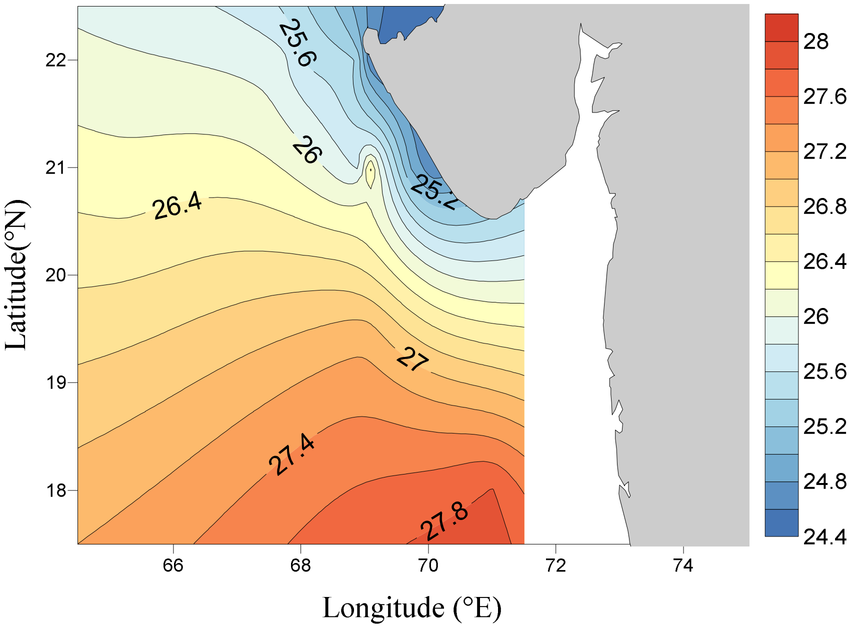


Figure 72. Variations in SST (ºC) along the NEAS during Phase-2, early spring inter monsoon of 2012

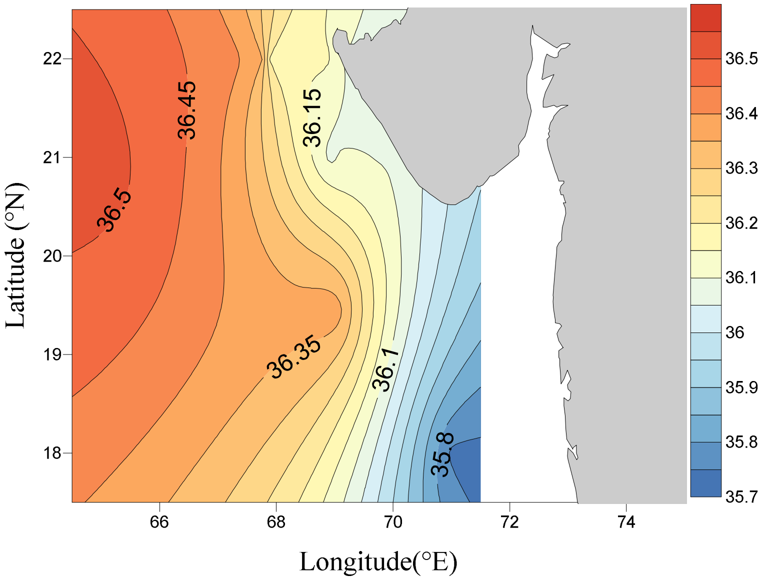


Figure 73. Variations in sea surface salinity along the NEAS during the Phase 2, early spring inter monsoon of 2012

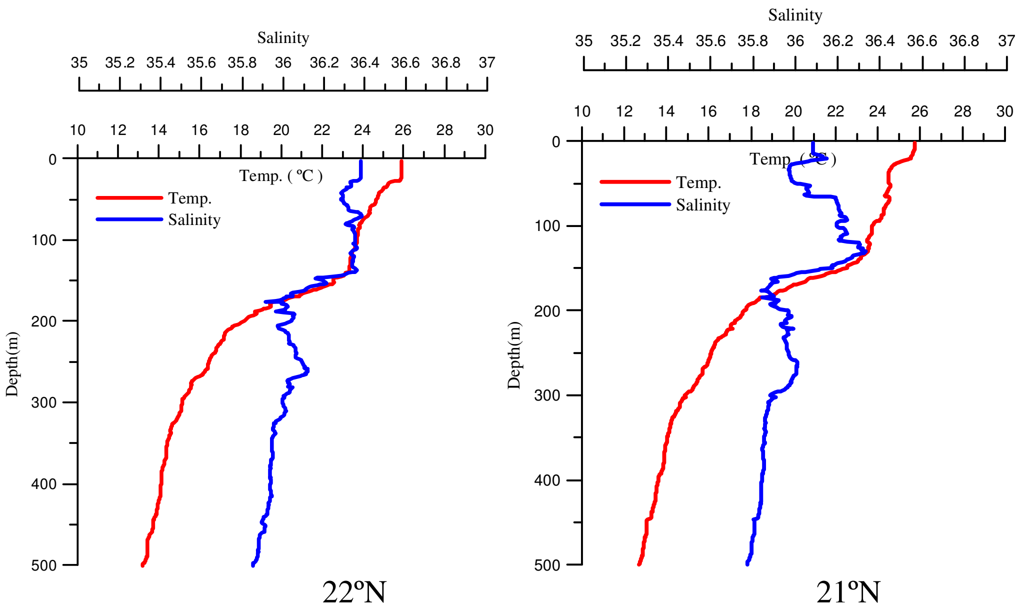


Figure 74. Vertical profiles of Temp. (ºC) and Salinity along 22ºN and 21ºN offshore waters along NEAS during early spring inter monsoon season

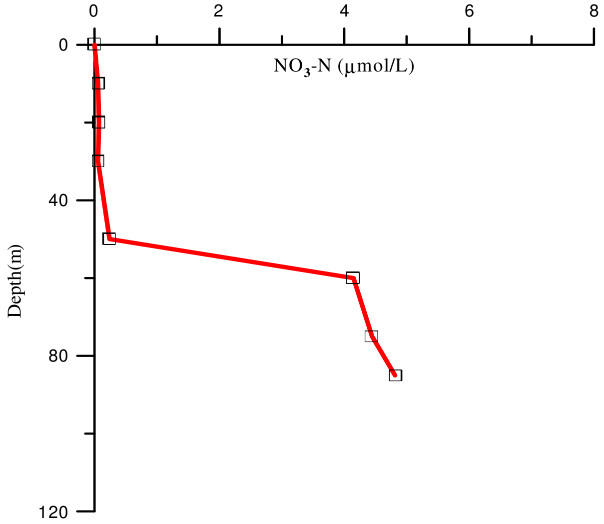


Figure 75. Vertical profiles of nitrate (NO_3-N) along offshore waters of NEAS during early spring inter monsoon season

5.2.2. Chlorophyll *a*- Phytoplankton biomass

During the period of observation surface chlorophyll *a* concentrations were lesser along the northern extent of the NEAS (22ºN), especially along the offshore waters (0.24 mg m^{-3}). Maximum chlorophyll *a* values were observed along 21ºN and 20ºN offshore areas (Figure 76). The offshore waters of 21ºN observed a surface chlorophyll *a* concentration of 3.91 mg m^{-3}. Towards the coastal waters the chlorophyll *a* values reached to ~3.75 mg m^{-3}. Highest surface chlorophyll *a* concentrations were observed along the offshore areas of 20ºN (24.8 mg m^{-3}), where there was a localized bloom patch of *Noctiluca scintillans*.

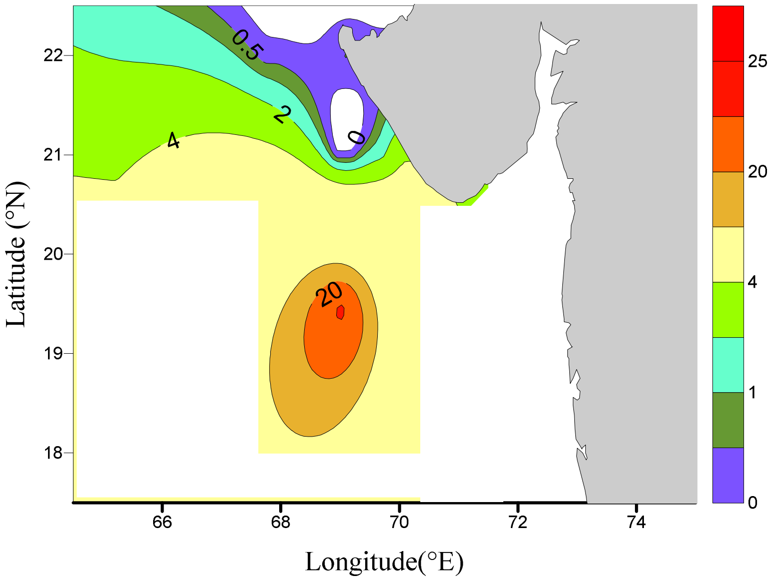


Figure 76. Variations in surface chlorophyll *a* along the NEAS during Phase- 2, early spring inter monsoon of 2012

5.2.3. Phytoplankton cell density- numerical abundance and diversity

Phytoplankton abundance decreased along the offshore region of 22°N and 21°N. The total phytoplankton cell density along the 21°N and 22°N offshore waters was ~200 cells L^{-1} and ~600 cells L^{-1} respectively. The coastal waters of 21°N was having an increased phytoplankton abundance with total cell density of 2.4x 10^{4}cells L^{-1} with a diatom cell density of 2.3x 10^{4}cells L^{-1} and dinoflagellate cell density of 900 cells L^{-1} (Figure 77). Phytoplankton cell densities were maximum along 20ºN offshore with a mixed bloom patch of the *Noctiluca scintillans* (5.4x 10^{4}cells L^{-1}) along with araphid pennate diatom *Thalassiothrix delicatula* (566 cell L^{-1}). Towards further south along 18ºN, phytoplankton cell density further decreased and was represented solely by *Ceratium* spp., (38 cells L^{-1}). Around 45 species were recorded during the phase. The diversity of phytoplankton community was high during the phase in comparison with that of the previous phase. The diversity index (H') along the offshore regions reached up to ~2.25 along the offshore areas with an average species richness of (d) 1 and decreased dominance index (λ'0.2). The coastal waters exhibited higher species richness (d~2) as well as diversity (H', 3.2) with decreased dominance (λ'0.1)

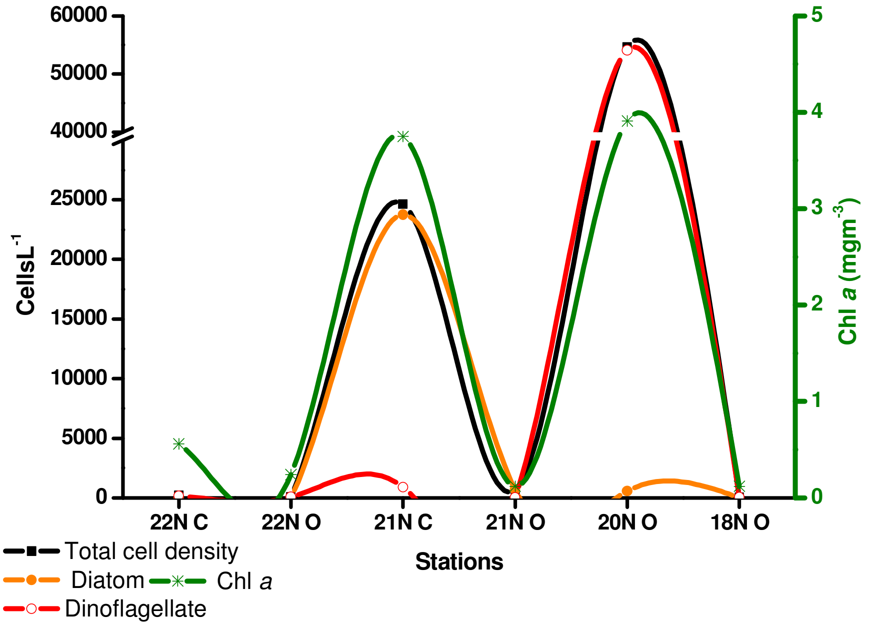


Figure 77. Variations in phytoplankton cell densities and chlorophyll *a* along the NEAS during Phase- 2, early spring inter monsoon of 2012

5.2.4. Phytoplankton community assemblage

Dinoflagellates dominated the phytoplankton community (~75-100%), except for the region along 21ºN, where the diatoms dominated (~96%) the coastal as well as offshore areas. Diatoms present were mostly of subclass Coscinodiscophycidae (centric, 55%). Bacillariophycidae were present mainly towards the coastal waters (raphid pennates, 24%) and Fragilariophycidae (araphid pennate, 21%) were present significantly along the *Noctiluca scintillans* bloom region (Figure 78 a,b).

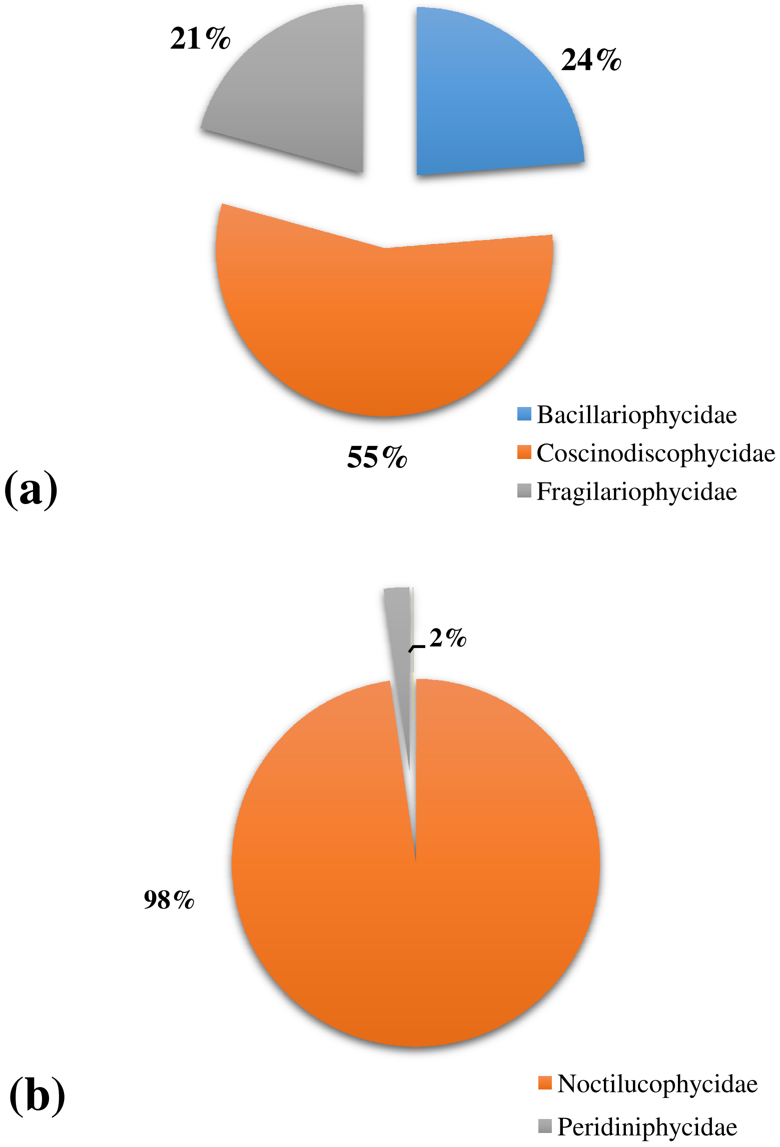


Figure 78. Percentage contribution of major subclass of diatoms **(a)** and dinoflagellates **(b)** along the NEAS during Phase-2, early spring inter monsoon of 2012

The region along 22ºN with decreased chlorophyll *a* and phytoplankton abundance consisted of a few cell densities of dinoflagellates such as *Gymnodinium* sp., *Ceratium furca*, *Corythodinium tessellatum*, *Oxytoxum* sp., and *Podolampas palmipes* (Figure 80). In the coastal waters of 22ºN phytoplankton community was dominated by dinoflagellates like *Ceratium* spp., and *Protoperidinium* spp. Diatoms present were a few cells of *Asteromphalus* sp., *Ditylum brightwellii* and *Meuneria* sp. In the coastal waters along 21ºN where there was comparatively higher cell density of diatoms, the dominant groups were *Chaetoceros* spp. (8.1x 10^3 cells L^{-1}), *Pseudo-nitzschia* sp. (5.2x 10^3 cells L^{-1}), and *Thalassionema nitzschioides* (3.3x 10^3 cells L^{-1}). Dinoflagellates present were mainly *Ceratium* spp., (300 cells L^{-1}), consisting mainly *C. furca, C. fusus, C. lineatum,* and *C. teres*) and *Protoperidinium* sp (500 cells L^{-1}). Towards the offshore waters centric diatoms like *Bacteriastrum delicatulum*, *Chaetoceros* spp., *Rhizosolenia* spp., were present (Figure79). In the region of maximum phytoplankton cell density (20ºN), the phytoplankton community consisted of *Noctiluca scintillans* (5.4x 10^4cells L^{-1}) along with araphid pennate diatom, *Thalassiothrix delicatula* (566 cells L^{-1}), dinoflagellates mainly *Protoperidinium* sp., *Ceratium* spp., Towards south (18ºN) only dinoflagellate represented the phytoplankton community and was represented by *Ceratium* spp. (38 cells L^{-1}). During the study period, *Trichodesmium erythraeum* filaments were observed in the phytoplankton community mainly towards 21ºN (27 filaments L^{-1}) and 22ºN offshore (12 filaments L^{-1}).

