Nutrient Dynamics in the EEZ of the West Coast of India with Special Reference to the Oxygen Minimum Zone and Denitrification

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by

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Certificate

We hereby certify that the thesis entitled "**Nutrient dynamics in the EEZ of the west coast of India with special reference to the oxygen minimum zone and denitrification**" submitted by Vijay John Gerson, Research Scholar (Reg. No. 2311), National Institute of Oceanography, Regional Centre, Kochi, is an authentic record of research carried out by him under our supervision, in partial fulfilment of the requirement for the Ph.D degree of Cochin University of Science and Technology in the faculty of Marine Sciences and that no part thereof has previously formed the basis for the award of any degree, diploma or associateship in any university.

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Preface

Investigations on nutrients have occupied an important role in oceanographic research, since the interactions among nutrients and planktonic organisms is the key to elucidate the biological productivity of oceans. The Arabian Sea is one of the most productive areas of the world oceans and is strongly affected by seasonal changes associated with monsoon. Investigation on distribution of nutrients and oxygen levels in the Arabian Sea could help shed light on how monsoons influence its productivity. Monsoons create peculiar currents in the Arabian Sea. In summer, the winds are from southwest to northeast and pushes water away from the Somali coast, the eastern edge of the Arabian Peninsula and the southwest coast of India. The water that leaves these areas, is replaced by water that wells up from depths and is very high in nutrients. In winter, the winds reverse to northeast, when the northeast Arabian Sea experiences winter cooling and convective mixing. The cold winds cause surface densification and sinking, which brings up some nutrients. These processes make the Arabian Sea unique with respect to air-sea exchange of biogenic gases.

The high biological production in the surface layers of the Arabian Sea and subsequent sinking of organic matter leads to increased oxygen demand in the intermediate waters. This leads to the development of intense oxygen deficient conditions within intermediate layers. Oxidation of large amounts of organic matter leads to acute oxygen deficiency and abstraction of oxygen from nitrate (denitrification). Denitrification in the Arabian Sea is estimated to be 1/3 rd of the global ocean denitrification, which has been shown to vary between seasons.

Thus, the Arabian Sea is an ocean basin where biological response is coupled with physical forcing which changes seasonally. Reversal of surface circulation initiated by monsoons, induces variable nutrient distribution and high light intensities drive phytoplankton growth process. In the present study, a comparison is made on hydrography and nutrient distribution in the eastern Arabian Sea with associated variability during different stages of monsoons. The study has been undertaken as a part of Marine Research-Living Resources (MR - LR) assessment of the Exclusive

Economic Zone (EEZ) of India, as source or sink of many chemical constituents sustaining potential fertility of this region. The present study focus on the extent of Oxygen Minimum Zone (OMZ) in the intermediate waters that leads to denitrification and its vertical and horizontal shifts in the region on an annual scale. The primary data on nutrients and dissolved oxygen are used to generate secondary inputs like Apparent Oxygen Utilization (AOU) and nitrate deficit (δN) and their relationship with potential temperature, salinity, density etc. The influence of physical processes like upwelling and winter convection on the property distribution is also discussed.

The thesis is presented in six chapters. The **first chapter** highlights the importance of nutrients and dissolved oxygen, their occurrence, fate and transport in the ocean. Review of previous literature, general hydrography, scope and objectives of the study are also included in this chapter.

The **second chapter** is named 'Materials and Methods', which cover the sampling methods and analytical procedures for the estimation of dissolved oxygen, nitrate, nitrite, phosphate, silicate, primary productivity and chlorophyll a. Methods used for the computation of AOU and δN are also included.

The **third chapter** deals with the hydrographic features in the study region. The evolutions of wind driven coastal upwelling along the southwest coast of India during the southwest monsoon and convective mixing due to winter cooling during northeast monsoon along the northwest coast are discussed. Distribution of nutrients and the biological responses during these two seasons is examined. In the **fourth chapter** physicochemical characteristics and associated biological response of the eastern Arabian Sea during the transition seasons; inter monsoon fall and inter monsoon spring are studied. The **sixth chapter** comprises the summary and conclusion of the thesis. The list of references cited is given at the end of thesis.

To sum up, present investigation proposes to relate the physical forcing in the Arabian Sea that leads to the anomalies in productivity in the EEZ of the west coast of India.

Acronyms and Abbreviations

AOU	Apparent Oxygen Utilization
AS	Arabian Sea
ASHSW	Arabian Sea High Salinity Water mass
BOB	Bay of Bengal
CTD	Conductivity - Temperature - Depth
CMLRE	Centre for Marine Living Resources and Ecology
DOD	Department of Ocean Development
DO	Dissolved Oxygen
E	East
e.g.	exempli gratia (Latin word meaning 'for the sake of example')
EEZ	Exclusive Economic Zone of India
EICC	East India Coastal Current
et. al.	et alii (Latin word meaning 'and others')
etc	et cetera (Latin word meaning 'and other similar things; and so on')
FORV	Fishery & Oceanographic Research Vessel
GF/F	Glass Fibre/Filter
GLOBEC	Global Ocean Ecosystem Dynamics
IIOE	International Indian Ocean Expedition
JGOFS	Joint Global Ocean Flux Studies
MLD	Mixed Layer Depth
MR-LR	Marine Research - Living Resources
N	North
NE	Northeast
NIO	National Institute of Oceanography
NO_2 - N	Nitrite - Nitrogen
NO_3 - N	Nitrate - Nitrogen
δN	Nitrate Deficit
PGW	Persian Gulf Watermass
PO_4 - P	Phosphate - Phosphorus
PP	Primary Productivity
psu	Practical Salinity Unit
SiO_4 - Si	Silicate - Silicon
SMC	Southwest Monsoon Current
SST	Sea Surface Temperature
SW	Southwest
UNESCO	United Nations Education, Scientific and Cultural Organisation
viz	videlicet (Latin word meaning 'namely')
WICC	West India Coastal Current
WOCE	World Ocean Circulation Experiment

Contents

Chapter 1

Introduction

The Northern Indian Ocean is different from other oceanic areas in terms of its geographical setting and circulation pattern. The Indian sub continent splits the region into two zones of vastly different hydrographical regimes. The north eastern Indian Ocean (Bay of Bengal) is an area of positive water balance, where a large excess of precipitation and river run off over evaporation leads to very low surface salinities. The northwestern Indian Ocean (Arabian Sea) on the other hand, is a region of negative water balance where evaporation far exceeds precipitation and run off. The Arabian Sea receives very little river run off as most of the rivers discharge into the Bay of Bengal (Subramanian, 1993). Consequently the surface and sub surface layers in the Arabian Sea (AS) are much more saline and relatively weakly stratified as compared to those in the Bay of Bengal (BOB). Both the regions are strongly affected by seasonal changes associated with the monsoons.

Over the years, studies on the relationship between the marine organisms and their environment have gained considerable importance. Phytoplankton forms the basis of the marine food chain, and considerable attention was given to understand the processes, which determine primary production in the marine environment. As do the terrestrial primary producers, the marine phytoplankton requires inorganic nutrients for their growth and sustenance. The importance of nutrients was recognized as early as the beginning of the last century, and the classical investigations of Cooper (1933) and Harvey (1957) have given a general understanding of the seasonal changes in nutrients and their influence on primary production. In temperate waters seasonal changes in light and temperature and the associated physicochemical factors trigger phytoplankton growth, which ultimately strips the seawater of nutrients and lead to oligotrophic condition.

1.1. Significance of the Arabian Sea

In the tropical seas, though this basic reasoning holds, the shorter cycles of utilization / regeneration offer a different scenario. Arabian Sea is an extremely complicated dynamic system where atmospheric forcings and the biological processes that occur within them impart temporal and spatial variability to the region and signals of important processes are quite strong (Morrison, 1998). In addition to strong monsoonal character of the atmospheric and oceanic circulation, the Arabian Sea has several other significant features. These include high surface nutrient concentration during the southwest and northeast monsoons and a well-developed oxygen minimum zone (OMZ) with largest volume of oxygen depleted waters ($O_2 < 10\mu M$). The rate of primary production is also high (Smith *et. al.,* 1998). The Arabian Sea is unique among low latitude seas because it is landlocked at around 25°N and is under marked continental influence. The physical and chemical properties of the Arabian Sea are mainly governed by the prevailing monsoon winds that reverse its direction seasonally and the annual cooling cycles. The coastal waters of the west coast of India are influenced by temporal and spatial changes and become seasonally stratified with an appreciable temperature and salinity gradient. This feature distinguishes this region from the other comparatively oligotrophic open ocean waters that are affected to a lesser degree by the trade winds and monsoonal changes. Physical forcings and the associated chemical changes in the shallow layers thus play a key role in the biological response.

The width of the continental shelf along the southwest coast of India is narrower on the southern side and gets broadened towards the north (Gopinathan and Qasim, 1974). A time dependent wind stress prevails along the west coast of India due to monsoons (Pankajakshan and Rama Raju, 1987); so does the phenomenon of upwelling (Sastry and de Souza, 1972, Ramamritham and Rao, 1973, Basil, 1983). The southwestern coastal waters are the most productive region along the coastal belt of India where intense upwelling occurs during the south west monsoon season. The high productivity in the shallow areas is accounted by the upwelling process and increased regeneration rate of nutrients due to relatively high temperatures accelerating all bacterial processes. The maximum production was reported nearer to the coasts, within 50m depths and gradually decreased towards the open ocean (Nair *et. al.,* 1973). Signatures of upwelling begin to appear along the southwest coast of India well before the onset of summer monsoon (April-May), which is characterized by low sea surface temperatures and high nutrients in the upper layers. Wind induced upwelling gets initiated slowly, propagates northwards and intensifies between June and August.

The Arabian Sea has long been recognized as a region of intense oxygen deficiency. The mid depth oxygen deficiency in the Arabian Sea is perhaps the most severely observed any where in the oceans, as the concentration between ~ 150 -1000m are less than 10μM within a large part of central and north eastern Arabian Sea (Naqvi and Jayakumar, 2000). This zone is also characterized by intense denitrification. Two maxima in nitrite concentration (NO_2^-) are observed in the northern Arabian Sea; a 'primary nitrite' maximum with low nitrite in the surface layers, with relatively high dissolved oxygen and a 'secondary nitrite' maximum due to the biochemical oxidation of organic matter by nitrate with very low oxygen concentrations at intermediate depths. Occurrence of this secondary nitrite maximum is believed to be an evidence of nitrate reduction in the region. Nitrate deficits have been calculated using the relationship of the Apparent Oxygen Utilization (AOU) with nitrate (NO_3^-) and nitrite (NO_2^-). The results indicate a steady northward increase in the nitrate deficit and in the depth range where denitrification occurs. These nitrate deficits extend down to considerable depth, whereas the nitrite is restricted to the first few hundred meters. The maximum of nitrate deficit (δN) occurs considerably below the secondary nitrite maximum (Naqvi *et. al.,* 1982)

1. 2. Nutrients

Nutrients, often referred to as biostimulants of fertilizers, comprise the dissolved inorganic forms of nitrogen, phosphorus and silicon that are utilized by photosynthetic organisms in the formation of organic matter. Nitrogen and phosphorus are described as 'biolimiting' elements, because the concentrations of these elements limit biological growth. Of late, there have been increasing instances of eutrophication of estuaries and coastal areas consequent to excessive release of nitrogen and phosphorus from agricultural run off and sewage effluents ('O Neill, 1985). The import and ecological significance of this problem have stimulated much new research on chemistry / geochemistry of nutrients in coastal aquatic systems.

Since nitrogen is the principal nutrient involved in biological activity, its distribution is controlled by biological process, resulting in the removal of this element from water in the upper euphotic layer. In some cases nitrogen compounds are completely removed from surface waters and this result in "limiting" further growth of the primary producers. Below the euphotic layer, decomposition of sinking dead cells and faecal pellets of living organisms occur, thereby liberating nitrogen compounds initially as ammonia, which is quickly oxidized to nitrate with nitrite as an intermediate product. The decomposition of organic matter is accompanied by the utilization of dissolved oxygen present in water.

1. 2. 1. Nitrogen Compounds

Nitrogen supplied through rivers mainly exists as dissolved nitrate, which is derived from rock weathering and drainage from agricultural lands. Nitrate is considered as the stable oxidation level of nitrogen in sea water (Grasshoff, 1983). This is an essential nutrient for the growth of many photosynthetic autotrophs and has been identified as the growth-limiting nutrient. Other important forms of nitrogen for biological process are nitrite, ammonia, and dissolved / particulate nitrogenous organic compounds. Nitrite is generally present in low concentrations, as an intermediate product of microbial reduction of nitrate, oxidation of ammonia and as an excretory product of plankton. In the marine environment, inorganic nitrogen compounds exist in their oxidizing or reducing forms. The equilibrium, generally, is:

$$NO_3^- \leftrightarrow NO_2^- \leftrightarrow NH_4^+$$

1. 2. 2. Phosphorus compounds

Ecological interest in phosphorus stems from its major role in biological metabolism in spite of its relatively subdued presence in the hydrosphere. Weathering of earth's crust and surface water transport deliver phosphorus to coastal waters through rivers. During the period of active growth of phytoplankton, the concentration of phosphorus along with other nutrient salts is greatly reduced in the aquatic environment. Upon death and decomposition of organisms and plants, phosphorous is returned to the water. Similarly during weathering, phosphorous is liberated as alkali phosphates. Together with water movements, these processes of removal and return give rise to seasonal variations in the distribution of this element (Koroleff, 1983).

1. 2. 3. Silicon

The source of silica to the marine environment is mainly through river discharges (Livingstone, 1963), with sub-marine hydrothermal emanations and glacial weathering (Warnke, 1970; Wolery and Sleep, 1976) also contributing substantially. Silicon is biologically essential for the growth and the formation of their skeletal materials in marine organisms like diatoms, radiolarians and sponges. The uptake of silicon by growing phytoplankton results in the depletion of silicon in the seawater. However, when these organisms die and disintegrate, silicon is rapidly liberated back into the marine environment. Silicon can also be used as an important tool in oceanography since the wide variability of its concentration could be used for tracing the mobility of water masses in the seas (Richards, 1958).

1. 3. Dissolved Oxygen

An appreciation of the characteristics of dissolved gases in seawater is important in understanding physical, chemical and biological process taking place in such natural waters. Super-saturation of oxygen in waters, which are equilibrated with respect to non-reactive gases, may suggest photosynthetic production of oxygen, while under-saturation indicates its biological utilization for respiration and chemical utilization for oxidation process. Weiss (1970) has formulated the temperature and salinity dependence on the solubilities of nitrogen, oxygen and argon gases. The dissolved oxygen distribution in sea is essentially regulated by physical processes, such as exchange across sea surface, circulation and horizontal diffusion and biochemical processes, such as, photosynthetic productivity and oxidation of organic matter. In coastal waters, circulation, upwelling, productivity and coastal input of organic matter chiefly regulate the dissolved oxygen distribution.