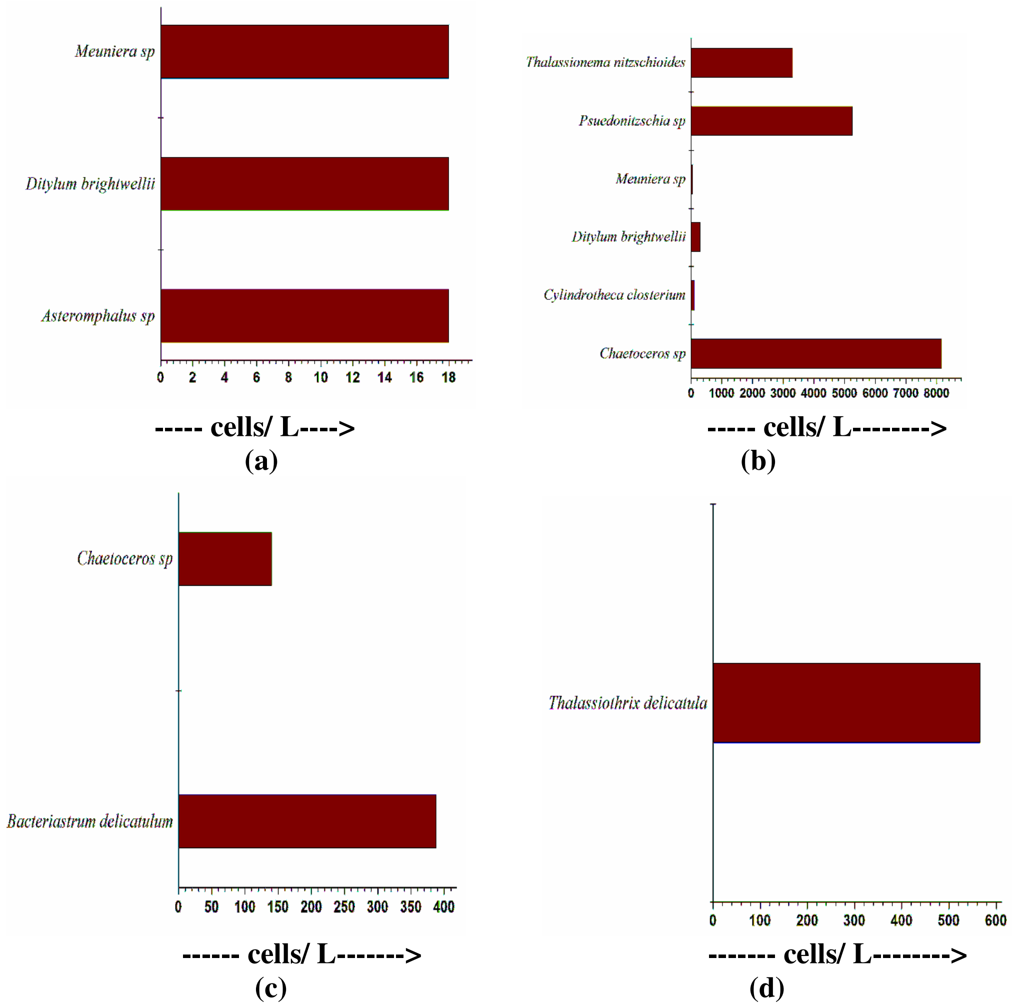


Figure 79. Community composition of diatoms along different stations during Phase 2 (early spring inter monsoon of 2012, **(a)** 22ºN Coastal **(b)** 21ºN Coastal **(c)** 21ºN Offshore **(d)** 20ºN region

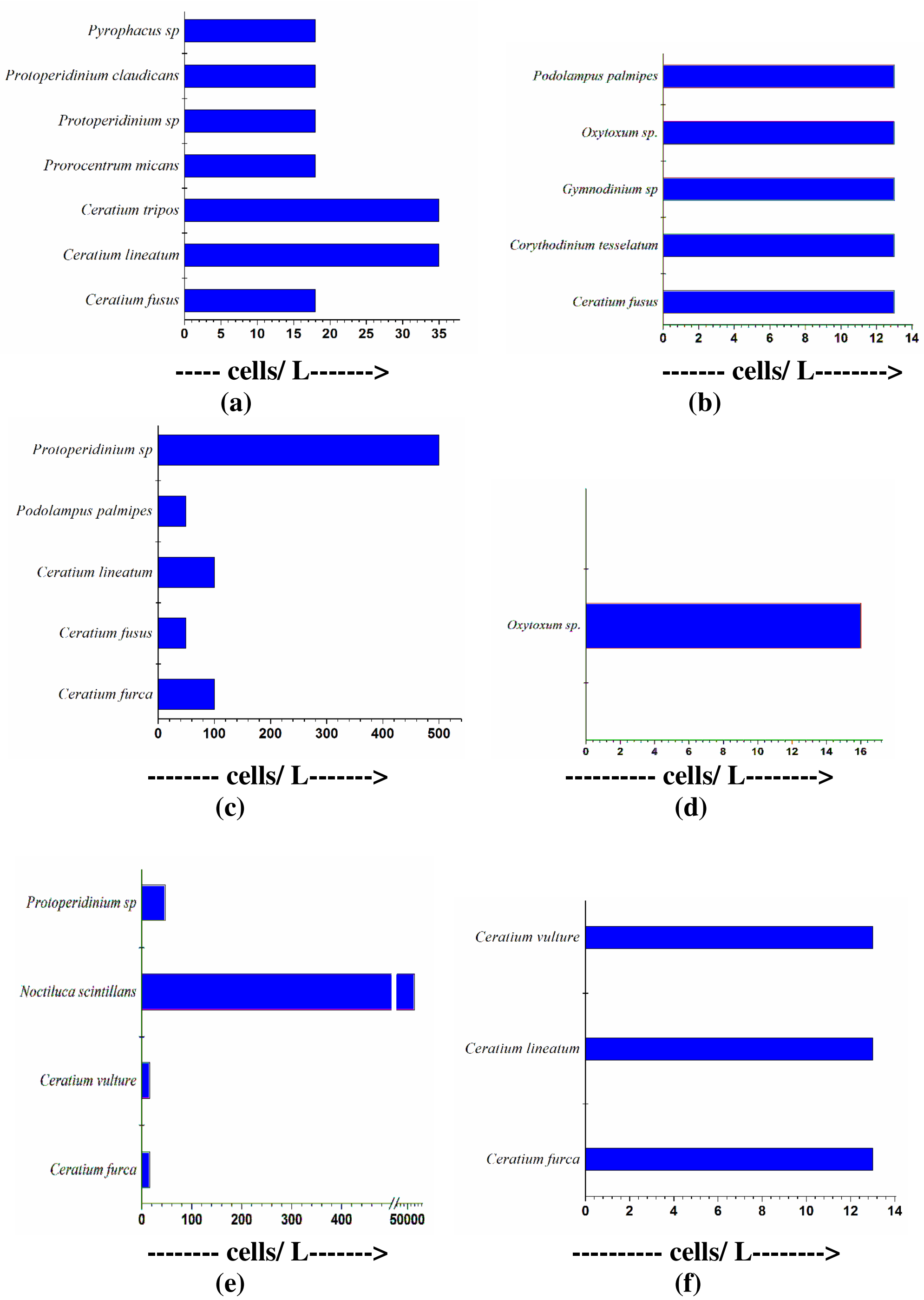


Figure 80. Community composition of dinoflagellates along different stations during early spring inter monsoon of 2012, **(a)** 22°N Coastal **(b)** 22°N Offshore **(c)** 21°N Coastal **(d)** 21°N Offshore **(e)** 20°N and **(f)** 18°N reference

5.3. Variability in the phytoplankton community structure during the late winter monsoon and early spring inter monsoon along the North Eastern Arabian Sea

The NEAS experienced an increase in the sea surface temperatures (SST) as well as decrease in salinity with the transition from winter to spring inter monsoon season (Figure 81). SST increased by ~1ºC along the offshore waters. The surface water nutrient concentrations observed significant decrease during the early spring inter monsoon. These changes are reflected in the chlorophyll *a* distributions as well as in the phytoplankton community and decreased during Phase- 2 (SIM).

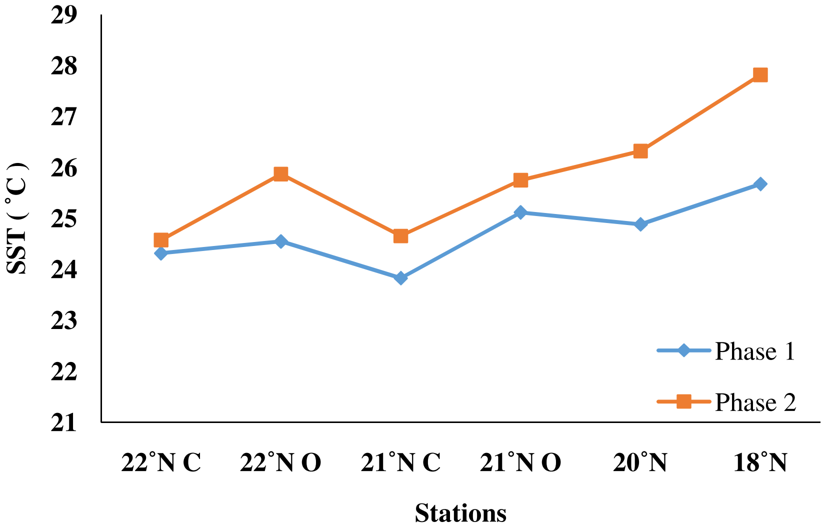


Figure 81. Variations in SST along the NEAS during late winter (Phase-1) and early spring inter monsoon (Phase-2) of 2012.

Phytoplankton abundance as indicated by the total cell density markedly decrease during Phase-2 with reduced diatom as well as dinoflagellate cell density. Except for the region along the coastal waters of 21ºN, northern Arabian Sea was observed to be very less productive in respect to the phytoplankton community. The proportion of diatoms to dinoflagellate decreased during Phase-2 especially along the offshore as well as southward waters. The community of phytoplankton was having lesser diversity as well as species richness during Phase-1 with increased dominance index. Whereas during Phase-2, even though the numerical abundance decreased the species diversity as well as richness increased with decreased dominance index. The higher dominance index observed during Phase-1 was accounted principally by the intense bloom of *Noctiluca scintillans* with single species diatom abundance along with the bloom patch (either *Cylindrotheca closterium* or *Haslea* sp.). However, Phase-2 observed multispecies assemblage of diatoms consisting of *Chaetoceros* sp., *Pseudo-nitzschia* sp., *Skeletonema costatum*, and *Thalassionema nitzschioides* with spatial variations in distribution.

During the study period occurrence of bloom incidence was more prominent towards 21ºN as well as 20ºN areas. From the k-dominance plot it is inferred that northern most region (22ºN) was having more diverse and even phytoplankton community whereas towards south diversity decreased with more dominance (Figure 82).

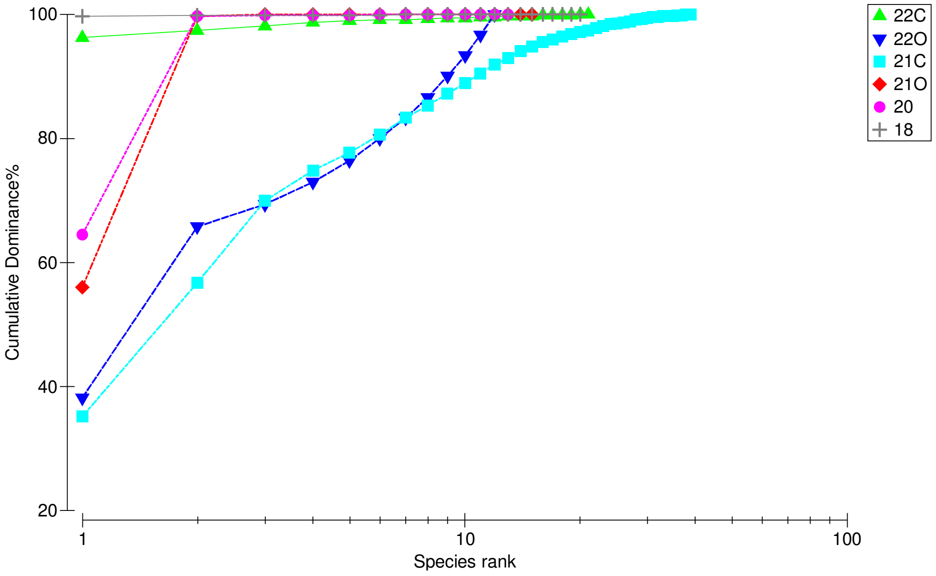


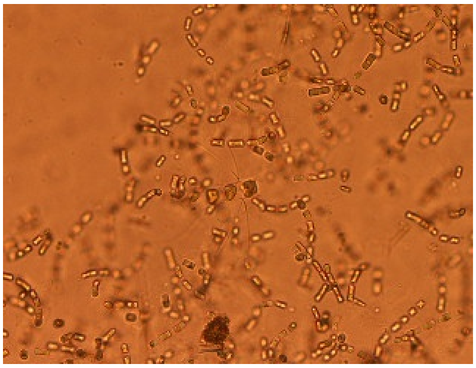
Figure 82. Station wise k- dominance plot for microphytoplankton during 2012

The phytoplankton community during Phase-1 was having markedly high phytoplankton cell density with both diatom as well as dinoflagellate bloom incidence. Offshore waters experienced massive bloom of *Noctiluca scintillans* along with aggregation of diatoms *Haslea* spp. and *Nitzschia* sp. The coastal waters of 22ºN were having significantly higher cell density of dinoflagellate *Scrippsiella* sp. Diatoms were contributed by Bacillariophycidae (raphid pennates, 87%) during Phase-1 followed by Coscinodiscophycidae (centric, 13%) and a few cells of Fragilariophycidae (araphid). During Phase-2 the contribution of raphid pennates decreased to 24% with increased proportion of centric forms (55%) as well as araphid pennates (21%).

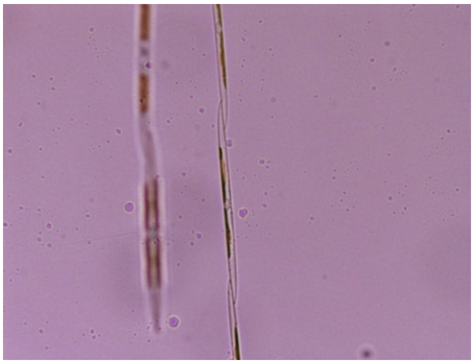
During Phase-2 diatom contribution was significant only along the regions of 21ºN and 20ºN. The centric diatom *Chaetoceros* sp. was the dominating centric diatom during Phase-1 as well as Phase-2. The species was distributed throughout the North Eastern Arabian Sea during Phase-1 whereas it was restricted to the region along 21ºN during Phase-2. Centrales like *Guinardia flaccida*, *Bacteriastrum delicatulum* were present during Phase-2 which was almost absent during Phase-1. However along 20ºN region where the bloom of *Noctiluca scintillans* was present, araphid pennate diatoms *Thalassiothrix delicatula* were observed in significant cell densities.

The raphid pennate diatom *Pseudo-nitzschia* sp. observed throughout the NEAS during Phase-1 was restricted to the coastal waters of 21ºN during Phase-2, with increased cell densities. *Haslea* sp. and *Cylindrotheca closterium* which were present in increased cell densities during Phase-1 was totally absent during the Phase-2 even in the region of *Noctiluca scintillans* bloom area. Araphid pennates represented mainly by *Thalassionema nitzschioides*, *Thalassiothrix longissima* and *Thalassionema frauenfeldii* during Phase-1 distributed throughout the region in smaller cell densities was restricted to 21ºN and 20ºN region with markedly higher cell densities of *Thalassionema nitzschioides* and *Thalassiothrix delicatula* along 20ºN region.

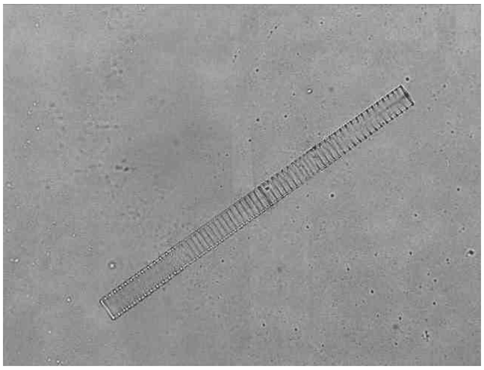
Among the class Dinophyceae (dinoflagellates), subclass Noctilucophycidae (*Noctiluca scintillans*) and subclass Peridiniphycidae were the major contributors during both the phases. The intensity of *Noctiluca scintillans* bloom decreased during Phase-2 in comparison with that of Phase-1 in both abundance and spatial distribution. Except for a bloom of *Scrippsiella* sp. along 22ºN coastal, there was no significant variation in the contribution of Peridiniphycidae towards the class Dinophyceae.



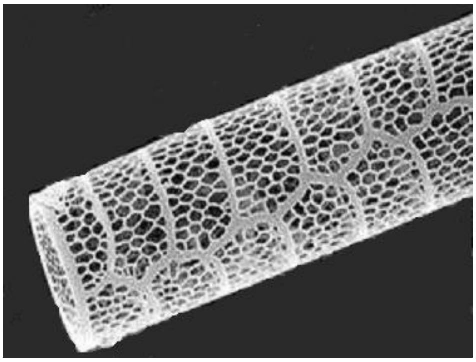
Chaetoceros socialis colony x 200



Pseudo-nitzschia pungens x400



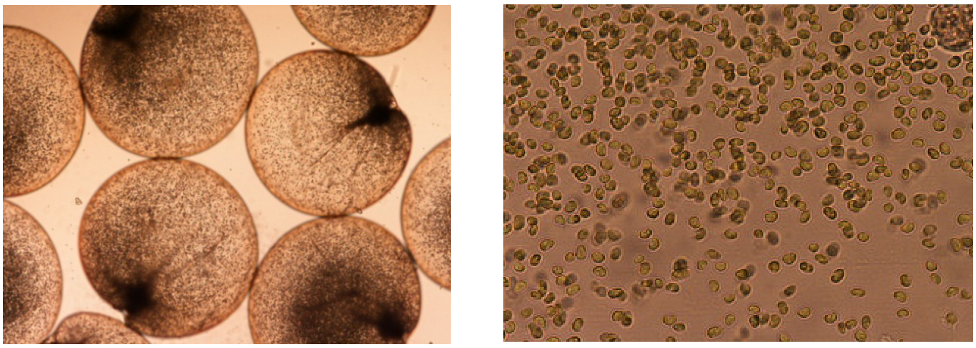
Leptocylindrus mediterraneus x200



Leptocylindrus mediterraneus (SEM)

Plate 8. Major diatoms observed during winter monsoon and early spring inter monsoon 2012 along NEAS.

Noctiluca scintillans bloom (arial view from onboard)

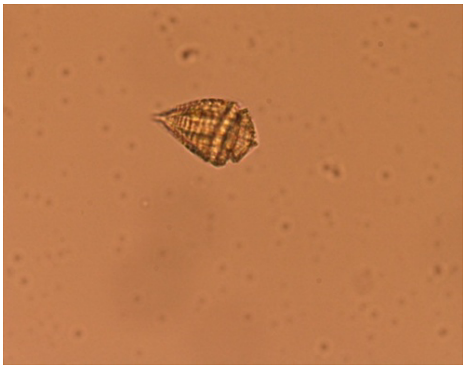


Noctiluca cells x 40

Pedinomonas noctilucae x 400
(endosymbiont inside *Noctiluca* cells)

Plate 9: Green tide of *Noctiluca scintillans* along NEAS duirng late winter monsoon and early spring inter monsoon 2012 (arial view and microphotographs)

Ceratocorys horrida x 400



Corythodinium tesselatum x 400

Scrippsiella sp. x 400

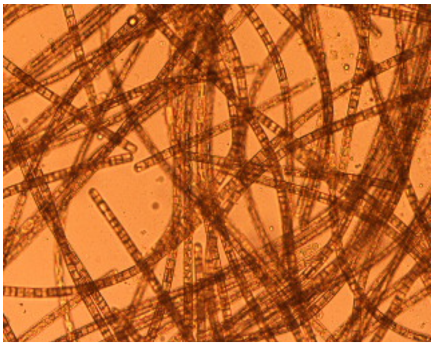
Dinophysis miles x 400

Dinophysis caudata x 400

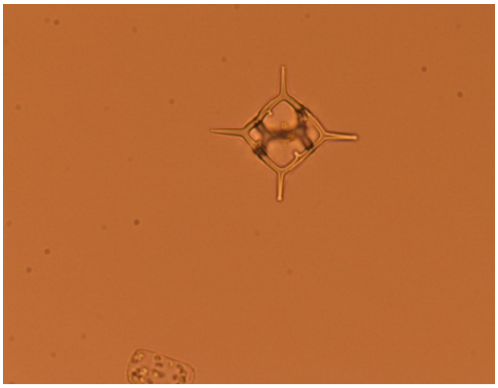
Ceratium teres x 200

Plate 10: Major dinoflagellates observed along NEAS during later winter monsoon and early spring inter monsoon 2012

Trichodesmium erythraeum x40



Trichodesmium erythraeum x 200



Dictyocha sp. x 400

Plate 11: Microphytoplankton observed along NEAS during Early spring inter monsoon 2012

Chapter 6

Discussion

I am forever walking upon these shores, betwixt the sand and the foam.
The high tide will erase my foot-prints, and the wind will blow away the foam.
But the sea and shore will remain forever.
— Kahlil Gibran, Sand and Foam, 1926

The Northern Eastern Arabian Sea is a tropical basin landlocked on the northern boundary at latitude of 25°N. The region is observed to exhibit variability in physico-chemical as well as biological factors in accordance with the biannual reversal in the tropical monsoon winds. The annual productivity patterns along the northern Arabian Sea reveals significantly higher biological production in terms of primary production as well as photosynthetic pigment concentrations during the north east monsoon or the winter monsoon season (Krey and Babenerd, 1976; Nair, 2010). This increased production along the north of Arabian Sea can be well correlated with the physical forcings that drive the hydrographic conditions during the season (Prasannakumar *et al.*, 2001).

Northern Eastern Arabian Sea during the winter monsoon season (November- March) is set by moderate wind forcing (wind stress / τ /- 0.07 N/m^2) arising from the high pressure region behind the Tibetan plateau (Tomczak and Godfrey, 1994). Low air temperature, almost 1ºC less than the SST along with lower relative humidity (70.3%) results in elevated evaporation rate of the surface waters (Weller *et al.*, 1998). This increased evaporation leads to the formation of dense cold surface waters that undergoes convective mixing, eroding the pycnocline and resulting in nutrient enriched deep mixed layer (Banse, 1984). The winter convection and accompanied vertical mixing that injects nutrients greatly enhances photosynthesis and chlorophyll *a* concentrations in the upper layers (Menzel and Ryther, 1961).

Lower surface temperature (SST < 26ºC) with increased salinity (36 psu) and deeper mixed layer (~100m) observed along the northern Arabian sea during the study period clearly supports the occurrence of convective mixing. The offshore areas off the Saurashtra Coast (22ºN and 21ºN) were having lower SSTs with high saline surface waters. The convection of these cold dense waters paved way for the deep mixed layers in these regions. In the oceanic waters along 18ºN (southern extend of NEAS) the influence of winter convection was least observed with increased surface temperatures (SST > 26ºC) and less saline surface waters resulting in shallow mixed layers. Even though earlier studies have shown that the region under the influence of winter convection extends southward at least up to 17ºN (Naqvi *et al.*, 2002), the present study observed the influence only up to 20ºN and beyond which almost oligotrophic waters with increased SST and shallow mixed layers existed. The sea surface temperature increased from 22.5ºC to 28.5ºC from north to south. Lower SST along the northern most regions and its subsequent increase towards southward extend of northern Arabian Sea typically occurs during winter monsoon season (Qasim, 1982). The pattern of surface warming from north to south is related to the cooling of land mass in the northern region. Inflow of arid cold air from the land might have resulted in the cooling of sea close to the land (Sankaranarayanan, 1978), since the northern Arabian Sea is land locked in its northern boundary.

Among the three years of analysis during different phases comparatively warmer waters were observed during 2009 study where the sea surface temperatures varied from 24.3ºC to 26.8ºC from Phase-1 to Phase-3. Even then the signatures of convective mixing were well evident during the season with intensity decreasing with the transition from one phase to another. Lowest SST was observed during Phase-1 and highest during Phase- 3. During

2011, lower sea surface temperatures persisted along the open ocean waters of the northern Arabian Sea. SST varied from 24ºC to 25.5ºC along the northern offshore regions from Phase-1 to Phase-3. The observed SST during the winter monsoon season very well goes in accordance with the previous studies in the area. Madhupratap *et al* (1996) and Prasannakumar *et al* (2001) reported the surface temperatures of ≤ 24ºC during the season along northern Arabian Sea.

Another major physical consequence of winter cooling is relatively high saline waters in the region. The observed sea surface salinities (SSS) varied from 36.5 to 35.5 with maximum salinity of 36.6 in the northern latitudes offshore areas (22˚N). SSS decreased both towards the coast as well as towards south (18ºN). The increased surface salinity results from the cooling effect of the dry northerly winds thereby resulting in the increased surface density and mixing of the water column. Due to the deep convections that occur during winter the depths of mixed layer (Z_{ML}) reaches ≥ 120m along the region beyond continental shelf in the north eastern Arabian Sea (Colborn, 1975; Banse, 1984; 1987). The depth of the mixed layer reached nearly 85m in the northern regions of prominent convective mixing. The mixed layer dynamics along northern Arabian Sea during winter monsoon is characterized by increase in depth with distance offshore and influenced by convective overturning (Lee *et al.*, 2000). Analysis of mixed layer variation during the north east monsoon of 1994-1995 (Weller *et al.*, 2002) recorded deepening of the daily averaged mixed layer to approximately 100m. Deepening of mixed layer is considered as one among the prime factors that results in the eutrophication of the oligotrophic waters (Madhupratap *et al.*, 1996). The depth of mixed layer during study period was more during Phase-1 and 2 but was observed to shoal up during Phase-3. Deepest mixed layers were observed during Phase-2 of winter monsoon 2011 (148 m) with low surface temperature (24ºC) and high saline surface waters (36.3). The region along 18˚N was having shallow mixed layer (~35m) in accordance with the increased SST (~26.5°C) as well as lower surface salinity (35.8).

The overturning of water column results in nutrient replenishment of upper layers. Arabian Sea nitrate concentration in the surface layer is below detection level except in the summer monsoon upwelling and winter monsoon convective mixing (Prasannakumar and Prasad, 1996). Surface nitrate concentrations not less than 1 µM has been reported from northern Arabian Sea during winter monsoon season mainly during February- March months (Kumar *et al.*, 2010). Nitrate values in par with these were observed during moderate to peak winter convection phases and the values varied from 0.8-1 µM in the offshore areas. Nitrate values in accordance with current observations were previously reported in the region during winter monsoon of March 2003 (Dwivedi *et al.*, 2008). There was significant variations in the surface nitrate concentrations both regionally as well as overall during 2011. Surface values varied significantly between 22ºN and 21ºN areas as well between coastal and offshore areas. Inter annually surface nitrate concentrations were higher during the winter monsoon of 2011 than in 2009 and might be due to the increased winter convective mixing during 2011. During the period of observation nitrate concentration was considerably higher throughout the water column at the northern stations (>1 µM) whereas along the southern regions near 17°N the surface waters were having nitrate concentrations ~0.1 µM.

Increased surface chlorophyll *a* concentrations occurs along the northern Arabian sea during the winter monsoon as a result of eutrophication by winter convections. The surface chlorophyll *a* concentrations without discriminating the bloom and non bloom stations was on an average 1.2 ± 0.85 mg m^{-3} along the open ocean regions and 1.6 ±1.3 mg m^{-3} along the coastal waters. Elevated chlorophyll *a* concentrations, reaching to nearly 2.6 mg m^{-3} was observed in the regions of intense open ocean phytoplankton blooms. Surface chlorophyll *a* consistent with these measurements was reported by

Dwivedi *et al* (2008). Studies on the *Noctiluca* bloom occurrence along the northern Arabian Sea by *in situ* and satellite measurements reported chlorophyll *a* concentrations in the range of 1-2 mg m^{-3} (Gomes *et al.*, 2009). Exceptionally higher surface chlorophyll *a* (~60 µg L^{-1}) was recorded along the intense bloom areas of *Noctiluca scintillans*. This occurred mainly during the late march period (year 2012) where thick patches of *Noctiluca scintillans* occurred (cell density 3x 10^6 cells L^{-1}).

The surface distribution of chlorophyll *a* showed increased concentrations along the coastal waters of northern Arabian Sea. The productivity of coastal waters was found to be higher during the winter monsoon and was previously established by Dey (2003). According to Tang *et al* (2005) this increased coastal production was with the river runoff received during November- December period. Narmada and Tapti are the major input sources of nutrients from up stream locations into northeast Arabian Sea. According to them the surface chlorophyll *a* is in the range of 0.05- 4 mg m^{-3} during the onset of winter monsoon along these waters.

As the winter conditions recede air temperature increases with increased solar insolation and advancement of spring inter monsoon (April-May). SST builds up (~28˚C) with shallow mixed layers (< 30 m) preventing the influx of nutrients to the upper water column thereby creating an oligotrophic stratified waters (Madhupratap *et al.*, 1996; Prasannakumar *et al.*, 2001). The productivity of Arabian Sea decreases during this time period (Bhattathiri *et al.*, 1996). SST increased to 25.8ºC to 26.7ºC during the early spring inter monsoon period along the northern Arabian. The surface temperatures along 22ºN and 21ºN offshore waters were ~26.5ºC whereas along 18ºN higher SST that reached to 27.8ºC was observed. Mixed layer depth shoaled up to < 30m along the region. There was considerable decrease in the chlorophyll *a* concentrations, where the values ranged from 0.1- 0.2 mg m^{-3} along the offshore areas. Previously Bhattathiri *et al* (1996) reported a lower chlorophyll *a* concentrations varying from 0.03- 0.04 mg m^{-3} along the open waters of NEAS during April-May period.

6.1 Phytoplankton community structure- an overview

Distribution and abundance of microphytoplankton in an ecological niche is truly influenced by the physico-chemical conditions prevailing in the region. The seasonal overturning of water column during winter monsoon season indubitably gives a positive stroke towards the phytoplankton community. Northern Arabian Sea especially the open ocean water remains less productive with fewer phytoplankton cell densities and gains mass and volume in terms of primary production during the winter monsoon season (Madhupratap *et al.*, 1996). The phytoplankton standing stock as per the numerical abundance shows an average phytoplankton cell density of 4x 10^5 cells L^{-1} in the open ocean waters and 1x 10^4 cells L^{-1} in the coastal waters. Observation of the phytoplankton community along the NEAS shows dominance of diatoms in the well productive waters with intermediate *Noctiluca scintillans* blooms having least diverse diatom community along with it. Earlier studies on the productivity patterns in the northern Arabian Sea during winter monsoon provide limited account on the species composition of the major primary producers, microphytoplankton (Sawant and Madhupratap, 1996; Matondkar *et al.*, 2007; Gomes *et al.*, 2008). A valid check list regarding the phytoplankton community composition in the area is still vague.

The majority of the scientific studies regarding the productivity of northern Arabian Sea during winter monsoon season focuses on the bloom of dinoflagellate *Noctiluca scintillans*. During the study period *Noctiluca scintillans* bloom was mainly observed during the early march period (Phase-2) of the winter monsoon season. The bloom was observed in patches with varying intensities along the offshore areas and rarely along the coastal water.

Except the occasional bloom of dinoflagellate *Noctiluca scintillans*, diatoms formed the phytoplankton functional group of the area. Diatoms (Class

Bacillariophyceae) are considered as the key phytoplankton groups present in the productive tropical waters**.** Phytoplankton community along the northern Arabian Sea during the winter monsoon was largely contributed by diatom population. Even though the water column turbulence was much lesser than that of summer monsoon upwelling (Luis and Kawamura, 2004; Shetye *et al*., 1985), diatoms were the predominant group utilizing the nutrient enriched waters due to convective mixing. Among the major three subclasses of diatoms like Coscinodiscophycidae (centric forms), Bacillariophycidae (raphid pennate forms), Fragilariophycidae (Araphid pennate forms), centric forms were the major contributors in the non bloom regions of *Noctiluca scintillans* as well as in the coastal waters. Diversity as well as abundance of centric diatoms was substantially high in the region. Even though there were several species observed, *Rhizosolenia hebetata* were the major centric forms along the offshore areas while *Chaetoceros lorenzianus*, *Chaetoceros* spp. were the major centrales along the coastal waters. Other centric diatoms notable were *Thalassiosira* sp., observed in single cells, chains and in mucilaginous colonies, *Leptocylindrus* spp., *Guinardia* spp. etc.

Raphid pennate diatoms were observed as monospecific proliferations as well as associated with *Noctiluca scintillans* blooms as mucilaginous aggregations. Major such species observed were *Navicula directa*, *Haslea* sp., *Nitzschia longissima* and *Cylindrotheca closterium* along the open ocean waters and *Pseudo-nitzschia* spp., along the coastal waters. Araphid pennates observed collectively along the near shore areas were *Thalassionema* spp. such as *T. nitzschioides* and *T. longissima* followed by *Thalassiothrix* spp. Pennate diatoms are observed to thrive well in open ocean conditions due to their morphological adaptations. The class is having majorly higher surface to volume ratio and therefore capable of assimilating nutrients even when their concentrations are lesser (Jane *et al*., 2008).

Even though dinoflagellates were comparatively weaker in population strength except for *N. scintillans*, certain species were observed in higher cell densities along the coastal waters which include *Ornithocercus magnificus* and *Scrippsiella* sp. Other than the coastal blooms, *Ceratium* spp., *Protoperidinium* spp. were observed ubiquitously along the coastal waters and *Gonyaulax polygramma* was observed in considerable cell densities along the offshore as well as coastal waters. In general armoured species (Subclass Peridiniphycidae) dominated the dinoflagellate community except *Noctiluca scintillans*.

Tropical waters have considerably small variations in community structure (Qasim *et al.,* 1972). The present study also did not experience wide fluctuations in community structure. Diatoms formed the dynamic constituent of the phytoplankton community. Solitary as well as chain forming diatoms have been previously reported as the predominant group along the west coast of India (Subrahmanyan, 1958a; 1958b; Devassy and Goes, 1988; Sawant and Madhupratap, 1996; Parab *et al.,* 2006).

Among the frequently observed diatoms, various species of *Chaetoceros* assemblages were observed mainly towards near shore areas with lower SST and surface salinity. *Chaetoceros lorenzianus* was the major species observed in the genus. The genus *Chaetoceros* occupies a wide variety of marine environment and forms one among the diverse groups present (Cupp, 1943). The abundance of *Chaetoceros* sp. along the Arabian Sea was earlier reported by Subrahmanyan (1946); Simonsen (1974); Kuzmenko (1975); Saifullah and Moazzam (1978) and detailed by Tabassum and Saifullah (2010) in the northern region. These studies also corroborate the abundance of *Chaetoceros* sp. along the neritic waters.