1. 4. Upwelling

Upwelling is a process of vertical motion in the sea whereby cool nutrient rich waters from comparatively deeper areas of the continental shelf are slowly brought towards the surface layers. Usually the water comes from depths not exceeding a few hundred meters. Upwelling may occur anywhere, but it is a particularly conspicuous phenomenon along the western coasts of the continents where prevailing winds carry the surface water away from the coast, resulting in an eastern boundary current (Smith and Bottero, 1977). Upwelling is characterized by an upsurge of water from the deeper depths to the surface while its original properties remain virtually unchanged. Because upwelling brings in subsurface water into the surface layer, it induces horizontal anomalies in the distribution of physicochemical properties that normally have significant vertical gradients. Such anomalies are often useful indicators of upwelling. Upwelling is characterized by a rapid decrease in temperature and dissolved oxygen concomitant with an increase in salinity and surface nutrients, particularly nitrates (Rochford, 1975). The clearest indication of upwelling is the upward slop of isotherms and associated isopycnals towards the coast (Bearman, 1989). The influence of upwelled water appears at a distance of more than 100 km from the shore line along the different upwelling areas (Defant, 1963 and Smed, 1982). Coastal upwelling is important for the productivity of the surface waters. Upwelling has important effects on the ecology of the marine life: a map depicting the areas of upwelling in the world ocean also rather adequately, serves as a map of the areas of high organic productivity.

The Arabian Sea, one of the major upwelling zones in the world, experiences upwelling from June to October (Banse, 1959; Naqvi *et. al.,* 2000). However unlike the other two better known upwelling centers located in the Arabian Sea off Somalia and Oman, upwelling along the Indian coast is not entirely forced by local winds; instead a remote forcing from Bay of Bengal involving a coastally trapped Kelvin wave appears to be an equally, if not more, important causative mechanism (Shankar, 2000).

1. 5. Convective mixing

The west coast of India is environmentally more sensitive than the east coast primarily because it is bordering one of the most sensitive habitats in the world, the Arabian Sea. The environmental property of northern Arabian Sea is unique which manifests in rich biological production through out the year through different processes and thus, explain the Arabian Sea 'paradox' (Madhupratap *et. al.,* 1996). The Northern Indian Ocean is a dynamic region influenced by the seasonally reversing monsoonal wind pattern (Banse, 1987 Bauer *et. al.,* 1991). Atmospheric forcing like enhanced evaporation under the influence of dry continental air from the north carried by the prevailing northeasterly trades and reduction in solar insulation imparts biochemical changes in the upper layer of the northern Arabian Sea. Subsequent cooling and convective mixing injects nutrients into the surface layers from the thermocline region, which in turn triggers primary production (Prasanna Kumar and Prasad, 1996).

1. 6. Oxygen Minimum Zone and Denitrification

The high rate of production of organic matter in the surface layers of northern Indian Ocean leads to an increase in oxygen utilization at intermediate depth. Probably the oxygen minimum zone observed at the intermediate depths of the Arabian Sea may be because of this oxidation of organic matter. The comparatively higher photosynthetic activity in the Arabian Sea than that of the average of all other oceans often lead to a greater concentration of the dead cells and detritus at the thermal discontinuity layer, which consume oxygen during decomposition (Sen Gupta *et. al.,* 1976). A certain amount of balance is maintained at the surface levels where the consumption of dissolved oxygen more or less equals the replenishment through the process of dissolution and photosynthetic activity (Naqvi *et. al.,* 1982). The supply of oxygen to the waters below the euphotic zone gets restricted by the existence of strong density gradient and poor horizontal advection due to semi-enclosed nature of northern Arabian Sea and results in severe depletion of oxygen below the thermocline and at intermediate depths (Naqvi and Qasim, 1983). Transport of southern waters is a significant source to supply oxygen to the Arabian Sea at intermediate levels, because of their much greater volume transport. Northward flow of southern

Indian Ocean waters at a depth range of 500 - 1000m was observed at equator (Quadfasel and Schott, 1982; Sharma, 1976).

Many of the marine organisms make use of nitrogen only in the combined forms, such as nitrate (NO_3^-) and ammonium (NH_4^+). The bulk of the oceanic water column is well oxygenated, making NO_3^- the predominant species of combined nitrogen in the sea (Naqvi *et. al.,* 1998). Many processes control the combined nitrogen inventory in the ocean. Inputs of nitrogen to the oceans occur mainly through river run off, atmospheric deposition and nitrogen fixation, while its loss is principally through conversion of combined nitrogen into N_2 (Codispoti and Christensen, 1985). This process is known as denitrification and is a major process controlling the oceanic inventory of nitrogen (Codispoti *et. al.,* 2001) Arabian Sea is a significant source of N_2O, and a major sink for fixed nitrogen mainly due to enhanced rates of denitrification that occur in the suboxic portions of the water column (Bange *et. al.,* 2005). Denitrification takes place when the oxygen concentrations are close to zero and bacteria utilize NO_3^- instead of O_2 as an oxidant for decomposing organic matter (Richards, 1965). In the water column, however, the oceanic currents supply enough O_2 at all depths to prevent the development of anoxia in most oceanic areas. However, there are three regions where some unusual oceanographic processes cause the oxygen demand to exceed its supply resulting in total oxygen depletion at the intermediate depths (Deuser, 1975). Two of these sites are located in the eastern tropical north and south Pacific, while the third is found in the northern Arabian Sea. Although these regions account for ~ 2% of the total oceanic area, they are extremely important from the biogeochemical and climatic point of view. This is because a high and temporally variable rate of dentrification in these regions has the potential to greatly alter the oceanic combined nitrogen inventory (Naqvi *et. al.,* 1998). The reduction of nitrate to free nitrogen by dentrifying bacteria is believed to occur through the following pathway (Payne, 1973):

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Nitrite (NO_2^-), the first intermediate of this reduction sequence, accumulates in the intermediate oxygen minimum zones (Richards, 1965). The secondary nitrite maximum in the Arabian Sea is located in the upper portion of the oxygen minimum zone, in contrast to the primary nitrite maximum commonly found at the base of the euphotic zone (Naqvi *et. al.,* 1998).

According to Gruber and Sarmiento (1997), on a global scale, the North Atlantic Ocean and the Mediterranean are major sources of fixed nitrogen, whereas the Indian Ocean and parts of the Pacific Ocean are sinks. The sink regions of the ocean are associated with the major regions of anoxia of the Arabian Sea and the northern and southern equatorial Pacific where denitrification is well known to occur.

1. 7. General Description of the study area

In an area surrounded by extreme climatic condition lies one of the earth's biologically rich bodies of water, the Arabian Sea, locked in the northwest corner of the Indian Ocean. The Arabian Sea is flanked by northeast Africa, the Arabian Peninsula and India. The landmasses, especially the Tibetan plateau to the north of India, influence weather conditions in formation of the powerful monsoon systems. Monsoons occur twice each year in this area, during summer and winter. During the summer monsoon warm air over the Arabian Sea moves north, producing heavy rains over some areas of Africa and India. A seasonal low-pressure area developing over central Asia during this period causes the wind system to blow persistently from the southwest. During the winter monsoon period, the cold dry winds blow from a high pressure source forming over the Tibetan plateau moving towards low pressure belt in the equatorial Indian Ocean.

The winds are very weak during the transition period, intermonsoon fall (October). In the southwest monsoon season, the winds are southerly to southeasterly in the region south of the equator and turn to southwesterly after crossing the equator due to Coriolis force. The winds during southwest monsoon are in general stronger and steadier than those during northeast monsoon. In the Arabian Sea, southwest monsoon prevails from June to September and October is the month of transition. The northeast monsoon prevails from November to February. March to May is another period of transition.

The study area, the Exclusive Economic Zone (EEZ) of the west coast of India, comprises a unique variety of biogeochemical provinces of euphotic, oligotrophic, upwelling and sub-oxic zones of interest.

1. 8. Exclusive Economic Zone

The Exclusive Economic Zone (EEZ) is one of the most revolutionary features of the convention on the Law of the Sea (Gunnar Kullenberg, 1999). The EEZ concept provides the jurisdiction over the resources in the zone to the coastal state. The EEZ adds a new province to the country and provides an added dimension to its development.

1. 9. General Hydrography

The Northern Indian Ocean is distinguished by the presence of seasonally reversing currents that may flow between Bay of Bengal and the Arabian Sea. These currents are located between the equator and approximately 10°N. Monsoonal coupling between atmosphere and ocean is vigorous and the seasonal shift in wind pattern causes complete semi- annual reversal of surface currents in the Arabian Sea. This gives rise to seasonal variation in surface water characteristics. The Summer Monsoon (June-September) Currents flows eastward (SWC) and the Winter Monsoon Current (WMC) flows westward during winter monsoon (November- February). According to Schott *et. al* (1990) inter monsoon transition occur during March-May (spring intermonsoon) and October (fall intermonsoon).

The westward WMC first forms south of Sri Lanka in November and is initially fed by the equator ward East India Coastal Current (EICC) .The WMC divides into two branches in the Arabian Sea. One branch continuing to flow westward, and other turning around the Lakshadweep high of southwest India to flow into the poleward West Indian Coastal Current (WICC). The SMC in the Arabian Sea is a continuation of the Somali current and the coastal current of Oman. It flows eastward and southward across the Arabian Sea and around the Lakshadweep low off southwest India.

The monsoonal winds are the key to physical forcing in the Arabian Sea. During winter the NE monsoon prevails (Carruthers *et. al,* 1959), whereas during summer (Wyrtki, 1973) the SW monsoon dominates. During summer the wind driven Ekman drift dominates over most of the Arabian Sea, overwhelming the geostropic flow at the surface, leading to a more complex vertical structure in the SMC. During winter geostrophy dominates since the NE winds in the Northern Arabian Sea are too weak to produce offshore Ekman transport (Madhupratap *et. al.,* 1996a).

Plant (1992) has shown that greater than 1000 $mgCm^{-2}\ d^{-1}$ productivity occurs at the southwest coast of India during summer monsoon. Recent studies of Madhu (2004) have shown that highest productivity occurs at south west coast of India (~ 1629 $mgCm^{-2}\ d^{-1}$) during summer and its intensity decreases towards north with rates as low as < 200 $mgCm^{-2}\ d^{-1}$. These authors have suggested that surface cooling, densification and reduced solar insulation lead to convective mixing which injects nutrients into the surface layers from the thermocline. Jyothi Babu *et. al* (2004) have reported an enhanced water column productivity (> 1000 $mgCm^{-2}\ d^{-1}$) in the northeast Arabian Sea.

Vertical temperature profile along the Kanyakumari transect (8°N) during summer monsoon, indicates the SST value of the coastal region was 2.6°C lower than the offshore region. And SST values recorded a steady decreasing trend from offshore region; which implies strong upwelling. Surface upwelling signals were weak at Kochi transect (10°N) as along shore component of the wind and associated forcing was not sufficient for it.

A temperature difference of ~3°C was noticed between northern and southern Arabian Sea during winter. Generally high Mixed Layer Depth (MLD) values (> 60m) were recorded during this season throughout the west coast by convective mixing with greater dimension in the northern transects. The surface salinity structure showed low values over southern transects (< 32psu) and values were higher over northern region (> 36.5psu). The lower salinity towards the south indicates the presence of Bay of Bengal waters, carried along southwest coast by pole ward moving undercurrent. The high saline surface water in the north indicates the presence of Arabian Sea high salinity water mass (ASHSWM).

1. 10. Scope and Objectives of the study.

Indian Ocean remained one of the least studied prior to the International Indian Ocean Expedition (IIOE, 1960-1965), a multi-institutional international venture ever attempted. The IIOE has unravelled myriads of problems associated with the unique geographic setting of the northern Indian Ocean. This has generated a renewed interest in the international community to study this area in greater detail. Several purpose-oriented projects such as Joint Global Ocean Flux study (JGOFS), World Ocean Circulation Experiment (WOCE) and Global Ocean Ecosystem Dynamics (GLOBEC) *etc* have been conducted in this region.

The Arabian Sea offers special interest due to its monsoon driven circulation and large seasonal scale variability. Many national and international studies have contributed significantly to the understanding of close coupling of the physical forcings and associated biogeochemical changes.

The present work aims at deciphering the processes that control the nutrient distribution along the EEZ of the west coast of India and to bring out its linkage with primary and secondary productivity. This work may assume utmost importance as very few studies have hitherto focused entirely on the EEZ of the west coast of India to address the biogeochemical responses brought about by monsoons. The present study examines the seasonal variations in physicochemical parameters and associated primary biological responses along the west coast of India, using the data collected from the EEZ of the west coast of India, under the Marine Research - Living Resources (MRLR) programme, of the National Institute of Oceanography, Regional Centre, Kochi and funded by Department of Ocean Development (DOD). This programme has been undertaken to collect oceanographic data and to bring out significant information on seasonal changes in the environmental features, under the naturally fluctuating environmental conditions of the EEZ of India.

This study targets to measure and understand the shelf ocean exchange in a typical coastal upwelling region of the southeast Arabian Sea and the influence of convective mixing along the northern part of the west coast of India. The study focuses more directly on coastal upwelling along the southwest coast of India, within the EEZ. The effects of coastal upwelling, eddy formation and the offshore advection are apparent in the present investigation. This has consequences to fisheries and climate, in energy transfer to the food chain and the increased sequestering of carbon in the ocean. This is being studied through a multidisciplinary approach aimed at the quantitative evaluation of the physical, chemical and biological process involved in the transfer of nutrients. An effort has been made in this regard for the identification of key dynamical processes governing the circulation, transport and cross shelf mixing of waters and their application to chemical and biological processes.

The study also focuses on the Oxygen Minimum Zone (OMZ) and dentrification observed along the EEZ of the west coast of India on a seasonal scale. A considerable amount of work on the OMZ of the Arabian Sea, carried out during the past two decades, has established its global significance. However, those studies largely focused along the central Arabian Sea, and to a lesser extent, along the shelf waters of the west coast of India. In the study, an attempt is also made to demarcate the geographical boundaries of the denitrification zone in the EEZ of India. The monsoons have been known to introduce strong seasonality in both the vertical particle fluxes (Nair *et. al.,* 1989) and the subsurface circulation (Swallow and Bruce, 1966; Swallow, 1984). The present work also focuses on the nature and magnitude of these variations, on a seasonal and inter annual scales.