Long chains of *Chaetoceros* sp. were observed along the coastal waters and were composed of several species of the genus occasionally dominated by *C. lorenzianus.* But offshore community consisted of limited numbers from the genus. *Chaetoceros* species like *C. curvisetus, C. decipiens, C. laciniosus, C.*

socialis were recorded with decreased intra species diversity showing that the diversity within the *Chaetoceros* species decreased towards offshore. Kuzmenko (1975) observed maximum diversity of the genus during the north east monsoon (February) in northern Arabian Sea and *C. curvisetus* as the dominant species. *Chaetoceros* spp. in general was observed to have significant correlation with the ambient physico-chemical condition such as the abundance was strongly positively correlated (significance at 0.01 level) with nitrate concentrations in the water column. The growth rates of *Chaetoceros* was found to be affected by the concentration of nitrate in culture based studies (Malone *et al*., 1975). Similarly the species observed preference towards low saline but cold waters preferably towards the near shore. Accordingly, abundance of *Chaetoceros* sp. was found to have a negative correlation with station depth (significance at 0.05 level) in the Pearson's correlation matrix. Low temperature preferences of *Chaetoceros* sp., especially *C. lorenzianus* were reported in the autumn phytoplankton studies in Baltic Sea ecosystem (Kownacka *et al*., 2013).

The genus *Rhizosolenia* was observed to be another major contributor towards the diatom assemblages in both coastal as well as offshore waters. The species composition of the genus varied temporally within the season as well as inter annually. *R. hebetata* was observed in abundance during 2009 but was of lesser in abundance during 2011 as well as 2012. The major *Rhizosolenia* species present during 2011 as well as 2012 winter monsoon season was *Rhizosolenia alata* (= *Proboscia alata*) along with *R. imbricata, R. setigera* and *R. bergonii* but their abundance was mostly observed towards coastal waters. In fact *R. hebetata* was having a positive correlation with sea surface salinity (significance at 0.05 level) but other species belonging to the genus were having negative correlation (significance at 0.01 level) with surface salinity as well as surface temperature. They were also having a positive correlation with nitrate concentrations at 0.05 level.

Rhizosolenia mats dominated by *R. hebetata* were observed along the offshore waters of NEAS and they harbour a diazotrophic cyanobacterial endosymbiont *Richelia intracellularis*. The frustules of *Rhizosolenia* containing *Richelia*, in general had one trichome per cell or at most two, located at the ends of the cell and with the heterocysts oriented to the valve. There is only one report on the occurrence of endosymbiont *Richelia intracellularis* within the diatom *Rhizosolenia hebetata* from Northern Arabian Sea (Padmakumar *et al.*, 2010d). Only few reports are available on these symbiotic associations from Indian waters, from palk bay along the south east coast of India (Madhu *et al.*, 2013) and from Bay of Bengal (Kulkarni *et al.*, 2010). This symbiotic association is benefitted to the host diatom in such a way that the endosymbiont enhances photosynthesis and can be helpful to *R. hebetata* which lacks well developed chloroplast (Janson *et al.*, 1995). *Richelia* in return gets physical protection from the diatom host (Kimor *et al.*, 1992). This symbiotic association might have been a steering factor for the development of *Rhizosolenia* mats in the region during the time period. During 2011 and 2012 such symbiotic associations were not observed and *Rhizosolenia* sp. abundance was mainly contributed by *Rhizosolenia alata* (= *Proboscia alata*), *R. imbricata, R. setigera, R. bergonii*, but in lesser numerical abundance. Interestingly, the diversity of the genus *Rhizosolenia* was found to be higher during 2012 with lesser numerical abundance as well as dominance.

The genus *Thalassiosira* was another centric diatom observed as solitary, in chains as well as in mucilaginous aggregations along the 21ºN mainly along the coastal waters. Eventhough the genus was observed along the open ocean waters in fewer cell densities their occurrence was comparatively rare. Major species observed under the genus were *T. delicatula, T. eccentrica, T. mala* and *T. subtilis*. Among this, *T. mala* was observed embedded in mucilaginous matrix and was observed abundantly along the coastal waters of 21ºN during the year 2012 and was rare or absent during 2009. *Thalassiosira* *mala* is one of the first or probably the first marine planktonic diatom to be reported harmful to shellfish. A bloom of this species discoloring the water of Tokyo Bay in September 1951 was considered responsible for the heavy financial loss by the death of the cultured bivalve mollusks (Takano, 1956; 1965). Takano remarked that mechanical damage of gills caused by gelatinous substances exuding from the diatoms prevented respiration of bivalves. Padmakumar (2010a) first reported the *T. mala* and its bloom from off Kochi along the west coast of Indian EEZ. Along the offshore waters usually solitary diatoms were observed including *T. eccentrica* and *T. delicatula*. The abundance of *Thalassiosira* sp. in polluted coastal waters was reported by Verlecar *et al* (2006) along the coastal waters of Karnataka. The increased occurrence of *Thalassiosira* sp. along the coastal waters off 21ºN latitude (Off Veraval) where there is increased anthropogenic activities in relation to fishery harbours (Bhadja and Kundu, 2012) can be considered due to their tolerance towards polluted waters.

Pennate diatoms as previously mentioned were observed mainly towards the offshore areas and was observed in mucilaginous aggregations. Even though centric diatoms were also observed in aggregations along the NEAS such an intense aggregation was observed only in the case of species *Rhizosolenia hebetata* other than pennate diatoms. The mucilaginous exudations from raphae especially in the case of raphid pennates (Bacillariophycidae) is considered to be the major source for aggregation formation (Drum and Pankratz, 1964). Thornton (2002) reviewed the mechanism of diatom aggregations and its subsequent ecological implications. Diatom aggregations occur when individual cells stick together following collision. Collision is mainly effected by turbulence, differential settlement, animal feeding and sticking together by production of extra cellular polymeric substances (EPS). The EPS production is considered as major driving force towards diatom aggregation in planktonic as well as benthic habitats.

Transparent Exopolymeric Substances (TEP), a form of EPS was identified in diatom cultures as well as natural sea water (Alldredge *et al.*, 1993) and these substances were observed to have important to the aggregation of diatom bloom in mesocosm studies (Passow *et al.*, 1994; Engel 2000).

A number of researchers previously reported the aggregation of both the pennate and centric diatoms, a few of which are, *Nitzschia* (Gotschalk and Alldredge, 1989; Degobiss *et al.*, 1995; Innamorati, 1995), *Chaetoceros* (Kranck and Milligan, 1988; Alldredge *et al.*, 1993; Kiørboe *et al.*, 1998), *Rhizosolenia* (Stachowitsch *et al.*, 1990; Penna *et al.*, 1993; Passow *et al.*, 1994), *Leptocylindrus* (Stachowitsch *et al.*, 1990; Marchetti, 1990; Kiørboe *et al.*, 1994), *Skeletonema* (Riebesell, 1991; Kiørboe *et al.,* 1994; Thornton *et al.*, 1999), *Thalassionema* (Marchetti, 1990; Riebesell, 1991; Penna *et al.*, 1993) and *Thalassiosira mala* (Padmakumar *et al.*, 2010a).

The intense aggregations of diatoms serve as a prominent source of marine snow, providing micro environments for biological activities in normally homogenised water column (Silver *et al.*, 1978) and also increase the size compatibility of diatom aggregations so that fishes and other organisms are able to feed. According to Thronton (2002) the biogeochemical affects of these aggregates influences the cycling of carbon, nitrogen, phosphorous and silicon in the marine ecosystem. The aggregations and their subsequent sinking enhance the flux of particulate organic matter towards the deep. Their effect can be through transport of organic matter from the euphotic zone to the deep sea and the increased biological activity within the aggregates. Even though there were small sized aggregates of *Chaetoceros* spp. as well as *Thalassiosira* sp. along the coastal waters, open ocean aggregates of pennates such as *Navicula* sp., *Nitzschia* sp., *Haslea* sp. were much intense. Centric diatom *Rhizosolenia hebetata* mat was observed in 2009 along the offshore as well as the coastal waters.

The open ocean aggregations of pennate diatoms like *Nitzschia* sp., *Haslea* spp., *Navicula* sp., *Cylindrotheca closterium* etc was observed along with the bloom patches of dinoflagellate *Noctiluca scintillans*. Diatom aggregations along with *Noctiluca scintillans* blooms were studied by Tiselius and Kiorboe (1998) and according to them the dinoflagellate *Noctiluca* itself acts as an aggregate feeder as these aggregates act as an immediate food source for the dinoflagellate. Some researchers suggest that the aggregation of diatom cells inhibit the grazing by copepod (Malej and Harris, 1993) but there are contradictory views that describes copepods as obligate aggregate feeder (Dagg, 1993) but the possible reason for the formation of diatom aggregates is yet to be studied in detail.

The occurrence of solitary as well as chain forming pennate diatom *Pseudo-nitzschia* was prominent along the coastal waters of NEAS with significantly higher concentrations along the coastal waters of 21ºN. The genus was also observed in a fewer cell densities throughout the NEAS in both coastal as well as offshore areas except for the southern boundary, 18ºN. *P. seriata* and *P. pungens* were the predominant diatoms from the genera observed abundantly towards the coastal waters. The coastal area affinity of *Pseudo-nitzschia* spp. was previously described by Bates *et al* (1998). Coastal waters were observed to have higher nitrate concentrations primarily because of coastal waters having land runoff and riverine discharge as well as nutrient input by convective mixing. Higher concentrations of dissolved inorganic nitrogen were observed to augment the abundance of *Pseudo-nitzschia* spp., in the coastal waters (Hasle *et al.*, 1996; Parsons *et al.*, 2002). The nitrate preference of *Pseudo-nitzschia* sp. was established by Carter *et al* (2005) from field and laboratories studies and these results suggests that the nitrogen sources from coastal runoff influences the development and maintenance of these toxic diatom blooms.

Psuedo-nitzschia is known to produce domoic acid (DA), a potent neurotoxin that can be devastating to aquatic life via trophic transfer in the food web (Fritz *et al.*, 1992; Bates *et al.*, 1998; Scholin *et al.*, 2000). In humans, DA exposure manifests itself as amnesic shellfish poisoning (ASP) following the consumption of contaminated filter-feeding molluscs (Bates *et al.*, 1989; Trainer *et al.*, 2007). Toxin production in *Pseudo-nitzschia* species has been found to show regional variations. Thus the same *Pseudo-nitzschia* species may be toxic in one part of the world but not in the other (Bates *et al.,* 1998). The production of toxin by the genera varies with several external as well as internal factors and about ten species of *Pseudo-nitzschia* are confirmed to produce toxin domoic acid (DA) (Bates, 2000; Lundholm *et al.*, 2003) which includes, *P. australis, P. calliantha, P. delicatissima, P. fraudulenta, P. multiseries, P. multistriata*, either *P. pseudodelicatissima* or *P. cuspidata, P. pungens, P. seriata* and *P. turgidula*.

During the early phase of winter monsoon 2009 increased abundance of *Pseudo-nitzschia seriata* was observed along the coastal waters of NEAS. But the toxic effects of the species cannot be determined without the toxin extraction studies from the species. The production of toxin by different species of *Pseudo-nitzschia* varies with various environmental factors like temperature, nutrient availability etc (Bates *et al.*, 1998). *P. pungens* as well as *P. pseudodelicatissima* was also observed in higher cell densities in the coastal waters during the season. The genus was observed throughout the winter monsoon but the composition as well as dominance varied time to time. The occurrence of toxigenic *Pseudo-nitzschia* species along our coasts is of concern, as it is possible that *Pseudo-nitzschia* spp. in the diet can result in the accumulation of domoic acid in the wild and cultured population of bivalve mollusks and fishes of the Veraval coast (21ºN).

Unlike the majority of raphid pennates (except *Pseudo-nitzschia* sp.) araphid pennates were more or less confined towards the coastal waters of both

21ºN as well as 22ºN. However the region along 18ºN was devoid of araphid pennate diatoms. The genus *Thalassiothrix* and *Thalassionema* were the major representatives from the class. The diversity of araphid pennates were higher during 2009 but was less diverse and more abundant during 2011. The increased abundance during the period can be attributed to increased cell density of *Thalassionema nitzschioides* during 2011 along the coastal waters especially during Phase-1 and Phase-2. The abundance of this species observed to be strongly negatively correlated with SST, SSS and depth. In addition their positive correlation with nitrate concentration confirms their affinity towards coastal waters. During 2009, the major araphid pennate observed along the region was *Thalassiothrix* sp., mainly *Thalassiothrix longissima*.

Detailed studies regarding the ecological aspects of family Thalassionemataceae is sparse, except for descriptions given by Hasle (2001). *Thalassionema nitzschioides* is described to be cosmopolitan in distribution (Hasle and Syvertsen, 1997) and survives in wide range of nutrient concentrations (Abrantes, 1988). Jane *et al* (2008) described the occurrence of *Thalassionema nitzschioides* in nutrient depleted conditions in the Bay of Bengal, however during the present study the species was observed mostly towards nutrient rich coastal waters of the NEAS. Low temperature preference of *Thalassionema nitzschioides* was studied by Liu (2008) in fresh water ecosystem. In the north eastern Arabian Sea ecosystem the affinity of *T. nitzschioides* is significantly higher at 0.001 level (Pearson correlation) towards low SST regions. Their increased abundance during year 2011 which was comparatively cooler period and preference towards the coastal waters of 21ºN and 22ºN can be attributed towards their low temperature preference. Moreover their occurrence was sparse towards the southern extend of NEAS (18ºN) with relatively high surface temperatures.

Dinoflagellate (class Dinophyceae) community along the NEAS was characterized by the blooms of *Noctiluca scintillans* which varied from small isolated patches to extensive intense blooms along the open ocean waters. Except for the mucilaginous aggregations of pennate diatoms such as *Haslea* sp., *Navicula* sp. along with *N. scintillans*, other phytoplankton groups especially dinoflagellate associations were sparse along with the bloom species.

Noctiluca scintillans, commonly known as “sea sparkle” spreads along a larger area of NEAS during winter monsoon with its opportunistic behaviour, higher growth rate and increased reproductive cycles within single season. The blooms of *Noctiluca* occur either as a *red tide* or as a *green tide* depending on their cell aggregation colour and are caused by its mode of nutrition. Along the eastern Arabian sea both the red and green coloured blooms of *Noctiluca* have been reported. (Naqvi *et al.*, 1998; Sahayak *et al.*, 2005; Gomes *et al.*, 2008; Padmakumar *et al.*, 2008, Padmakumar *et al.*, 2010c; Madhu *et al.*, 2012). Green *Noctiluca* harbours green coloured photosynthetic prasinophyte endosymbiont *Pedinomonas noctilucae* (Subr.) Sweeney and red *Noctiluca* devoid of these endosymbionts, thrives on heterotrophic mode of nutrition by feeding on other organisms (Phagotrophy) mainly diatoms (Kirchner *et al.*, 1996; Padmakumar *et al.*, 2010c; Harrison *et al.*, 2011). The *Noctiluca* blooms along northern Arabian Sea occurs in green colour owing to the presence of innumerable motile prasinophyte endosymbionts *Pedinomonas noctilucae* within the cells (Sweeney, 1976).

Extensive occurrences of *Noctiluca* blooms along NEAS during late winter monsoon as well as early spring inter monsoon gained scientific attention in the recent years. Early studies in the northern Arabian Sea suggested that the high production during winter monsoon was due to the diatoms and they played key role in increased production of the area (Banse, 1987). Later on various reports on the occurrence of *Noctiluca scintillans* blooms paved way for the identification of this dinoflagellate as a vital part in the winter blooms. The importance of *Noctiluca scintillans* during the winter production in NEAS was recently studied in 21st century (Matondkar *et al.*, 2004; Sarangi *et al.*, 2005; Dwivedi *et al.,* 2006; Gomes *et al.*, 2008; Dwivedi *et al.*, 2008; Padmakumar *et al.*, 2008; Prakash *et al.*, 2008; Gomes *et al.*, 2009). Even after extensive and dedicated studies to trace the dynamics of bloom, it's triggering or initiation mechanism is still under controversy. Satellite imagery studies shows the emergence of high chlorophyll patches in the Oman gulf which shows advection towards central as well as eastern Arabian Sea with the progression of winter monsoon and peaks in the area during late winter monsoon as well as early spring inter monsoon (Gomes *et al.*, 2008).

Occurrence of *Noctiluca scintillans* as well as its spatial and temporal variations is indispensable in the microphytoplankton community studies along the NEAS especially during winter monsoon season. Significant inter annual as well as intra seasonal (Phase wise) variations were observed in the distribution and abundance of *Noctiluca scintillans* which was closely related with the population dynamics of other microphytoplankton thriving in the region. Scrutinization of the available data sets confirms that maximum abundance of *Noctiluca scintillans* occurs during March (cell densities varied from 1.4- 2.4x 10^4 cells L^{-1}). Spatially, there were persistent blooms of *Noctiluca* along the offshore areas of 22ºN throughout the season in all the years. This can be attributed to the persevering convective mixing signatures in the area as indicated by low SST, high surface salinity and deep mixed layers.

Comparative analysis of temporal variation in phytoplankton abundance during winter monsoon and its transition to spring inter monsoon observed intensity of *Noctiluca scintillans* blooms during late winter monsoon period. This confirms the fact that optimum bloom period of *Noctiluca scintillans* occurs during March, probably mid March. In addition to this there observed a shifting in the peak bloom period of *Noctiluca scintillans* from early March in 2009 to mid march in 2011 and further towards late march in 2012 with slight extension towards the spring intermonsoon period (1st week of April). Hence the seasonal abundance of *Noctiluca scintillans* observed a delay in the waning phase of bloom and was yearly strengthening during the month of March. Madhu *et al* (2012) reported enhanced chlorophyll *a* concentrations and intense *Noctiluca scintillans* blooms during the same period (March) from the studies conducted during the year 2000. According to them the detrainment process occurring in the NEAS supports these extensive blooms. The detrainment process as described by McCreary *et al* (1996) briefs about the rapid stabilization of oceanic waters in NEAS after winter monsoon entrainment due to convective mixing. This faster stabilization occurs as a consequence of decreased wind speed and increased SST, thereby shoaling of the mixed layers. Hence the stabilized water column with increased nutrients by convective mixing leads to extensive blooms. This can very well be correlated with the intense blooms of *Noctiluca scintillans* during early spring inter monsoon (April first week) observation during 2012. During the time period even though winter convections had subsided and mixed layer shoaled up, bloom of *N. scintillans* were observed in the offshore areas of NEAS. The intense nutrient enrichment during the previous episode of mixing favoured the existence of bloom even towards early spring inter monsoon period that is generally considered as oligotrophic period.

Interestingly, there was an increasing trend in the yearly intensity and expanse of *Noctiluca scintillans* blooms along the NEAS during winter monsoon. The abundance as well as citing areas of bloom incidence was found to increase with years. The *Noctiluca* cells observed in bloom patches were found to coexist with mucilaginous aggregations with pennate diatoms. The mucilage production and its ecology has been discussed earlier in the session. The aggregations were not always found along with bloom but, when found associated, the dominant percentage of *Noctiluca scintillans* in the phytoplankton community was lesser, nearly 50%. When found without aggregations, *Noctiluca* cells occupied nearly 90-95% of the total microphytoplankton community. The aggregating diatoms varied yearly although no phase wise variations were observed. The major pennate diatoms found in mucilaginous aggregation during years of study were *Navicula directa* along with centric diatom *Rhizosolenia hebetata* which was observed in extensive mats throughout NEAS (2009), *Haslea* sp. (2011) and *Haslea* sp. and *Cylindrotheca closterium* (2012).

Despite the fact that the green *Noctiluca scintillans* regularly forms massive blooms in many areas of Southeast Asia (Elbrächter and Qi, 1998), our knowledge of its biology is very sparse; it is, in fact, restricted to a single paper published by Sweeney (1971). In laboratory studies the author demonstrated that the green *N. scintillans* could survive and divide in the light without the addition of food for at least one month. But when the illumination was cut off, in darkness, the symbiotic flagellate disappeared and the *N. scintillans* cells died within a few days unless a food organism, *Dunaliella tertiolecta* (Butcher), was added. Thus, her results indicate that *N. scintillans* in the presence of the endosymbiont utilizes the photosynthetic activity of the endosymbiont for growth and multiplication however in the absence of the endosymbiont the dinoflagellate switch on to heterotrophic mode of nutrition. According to these studies the instability of the symbiosis between *Pedinomonas noctilucae* and *N. scintillans* suggests that the symbiotic relationship represents a primitive stage in the establishment of symbiosis.

The co-occurrence of green *Noctiluca* with that of pennate diatoms need further *in situ* as well as culture based studies for clarification. According to Buskey (1995) diatoms were the most preferred food of *Noctiluca*. However during the present study the occurrence of diatoms inside the food vacuole were occasional in occurrence thus sufficient evidence regarding the phagotrophic behaviour of *Noctiluca scintillans* cannot be established.. Moreover studies on the diatom colonization in *Noctiluca* bloom area in

Benguela current states that these diatom aggregates are formed by regular coagulation of diatom cells (Tiselius and Kiorboe, 1998). The pennate diatom aggregation relation with *Noctiluca scintillans* blooms can also be a matter of coincidence that the winter convection and increased supply of nutrients provided a condition favourable for the species to flourish and since the pennate diatom produce mucilaginous secretions through their raphae the aggregation can be due to these secretions.

Except the *Noctiluca scintillans* blooms, armoured dinoflagellates of class- Peridiniphycideae occupied the dinoflagellate community along the offshore as well as coastal areas and class Dinophysiphycidae occupied the coastal waters with occasional blooms. Dinoflagellate other than *Noctiluca scintillans* experienced maximum abundance towards the coastal waters of 21ºN (Veraval coast) in comparison with that of 22ºN (Dwaraka coast). A comparative study on the sea water quality of these areas (Bhadja and Kundu, 2012) reveals that Veraval coast is highly influenced by anthropogenic activities than the Dwaraka Coast. Veraval coast is a part of the major commercial fishing centre in Asia and thereby receiving a large amount of anthropogenic waste materials, oil, effluents , domestic sewage and waste waters from heavy industries and small scale fish processing plants of the city (Bhadja and Vaghela, 2013). This difference can be the major reason for varied dinoflagellate community structure as well as diversity along these two coastal areas. The dinoflagellates of class Dinophysiphycidae were found more towards 21°N, which include *Ornithocercus* spp. and *Dinophysis* spp.

6.2 Interannual variability

Phytoplankton community structure of NEAS experienced interannual variability during the winter monsoon season. The variability can be attributed to both abundance as well as distribution of different subclasses of phytoplankton. The changes in phytoplankton community structure can be associated with fluctuations in the environmental conditions mainly physical factors. Analysis of the physical characteristics observes comparatively higher Sea surface temperature during 2009 than that of 2011 (Figure 83). The average sea surface temperature during 2009 was 26ºC, whereas during 2011 much lesser SST of av. 24.7ºC was observed.

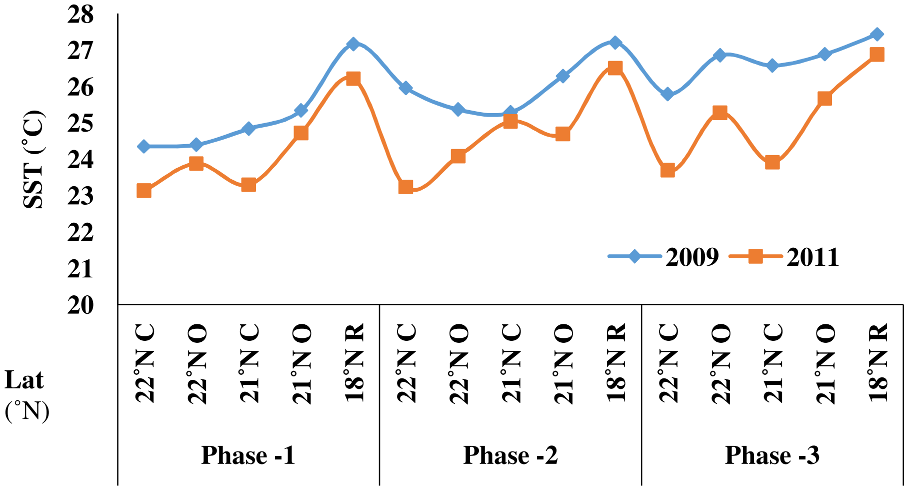


Figure 83. Variation in SST (ºC) between 2009 and 2011 winter monsoon

The SST of open ocean waters of NEAS during winter monsoon of 2009 was higher than that of 2011. The possible reason for this higher SST was scrutinized using various satellite data sets. To analyze the influence of Indian Ocean Dipole (IOD) on the SST, dipole mode index was processed. Intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is referred as the positive IOD and when it is negative, it is referred as negative IOD. Dipole mode index (DMI) data was obtained from low latitude climate prediction research by Japan agency for Marine Earth Science and Technology (JAMSTEC, http://www.jamstec.go.jp/frcgc/research/d1/iod/e/iod/dipole_mode_index.html. From the analysis it was observed that considerably higher DMI during 2009 than that of 2011 during the study period. Even though a significantly higher DMI was not observed, 2009 recorded comparatively higher DMI than that of 2011. Figure 84 shows the Dipole Mode Index divided by standard deviation variation over 2002-2012.

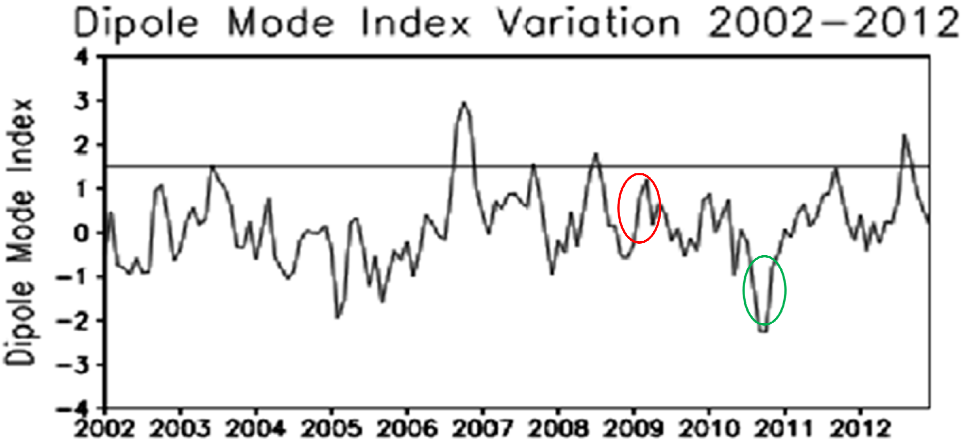


Figure 84. Dipole Mode Index divided by standard deviation variation over 2002- 2012 (Mo Lan, 2013). The study period 2009 (red circle) and 2011 (green circle) is highlighted.

This variation has primarily reflected in the chlorophyll *a* concentration which was on an average 0.96 mg m^{-3} during 2009, whereas a higher value of 1.57 mg m^{-3} occurred during 2011. The studies on phytoplankton pigment contribution in equatorial Pacific also showed a decrease in the total chlorophyll during El Nino events characterised by increased SST (Rousseux and Gregg, 2011). Apart from the total chlorophyll concentrations large scale shifts in the phytoplankton groups as that of equatorial Pacific is lacking in the NEAS. The convective mixing process caused by winter monsoon might a reason for the absence of a prominent shift in phytoplankton community structure. Even then there were considerable variations in the phytoplankton cell densities between the two years with increased cell densities during 2011. The total cell density of phytoplankton was lesser during 2009 (Figure 85) when compared to that of 2011. Increased SST in 2009 might be a reason for this reduction in phytoplankton abundance. Such observations are often encountered in the studies in Equatorial Pacific (Rousseux and Gregg, 2011) and North Chile coast (Avaria and Munoz, 1987). ANOSIM test conducted between the phytoplankton community of NEAS during 2009 and 2011 winter monsoon observed clearly separable community assemblage during the two years (R = 0.6; p = 0.1%). The cluster analysis of the Bray Curtis similarity matrix observed 2009 and 2011 stations standing apart in two main clusters (Figure 86).

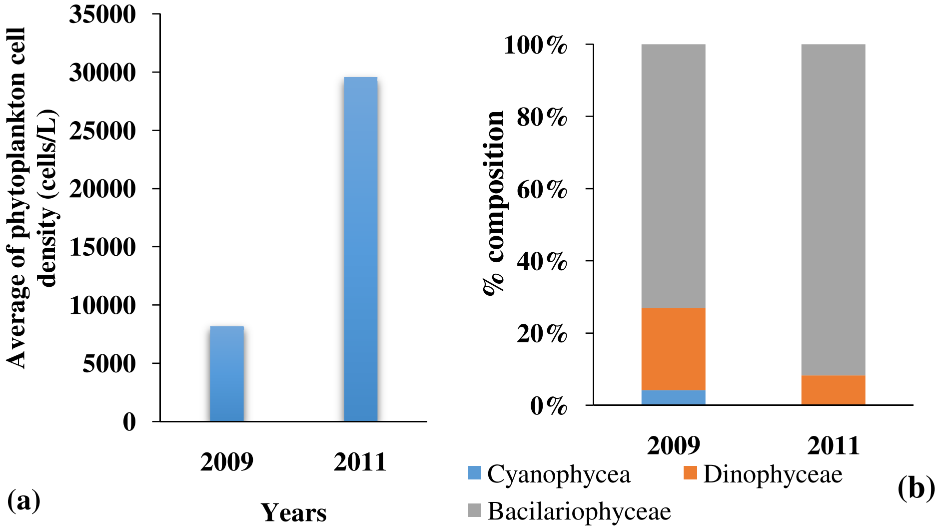


Figure 85. Variations in the microphytoplankton abundance **(a)** and percentage composition **(b)** during winter monsoon of 2009 and 2011

The compositional variations in the phytoplankton community were contributed mainly by the presence of cyanophycean constituents represented primarily by *Trichodesmium erythraeum*. The filaments of *Trichodesmium erythraeum* was present significantly towards the southern latitudes (18ºN) during 2009 and was completely absent during 2011. Even though the surface temperature prevailed in the region is not optimum for *Trichodesmium* bloom (Sellner, 1997), the presence of filaments can be due to preferably higher SSTs than in the later year along with the oligotrophic conditions. The year 2009 was observing remarkably higher occurrence of *Trichodesmium* bloom along the west coast during spring inter monsoon that extended even towards the early phase of summer monsoon (Padmakumar *et al*., 2010b).

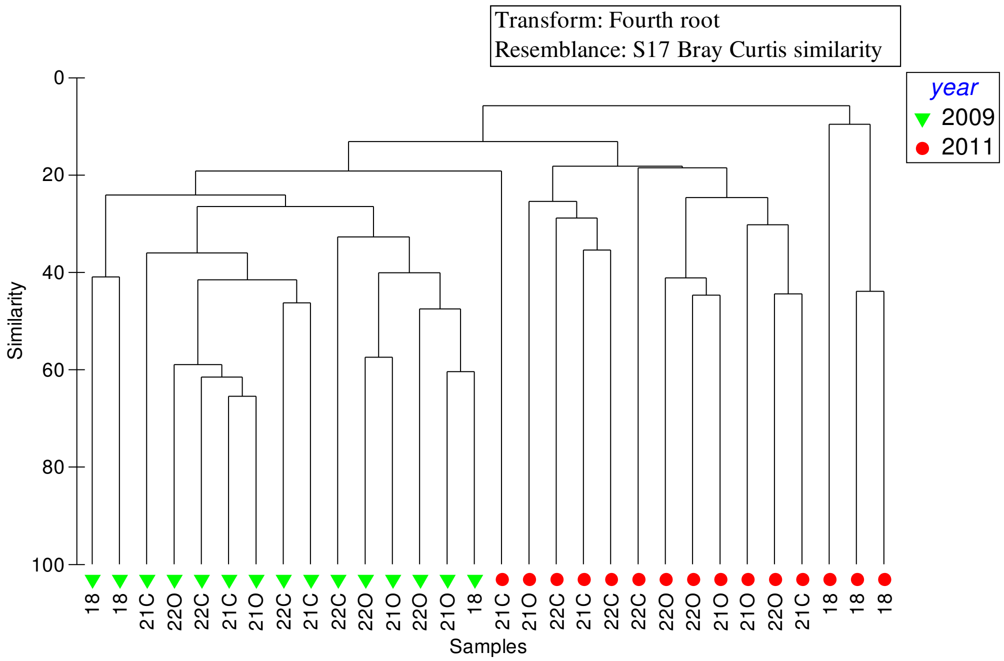


Figure 86. Dendrogram using microphytoplankton abundance along NEAS during winter monsoon of 2009 and 2011

The studies on the shift in the phytoplankton community along with ENSO events are sparse. Analysing the limited reports on the aspect, most observations suggest a decrease in the diatom cells during the time period (Rousseux and Gregg, 2011). There was a considerable increase in total cell density of phytoplankton especially diatoms during winter monsoon of 2011 than 2009 period. The major diatom contributor during 2009 was centric form *Rhizosolenia hebetata*, which occurred in extensive mats along offshore waters of NEAS during the entire winter monsoon. Whereas the raphid pennate diatoms increased during 2011 and mucilaginous aggregations of pennate diatoms were observed (Figure 87).

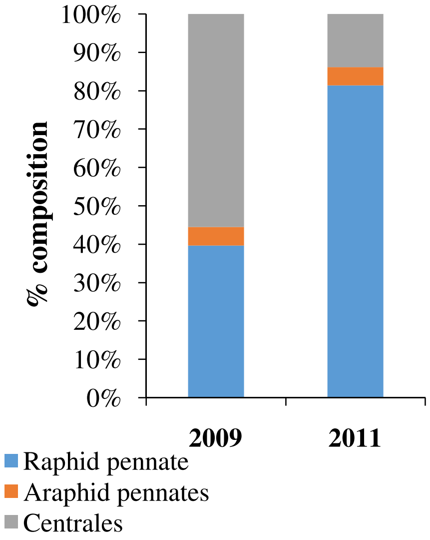


Figure 87. Variations in diatom community during the winter monsoon of 2009 and 2011

The phytoplankton community was comparatively heterogeneous during 2009 with increased diversity as well as species richness. The dominance in the phytoplankton community was less pronounced in 2009 whereas during 2011 dominance increased along with increase in numerical abundance. Subsequently, during 2011 diversity decreased especially along the offshore regions. The dominance of raphid pennate diatoms which occurred in mucilaginous aggregations along the offshore waters accounted much for the decreased diversity during 2011. More over these aggregations were mostly contributed by single species of diatom sustaining along with *Noctiluca* bloom. During 2009 winter monsoon centric diatoms dominated both coastal as well as offshore areas and the mucilaginous aggregations were less prominent along with *Noctiluca scintillans* bloom. Centric diatom community was highly diverse with more number of genus as well as species richness and hence the whole phytoplankton community appeared to be diverse and having higher species richness during 2009.

Considering the distribution of *Noctiluca scintillans*, blooms were observed in both these years. The intensity of bloom formation was more pronounced in 2011 than that of 2009. Wide spread bloom patches were observed during 2011 covering the offshore areas of both 22ºN and 21ºN whereas the occurrence of bloom patches were confined to one or two sites during 2009. Lower surface temperatures and increased nutrient concentrations might be factor supporting these extensive blooms during the time period (Prasannakumar *et al.*, 2001; Gomes *et al.*, 2008). The variations observed in phytoplankton abundance as well as composition during the two years of winter monsoon 2009 and 2011 suggests significant inter annual variations in phytoplankton community structure. Comparatively higher SST prevailed in the region during winter monsoon of 2009, whereas lower SST and increased nutrients injection during strong winter convective mixing of 2011 can be the major causative factors for this inter annual variability.