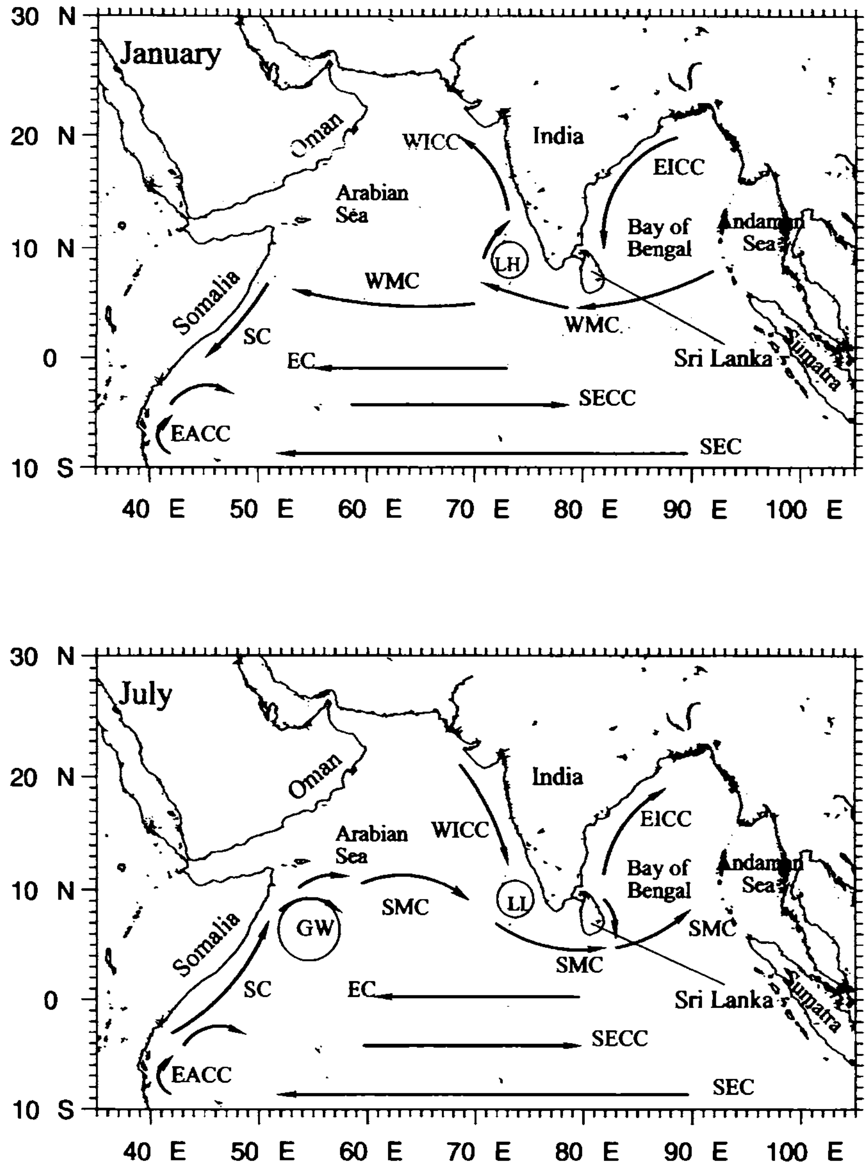

Figure 1.1. Schematic representation of the circulation during January and July in the Northern Indian Ocean (Schematics from Shankar, *et. al.*, 2002)

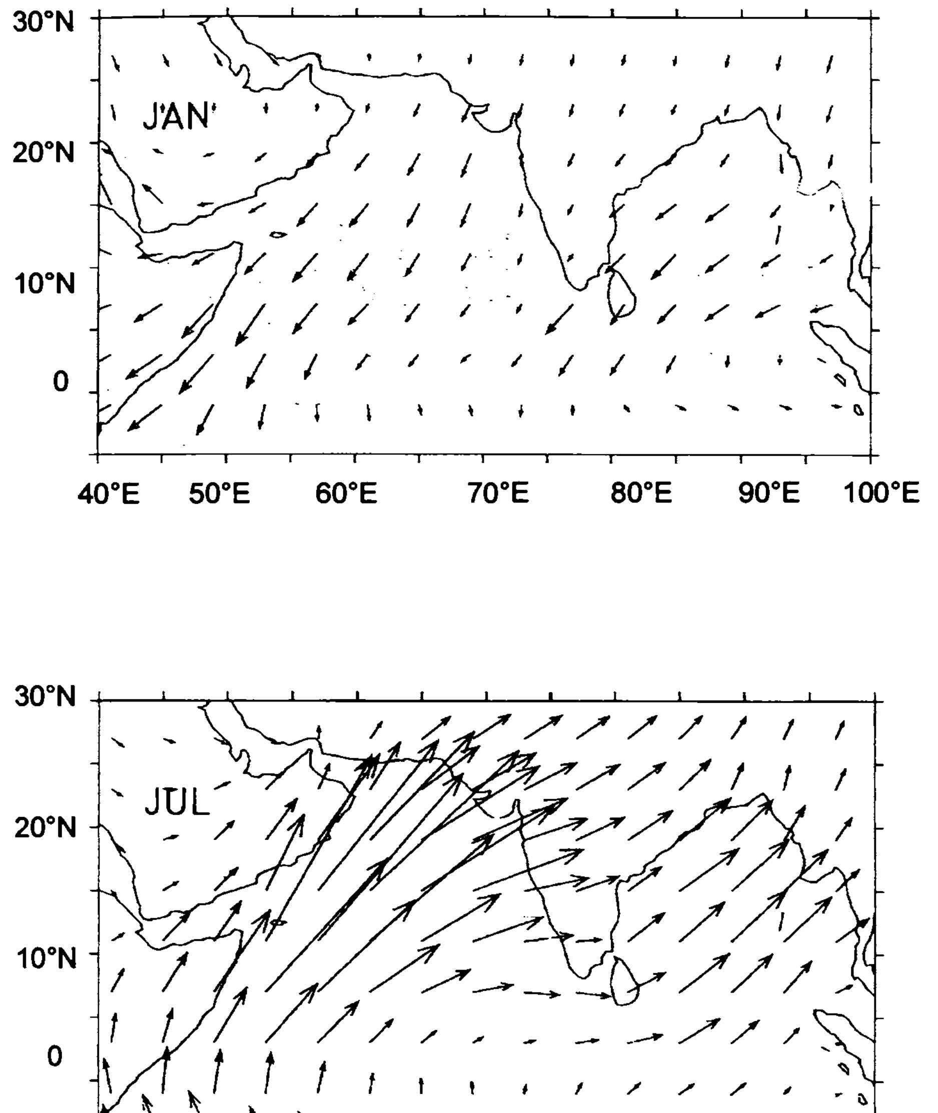

Figure 1.2. Schematic representation of surface wind stress during January and July in the Northern Indian Ocean (Schematics from Hellerman & Rosenstein, 1983).

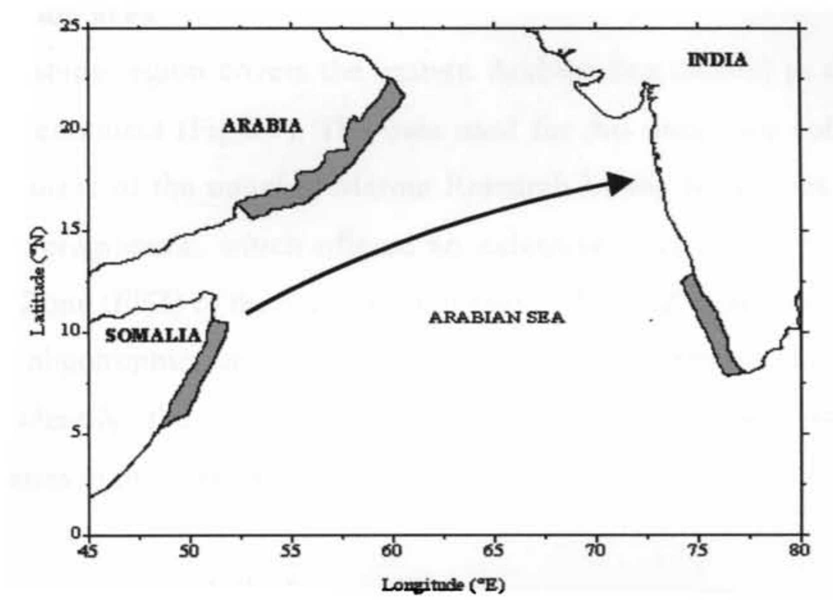

Fig. 1.3. Diagramatic representation of Findlater Jet and upwelling areas. Bold arrow shows the axis at the jet. Shaded areas along Somali, Arabia and the southwest coast of India show regions of coastal upwelling.

Chapter 2

Materials and Methods

2. 1. The study area

The study region covers the eastern Arabian Sea located to the west off Indian sub continent (Fig.2.1). The data used for this study are collected from different cruises of the ongoing Marine Research-Living Resources (MR - LR) assessment programme, which offered an extensive coverage of the Exclusive Economic Zone (EEZ) of the west coast of India. The EEZ comprises a variety of eutrophic, oligotrophic, upwelling and sub-oxic environments. Thus, there is a need to identify the impact of seasonal changes on the environmental characteristics in the study area.

2. 2. Sampling and Analytical procedures

Water samples were collected during the various cruises of FORV Sagar Sampada conducted under the ongoing MR-LR programme funded by Department of Ocean Development, Center for Marine Living Resources and ecology (CMLRE) Kochi. This is a multi disciplinary programme, since 1998, with extensive and systematic seasonal coverage in the EEZ of India. The seasons during which the data have been collected are divided into four; winter monsoon (northeast) (November-February), spring intermonsoon (March-May), summer monsoon (southwest) (June-September) and fall intermonsoon (October). The classifications of the seasons are in accordance with the JGOFS studies (Madhupratap *et. al.*, 2003).

The hydrographic surveys conducted along the west coast of India were at a one degree longitudinal interval and two degree latitudinal interval between 8°N & 22°N and 66°E & 77°E. The water samples were collected using Rosette Sampler fitted with Niskin water bottles of 1.7 litre capacity, from different standard depths (*viz.* 0, 10, 20, 30, 50, 75, 100, 150, 200, 300, 500, 750 and 1000m).

2. 3. Temperature and salinity

The Sea surface temperature was measured using a bucket thermometer. The temperature - salinity profiles were measured using the CTD probe (Sea Bird Electronics, Inc., USA, model: SBE - 911 plus). The salinity values from the CTD were corrected using the values obtained from the Autosal (Guildline, model 8400A) on board.

2. 4. Dissolved Oxygen

Dissolved oxygen was determined by the Winkler Titration method as modified by Carpenter (1965) and recommended by Strickland and Parsons (1972). The titration was based on standard iodimetry and was carried out using a digital Dosimat. The principle of the determination and the possible sources of systematic errors are discussed by Grasshoff (1983).

2. 5. Nutrients

Nutrients like nitrite, nitrate, silicate and phosphate were analyzed using Segmented Flow Auto Analyzer (SKALAR) on board Sagar Sampada.

2. 5. 1. Nitrite (NO_2 - N)

Nitrite is measured by the method of Bendschneider and Robinson (1952). In this method, nitrite in the water sample when treated with sulphanilamide in acid solution results in a diazo compound, which reacts with N - 1 - naphthyle ethylene diamine dihydrochloride to form an azo dye. The absorbance of this colour complex is measured at 543 nm.

2. 5. 2. Nitrate (NO_3 - N)

Nitrate was analyzed by the method of Morris and Riley (1963). Nitrate in water sample was quantitatively reduced to nitrite by passing through a reduction column filled with copper coated cadmium granules and measured as nitrite. During the reduction stage ammonium chloride buffer is added to the sample to maintain a stable pH (Grasshoff *et. al.*, 1983).

2. 5. 3. Silicate (SiO_4 - Si)

Determination of dissolved silicate in seawater is based on the formation of yellow silicomolybdic acid when an acid sample is treated with a molybdate solution (Grasshoff, 1983). This is further reduced by ascorbic acid in presence of oxalic acid (to prevent phosphate interference) to a blue coloured complex (molybdenum blue). This blue colour is measured at 810 nm.

2. 5. 4. Phosphate (PO_4 - P)

Phosphate is determined by the formation of phosphomolybdenum blue complex in an acid solution containing molybdic acid, ascorbic acid and trivalent antimony. This method was developed by Murphy and Riley (1962) recommended by Strickland and Parsons (1972). A variation of this method was described by Grasshoff *et. al.*, (1983). Absorbance is measured at 882nm.

2. 6. Methodology - Computations

2. 6. 1. Apparent Oxygen utilization (AOU)

Apparent oxygen utilization (AOU) is the amount of oxygen utilized during biological respiration. This is calculated by the difference between expected oxygen solubility (a function of temperature and salinity) and observed oxygen concentration i.e.,

$$AOU = O_{2\,(exp)} - O_{2\,(obs)}$$

The oxygen solubility was calculated according to Green and Carritt (1967):

2. 6. 2. Nitrate deficit

Nitrate deficit indicates the extent of nitrate lost as a result of denitrification occurring under suboxic conditions in water. It is obtained as the difference between the nitrate concentration expected in the absence of denitrification and the sum of observed nitrate and nitrite concentrations

$$\delta N = NO_3^-{}_{(exp)} - (NO_3^-{}_{(obs)} + NO_2^-)$$

Naqvi and Sen Gupta (1985) have proposed the use of 'NO' (nitrate tracer), a derived semiconservative property, to compute nitrate deficits. Broecker (1974) originally proposed NO as following

$$NO = O_2 + 9.1\ (NO_3^- - NO_2^-)$$

This approach is based on the assumption that NO behaves conservatively outside the denitrification zone and should therefore exhibit linear relationship with potential temperature, in accordance to the linear salinity-potential relation Naqvi *et. al* (1990) proposed the following set of revised equations to compute the nitrate deficit:

$NO = 415.934 - 8.9740\,\theta$ $\quad 10.39 \leq \theta \leq 27°C$

$NO = 490.254 - 16.126\,\theta$ $\quad \theta \leq 10.39°C$

$$\delta N = (NO - O_2)/9.1 - NO_3 - NO_2$$

Here θ refers to potential temperature (°C) and 9.1 is derived from Redfield ratios of oxygen and nitrate.

2.7. Primary production

Primary productivity measurements were made according to Indian JGOFS protocol (UNESCO, 1994) using ^{14}C - technique introduced by Steeman Nielsen

(1952). For measuring primary productivity, water samples were taken from seven standard predetermined depths such as 0, 10, 20, 50, 75, 100 & 120 metres in the euphotic zone using 1.8 litre Niskin samplers between the time period of 0400 and 0500 hr. Samples were immediately sieved through a 200µm mesh to remove large zooplankton. Water samples from each depth were transferred to five clean Nalgene PC bottles of 300ml capacity. To each PC bottle containing seawater sample 1ml of aqueous solution of 5µCi (185 kbq) of radioactive carbon (^{14}C was obtained from BRIT, Department of Atomic Energy, Mumbai) was added. From one bottle, 100ml sample was filtered on to 47mm GF/F (nominal pore size 0.7µm) filter paper for determining the initial adsorption of the ^{14}C by the particles in the bottle. From the remaining bottles from each depth, one was covered with aluminium foil and transferred to a black bag to determine the dark production. Thus, one dark and three light bottles were used from each depth for *in-situ* incubation for 12 hours from sunrise to sunset. The bottles were deployed *in-situ* to suspend them at the appropriate depths of their origin using polypropylene line attached to a buoy. Upon retrieval, samples in each light and dark bottles were filtered on to GF/F filter and the filters were transferred to scintillation vials. 0.5N HCl was added to each vial and capped overnight. All vials were held at room temperature until the radioactivity was counted. Before counting all vials were uncapped and left open overnight. Five ml of liquid scintillation cocktail (SISCO-Bombay) was added and the radioactivity counted in a liquid scintillation system (Wallac 1409, DSA- Perkin Elmer- USA). The count (disintegration per minute - DPM) rates were converted to daily production rates (mgC m^{-3} d^{-1}). The daily production rate of various depths was used to calculate the water column integrated production (mg C $m^{-2}d^{-1}$).

Calculation:

Primary production (mg C m^{-3} day^{-1}) = $1.05 \times S_{DPM} \times W / S_A \times T$

Sample Activity (SA) = $V^* T_{DPM} / A_{vol}$

Where,

DPM = Disintegration Per Minute

S_{DPM} = DPM s in filtered sample

T_{DPM} = Total ^{14}C DPMs (in 0.25ml)

A_{vol} = Volume taken to measure sample activity

V = Volume of filtered sample (litres)

T = Time (days)

1.05 = correction for the lower uptake of ^{14}C compared to ^{12}C

W = Dissolved Inorganic Carbon (DIC) concentration in sample (~25000 mg C m^{-3})

The depth wise production was integrated to obtain the production for the entire euphotic zone (Dyson *et. al.*, 1965).

Column production (mg C $m^{-2}day^{-1}$)

$$= [(d_1-d_0)(a_0+a_1)/2 + (d_2-d_1)(a_1+a_2)/2 + \ldots\ldots\ldots]$$

Where, d_0, d_1, d_2 are the depths sampled; a_0, a_1, a_2 are the respective production rates.

2. 8. Chlorophyll *a*

For the estimation of chlorophyll *a*, one litre of water from each standard depth was filtered under low vacuum through GF/F (nominal pore size 0.7μm) filters with the addition of one or two drops of Magnesium carbonate solution and was kept in a refrigerator (Strickland and Parsons, 1972). The acetone extract was made up to 10ml by adding 90% acetone and the absorbance was measured in a spectrophotometer (Perkin-Elmer UV/Vis) using 1cm cuvette against 90% acetone as blank at different wavelengths of 750, 664, 647, 630, 510 & 480 nm. The amount of the plant pigment in the original seawater sample was calculated using the equation (SCOR/UNESCO).

Chlorophyll a = 11.85 E 665 - 1.54 E 645 - 0.08 E 630

mg Chlorophyll/m^3 = C/V x 10

Where,

C = value obtained from the formula given above

V = volume of water filtered in litres

10 = volume of 90% acetone

Chlorophyll *a* calculated for each depth was integrated to obtain the column values using the relation given earlier in column primary production calculation.

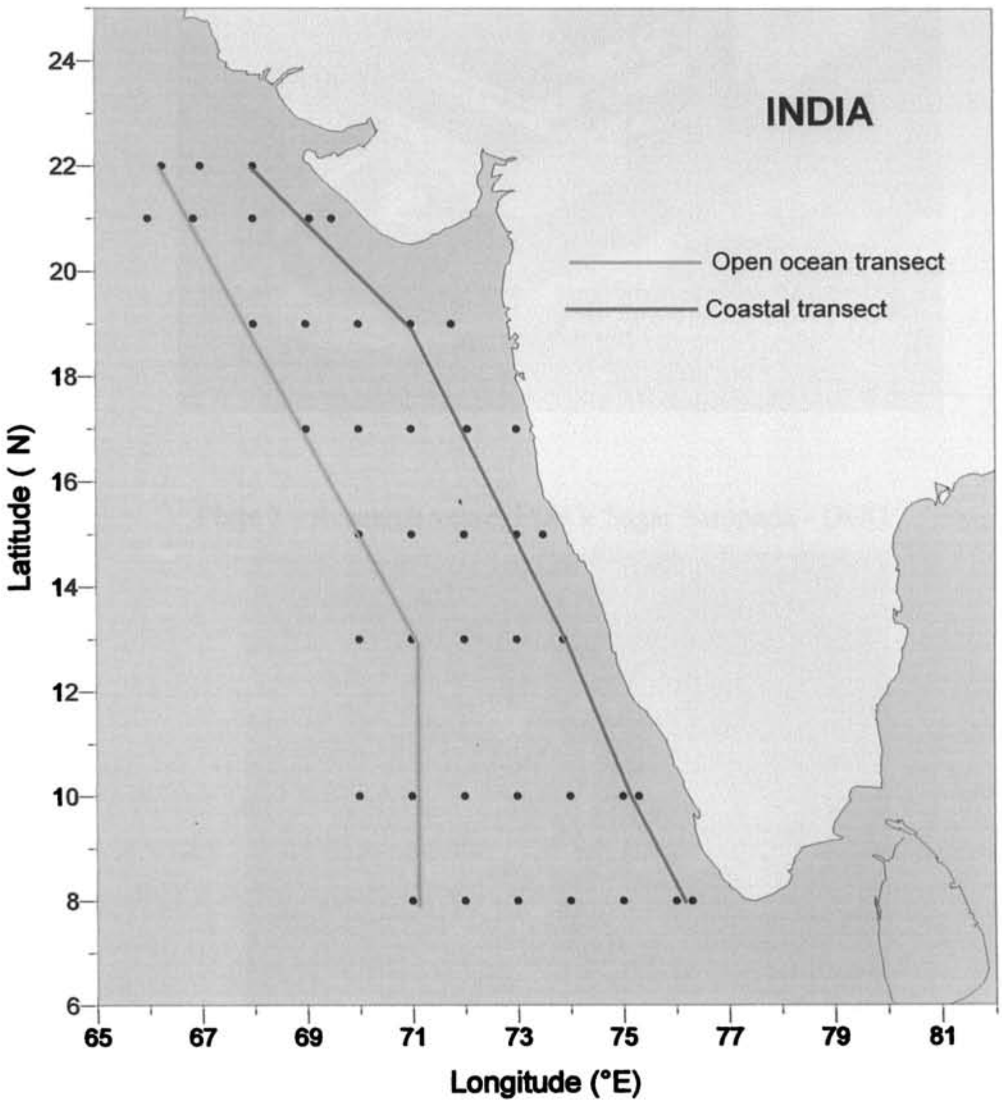

Figure 2.1 - Station locations

Plate 1 - Research vessel FORV Sagar Sampada - DOD

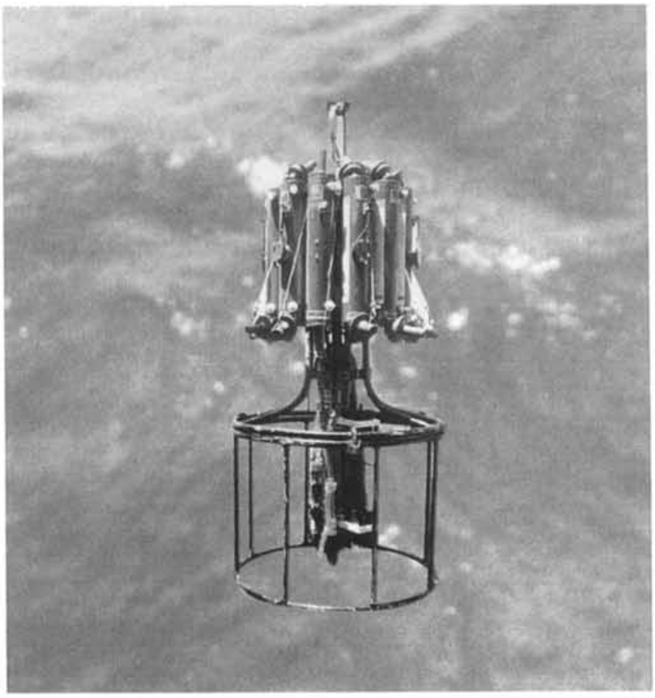

Plate 2 - Sea Bird CTD with Niskin sampler

Chapter 3

Hydrography of the Arabian Sea during summer and winter

3. 1. Introduction

The Indian Ocean is unique compared to other world oceans in having its northern end land locked by the Asian continent. Owing to the peculiar geographical locations both the Arabian Sea and Bay of Bengal is influenced by intense, annually reversing monsoon winds and seasonally varying sea surface circulation. The west coast of India experiences a time dependant wind stress due to monsoons (Pankajakshan and Rama Raju, 1987). The coastal zone of the southwest coast of India is one of the major zones of upwelling in the globe. Two distinct hydrographic features in the west coast of India, wind driven coastal upwelling, along the southwest coast during the southwest monsoon (June-September) and convective overturning of surface waters due to winter cooling during the northeast monsoon (December-March) along the northwest coast. The major transport of most of the nutrients into the surface layer is a consequence of upwelling and vertical mixing (Spencer, 1975; Vaccoro, 1965). These processes are diverse as follows: -

1. The upwelling is the process by which it replaces the surface waters with nutrient rich sub surface waters of deeper origin whereas in vertical mixing the deeper waters get mixed with the surface waters were the surface nutrient concentrations remains intermediate between the values in the initial surface layer and the deeper layers.

2. Wind induced upwelling depends critically on wind direction, on the other hand vertical mixing is enhanced by strong winds and is relatively insensitive to wind direction.

The factors mentioned above leads to large nutrient addition to the surface layers, caused by vertical mixing, which tend to be associated with winter conditions. During winter, oxygen deficient conditions develop within intermediate layers due to oxidation of organic matter, which leads to nitrate consumption through denitrification (discussed in detail in Chapter 5). Physically induced chemical changes in the shallow waters appear to play a key role in phytoplankton response, which enhances the productivity.

3. 2. Upwelling along the southwest coast of India

3. 2. 1. Surface Layers

The concentrations of inorganic nutrients are generally very low within the surface layers in the Arabian Sea. This is evidently true for nitrate, the most abundant form of inorganic combined nitrogen in the sea (Vaccaro, 1965), which often occurs below the detection limits in surface waters. Supply of new nitrogen through vertical eddy diffusion as well as by nitrogen regenerates such as ammonia and urea through zooplankton excretion, play an important role in regulating the primary production in the surface layers (Wafar *et. al.,* 1986). However during southwest monsoon, vertical advection of nutrient rich sub surface waters supply large quantities of new nitrogen to the euphotic zone, along the southwest coast of India due to upwelling

With the onset of summer monsoon, under the influence of south westerly winds along the west coast of India, the surface waters drift away from the coast and are replaced by colder (27°C), nutrient rich and often oxygen depleted waters from the subsurface, forced by an Ekman flux normal to the coast. Figure 3.1

shows the horizontal distribution of Sea Surface Temperature (SST) and Mixed Layer Depth (MLD) during summer monsoon. The SST distribution during the southwest monsoon cruise clearly shows colder water (~ 27°C) at the southwest coast and a warmer water region (> 28°C) along the offshore areas. Further offshore the water temperature increases beyond 29°C. The MLD near the coast was comparatively less (< 25m) whereas in the open ocean waters it increased to > 80m (Fig.3.1)

In figure 3.2, distribution of dissolved oxygen and nitrate at 20m during summer are depicted. In this layer a patch of low oxygen and high nitrate concentration was observed throughout the near shore region up to 15°N indicating the presence of upwelled waters near the coast. 12μM contour of nitrate was concentrated near the southern tip of the west coast of India (8-10°N). The oxygen value along the same region observed to be below 70μM, indicating that the magnitude of upwelling was intense along the southern coast. However along the offshore region oxygen value increased up to 200 μM with non-detectable levels of nitrate. To the north of 15°N along the west coast of India the influence of the southwest monsoon was least felt (Fig.3.2). The values of nutrients east of 75°E were high for the south west coast. This is particularly evident from the distribution of nitrate at 30m (Fig.3.2), were values > 10 μM were found, compared to values of 0 - 2 μM elsewhere on the south west coast.

A graphical representation of temperature, salinity, dissolved oxygen and nutrients at 20m depths along the upwelling transect (8°N) is shown in figure 3.3, for the southwest monsoon period. The temperature profile shows a restricted inshore zone of lower temperature (< 28°C) near the coast. This region also has enhanced nutrient concentrations (NO_3-N > 4μM, PO_4-P > 0.7μM and SiO_4-Si > 4μM) resulting from the Ekman coastal upwelling. The coastal zone shows an enhanced salinity of 35.3 psu.

Water temperature increased gradually with distance off shore over 29.8°C in the more stratified thermally stable oligotropic waters beyond west of 76°E. In contrast, the nutrient concentrations decreased towards off shore direction. At 71°E nitrate concentration was < 2μM and increased progressively until at 76°E to concentration of 12μM (Fig.3.2). Phosphate concentration in this water layer also becomes depleted with increasing distance off shore.

3. 2. 2 Vertical water column hydrography

The concentrations of nutrients as well as temperature, salinity and density in the water column indicated marked structural features during summer monsoon upwelling (Fig.3.4 & 3.5). The water column was sampled up to 1000m depths, but only data for the upper 200m are presented here because marked structural features are only seen in the upper water column, and most of these details would be lost if contours are shown for the entire 1000m. The temperature contour for the southwest monsoon cruise showed the upwelling of the deep cold waters from below the thermocline, and the depth of the thermocline increased with distance from shore to offshore. Closer to the coast, the region of Ekman coastal upwelling had lower water temperatures and greater enrichment of nutrients.

During the southwest monsoon, water from at least 60m deep along 71°E is found to surface near the coast in the 8°N transect (Fig.3.5). Along this transect the near shore surface waters (~ 50m) are characterised by comparatively low oxygen (DO < 180μM) and enhanced nutrient concentrations (NO_3-N, SiO_4-Si > 2μM). The 2μM contour of nitrate and silicate observed at 60m depth along 71°E could be traced at the surface waters along 76°E near the coast. In general contours of parameters such as temperature, DO, NO_3 - N, SiO_4 - Si at all depths up to 200m were found to be up sloping towards the coast. During this season the oxygenated surface waters (D.O < 180μM) were observed to be displaced to the west of 74°E along the southwest coast of India.

Along 10°N the magnitude of upwelling was relatively weak because the atmospheric forcings at this period was not sufficient to lift the deeper waters to the surface. But, the less oxygenated nutrient rich deeper waters could be traced up to the sub surface layers (10m) near the coast (Fig. 3.5).

Along the off shore stations, there was nutrient depletion in the photic zone (~ 50m), and were typically below detectable levels. The 2µM contour of nitrate and silicate along off shore stations were at ~ 50m deep, and shoaled up towards the surface between 75 - 77 °E. The upwelling was well described by nitrate and silicate concentration contour (Fig.3.5) and the 6µM contour of nitrate was at 75 m depth in the open ocean (71°E), and shallowed to 25m along the coast. Phosphate concentration also showed the effect of upwelling. Along 71°E, in the oligotrophic waters, phosphate values were ~ 1µM at 75m, but at 77°E these concentration were found in the upper 25m due to upwelling.

3. 2. 2.a. Temperature

During southwest monsoon season the Sea Surface Temperatures are relatively lower in the south western inshore waters, and increase towards northern latitudes registering relatively high values to the north of 13°N (Fig.3.1). A surface temperature minima (~ 27°C) was recorded along the southwestern coastal stations. In general there was an increasing trend with distance from the coast reaching a maximum of ~ 29°C in the open ocean surface waters. The cold surface layers in the southwestern coastal waters, develops as a result of upwelling of sub surface waters due to wind and associated Ekman transport.

Figure 3.4 shows the vertical distribution of temperature along 8°N and 10°N and 13°N transects which are perpendicular to the coast. It is evident from the figure that 20-28°C isotherm appear in the upper 100m layer and less than 16°C was observed below 150m depth. An upward tilt of isotherms was observed in the upper 150m layer particularly in the 8°N transect. Along this transect the

28°C contour moves upwards from a depth of 60m to the surface near the coast. Isotherms of 20 - 26°C move upwards from a depth of 150 - 75m to near surface waters closer to the coast.