6.3 Short term dynamics in microphytoplankton community structure

6.3.1 Intra seasonal variations in microphytoplankton community during winter monsoon

Short term variations in phytoplankton community structure were less pronounced within the winter monsoon season. Lower SST combined with increased sea surface salinity and deeper mixed layers during Phase-1 (February, both 2009 and 2011) favoured a diverse and abundant centric diatom community. Gomes *et al.*, 2009 reported a community dominated by diatoms and dinoflagellates in the region during winter monsoon seasons. February (Phase- 1) experienced moderate to intense convective mixing (Banse and McClain, 1986) and the water column was highly instable in comparison with other two phases, leading to the sustenance of chain forming centrales *Chaetoceros* spp., mainly *C. lorenzianus*, *Rhizosolenia* spp., *Guinardia* spp., *Thalassiosira* spp., etc during Phase-1. These chain forming diatoms are known to thrive in instable well mixed low temperature waters (Lassiter *et al*., 2006). Even though these diatoms were also recorded during latter phases their percentage contribution towards the total phytoplankton community decreased. Precisely the order of dominance of diatoms varied with phases. Quantitative variations observed whereas qualitative variations were meagre.

Previous reports on winter bloom in NEAS describes the occurrence of blooms during February as well as March (Sarangi *et al*., 2005; Dwivedi *et al*., 2006; Gomes *et al*., 2008; Dwivedi *et al*., 2008; Padmakumar *et al*., 2008; Prakash *et al*., 2008; Gomes *et al*., 2009). However from the three years of analysis (viz., 2009, 2011 and 2012) intense and increased expanse of *Noctiluca scintillans* bloom observed during early to mid March (Phase-2), which leads to the assumption that this phase as the optimum bloom development period for this species in NEAS.

Variations in the physical condition prevailing in the region can be considered as the major causative factor for this preference. Phase-1 can be considered as a period of moderate convective mixing with less stabilized water column. But as the season proceeds to Phase-2, intensity of winter convention decreases and due to the detrainment process, the rapid stabilization of water column occurs (McCreary *et al*., 1996). This might have favoured the extensive blooms of *Noctiluca scintillans*. Since SST has not increased beyond 25ºC and the sufficient nutrients have already occurred in the water column during earlier mixing, conditions conducive for the blooms prevailed (Padmakumar *et al*., 2008).

Detrainment of water column leads to shoaling of mixed layer (McCreary *et al*., 1996). As the convective mixing process sustains for 3- 4 months (December- early March) enormous amounts of nutrients reach the euphotic column (Wiggert *et al.,* 2000). Stabilized nitrate rich water column with increased depth average light intensity due to shallow mixed layer favours phytoplankton growth (Raymont, 1980). Raphid pennate diatoms that were present earlier utilize this condition and owing to their rapid growth rate than centric forms (Turpin and Harrinson, 1979) and these forms flourish. The proliferations of pennates were observed to occur along the offshore regions as monospecific mucilaginous aggregations. Intense *Noctiluca scintillans* blooms as well as mucilaginous aggregations of monospecific diatoms together resulted in decreased diversity as well as increased dominance indices during Phase-2. Unlike the first two phases, Phase-3 formed the transition stage from winter monsoon to spring inter monsoon season having comparatively higher SST and more characteristic of spring inter monsoon with shallow mixed layers (Gardner *et al*., 1999). The intensity of *Noctiluca scintillans* bloom slightly decreased during Phase-3. Diatom community retreated towards centric forms with exception along certain offshore patches that still sustained raphid pennate diatom blooms.

Hence intra seasonal (phase wise) variability in phytoplankton community structure was observed in diversity, abundance as well as composition. Although absolute variations were not deduced intra seasonally, noticeable alterations were observed in micro phytoplankton community along the NEAS.

6.3.2 Variability of microphytoplankton community during the transition from Winter Monsoon to Spring Inter Monsoon

Phytoplankton is considered as excellent indicators of rapid environmental change (Thyssen *et al*., 2008; Lasternas *et al*., 2011). Diversity as well as taxonomic composition can be considered as the *modus operandi* for analyzing the fluctuations in physicochemical factors in the aquatic environment (Ptacnik *et al*., 2008). The abundance as well as compositional variations in phytoplankton community along the NEAS in the course of transition from winter monsoon to spring inter monsoon indicates the responses of marine organisms towards seasonal variations at the primary level. Earlier shipboard studies in the eastern Arabian sea explicates on the dramatic changes in phytoplankton communities in accordance with wind driven changes during seasons (Banse, 1987; Bauer *et al*., 1991; Latasa and Bidigare, 1998). Satellite based as well as moored observations also indicates on the changes between different classes of primary producers (Banse and McClain, 1986; Brock and McClain, 1992; Gomes *et al*., 2009).

The stratification of water column with onset of oligotrophic conditions such as increased SST and shallow mixed layer, influence the phytoplankton community structure. The surface chlorophyll *a* values decreased steadily except for the region of *Noctiluca scintillans* bloom. Lower nitrate concentrations (< 0.1 µM), higher surface temperatures (~27˚C) and shallow mixed layers (< 20m) lead to decreased phytoplankton standing crop in the region that experienced higher production during winter monsoon. Interestingly, these variations were observed within 1-2 weeks of time period leading to the confirmation of short term variations in the community structure of primary producers.

The diversity of microphytoplankton along the NEAS increased during early spring inter monsoon. Massive blooms of pennate diatoms such as *Haslea* spp., as well as dinoflagellates subsided and were replaced by more diverse community of centric diatoms. Centric diatom group are known to thrive in lesser nutrient conditions. Cosmopolitan centric diatoms like *Chaetoceros* spp., *Bacteriastrum delicatulum*, *Ditylum brightwellii*, *Meuneria* sp. sustained in the more stable, less nutrified waters. With the persistence of these environmental conditions multiplications of nitrogen fixing cyanobacteria like *Trichodesmium erythraeum* flourishes and forms extensive blooms (Capone *et al*., 1998). The regions along the coastal waters off Veraval (21ºN) is observed to have increased anthropogenic runoff due to extensive fishery as well as industrial settlements (Bhadja and Vaghela, 2013). Comparatively higher nutrient concentrations in these coastal waters even during spring inter monsoon is mainly due to these activities and might have supported the increased abundance of phytoplankton. Unless for the coastal productive waters the phytoplankton community shifted towards less dominant more diverse centric diatom contributed community during early spring inter monsoon.

6.4 Microphytoplankton studies and futuristic approach

Microphytoplankton community structure and its variations are an inseparable component in primary production dynamics of a marine system. Winter monsoon period drag scientific interest to oceanographers, as it is the productive phase of Arabian Sea which is considered a natural laboratory. The present study with its intense sampling strategies provides an authentic checklist of microphytoplankton during winter along NEAS. Spatial and temporal analysis of the phytoplankton community observes significant variations with hydrographic factors which is more evident interannually. The study observes significant changes within the phytoplankton community structure with the variations in the sea surface temperatures. This underlines the possible impact of climate change on the primary producers.

Even though many previous studies have attempted the production dynamics of the region they were all confined to limited area or limited period of time. The study recorded nearly 190 species from NEAS during the period of observation. The species wise data generated can be used for various validation programs of satellite based researches. The data generated by the study is currently used for bloom specific algorithm development and in future can be utilized for species specific algorithm development. The study provides detailed outlook on the quantitative and qualitative account on the primary producers of the area. Monospecific and multispecies planktonic aggregations and extracellular mucous productions were identified along open ocean waters during NEAS which can be further utilized for carbon flux studies and associated biogeochemistry of the area.

The study area falls mainly along the inshore and offshore areas off Gujarat coast or broadly the Saurashtra coast. Gujarat is a state well known for high fishery potential and increased fish landings and is considered as the major fish producing maritime state. The major fish landing in the Gujarat fishing zone include Ghol, Pomfrets, Sciaenids, Threadfins, Bombay duck, Prawns etc. Moreover the area is identified as one among the PFZ (Potential Fishing Zone) advisories along the Indian coast. The spurt of phytoplankton production feed the secondary and tertiary producers ultimately favoring the fishery potential of the area. Since the study deals with both open ocean and coastal waters of NEAS the information attained can be employed for the fishery prediction models in identifying fishing zones and assessment studies. More over the increase of toxin producing diatoms like *Pseudo-nitzschia* spp. along the coastal waters indicate a cause of concern regarding the harmful effects that demands regular monitoring programs in these fishing zones.

Chapter- 7

Summary and Conclusion

"The sea, once it casts its spell, holds one in its net of wonder forever."
— Jacques Yves Cousteau, Oceanographer

North Eastern Arabian Sea (NEAS) or the northern counterpart of eastern Arabian Sea is a region expressing variable responses according to the biannual reversal of monsoon winds. The north east monsoon (winter monsoon, November- March) characterized by moderate wind forcings, low air temperature, low relative humidity results in increased evaporation of the surface waters and promotes convective mixing. This mixing erodes the pycnocline and injects nutrients to the euphotic column thereby stimulating biological production. As the winter monsoon recede air temperature increases with increased solar insolation and advancement of spring inter monsoon (April- May). SST builds up (~28°C) with shallow mixed layers (< 30 m) preventing the influx of nutrients to the upper water column thereby creating an oligotrophic stratified waters.

The responses of the major primary producers, microphytoplankton towards the winter monsoon season as well as its transition towards spring inter monsoon season was assessed in detail during the study along the NEAS. The microphytoplankton community structure was overviewed during the winter monsoon season for three years *viz* 2009, 2011 and 2012. In order to examine the intra seasonal variability, the community was assessed for three times *viz* early February (Phase-1), late February to early March (Phase-2) and late March (Phase-3) considering it as three phases respectively during year 2009 and 2011. The responses of phytoplankton community during transition of season from winter monsoon to spring inter monsoon was analyzed during

2012 by two phase study *viz.*, late March and early April respectively. The study was conducted majorly along two latitudes 22ºN and 21ºN where the signatures of winter cooling were prominent and along 18ºN where there was least influence of winter cooling.

Low SST (< 26ºC) with increased salinity (~36 psu) and deeper MLDs (~100m) were observed along the NEAS during the study period which shows the signatures of convective mixing. The offshore areas off the Saurashtra Coast (22ºN and 21ºN) were having lower SSTs with high saline surface waters. The convection of these cold dense waters paved way for the deep mixed layers in these regions. In the oceanic waters along 18ºN (southern extend of NEAS, Ref. station) the influence of winter convection was least observed with increased SST (> 26ºC) and less saline surface waters resulting in shallow mixed layers (< 20m). Thus a pattern of surface warming from north to south was observed during the study period along the NEAS. Relatively high saline waters occupied in the northern offshore areas that varied from 36.5 to 35.5 with maximum salinity of 36.6 in the northern offshore areas (22˚N). SSS decreased both towards the coast as well as towards south (18ºN). Cool saltier surface waters lead to deep convections and consequently the depth of mixed layer reached to ~100m. Mixing of the water column elevate the nitrate concentrations in the euphotic column and the surface nitrate were ~1 µM in the region

Eutrophication of the surface water column as a result of winter convective mixing resulted in higher surface chlorophyll *a* concentrations. On an average the surface chlorophyll *a* along the NEAS during winter monsoon season was 1.2 ± 0.85 mg m^{-3} along the open ocean regions and 1.6 ± 1.3 mg m^{-3} along the coastal waters. Exceptionally higher surface chlorophyll *a* (~ 60 mg m^{-3}) was recorded along the intense bloom areas of dinoflagellate *Noctiluca scintillans*. Subsurface chlorophyll maximum was rarely observed along the region during the season. The southern extend of NEAS (18ºN) where the signatures of convective mixing were either weak or absent, lower surface chlorophyll *a* concentrations (~0.3 mg m^{-3}) were observed.

The winter time eutrophication as a result of convective mixing and deepening of MLD support the growth of phytoplankton community along the NEAS. Northern Arabian sea especially the open ocean waters remains less productive with fewer phytoplankton cell densities and gains mass and volume in terms of primary production during the winter monsoon season. The phytoplankton standing stock as per the numerical abundance shows an average phytoplankton cell density of 4x 10^5 cells L^{-1} in the open ocean waters and 1x 10^4 cells L^{-1} in the coastal waters. The phytoplankton community along the region observes dominance of diatoms along with intermediate blooms of dinoflagellate *Noctiluca scintillans* that varies spatially and temporally during the season along the offshore areas of NEAS. Phytoplankton community along the NEAS during the winter monsoon was largely contributed by diatom (Class Bacillariophyceae) population.

The diatom subclass Coscinodiscophycidae (centric forms) was the major contributors in the non bloom regions of *Noctiluca scintillans* as well as in the coastal waters. The genus *Rhizosolenia* represented mainly by *Rhizosolenia hebetata* was the major centric diatom present along the open ocean waters. Other representatives from the genus included *R. imbricata, R. alata, R. styliformis* etc. *Chaetoceros* was the major centric diatom genus present along the coastal waters and was dominated by *Chaetoceros lorenzianus* followed by *C. curvisetus, C. decipiens, C. laciniosus* etc. Other centric diatoms notable were *Thalassiosira* sp. (observed in single cells, chains and in mucilaginous colonies), *Leptocylindrus* spp., *Guinardia* spp. etc. Another major diatom subclass observed predominantly along the open ocean waters were Bacillariophycidae (raphid pennate forms). These groups were observed as monospecific proliferations as well as associated with *Noctiluca scintillans* blooms as mucilaginous aggregations. Major such species observed were *Navicula directa*, *Haslea* spp., *Nitzschia longissima*, *Cylindrotheca closterium* etc. along the open ocean waters and *Pseudo-nitzschia* spp., along the coastal waters. The diatom subclass Fragilariophycidae (araphid pennate forms) were observed collectively along the near shore areas were *Thalassionema* spp. such as *T. nitzschioides* and *T. longissima* followed by *Thalassiothrix* spp.

The dinoflagellate (class Dinophyceae) *Noctiluca scintillans* is considered as the marker species of winter monsoon season along the NEAS. Green *Noctiluca* which harbours green photosynthetic prasinophyte endosymbiont *Pedinomonas noctilucae* (Subr.) Sweeney was observed in extensive blooms along the open ocean waters of NEAS during winter monsoon season with extension of bloom events towards the early spring inter monsoon. Other than the *N. scintillans*, dinoflagellate community is weaker in the region when compared with the diatoms. In general armoured species (Subclass Peridiniphycidae) dominated the dinoflagellate community except *Noctiluca scintillans*. Certain Peridiniphycids were observed in higher cell densities along the coastal waters which include *Ornithocercus magnificus*, *Scrippsiella* sp. etc. Other than the coastal blooms, *Ceratium* spp., *Protoperidinium* spp., were observed ubiquitously along the coastal waters and *Gonyaulax polygramma* was observed in considerable cell densities along the offshore as well as coastal waters.

The green tide of *Noctiluca scintillans* were observed along the offshore areas of NEAS (cell densities varied from 1.4 to 2.4x 10^4 cells L^{-1}). The occurrence of bloom as well as intensity was maximum during Phase-2 (early March) of the winter monsoon study. Spatially, there were persistent blooms of *Noctiluca* along the offshore areas of 22ºN throughout the season in all the years. This can be attributed to the persevering convective mixing signatures in the area as indicated by low SST, high surface salinity and deep mixed layers.

Comparative analysis of temporal variation in phytoplankton abundance during winter monsoon and its transition to spring inter monsoon observed intensity of *Noctiluca scintillans* blooms during late winter monsoon period. This confirms the fact that optimum bloom period of *Noctiluca scintillans* occurs during March, probably mid March. In addition to this there observed a shifting in the peak bloom period of *Noctiluca scintillans* from early March in 2009 to mid March in 2011 and further towards late March in 2012 with slight extension towards the spring intermonsoon period (1st week of April). Hence the seasonal abundance of *Noctiluca scintillans* observed a delay in the waning phase of bloom and was yearly strengthening during the month of March. Apart from the phase wise as well as regional variation observed, there was an increasing trend in the intensity and expanse of *Noctiluca scintillans* blooms along the NEAS during winter monsoon. The abundance as well as citing areas of bloom incidence was found to increase with years.

The *Noctiluca scintillans* bloom patch was observed to coexist with certain diatoms in mucilaginous or mat like aggregations in certain events. The aggregating diatoms varied yearly and usually pennate diatoms were found in such aggregations. These coexisting diatoms include *Navicula directa* along with centric diatom *Rhizosolenia hebetata* which was observed in extensive mats throughout NEAS (2009), *Haslea* spp. (2011) and *Haslea* spp. and *Cylindrotheca closterium* (2012). The aggregations were not always found along with bloom but, when found associated, the dominant percentage of *Noctiluca scintillans* in the phytoplankton community was lesser, nearly 50%. When found without aggregations, *Noctiluca* cells occupied nearly 90-95% of the total microphytoplankton community.

The three phase (Phase-1, 2 and 3) analysis of the microphytoplankton community during winter monsoon season observed considerable variations contributing to the short term dynamics of community during winter monsoon season. Phase-1 (February) characterized by lower SST combined with increased SSS and deeper MLDs favoured a diverse and abundant centric diatom community. Chain forming centrales *Chaetoceros* spp., mainly *C. lorenzianus*, *Rhizosolenia* spp., *Guinardia* spp., *Thalassiosira* spp., etc were the dominant component during the phase. Even though these groups were present in the succeeding phases their percentage contribution was lesser.