In 10°N transect the 28°C isotherm lifting from a depth of 60m reaches only up to 20m near the coast (Fig.3.4). Up sloping of isotherms between 75 - 150m water columns is also weak towards the coast. From the distribution pattern it is evident that the upwelling mechanism is weaker in the 10°N transect, during the onset of the southwest monsoon.

Along the 13°N transect the surface waters remained warmer (~ 30°C). Unlike the other two transects (8°N & 10°N) the upsloping of isotherms towards the coast were absent along 13°N. The surface waters are found to be well stratified in this transect (Fig.3.4).

3. 2. 2.b. Salinity

The vertical sections of salinity along transect 8°N and 10°N and 13°N are shown in figure 3.4 during summer monsoon. In 8°N transect, salinity in the surface layers (~ 50m) varied between 34.7psu to 35.1psu in the offshore waters (west of 74°E). A tongue of high saline water (> 35.7psu) was present beyond the shelf at depths between 50 to 100m. The 35.1psu isohaline from a depth of 50m, surfaces near the coast. The surface waters near the coast is having comparatively high salinity than the open ocean waters along 8°N transect, with decreasing gradients towards off shore (~ 0.1 psu per 50 km).

Along 10°N transect the upsloping of isohalines are weak. 35.3 psu isohaline shows a slight upsloping from a depth of ~ 50m to ~ 20m. A well stratified salinity structure was observed below 50m, except a patch of high saline (~ 36 psu) waters between 60 - 75m depth indicating the presence of Arabian Sea High Salinity Water (ASHSW) in the transect.

The surface waters along the coastal side of the 13°N transect was comparatively less saline (~ 34.9psu) than the open ocean surface waters (> 35.8psu). An intrusion of high saline waters (> 36.0psu) from the open ocean was evident in this transect between 25 - 100m depth.

3. 2. 2.c. Density

Typical formation of the development of a density field along 8°N, 10°N and 13°N is illustrated in figure 3.4. Comparatively low denser waters (< 22.0 Kgm^{-3}) were observed in the open ocean region, whereas relatively denser (> 22.0 Kgm^{-3}) waters concentrate towards near shore waters. The 22.5 Kgm^{-3} isopycnal inclines upwards over the shelf and surfaced at the near shore region along 8°N transect. During the upwelling event 22 Kgm^{-3} isopycnal moved offshore at the surface. Later less dense water appeared near shore as the denser water at the surface moved seaward to ~150 km away from the shore (Fig.3.4). Along 10°N transect the 22 Kgm^{-3} isopycnal reached only to ~ 20m from a depth of 50m. However, at 13°N transect the density of the coastal surface waters are comparatively lower (21.7 Kgm^{-3}) than the open ocean surface waters (22.3 Kgm^{-3}).

3. 2. 2.d. Dissolved oxygen

Along 8° N transect the oxygen values are uniform in the upper 25m in the coastal region and 50m in the offshore region. The oxygen values decreased sharply within the upper 200m, from 200μM to 30μM. The oxygen at the surface shows gradual decrease in concentration towards the coast and the values vary from 190μM to 170μM. This feature is associated with a decrease in surface temperature from offshore to coastal region. The oxygen content decreased sharply from 130μM at 50m to 30μM at 150m along the shelf (Fig. 3.5).

A similar variation in surface oxygen values between 190µM - 170µM was also evident from the distribution of dissolved oxygen along the 10°N transect. A sharp decrease from 200µM to 10µM is observed within the upper 200m water column along the shelf region (Fig.3.5). Concentration of 170µM contour of oxygen at 75m depth along 68°E was elevated to a depth of 25m at the coastal region. Low oxygenated waters with values less than 10µM were observed at the mid shelf at about 125m (Fig.3.5).

3. 2. 2.e. Nitrate

The concentration levels of nitrate, along the southwest coast of India varied between non-detectable levels to 30µM in the upper 200m water column, during southwest monsoon. The coastal waters along 8°N and 10°N registered relatively higher concentrations of nitrate (~ 2µM) in the surface layers (~ 50m) when compared to the offshore waters. This is due to the upwelling of deeper nutrient rich waters nearer to the surface. Along 8°N transect, 2µM contour of nitrate from a depth of about 50m at 71°E reached upto the surface near to the coast. However, along 10°N transect the 2µM nitrate contour could reach only up to 10m depth near the coast from the deeper waters in the oceanic region. The upward movement of isolines is in coherence with that of isotherms and isohalines (Fig.3.4) indicating upwelling along southern transects. Along 10°N transect 8µM contour of nitrate (~ 75m) runs towards the coast without any gradient, makes a sharp up sloping near the continental shelf at about ~ 25m, east of 75°E (Fig.3.5).

3. 2. 2.f. Silicate

During southwest monsoon the silicate concentrations ranged from non-detectable levels to 65µM between surface to 100m depth. The vertical distribution of silicate exhibits an increasing trend with depth. All the nearshore stations along 8°N and 10°N transect showed higher values of surface silicate and the highest concentration (20μM) were encountered in the shelf waters along 8°N transect. In the shelf waters of 10°N transect the silicate were comparatively low. In the Arabian Sea shelf waters were enriched with nutrients due to upwelling during southwest monsoon. In the surface layers (~ 50m) of offshore waters, silicate values were below detectable levels (Fig.3.5). Along 8°N transect the 2μM contour of silicate observed at ~ 50m in the off shore region, intrude to the surface near the coast (Fig.3.5). The 2μM silicate contour at the 10°N transect reach up to ~ 25m, but not to the surface, owing to the weak upwelling (Fig.3.5).

3. 2. 2.g. Phosphate

Figure 3.5 shows the vertical distribution of inorganic phosphate along 8°N and 10°N and 13°N during summer. The surface phosphate concentrations are high along 8°N and 10°N transects due to upwelling. The 1μM contour observed at 75m along 71°E was elevated to 25m along 77°E in both the transects. Such an elevation in the phosphate contours towards the coast were evident in the entire 200m depth. The phosphate concentrations increased rapidly to the deeper waters.

3. 2. 2.h. Biological Response

During summer monsoon, coastal belt of the southwest India shows the maximum surface and column chlorophyll *a*. The depth integrated PP ranged from 179 to 1629 mg C m^{-2} d^{-1} (avg 503 mg C m^{-2} d^{-1}) and the chlorophyll *a* values ranged between 8.7 - 44.7 mg m^{-2} (avg 23.2 mg m^{-2}) (Table.3.1). An increase in biological production was noticed in the coastal region along the southwest coast and the highest PP and chlorophyll *a* concentrations were observed off 8°N suggesting active upwelling.

3. 2. 3. Discussion

The hydrographic observations described above have been interpreted as indicative of upwelling. The hydrographic data confirmed that the upwelling processes is initiated in the south along with the onset of southwest monsoon and slowly propagates towards north with time. During southwest monsoon appreciable upwelling was encountered off the south west coast of India, only along 8°N transect, which showed coolest, high nutrient and lowest oxygen surface water situated near the coast. Along the 10°N transect only weak upwelling was observed and it was absent at 13°N (Fig.3.5). The high nitrate patch obtained near the south west coast during southwest monsoon clearly demonstrate the area of upwelling along the coast which extends up to about 15°N (Fig.3.2). Higher concentrations of dissolved silicate and phosphate also has been noticed in these areas. The areas of upwelling could be easily identified by their low sea surface temperature (Fig.3.1) and associated nutrients and oxygen concentration.

During southwest monsoon Ekman Drift has been observed to dominate over most of the southwest coast of India. In the eastern Arabian Sea geostropic current also makes a significant contribution (Shankar, 2000). However, it was found that the wind driven mixing is stronger than the Ekman pumping and the horizontal advection during summer monsoon (Lee *et. al.*, 2000) and the wind system along the south west coast of India favours coastal upwelling (Shetye *et. al.*, 1984, Muraleedharan *et. al.*, 1995, Maheswaran *et. al.*, 2000). The persistence of most upwelling depends upon the direction and strength of the local winds (Barber and Smith 1981). The upwelling can be a result of up bringing of high speed bottom current associated with specific bottom topography where cold water is forced towards the surface at the shelf or slop region. The remarkable shoaling of thermocline towards the coast is an indication of active upwelling, which is again reflected in the density structure (Muraleedharan and Prasanna Kumar, 1996). Strong stratification at the sea surface due to upward pushing of thermocline by the upwelling causes a mixed layer thinning. From the nutrient data and associated physical processes, it is clear that the upwelling brought nutrient rich bottom water to the euphotic surface layers. Upwelling signatures were on a wide area along the south west coast of India spanning from 8°N to 15°N and extending to about 150 km from the coast (Fig.3.2). Upwelling is generally related to wind induced Ekman transport where cold and nutrient rich bottom and subsurface waters enter the photic zone, which could foster enhanced primary productivity in the area. (Mann and Lazier, 1996; Divakar Naidu *et. al.*, 1999). The processes of upwelling accelerates the chlorophyll a and promote primary production in the south west coast of India during southwest monsoon where chlorophyll *a* and primary production were higher than northwest coast (44.7 mg m^{-2} & 1629 mg C $m^{-2} d^{-1}$).

The upwelling of cold and nutrient rich bottom water displaces the interface between the surface and bottom water, where a frontal structure is established i.e. marked changes in parameters within comparatively short horizontal distances. The frontal structure can be identified by the decreasing gradients in temperature, decrease in MLD and increasing gradients in nitrate concentrations towards the coast (Fig.3.1 & 3.2). A surface temperature gradient of 0.2°C per 20 km was observed in the upwelling front. However, the upwelling along the west coast of India was localized and restricted to the southwestern coast. Values of nutrients east of 75°E were high for the south west coast. This is mostly obvious in the distribution of nitrate (NO_3^-) at 30m (Fig.3.6a) where values > 6μM were found compared to values of 0-2μM found elsewhere on the south west coast. The higher concentrations of nutrients in the upwelling sector exist off southwestern tip of India. The upwelled waters cannot be traced north of 15°N as the physical forces triggering the upwelling mechanism are weak (Fig.3.6a). Distribution of nitrate (NO_3^-) off the extreme southwest coast of India endorse, the upwelled waters are not advected far off shore (Fig.3.2). The summer circulation in the Arabian Sea could transport the upwelled nutrients, westward from the coastal upwelling zone (Shankar *et. al.*, 2002). The westward displacement of the surface waters from the eastern Arabian Sea, during summer is restricted to the southwest coast of India (de Souza *et. al.*, 1996).

3. 3. Convective mixing along northwest coast of India during winter monsoon

During the northeast monsoon period (November-February) the current reverses advecting less saline equatorial surface waters from the equatorial region, causing sinking or retreat of Arabian Sea waters (Johannssen *et. al.*, 1987; Pankajakshan and Aravind Ghosh, 1992; Muralidharan *et. al.*, 1995; Hareesh kumar and Basil Mathew., 1997). Weakening of anticyclonic gyre and its slight contraction to the south and west evidence the relaxation of southwest monsoon forcing. Associated with westward propagation, the southward flow along the west coast of India propagates offshore (David and Kindle, 1994). Convective mixing plays an important role in churning up of surface and subsurface waters during winter monsoon especially in the northern Arabian Sea. The waters along the northwestern part of the coast are well mixed and colder.

3. 3. 1. Surface layers

Distribution of nitrate at different depth strata in the surface layers (upto50m) during winter is illustrated in figure 3.6, which clearly visualized the water column behaviour during the season. The effect of winter cooling maintained high concentration of nitrate (2μM) in the northern latitudes (north of 15°N). A gradual increase in the concentration of nitrate towards the open ocean was noticed in the northern latitudes. Increase of nutrients in the surface layers due to winter cooling is not observed in the southern latitudes (south of 15°N). Different horizontal profiles of nitrate in the upper 30m water column holds 1-

3 µM of nitrate, with a westward increase in its gradients (Fig.3.6b). Generally, the 1 µM contour of nitrate was nearer to the coast and 3 µM well offshore. Whereas in the northern latitudes the distribution of nitrate at different depths upto 30m shows almost similar characteristic features (Fig. 3.6b).

3. 3. 2. Hydrography of the vertical water column

3. 3. 2.a. Temperature

A depth wise temperature profile during the northeast monsoon along different northern transects are given in figure 3.8. The thermal structure during this season along 22°N transect showed a weakly stratified surface layer up to 50m (Fig.3.8). The 26°C contour, which gets spread in the 50m water column, indicates the homogenous character of the water column. Below 50m depth the isotherms were well stratified as the depth increases. A similar homogenization was also observed along the other two northern transects investigated (17°N & 19°N) where a 1°C increase in temperature is noticed indicating that the effect of winter cooling is more towards the northern most transect (Fig.3.8). The surface distribution of temperature showed a marked difference of 3.2°C between southern and northern Arabian Sea (Fig.3.7). The deep MLD (~ 70m) observed during this period of the year (Fig.3.7) indicated the intense convective mixing and associated dynamics of the mixed layer.

3. 3. 2.b. Salinity

The vertical distribution of salinity along 17°N, 19°N and 22°N is illustrated in figure 3.8. Along 17°N the coastal surface waters were comparatively less saline (< 35.7psu) than the open ocean surface waters (> 36psu). Intrusion of high saline (> 36.3psu) waters were evident between 20 - 75m depth along the open ocean region of the transect. Such an intrusion was also observed at 19°N

(Fig.3.8). Along the 22°N transect a sharp vertical mixing was evident in the open ocean surface waters, making it homogenously distributed in salinity (~ 36.7psu).

3. 3. 2.c. Density

The vertical density structure in the upper 200m water column along 17°N, 19°N and 22°N is shown in figure 3.8. Existence of denser waters at the surface in the open ocean region was observed in all the three transects investigated (17°N, 19°N & 22°N). At 17°N, 22.4 Kgm^{-3} isopycnal observed at ~75m along 73°E was traced at ~10m along 69°E (Fig.3.8). A similar enhancement of isopycnals towards the open ocean region was also evident along 22°N, where the 24.2 Kgm^{-3} isopycnal observed at 69°E surfaced west of 68°E (Fig.3.8). The surface waters along 22°N were found to be less stratified than the other two transects (17°N & 19°N).

3. 3. 2.d. Dissolved oxygen

Vertical distribution of dissolved oxygen along 17°N, 19°N and 22°N transects (Fig.3.9) projects a homogenously distributed surface water with comparatively less saturated dissolved oxygen (DO ~ 190µM). The concentration of dissolved oxygen decreases rapidly below 50m depth and reaches values as low as 10µM in the deeper waters. Waters with DO less than 10µM was located at varying depths along the northern transects investigated (17°N, 19°N and 22°N). Along 22°N the less oxygenated region was below 150m depth, along 19°N transect it was located adjacent to the continental shelf and at 17°N transect it was below 200m depth. Distribution of dissolved oxygen along 17°N transect showed a gradual decrease in concentration up to 75m and below this depth the DO showed an irregular pattern of distribution in the water column. In this water column (below 75m) ~ 50µM of DO was observed east of 71°E near the continental shelf and 20 µM to the west of 70°E towards the open ocean.