During Phase-2 (Early March) the intensity of winter convention decreases and due to the detrainment process, the rapid stabilization of water column occurs and the occurrence of the bloom green *Noctiluca scintillans* was prominent during the phase. Lower SST (< 25ºC) and sufficient nutrients present due to earlier convective mixing provided conditions conducive for the bloom. Among the diatom community raphid pennate diatoms dominated the offshore waters especially along the offshore areas as well as in the bloom regions of *N. scintillans*. These diatoms were observed in monospecific mucilaginous aggregation. *Haslea* spp., *Navicula directa, Nitzschia* sp., *Cylindrotheca closterium* etc. were the major pennates present.

Comparatively higher SST and more characteristic of spring inter monsoon with shallow MLDs were observed during Phase-3 (late March) and can be considered as a transition phase from winter monsoon to spring inter monsoon. The intensity of *Noctiluca scintillans* blooms decreased and diatom community retreated towards centric forms with exception along certain offshore patches that still sustained raphid pennate diatom blooms. Hence the microphytoplankton community structure in the NEAS exhibited short term dynamics with respect to the composition as well as the order of dominance in the community.

Inter-annual variability of the phytoplankton community during winter monsoon season was assessed during the year 2009 and 2011. Environmental factors exhibited significant variations between the year 2009 and 2011 winter monsoon. The SST of open ocean waters of NEAS during winter monsoon of 2009 (av. 26ºC) was higher than that of 2011 (av.24.7 ºC). The SST variations were related with lower Dipole Mode Index (DMI) along Indian Ocean during 2011 than that of 2009. Moreover the depths of MLDs as well as nitrate concentrations were also high during 2011 with low temperature and high salinity surface waters. In accordance with these variations the surface chlorophyll *a* also exhibited quantifiable difference. The surface values which was on an average 0.96 mg m^{-3} during 2009 increased to 1.57 mg m^{-3} during 2011. The phytoplankton community during the winter monsoon of these two years showed significant variation (R=0.6; Sig: 0.1%) and the year with lower DMI was observed to be more productive with respect to the microphytoplankton assemblage.

The microphytoplankton community was comparatively heterogeneous during 2009 with increased diversity as well as species richness. The dominance in the phytoplankton community was less pronounced in 2009 whereas during 2011 dominance increased along with increase in numerical abundance. The presence of Cyanophycean constituents represented primarily by *Trichodesmium erythraeum* during 2009 significantly towards the southern latitudes (18ºN) and their total absence during 2011 was major composition variation within the microphytoplankton community. Moreover the total cell density of phytoplankton especially diatoms increased during 2011. Within the diatom community, centric diatoms were the major subclass present represented by *Rhizosolenia hebetata*, whereas the raphid pennate diatoms increased during 2011 as mucilaginous aggregations.

The bloom intensity as well as expanse of *Noctiluca scintillans* was more pronounced in 2011 winter monsoon than that of 2009. Wide spread bloom patches were observed during 2011 covering the offshore areas of both 22ºN and 21ºN whereas the occurrence of bloom patches were confined to one or two sites during latter. In brief the microphytoplankton abundance as well as composition experienced significant inter annual variability during the year 2009 and 2011 winter monsoon. The variability in physico chemical characteristics can be attributed towards these variations confirming the coupling of hydrographic parameters with biological responses.

The overall attempt of the study was aimed to understand the microphytoplankton community composition and its variations along a highly complex and dynamic marine ecosystem, the northern Arabian Sea. The data generated provides a first of its kind knowledge on the major primary producers of the region. There appears significant response among the microphytoplankton community structure towards the variations in the hydrographic conditions during the winter monsoon period. Interannually, variations were observed within the microphytoplankton community associated with the variability in temperature patterns and the intensity of convective mixing. Changing bloom pattern and dominating species among the phytoplankton community open new frontiers and vistas towards more intense study on the biological responses towards physical processes. The production of large amount of organic matter as a result of intense blooming of *Noctiluca* as well as diatoms aggregations augment the particulate organic substances in these ecosystem. This definitely influences the carbon dynamics of the northern Arabian Sea. Detailed investigations based on time series as well as trophodynamic studies are necessary to elucidate the carbon flux and associated impacts of winter-spring blooms in NEAS. Arabian sea is considered as one among the hotspot for carbon dynamics and the pioneering records on the major primary producers fuels carbon based export production studies and provides a platform for future research. Moreover upcoming researches based on satellite based remote sensing on productivity patterns utilizes these insitu observations and taxonomic data sets of phytoplankton for validation of bloom specific algorithm development and its implementation. Furthermore Saurashtra coast is considered as a major fishing zone of Indian EEZ. The studies on the phytoplankton in these regions provide valuable raw data for fishery prediction models and identifying fishing zones. With the baseline data obtained further trophodynamic studies can be initiated in the complex productive North Eastern Arabian Seas (NEAS) ecosystem that is still remaining unexplored.

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List of microphytoplankton identified along NEAS during winter monsoon 2009

Phase	Phase - 1					Phase - 2					Phase - 3				
Station	**22º C**	**22ºO**	**21ºC**	**21ºO**	**18ºN**	**22ºC**	**22ºO**	**21ºC**	**21ºO**	**18ºN**	**22ºC**	**22ºO**	**21ºC**	**21ºO**	**18ºN**
Class - Bacillariophyceae															
Amphora sp	+	-	-	-	-	-	-	+	-	-	+	-	-	-	-
Asterionellopsis glacialis	+	+	+	-	-	-	-	+	-	-	-	-	-	-	-
Bacteriastrum hyalinum	-	-	+	+	-	-	-	-	-	-	+	-	-	-	-
Chaetoceros concavicornis	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros curvisetus	-	-	-	+	-	-	-	-	-	-	-	-	+ +	-	-
Chaetoceros decipiens	-	-	+	+	-	-	+	-	-	+	-	-	+	-	-
Chaetoceros diversus	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Chaetoceros laciniosus	-	-	-	+	-	+	+	+	-	-	-	-	-	-	-
Chaetoceros lorenzianus	+	+ +	+ +	+ + +	-	+	+	+	-	+	+	-	+	-	-
Climacodium frauenfeldianum	-	-	+	-	-	-	-	-	-	+	+	-	-	-	-
Climacosphenia moniligera	-	-	-	-	-	-	-	-	-	+	-	-	+	-	-
Coscinodiscus radiatus	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Cyclotella stylorum	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Dactyliosolen fragilissimus	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
Ditylum brightwellii	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Eucampia zodiacus	+	+	+	+	-	-	-	-	-	+	+	-	+	-	-
Fragilaria oceanica	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Grammatophora sp.	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
Guinardia striata	+ +	+	+ +	+	-	-	-	-	-	-	-	-	-	-	-
Guinardia flaccida	+	+	-	+	-	-	-	+ +	-	-	+	-	+ +	-	-
Haslea trompii	+	-	+	+	-	-	-	-	-	-	-	-	-	-	-
Haslea wawrikae	-	-	-	-	-	+	+	-	+	-	+	+	+	+	-
Hemiaulus hauckii	+	-	-	+	-	-	-	-	-	-	+	-	+	-	-

Hemiaulus sinensis	+	-	-	+	-	-	-	-	-	-	+	-	-	-	-
Hemidiscus cuneiformis	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Leptocylindrus sp	+	+	+	+	-	-	-	+	-	-	+	-	+	-	-
Navicula directa	+	++	+	+	-	-	+	+	+ + +	+	+	+	-	+	+
Nitzschia closterium	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
Nitzschia longissima	+	+ + +	+	+	+	-	-	+	-	+	-	+	+	-	-
Nitzschia pungens	-	-	-	-	-	-	-	-	-	+	-	+	+	-	-
Odontella aurita	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Odontella mobiliensis	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-
Odontella sinensis	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Planktoniella sol	+	-	+	+	-	-	-	-	-	-	+	-	-	-	-
Pleurosigma elongatum	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Pleurosigma normanii	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-
Pseudo-nitzschia sp	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Pseudo-nitzschia lineola	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
P. pseudodelicatissima	-	-	+	+	-	-	-	-	-	-	+	-	+	-	-
Pseudo-nitzschia seriata	+	+ +	+ +	+ +	-	-	+	+	+ +	-	-	-	+ + +	-	-
Pseudosolenia calcar avis	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Rhizosolenia alata	-	-	-	-	-	-	-	-	-	-	+	+	+	-	+
Rhizosolenia formosa	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhizosolenia hebetata	+ +	+ + +	+ +	+ + +	+	+	+ + +	+	+ + +	+	+	+ + +	+ +	+ + +	+ +
Rhizosolenia hyalina	-	-	+	+	-	+	+	-	+	+	+	+	+	+	+
Rhizosolenia imbricata	-	+	-	+	-	-	-	-	-	-	-	-	-	-	-
Rhizosolenia stolterfothii	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Skeletonema costatum	+	-	+	+	-	-	-	-	-	-	-	-	-	-	-
Surirella sp.	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Thalassionema frauenfeldii	-	-	-	-	-	-	-	-	-	-	+	-	+	-	-

Thalassionema nitzschioides	-	+	+	+	-	-	-	+	-	-	-	-	+	-	-
Thalassiosira sp.	+	+	+	+	+	-	+	-	+ +	+	-	-	+	-	-
Thalassiosira subtilis	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Thalassiothrix longissima	+	+	+	+	-	+	+	+	-	+	+ +	+	+ + +	-	-
Class - Dinophyceae															
Amphisolenia bidentata	-	-	-	-	-	+	-	-	-	+	-	-	+	-	-
Ceratium carriense	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Ceratium declinatum	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
Ceratium extensum	-	-	-	+	-	-	+	-	-	+	-	-	-	-	-
Ceratium furca	+	+	+	+	-	-	-	+	+	-	+	-	-	+	+
Ceratium fusus	+	-	+	-	-	-	-	-	-	-	-	-	-	-	+
Ceratium inflatum	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
Ceratium kofoidii	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ceratium macroceros	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-
Ceratium trichoceros	-	-	-	+	-	-	+	-	+	-	-	-	-	-	-
Ceratium tripos	-	-	-	+	-	-	-	-	-	+	-	-	-	-	-
Corythodinium tessellatum	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
Dinophysis hastata	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Dinophysis miles	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Dissodinium pseudolunula	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
Gonyaulax polygramma	-	+	-	+	+	-	+	+	+	+	+	+	-	+	+
Gonyaulax sp.	-	-	-	-	-	-	-	-	-	-	-	+	-	+	-
Gymnodinium sp	-	-	+	+	-	-	-	-	-	-	-	-	-	+	+
Noctiluca scintillans	-	+	-	+	-	+	+	-	+ + +	-	-	+ + +	-	-	-
Ornithocercus magnificus	-	-	-	+	+	-	-	-	-	-	-	-	-	-	-
Oxytoxum sp.	-	-	-	-	-	-	+	-	+	+	-	-	-	-	-

Phalacroma rotundatum	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Podolampas sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-
Podolampas bipes	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prorocentrum concavum	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
Prorocentrum lima	-	-	-	-	+	+	-	-	-	-	-	-	-	-	-
Prorocentrum micans	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
Protoperidinium sp	+	-	+	+	+	-	-	-	-	-	-	-	-	-	-
Protoperidinium oceanicum	+	+	-	+	+	-	+	-	+	+	+	-	+	-	-
Pyrodinium sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Pyrophacus steinii	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
Scrippsiella trochoidea	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Class - Cyanophyceae															
Trichodesmium erythraeum	+	-	-	-	+	-	-	+	-	+ +	-	-	+ +	-	-
Calothrix sp	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Others															
Dictyocha fibula	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Dictyocha octanaria	+	-	+	-	-	-	-	+	-	-	-	-	+	-	-

+ stands for 1 to 500 cells/ L
++ stands for 500 to 2000 cells/L
+++ stands for > 2000 cells/L
- stands for absent

List of microphytoplankton identified along NEAS during winter monsoon 2011

	Phase - 1					Phase - 2					Phase - 3				
	22º C	22ºO	21ºC	21ºO	18ºN	22ºC	22ºO	21ºC	21ºO	18ºN	22ºC	22ºO	21ºC	21ºO	18ºN
Class - Bacillariophyceae															
Amphora sp	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
Asteromphalus sp	-	-	+	+	-	+	-	-	-	-	-	-	-	-	-
Bacteriastrum hyalinum	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Bacteriastrum furcatum	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Cerataulina pelagica	-	-	+ + +	-	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros affinis	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros compressus	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
Chaetoceros sp.	-	+ +	+ + +	+	-	+	+	+	-	+	+ + +	-	+ + +	+	-
Chaetoceros socialis	-	-	-	-	-	-	-	-	-	-	-	-	+ + +	-	-
Chaetoceros coarctatus	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Chaetoceros curvisetus	-	+	-	-	-	-	-	+	-	-	-	-	+	-	-
Chaetoceros decipiens	-	+	-	-	-	-	-	+	-	-	-	-	-	-	-
Chaetoceros didymus	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Chaetoceros laciniosus	-	+	-	-	-	-	-	+	-	-	-	-	+	+	-
Chaetoceros lorenzianus	-	+ +	-	-	-	-	-	+	-	-	-	-	+ + +	-	-
Chaetoceros messanensis	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros tortissimus	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-
Coscinodiscus sp.	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Cylindrotheca closterium	-	-	+ + +	-	-	-	-	-	-	-	-	-	-	-	-
Dactyliosolen fragilissimus	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
Detonula sp	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Detonula pumila	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-

Ditylum brightwellii	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Eucampia sp.	-	+	-	+	+	-	-	+	-	-	+	-	-	-	-
Guinardia sp.	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Guinardia striata	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
Guinardia flaccida	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
Haslea sp.	+	+	-	-	-	-	+ +	+	-	-	+	+ + +	-	+	-
Haslea gigantea	-	-	-	-	-	-	-	-	-	-	-	+ + +	-	-	-
Haslea gretharum	-	-	-	-	-	-	-	-	-	-	-	+ + +	-	-	-
Hemiaulus sp	-	-	+ +	-	-	-	-	-	-	-	-	-	+	-	-
Hemidiscus sp	-	+	-	-	-	+	-	-	-	-	-	-	-	-	-
Lauderia sp	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
Lioloma sp	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-
Leptocylindrus sp	-	+	+	-	-	+	-	+	-	-	-	-	-	-	-
Leptocylindrus danicus	-	-	-	-	-	-	-	-	-	-	-	-	+ +	+	-
Leptocylindrus mediterraneus	-	-	-	-	-	-	-	-	-	-	-	-	-	+ + +	-
Meuniera sp	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Meuniera membranacea	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Navicula sp	-	+	+	+	-	-	-	-	+	+	-	+	-	-	-
Nitzschia sp	-	-	+	-	-	+	-	+	-	-	-	-	-	-	-
Nitzschia longissima	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
Nitzschia pungens	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Odontella sp	-	-	+ +	-	-	-	-	-	-	-	+	-	-	-	-
Planktoniella sol	-	+	+	-	-	-	-	+	+	-	-	-	-	+ +	-
Pleurosigma sp	-	+	+	-	-	-	-	-	-	-	+	-	-	-	-
Pseudo-nitzschia sp	-	+	+ + +	+	-	-	-	-	-	-	-	+	-	-	-
Pseudo-nitzschia pungens	-	-	-	-	-	-	-	-	-	-	-	-	+ + +	-	-
Pseudo-nitzschia seriata	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-

Pseudoguinardia sp.	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
Rhizosolenia sp.	-	+	+	+	-	+	-	-	-	+	+	-	-	-	+
Rhizosolenia alata	+	+	-	-	-	-	-	+	-	-	-	+	-	+	-
Rhizosolenia bergonii	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-
Rhizosolenia calcar-avis	-	+	-	-	-	-	-	+	-	-	-	+	-	-	-
Rhizosolenia hebetata	-	+	-	-	-	-	+	+	+	-	-	+	+	+	-
Rhizosolenia robusta	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhizosolenia stolterfothii	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-
Rhizosolenia setigera	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Schroederella delicatula	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Skeletonema costatum	-	-	-	-	-	-	-	-	-	-	-	-	+ +	-	-
Surirella sp.	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Tabellaria fenestrata	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Thalassionema sp.	-	-	+	-	-	+	-	+	-	-	-	-	-	-	-
Thalassionema frauenfeldii	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Thalassionema nitzschioides	-	-	+ + +	+	-	+	+	-	-	-	+ + +	-	+	-	-
Thalassiosira sp.	-	+	+ + +	+	+	-	+	-	-	+	+	+	+	-	-
Thalassiothrix sp.	-	+	+	-	-	-	-	-	+	-	-	-	-	-	-
Class - Dinophyceae															
Alexandrium sp	-	-	+	+	-	-	-	-	+	-	-	+	-	-	-
Amphisolenia bidentata	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
Ceratium sp	-	-	-	-	-	+	+	-	-	+	-	-	-	-	-
Ceratium furca	+	+	+	+	-	+	+	+	+	-	-	+	-	-	-
Ceratium fusus	+	-	+	+	-	-	-	-	+	-	-	+	-	-	-
Ceratium lineatum	-	-	+	-	-	-	-	+	-	-	-	-	-	+	-
Ceratium longipes	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-

Ceratium macroceros	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Ceratium pentagonum	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Ceratium symmetricum	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-
Ceratium tripos	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
Ceratocorys horrida	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-
Corythodinium tessellatum	-	-	-	-	-	-	+	+	+	-	-	+	-	-	-
Dinophysis acuminata	-	-	-	-	-	+	-	+	-	-	-	-	-	-	-
Dinophysis miles	+	-	+	-	-	+	-	-	-	-	-	-	-	-	-
Gonyaulax polygramma	-	-	-	-	-	-	+	+	+	-	-	+	+	+	-
Gonyaulax sp.	+	-	-	+	-	+	-	-	-	-	+	+	-	-	-
Noctiluca scintillans	-	+	-	-	-	-	+ + +	-	+ + +	-	-	+ + +	-	-	-
Ornithocercus sp	-	+	+	+	-	+	+	-	-	-	-	-	-	-	-
Ornithocercus steinii	-	-	-	-	-	-	-	+	-	-	+	-	-	+	-
Ornithocercus magnificus	+ + +	-	-	-	-	-	-	-	-	-	-	-	-	+	-
Oxytoxum sp.	-	-	-	+	-	-	+	-	-	-	-	+	-	-	-
Podolampas bipes	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Podolampas palmipes	-	-	-	+	-	+	-	+	-	-	-	+	-	-	-
Prorocentrum sp	-	-	-	+	-	-	-	-	-	-	-	-	-	+	-
Prorocentrum balticum	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
Protoperidinium sp	+	+	+	-	-	+	-	+	+	+	+	+	+	+	+
Protoperidinium claudicans	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
Protoperidinium depressum	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Protoperidinium leonis	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
Protoperidinium oceanicum	-	+	-	-	-	-	-	+	-	-	-	-	-	-	-
Protoperidinium pellucidum	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Pyrophacus sp	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
Pyrophacus steinii	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-

Pyrocystis fusiformis	**-**	**-**	**-**	**-**	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Class - Cyanophyceae															
Trichodesmium erythraeum	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**+**	**+**	**-**	**-**	**-**
Others															
Dictyocha sp	**+**	**+**	**-**	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Dictyocha fibula	**-**	**-**	**+**	**-**	**-**	**-**	**+**	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

+ stands for 1 to 500 cells/ L

++ stands for 500 to 2000 cells/L

+++ stands for > 2000 cells/L

- stands for absent

List of microphytoplankton identified along NEAS during Winter monsoon and Early spring inter monsoon 2012

	Phase - 1						**Phase - 2**					
	22°C	**22°O**	**21°C**	**21°O**	**20°O**	**18°N**	**22°C**	**22°O**	**21°C**	**21°O**	**20°O**	**18°N**
Class - Bacillariophyceae												
Asterionellopsis glacialis	-	-	-	-	-	-	-	-	+	-	-	-
Asteromphalus sp	+	-	+	-	-	-	+	-	-	-	-	-
Bacteriastrum hyalinum	-	-	+	-	-	+	-	-	-	-	-	-
Bacteriastrum delicatulum	-	-	-	-	-	-	-	-	-	++	-	-
Chaetoceros sp.	+	-	++	-	+	+	-	-	+++	+	-	-
Chaetoceros curvisetus	-	-	-	-	-	+	-	-	-	-	-	-
Chaetoceros laciniosus	-	-	-	-	-	+	-	-	-	-	-	-
Chaetoceros lorenzianus	-	-	+	-	-	-	-	-	-	-	-	-
Chaetoceros peruvianus	-	-	+	-	-	-	-	-	-	-	-	-
Climacodium frauenfeldianum	-	-	-	-	-	-	-	-	-	+	-	-
Coscinodiscus sp.	+	-	+	-	-	+	-	-	+	-	-	-
Cylindrotheca closterium	-	-	-	+++	-	-	-	-	+	-	-	-
Ditylum brightwellii	+	-	-	-	-	-	+	-	+	-	-	-
Guinardia striata	-	-	-	-	-	-	-	-	+	-	-	-
Guinardia flaccida	-	-	-	-	-	+	-	-	++	-	-	-
Gyrosigma sp.	-	+	-	-	-	-	-	-	-	-	-	-
Haslea sp.	-	-	-	+++	+++	-	-	-	-	-	-	-
Hemiaulus sinensis	-	-	-	-	-	+	-	-	-	-	-	-
Hemidiscus sp	-	-	-	-	-	-	-	-	-	-	-	-
Hemidiscus cuneiformis	-	-	-	-	-	-	-	-	-	-	-	-
Lauderia sp	-	-	+	-	-	-	-	-	++	-	-	-
Leptocylindrus danicus	-	-	-	+	-	+	-	-	+	-	-	-
Meuniera sp	-	-	-	-	-	-	+	-	+	-	-	-

Navicula sp	-	-	+	-	-	-	-	-	++	-	-	-
Nitzschia sp	-	-	-	++	-	-	-	-	-	-	-	-
Nitzschia longissima	-	-	-	-	-	-	-	-	+	-	-	-
Odontella sp	-	-	-	-	-	-	-	-	+	-	-	-
Odontella aurita	-	-	+	-	-	-	-	-	-	-	-	-
Planktoniella blanda	-	-	-	-	-	-	-	-	+	-	-	-
Pleurosigma sp	+	-	-	-	-	-	-	-	+	-	-	-
Pseudo-nitzschia sp	+	+	++	-	-	+	-	-	+++	-	-	-
Rhizosolenia alata	-	-	-	-	+	+	-	-	++	+	-	-
Rhizosolenia hebetata	-	-	-	-	+	-	-	-	-	-	-	-
Rhizosolenia imbricata	-	-	+	-	-	-	-	-	-	-	-	-
Rhizosolenia stolterfothii	-	-	-	-	-	+	-	-	-	+	-	-
Rhizosolenia styliformis	-	-	-	-	-	-	-	-	-	+	-	-
Skeletonema costatum	+	-	+	-	-	-	-	-	++	-	-	-
Streptotheca tamesis	-	-	-	-	-	++	-	-	-	-	-	-
Stephanopyxis palmeriana	-	-	-	-	-	+	-	-	-	-	-	-
Tabellaria fenestrata	-	-	+	-	-	-	-	-	++	-	-	-
Thalassionema sp.	-	-	+	-	-	-	-	-	-	-	-	-
Thalassionema frauenfeldii	-	-	-	+	-	-	-	-	-	-	-	-
Thalassionema nitzschioides	+	-	+	-	-	+	-	-	+++	-	-	-
Thalassiosira sp.	+	+	-	-	-	-	-	-	+	+	-	-
Thalassiothrix sp.	-	-	-	-	-	-	-	-	++	-	-	-
Thalassiothrix delicatula	-	-	-	-	-	-	-	-	-	-	++	-
Thalassiothrix longissima	+	+	-	+	+	+	-	-	-	-	-	-
Class - Dinophyceae												
Ceratium furca	-	+	-	-	+	-	-	-	+	-	+	+

Ceratium fusus	-	-	-	-	-	-	+	+	+	-	-	-
Ceratium kofoidii	+	-	-	-	-	-	-	-	-	-	-	-
Ceratium lineatum	+	-	+	-	-	-	+	-	+	-	-	+
Ceratium massiliense	-	-	-	-	-	+	-	-	-	-	-	-
Ceratium symmetricum	-	-	-	-	+	-	-	-	-	-	-	-
Ceratium teres	-	-	-	-	-	-	-	-	+	-	-	-
Ceratium tripos	-	-	-	-	-	-	+	-	-	-	-	-
Ceratium vulture	-	-	-	-	-	+	-	-	-	-	+	+
Corythodinium tessellatum	-	-	-	-	-	-	-	+	-	-	-	-
Gonyaulax sp.	+	-	-	-	+	-	-	-	-	-	-	-
Gymnodinium sp	-	-	-	-	-	-	-	+	-	-	-	-
Gyrodinium sp	-	-	+	-	-	-	-	-	-	-	-	-
Noctiluca scintillans	-	+	-	+ + +	+ + +	-	-	-	-	-	+ + +	-
Oxytoxum sp.	-	-	-	-	-	-	-	+	-	+	-	-
Podolampas palmipes	-	-	-	-	-	-	-	+	+	-	-	-
Prorocentrum gracile	-	-	+	-	-	-	-	-	-	-	-	-
Prorocentrum micans	+	-	-	-	-	-	+	-	-	-	-	-
Protoperidinium sp	+	-	+	+	-	-	+	-	+ +	-	+	-
Protoperidinium claudicans	-	-	-	-	-	-	+	-	-	-	-	-
Pyrophacus sp	-	-	-	-	-	-	+	-	-	-	-	-
Scrippsiella trochoidea	+ + +	-	-	-	-	-	-	-	-	-	-	-
Zygabikodinium lenticulatum	-	-	-	-	-	-	-	-	+	-	-	-
Cyst like cells	-	-	-	-	+	-	-	-	-	-	-	-
Class - Cyanophyceae												
Cyanobacterial filaments	-	-	-	-	-	-	-	+	-	-	-	-

Others												
Dictyocha sp	-	-	+	-	-	-	-	-	-	-	-	-

+ stands for 1 to 500 cells/ L

++ stands for 500 to 2000 cells/L

+++ stands for > 2000 cells/L

- stands for absent

Annexure- 1

1. Diatom morphology and classification

The nature of diatoms were a matter of study until the mid of 19th century. Later Kutzing's monograph of 1844 authentically treated all diatoms as plants. Between 1844 and 1900 diatom classification progressed with the development of microscope. The hallmark of diatom is the cell wall that is heavily or thinly impregnated with silica ($SiO_2.nH_2O$). The wall is multipartite always consisting of two large intricately sculptured units called valve or theca together with several thinner lining structures termed as girdle elements or cincture. The valves lie at each end of the cell and the girdle elements surround the region in between. The cell wall component often loosely called the frustules fit together very closely (Figure 1).

The vegetative reproduction of diatoms by binary fission leads to the formation of two new individuals where in each one receives a theca or valve. The theca received from parent is called Epitheca. The other valve or theca that is synthesized by daughter cell is called Hypotheca. The hypotheca always overlaps the edges of the epitheca, like the two halves of the petri dish.

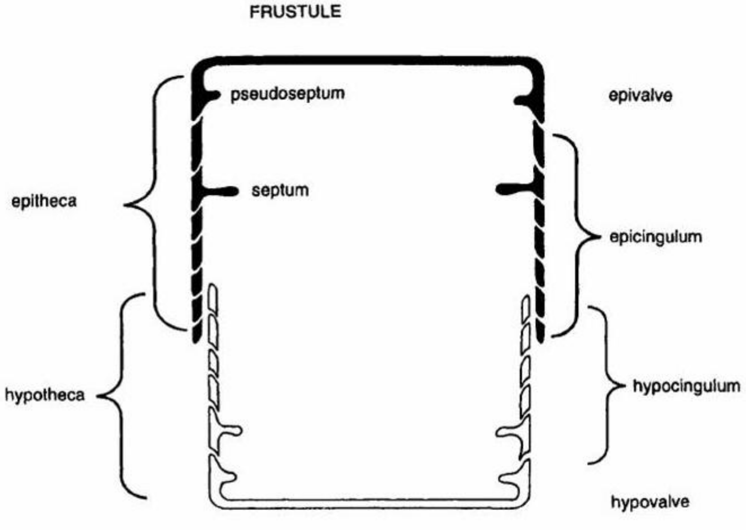

Figure 1. Structure of a diatom frustule (Tomas, 1997)

The classification system developed by Simonsen (1979) and further modified by Round *et al* (1990) is currently the most commonly accepted. Centric diatoms which are commonly found as marine plankton can be divided into three sub-orders based primarily on the shape of the cells, the polarity and the arrangement of the processes (Figure 2). These are the Coscinodiscineae, with a marginal ring of processes and no polarity to the symmetry, the Rhizosoleniineae with no marginal ring of processes and unipolar symmetry, and the Biddulphiineae with no marginal ring of processes and bipolar symmetry. A group of pennate diatoms possess a longitudinal slit called raphe along the long axis through which the living diatom secretes mucilage and may attach to a substrate or move by gliding over the substrate.

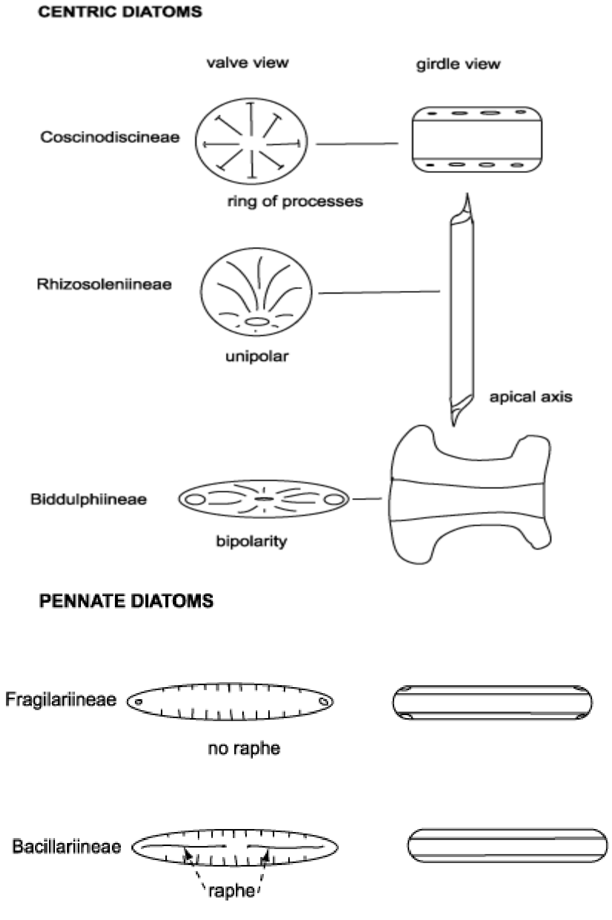

Figure 2. Schematic representation of centric and pennate diatoms (Hasle and Syvertsen, 1997)

2. Dinoflagellate morphology and classification

At the ultra structural level dinoflagellates have a common cell covering structure. The covering can be smooth and relatively unarmoured or naked (athecate) or it can constitute a cell wall of polysaccharide plates with spines and flangs or armoured (thecate). The cell is divided into lower half and upper half separated by the cingulum (transverse furrow). The upper half generally called episome is named as epicone in athecate cells and epitheca in thecate forms. Similarly the lower part, hyposome is called hypocone in athecate and hypotheca in thecate forms (Figure 3). A longitudinal groove, the sulcus may occur on the ventral side of the organism and divides the cell into right and left halves. The characteristic forward spiral movement of the organism is attained by the use of two flagella; a longitudinal flagellum that extends posteriorly and a transverse flagellum that encircles the cell.

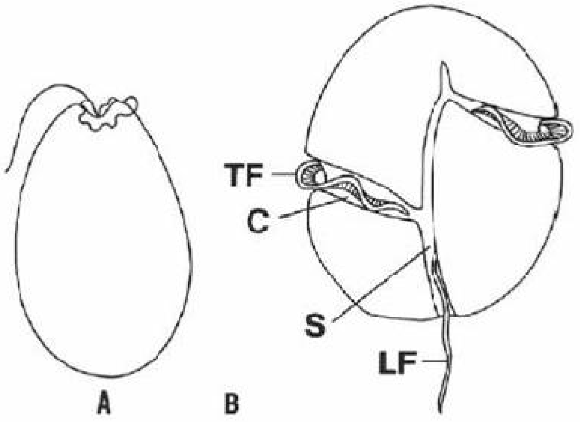

Figure 3. Diagram of a typical dinoflagellate (A) Lateral view of a desmokont cell illustrating anterior location of two dissimilar flagella (B). Ventral view of dinokont cell type illustrating location of two dissimilar flagella, both housed in furrows. Longitudinal flagellum (LF), transverse flagellum (TF), Cingulum (C), sulcus (S) (Steidinger and Tangen, 1997).

List of acronyms and abbreviations

AS	Arabian Sea
Chl *a*	Chlorophyll *a*
CMLRE	Centre for Marine Living Resources and Ecology
CTD	Conductivity Temperature Depth
DMI	Dipole Mode Index
EAS	Eastern Arabian Sea
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
ESIM	Early Spring Inter Monsoon
FORV	Fisheries Oceanographic Research Vessel
HAB	Harmful Algal Bloom
IIOE	International Indian Ocean Expedition
IOD	India Ocean Dipole
JGOFS	Joint Global Ocean Flux Studies
LWM	Late Winter Monsoon
MLD	Mixed Layer Depth
NEAS	North Eastern Arabian Sea
PFZ	Potential Fishing Zone
PRIMER	Plymouth Routines in Multivariate Ecological Research
SEAS	South Eastern Arabian Sea
SIM	Spring Inter Monsoon
SST	Sea Surface Temperature
SSS	Sea Surface Salinity
TCD	Total Cell Density
WCM	Winter Convective Mixing
WM	Winter Monsoon

Publications

1. Sabu. P, C.R. Asha Devi, **Lathika Cicily Thomas**, V.N. Sanjeevan and G.V.M. Gupta (2015). Characteristics of a cyclonic eddy and its influence on Mesozooplankton community in the Northern Bay of Bengal during early Winter Monsoon. *Environmental Monitoring and Assessment,* (2015) 187:330, DOI 10.1007/s10661-015-4571-x. IF= 1.679.

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9. Padmakumar K.B, **Lathika Cicily Thomas**, Anu Shaji, T.P. Maneesh and V.N. Sanjeevan (2012). Symbiosis between the stramenopile protist *Solenicola setigera* and the diatom *Leptocylindrus mediterraneus* in the North Eastern Arabian Sea. *Symbiosis*, Vol. 56, 97-101. DOI 10.1007/s13199-012-0160-8. IF= 0.941.

10. Padmakumar K.B, **Lathika Cicily Thomas**, Salini T. C, Elizabeth John, N. R. Menon and V. N. Sanjeevan (2011). Monospecific bloom of noxious raphidophyte *Chattonella marina* in coastal waters of South West coast of India. *International Journal of Biosciences*, Vol.1, No.1: 57-69.

11. Padmakumar K.B, B.R. Smitha, **Lathika Cicily Thomas**, C. L. Fanimol, G. SreeRenjimma, N. R. Menon and V. N. Sanjeevan (2010). Blooms of *Trichodesmium erythraeum* in the South Eastern Arabian Sea during the onset of 2009 Summer Monsoon. *Ocean Science Journal*, Vol. 45 (3): 151-157.