3. 3. 2.e. Nitrate

In all the northern transects (17°N, 19°N and 22°N) distribution of nitrate characterize the vertical mixing of surface layers with an offshore increase in concentration (Fig.3.9). The vertical distribution of nitrate reveals a marked enhancement in the upper 50m water columns in the open ocean region due to convective mixing. The effect of convective mixing is not so prominent in the coastal waters as evidenced by nitrate levels, which is often below detectable limit. Along 19°N transect the concentration of nitrate between 100-200m was comparatively less (~ 20μM) when compared to the 22μM contour of nitrate for the same column along 22°N transect. Whereas at the same depth range along 17°N transect the nitrate values varied between 18-22μM. The 2μM contour of nitrate observed at about 50m east of 71°E was found to spread over the surface waters, west of 71°E along 17°N transect and enriched a wider area in the oceanic region. In 17°N and 22°N transects also such an elevation in the 2μM nitrate contour was observed enhancing the oceanic nitrate concentration (Fig.3.9).

3. 3. 2.f. Silicate

Along 19°N and 22°N transects the surface silicate contours showed an up sloping tendency towards the open ocean region (Fig.3.9). In the 22°N transect the 2μM contour of silicate reached up to 20m whereas in 19°N it reached only to a depth of 40m. However the upsloping of silicate contours were absent along 17°N. Concentration of silicate increased towards depth reaching a maximum of 28μM at 200m.

3. 3. 2.g. Phosphate

Figure 3.9 depicts the distributional pattern of phosphate along 17°N, 19°N and 22°N during winter. The surface waters (~ 50m) along 22°N transect were rich in phosphate (> 0.6μM). The surface waters along 19°N registered phosphate concentration > 0.4μM. However the concentration of phosphate along 17°N decreased below 0.4μM. The phosphate values in the 200m water column ranged between 0.2 to 2μM. In the deeper waters (200m) along 17°N transect, the phosphate concentration was less compared to the other transects.

3. 3. 2.h. Biological Response

The biological production showed noticeable difference between northwest and south west coast during winter. In this season, column chlorophyll *a* ranged between 4.1 – 82.4 mg m^{-2} with an average value of 10.1 mg m^{-2} (south west coast) and 53.4 mg m^{-2} (north west coast)(Table.3.1). The integrated PP ranged from 141 to 1854 mg C m^{-2} d^{-1} having an average value of 238 mg C m^{-2} d^{-1} in the southwest and 1262 mg C m^{-2} d^{-1} in the north west coast. Waters off Veraval (21°N & 69°E) showed maximum PP and chlorophyll *a*, which was about 7 – 8 fold higher than the south west coast.

3. 3. 3. Discussion

The distributional patterns of various physicochemical parameters mentioned above are the result of winter mixing along the north west coast of India. The thermal structure during northeast monsoon season showed a weakly stratified surface layer extending to ~ 70m depths, which indicated deep mixed layers related to winter cooling and overturn. The low sea surface temperature in the northern latitudes explains the perspicuous peak winter conditioning prevail over there (Fig.3.7). The convective mixing process and the injection of nutrients to the surface layers appears to be weak at the near shore stations, and intensify towards the open ocean areas (Fig.3.9). During winter, the cooling and the subsequent homogenization, the surface water mixes with the water below (Jyothibabu *et. al.*, 2004). Enrichment of nutrients in the mixed layer is often followed by a relatively high chlorophyll *a* and enhanced primary production along the northern latitudes especially at 21°N during northeast monsoon, though the southern latitudes during this season are short of chlorophyll *a* and primary production.

Pattern of dissolved oxygen and nutrients during northeast monsoon clearly reveals the northward swell in the magnitude of convective mixing (Fig.3.9). The atmospheric forcings that lead to the observed changes in the upper layer of the northern Arabian Sea is a combination of enhanced evaporation under the influence of dry continental air from the north carried by the prevailing northeasterly trade winds and reduction in solar insulation. This might partly be a causative reason for the observed low saturation of dissolved oxygen in the northern latitudes during northeast monsoon. The exchange of oxygen between the surface and sub surface layers through vertical mixing plays a key role in determining the extent of denitrification in the Arabian Sea (Naqvi, 1991). Subsequent cooling and convective mixing injects nutrients into the surface layers from the thermocline region, which in turn triggers the primary production (Prasannakumar *et. al.*, 1996). Upwelling is not only associated with local winds, but also with the more large scale monsoonal condition which drives the anticyclonic Arabian Sea monsoon gyre (Shetye *et. al.*, 1990).

Season	**Primary productivity (mgC $m^{-2} d^{-1}$)**			**Chlorophyll *a* (mg m^{-2})**		
	Range	**Station observed maximum**	**Physical processes**	**Range**	**Maximum**	**Physical processes**
Summer monsoon	179-1629	8°N: 77°E	Upwelling	8.7-44.7	8°N: 77°E	Upwelling
Winter monsoon	141-1854	21°N: 69°E	Winter cooling	4.1-82.4	21°N: 69°E	Winter cooling

Table 3.1. Biological production (primary) in the eastern Arabian Sea during different seasons

3. 4. Conclusion

The seasonal environmental patterns discussed in this chapter are the result of summer stratification along the southwest and winter mixing along the north west coast of India respectively. The resulting monsoon forcings brings about large scale fertilization of surface waters through upwelling in summer and convective mixing in winter. Signatures of upwelling is characterized by low sea surface temperature values and high values of nutrients in the upper ocean, which begin to appear when the monsoonal trade winds become active from the month of May onwards and the wind-induced upwelling initiated, slowly propagate northwards and intensify along west coast of India during June to August (David *et. al.,* 1994). It can be presumed that maximum vertical convection of surface layers along the northeastern Arabian Sea takes place after the surface warming has tapered and winter mixing is well underway. The Indian monsoon system not only governs the productivity and particle flux (Haake *et. al.,* 1993) but also evaporative precipitation balance (Sarkar *et. al.,* 2000). The manifold climatic changes fall annually impart a vigorously deviating environmental nature to the west coast of India.

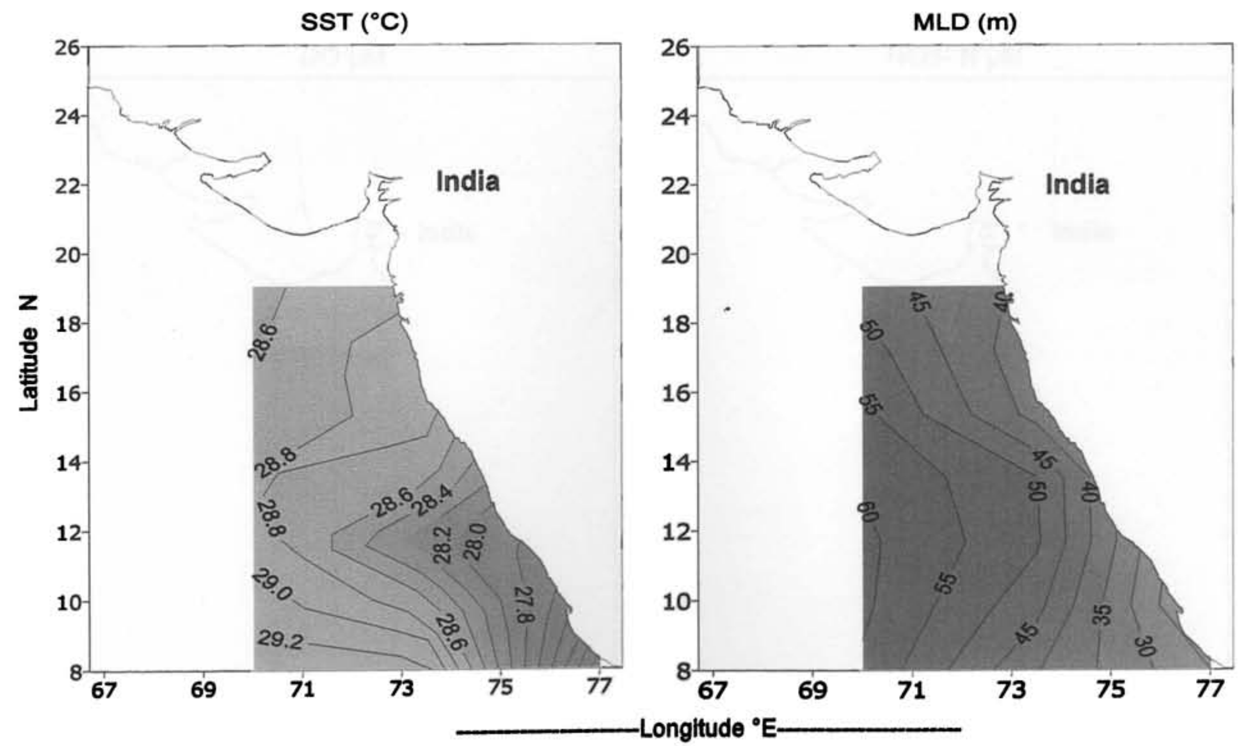

Figure 3.1. Distribution of SST and MLD along the west coast of India during summer

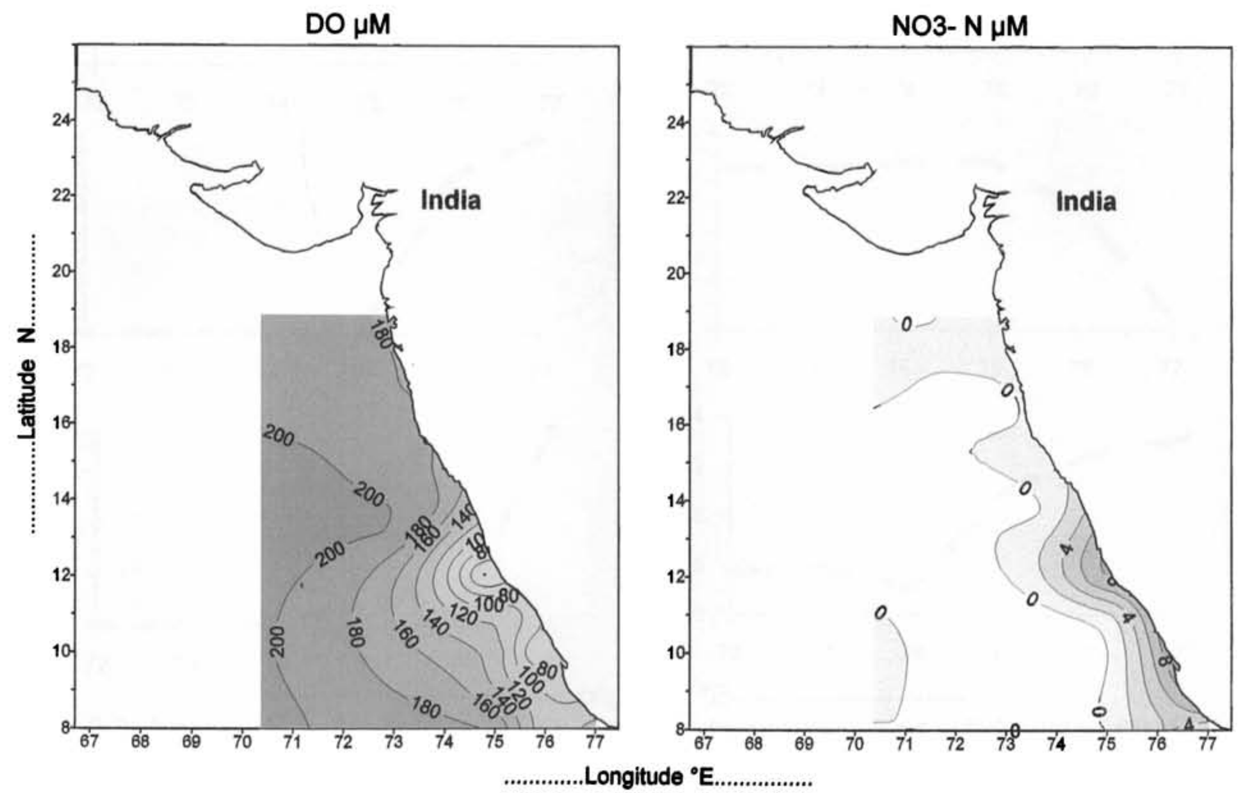

Figure 3.2. Horizontal distribution (20m) of DO and nitrate in summer

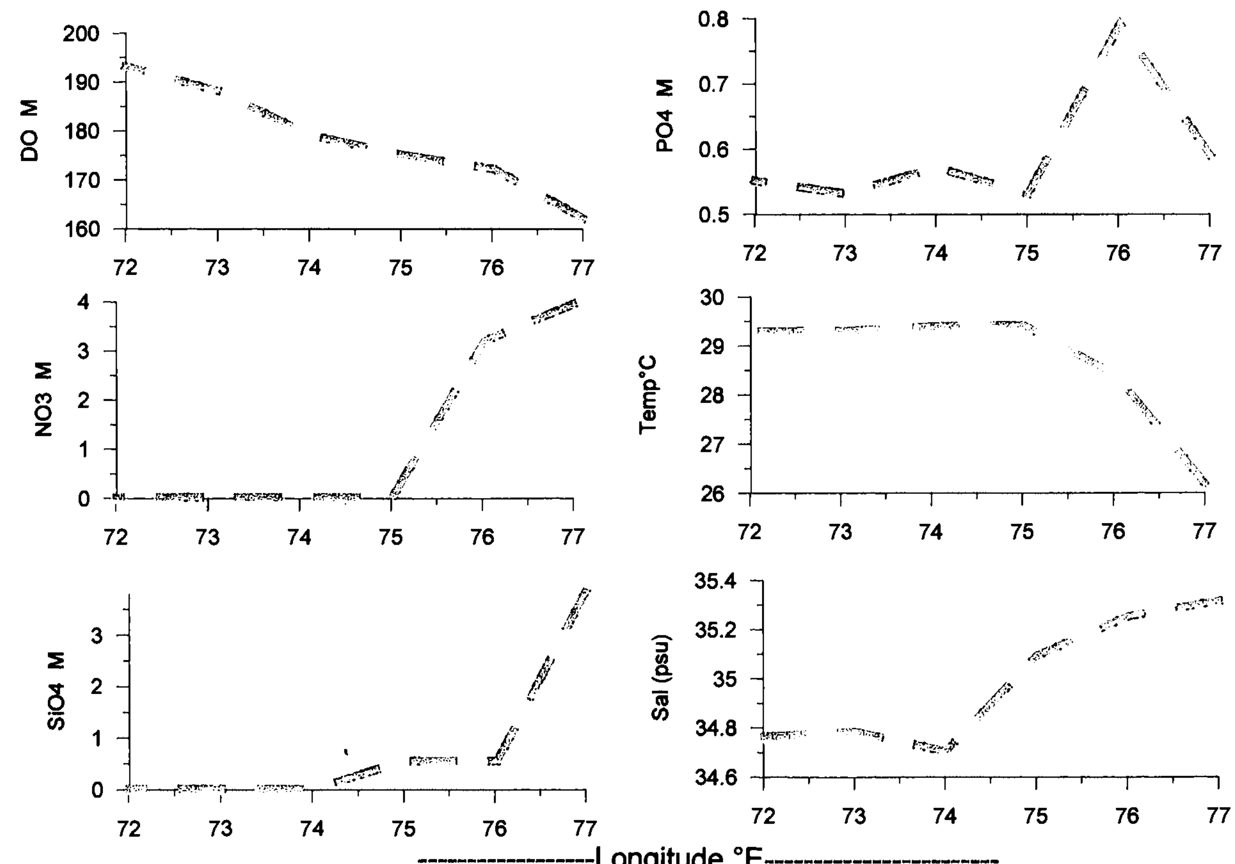

Figure 3.3. A subsurface Distribution of DO, nutrients, temperature and salinity along 8°N in the Arabian Sea during summer

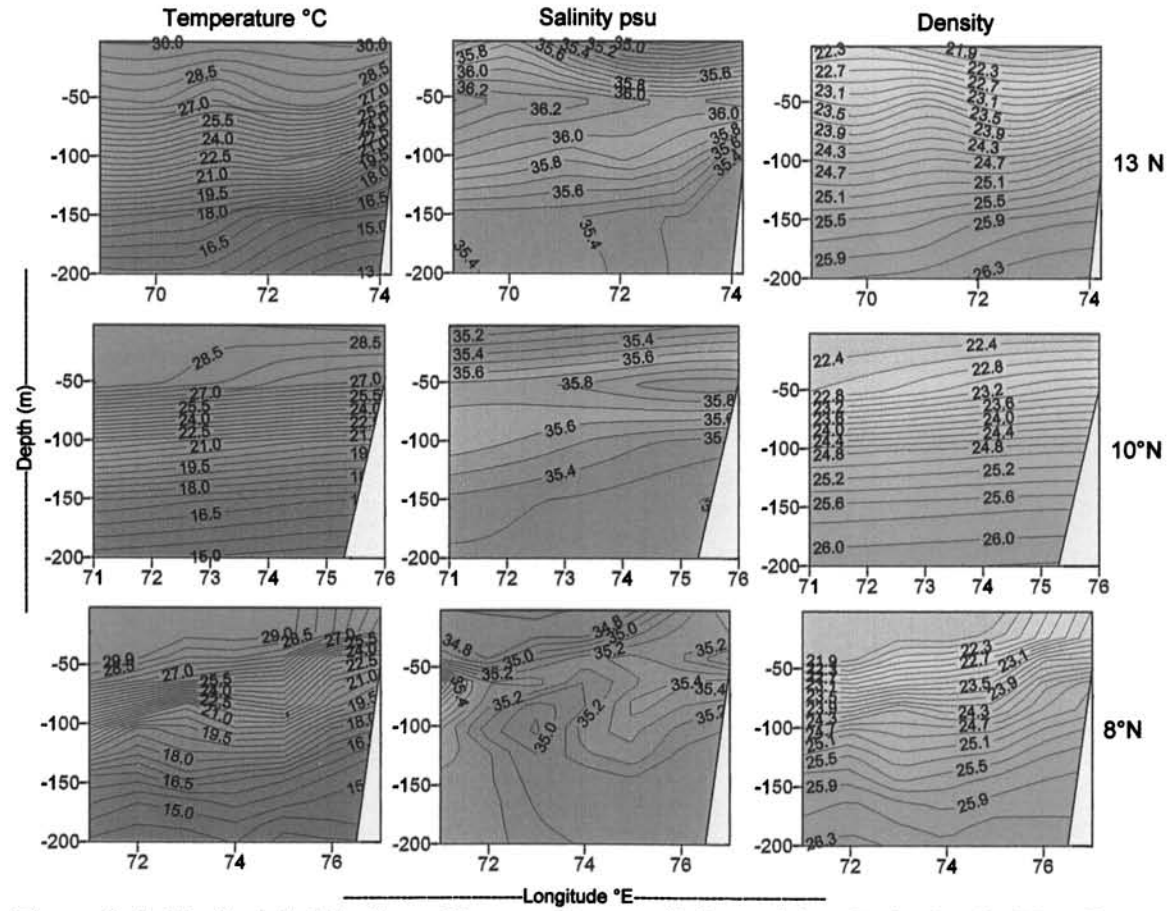

Figure 3.4. Vertical distribution of temperature, salinity and density in the Arabian Sea during summer

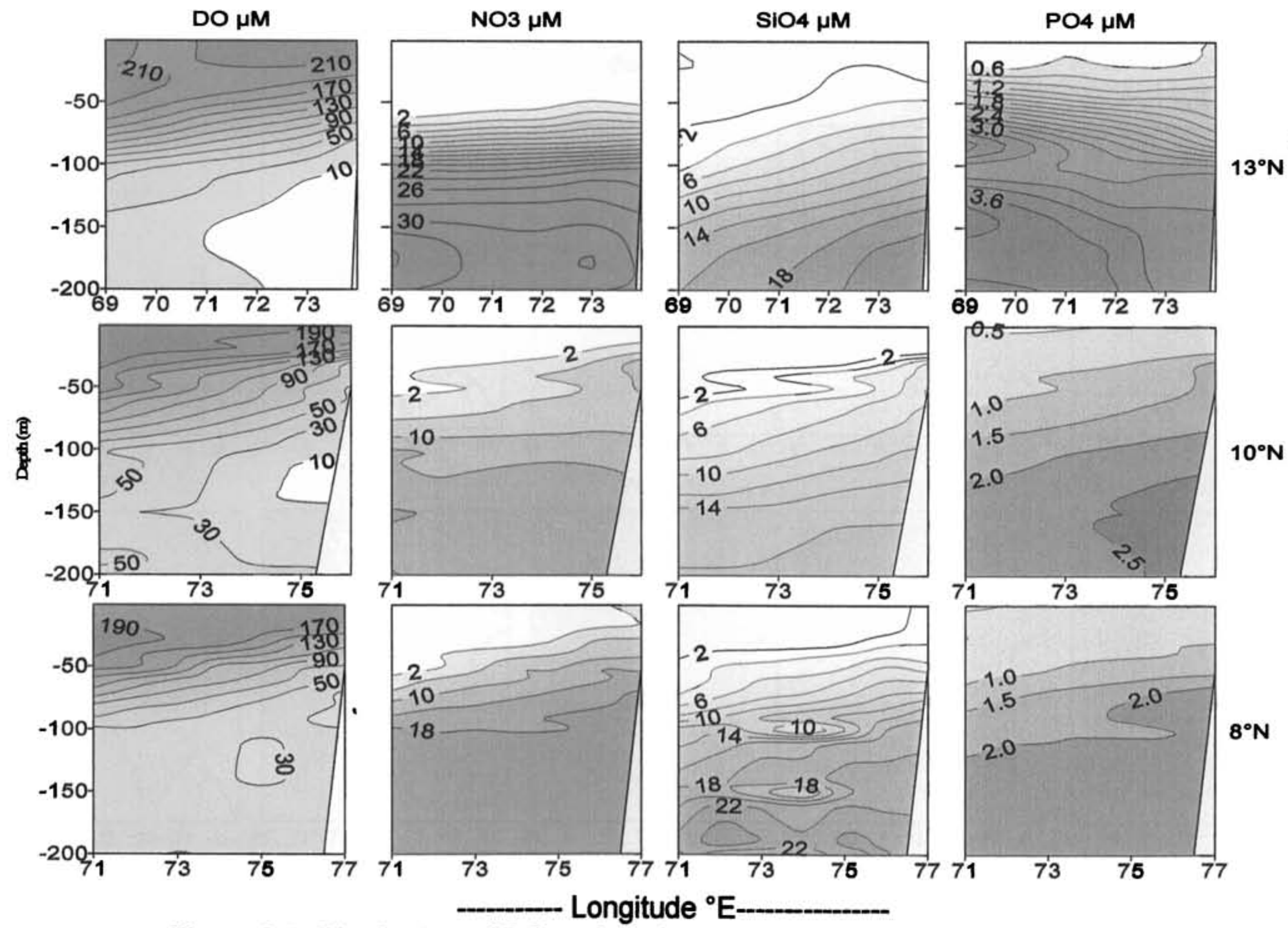

Figure 3.5. Distribution of DO and nutrients in the Arabian Sea during summer

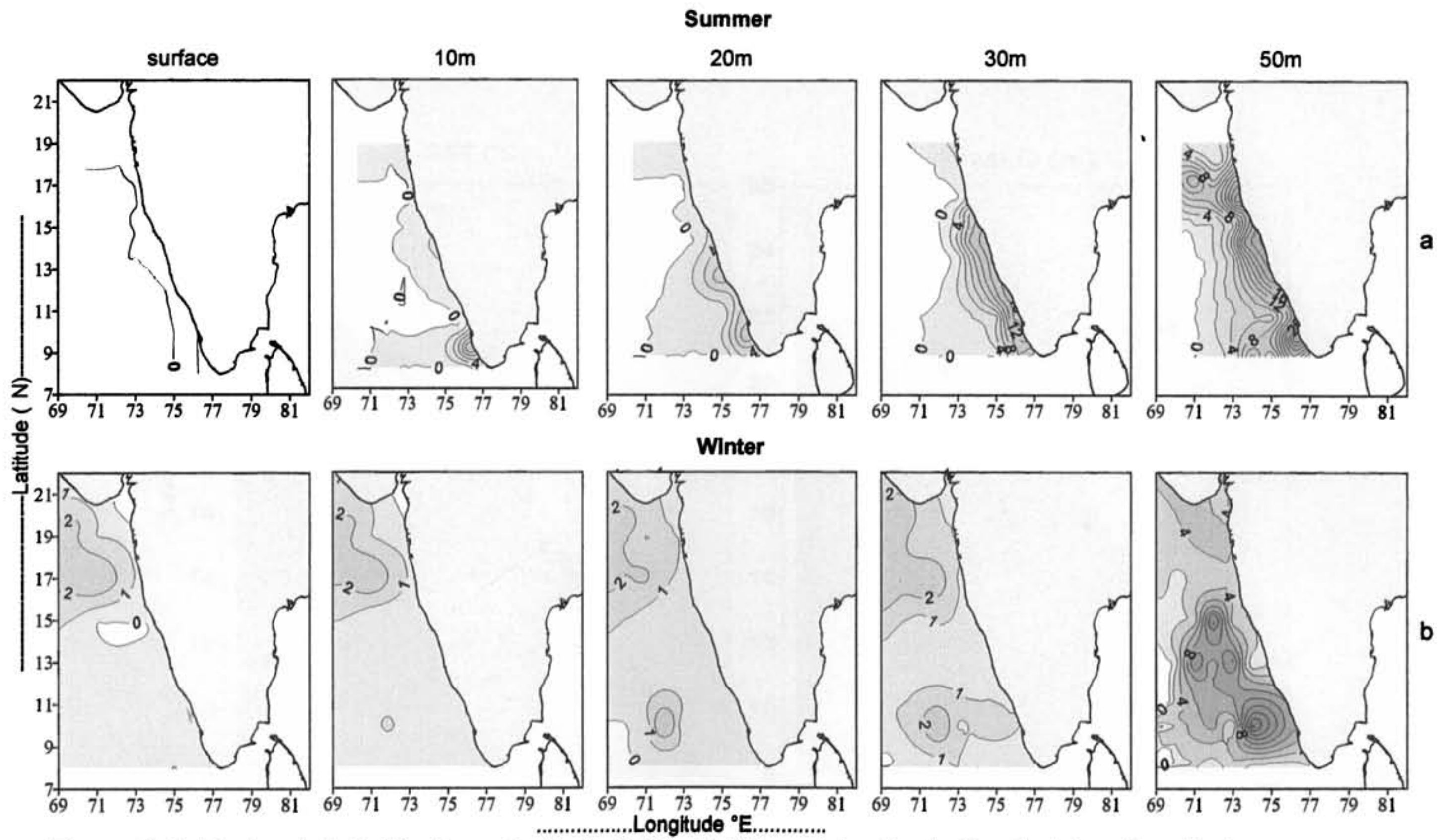

Figure 3.6. Horizontal distribution of nitrate (μM) at different depths in the Arabian Sea during summer and winter

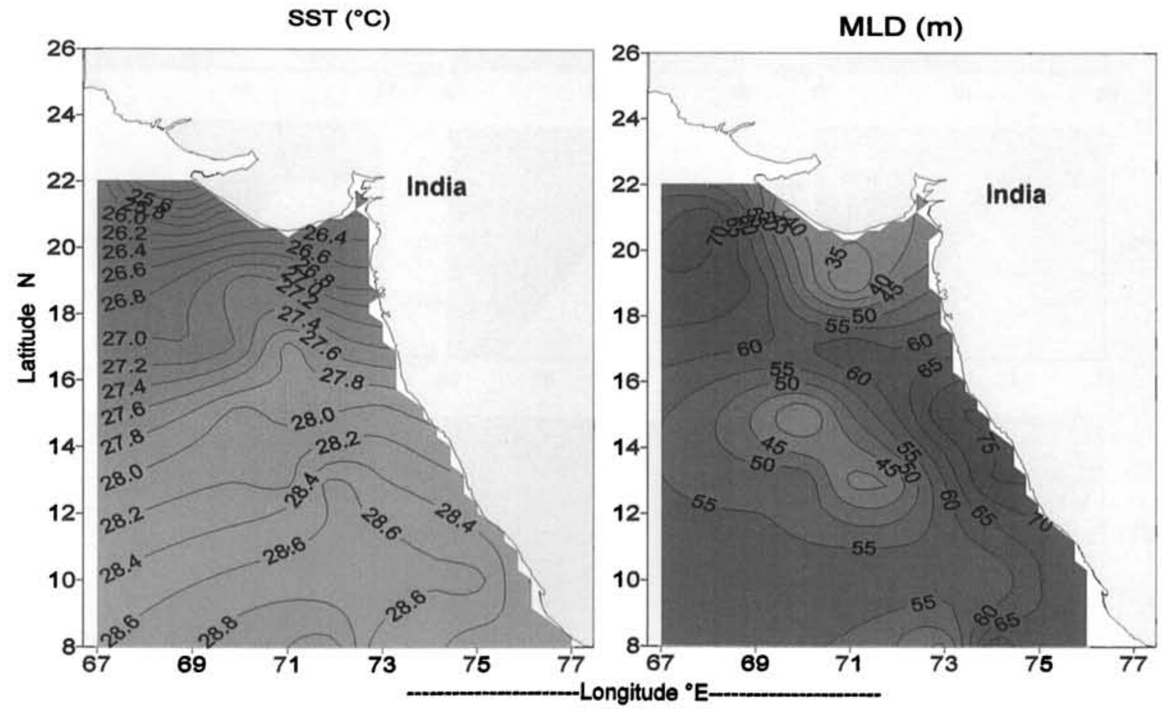

Figure 3.7. Distribution of SST and MLD along the west coast of India during winter

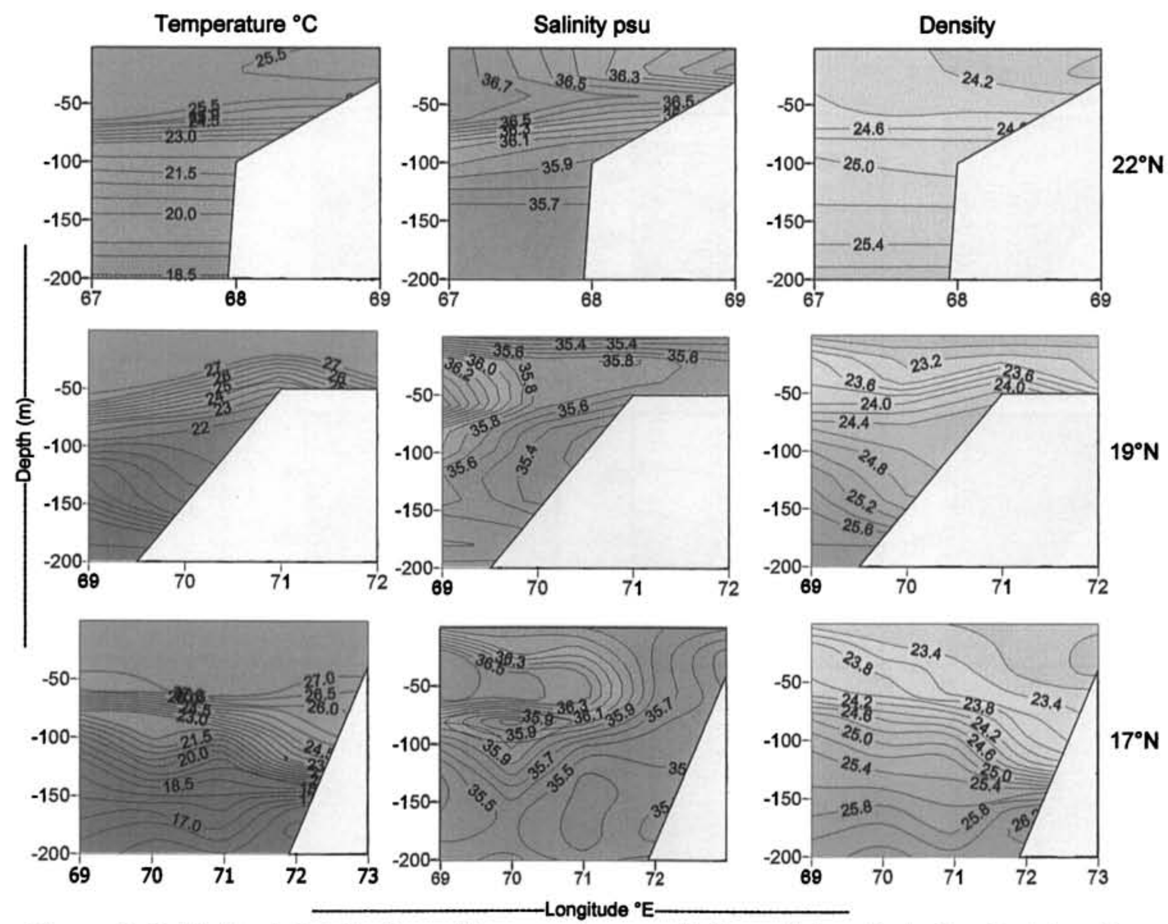

Figure 3.8. Vertical distribution of temperature, salinity and density in the Arabian Sea during winter

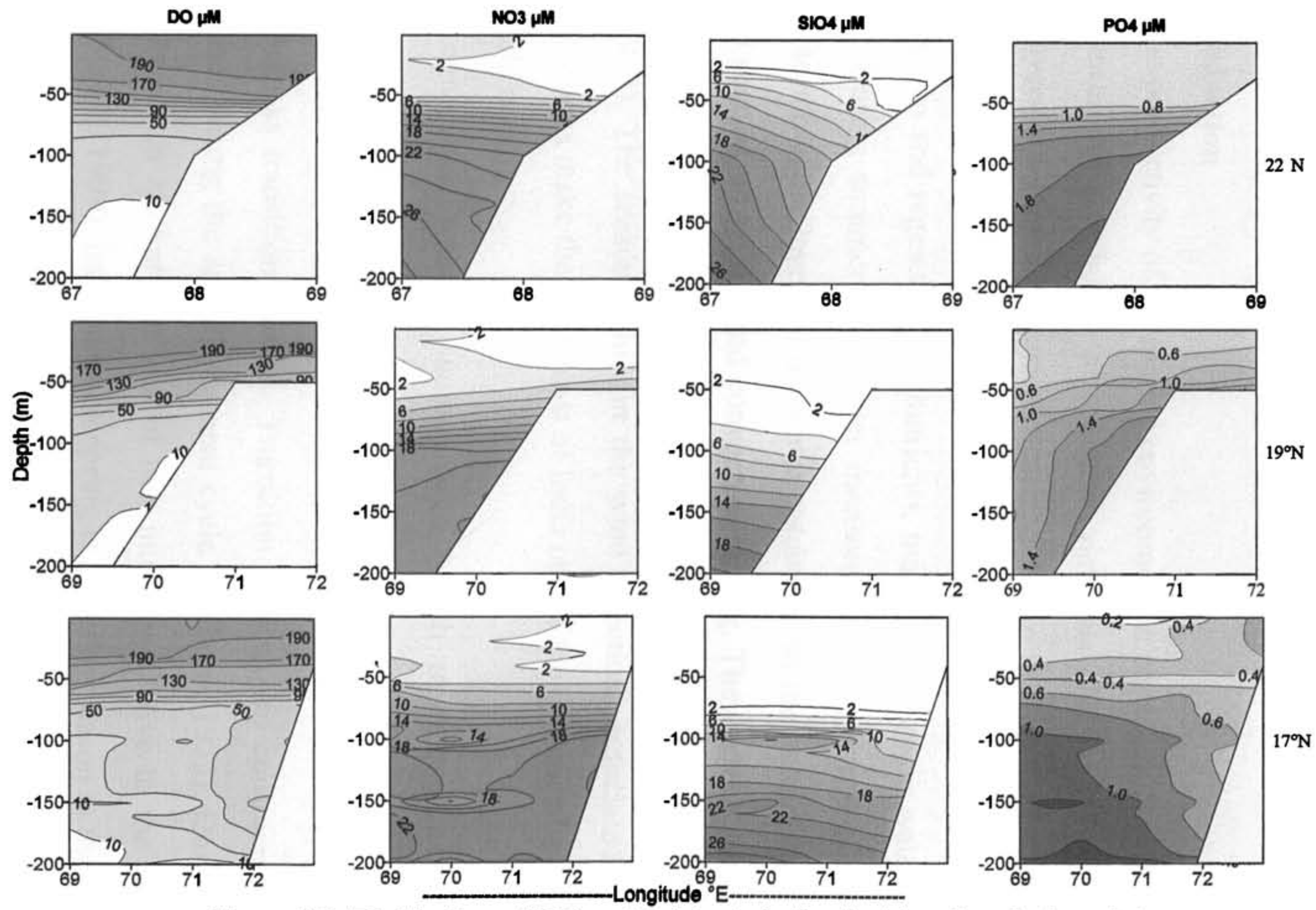

Figure 3.9. Distribution of DO and nutrients in the Arabian Sea during winter

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Chapter 4

Hydrography of the Arabian Sea during Intermonsoons

4.1. Introduction

The productivity of the marine environment in particular is related to the concentration and distribution of inorganic nutrients dissolved in water. The surface layers are generally nutrient depleted during this period (~ 50m). The organic matter deposited in the bottom sediments undergoes bacterial decomposition and regenerate the nutrients, making the bottom waters rich in nutrients. During summer and winter monsoon seasons, nutrients are made available to the upper layers of the water column from the bottom by physical processes such as upwelling and convective mixing. The current patterns also play an important role in bringing the nutrients into the surface layers (de Souza *et. al.*, 1979). The seasonal shift in the wind directions associated with the Indian monsoons make the west coast of India one of the dynamically rich areas of the world oceans.

Intermonsoon seasons running from March to May (intermonsoon spring) and a shorter season between mid September to November (intermonsoon fall), are quite different from both monsoon seasons, which are referred here as transition seasons. Transition seasons are considered as the warm phases during the annual seasonal cycle (Colborn, 1975). During these seasons the winds are variable and of low intensity relative to the monsoon seasons (Burkill, 1999). Intermonsoon spring is a heating season in the Arabian Sea. The surface waters of the central Arabian Sea possess non-detectable levels of nutrients and showed lowest chlorophyll *a* concentration and primary productivity (Prasanna Kumar *et. al.*, 2000).

Extreme atmospheric forcing prevails in the Arabian Sea during summer and winter, making it highly productive. During the transition between these two extreme seasons, the EEZ of the west coast of India maintains its productivity moderately high because of the injection of nutrients to the surface layers due to the prevailing extended favourable atmospheric conditions. The characteristics of the surface forcing in the EEZ of the west coast of India during intermonsoons are quite similar to the monsoon seasons. During intermonsoon fall physicochemical parameters showed the influence of an upwelling system with relatively colder, nutrient rich waters being advected into mixed layers of the surface. Recognizable winter signatures in the upper ocean temperature and in mixed layer depth were associated with intermonsoon spring season. In this chapter, an attempt is made to focus on some of the prominent features lingering along the EEZ of the west coast of India during the transition seasons.

4.2. Intermonsoon fall

4.2.1. Surface layers

The sea surface temperature and MLD distribution along the west coast of India are given in figure 4.1. At the surface, the temperature ranged from 28°C to 30°C with a distinct decrease from open ocean to the coast along the south west coast of India. In the coastal waters along the west coast of India (between 8°N – 13°N) the SST drops below 28.2°C imparting less intense upwelling characteristics. Relatively thin MLD was observed between 10°N and 15°N. During intermonsoon fall, variable winds with a prominent southwesterly wind were observed along the west coast of India (Maheswaran, 2004). A shallow MLD was observed near the shore (20 - 30m) whereas it was deeper along the open ocean waters (~ 60m).

Horizontal distributions of nitrate at different surface layers are portrayed in figure 4.3a. In intermonsoon fall, under the combined action of the prevailing southwesterly wind and the existing upwelling thrust from the deeper waters, an enhancement in nitrate concentration occurred in the near surface waters along the southwest coastal waters of India between 10°N and 15°N. The nitrate concentration between 1- 10μM was found to spread over the coastal waters south of 15°N in a narrow band at 20m and 30m depths (Fig. 4.3a). In contrast, the concentration of nitrate north of 15°N and the open ocean was very low.

The elevated nitrate (> 2μM) patch along this region coincided approximately with the comparatively low oxygenated (DO < 170μM) region (fig. 4.2). The saturated (DO > 200μM) surface waters were pushed away from the coast during this season. The northern parts of the west coast were also saturated with oxygen (DO > 200μM).

4.2.2. Hydrography of the vertical water column

4.2.2.a. Temperature

Vertical sections of temperature along 8°N, 10° and 13°N are presented in figure 4.4. An upsloping of isotherms towards the coast was observed within the 100m depths. Eventhough the upsloping in the deeper waters along 13°N was weak compared to 8°N and 10°N, the 28°C contour reached the near surface waters towards the coast. Along 8°N and 10°N transects the 28°C isotherm from a depth below 50m surfaced near the coast. However this trend was absent in the sub-thermocline region and the isotherms were running parallel to the transect.

4.2.2.b. Salinity

The salinity near the coast was low (< 34.9 psu) compared to the offshore surface waters (> 35.3) as evident from figure 4.4. Intrusion of ASHSW (~ 36 psu) from the western longitudes were identified at a depth range of 20 – 60m. However, the ASHSW existing below the surface layers showed a coastward upsloping tendency in all the three transects. Salinity ranged between 34.5 and 36.3 psu.

4.2.2.c. Density

The vertical density structure during intermonsoon fall within the 200m water column is given in figure 4.4. Density during this season ranged between 22.1 Kgm^{-3} and 26.4 Kgm^{-3}. The surface waters along the coast occupied the lowest density. Conversely the subsurface density contours showed a slight up sloping tendency towards the coast.

4.2.2.d. Dissolved Oxygen

The southern transects (8°N, 10° & 13°N) were characterized by elevating oxyclines towards the coast in the upper 100m water column. Along 8°N, the 180µM contour of DO reached only upto 40m near the coast where it sneaks to about 20m along 10°N and 13°N transects. In the vertical sections, the water between 100m and 200m depth had low oxygen concentration (Fig. 4.5.). At 8°N transect these depths contained 40µM oxygen. Dissolved oxygen decreased considerably reaching below 20µM towards 10°N and 13°N transects. A severe decrease in concentration (DO $<$ 10µM) was observed between 100 and 150m along the 13°N transect in the shelf region (Fig. 4.5).

4.2.2.e. Nitrate

The vertical distribution of nitrate showed an upsloping of contours throughout the depth range considered (200m), except in 13°N (Fig. 4.5). Along 8°N and 10°N transects, the 1µM contour of nitrate slopes up to 20m near the coast from a depth of ~ 50m. In the 13°N transect where the signals of upwelling are more prominent, the 1µM reached almost near to the surface from 30m offshore. In this transect there was a drop in nitrate concentration between 100 and 200m, which approximately coincided with the region of oxygen-depletion (DO < 10µM). In contrast, the isolines of nitrate between 100 and 200m along 8°N and 19°N was found to sharply shoot up towards the surface layers. The 25µM contour observed below 200m moved up to 75m (Fig. 4.5).

4.2.2.f. Silicate

Coastal upsloping of 1µM silicate contours in 8°N, 10° and 13°N transects was similar to nitrate distribution during this season. Silicate concentrations between 100 and 200m depths also showed a marked upslope towards the surface layers except in 13°N transect. Along 13°N a similar down sloping of silicate contours between 100 and 200m was recorded as that of nitrate (Fig. 4.5). The 17µM contour of silicate observed at ~100m depth along 72°E was found to deepen below 200m along 74°E.

4.2.2.g. Phosphate

In all the transects studied (8°N, 10° and 13°N) phosphate registered comparatively high concentrations along the coastal surface waters. Isoline of phosphate with 0.7µM concentration, surfaced in all the transects except 10°N. The maximum spreading of phosphate concentrations towards the open ocean was observed along13°N transect (Fig. 4.5). Contours below 100m depth showed an upward tilt towards the coast at 8° and 10°N transects whereas at 13°N these contours was running parallel to the transect.

4.2.3. Discussion

Being a period of transition in the eastern Arabian Sea, the intermonsoon fall represents the retreat phase of the southwest monsoon. The season was characterized by relatively higher southwesterly winds. Waters along the south west coast of India (8°N, 10° and 13°N) were characterized by the upsloping isotherms towards the coast. During this period the vertical transports were weak since the surface currents were retarded (Culter and Swallow, 1984;

Shenoi and Shetye, 1988). The MLD gets thinner towards the coast.

A significant inference during this season was a coastward upwelling that could define the distribution of nutrients in the surface layers in the EEZ of the west coast of India. Vertical profiles of DO and nutrients showed a less intense cross shelf upsloping. The coastal shelf between 10°N and 15°N could be recognized as an upsloping zone, with cool, low oxygenated and nutrient rich waters. The upwelling characteristics were observed to be retreating from the 8°N transect, a region where the signatures of upwelling begins with the onset of the southwest monsoon.

The surface waters along the northern transects (north of 15°N) were nutrient depleted with high-oxygenated waters (Fig. 4.3). A severe depletion in oxygen concentration was observed near the continental shelf along the 13°N transect (Fig. 4.5) which could be attributed to the existence of the productive surface waters near the coast due to the late existence of upwelling characteristics in the region. Naqvi *et. al* (2000) have reported intense suboxic conditions along the west coast of India during October. The sub surface oxygen depletion along the southwestern Indian shelf is primarily because of the nutrient enrichment through upwelling. This seasonal and shallow, suboxic zone also have a significant role in the overall denitrification process in the Arabian Sea (Naik and Naqvi, 2002). An intense depletion of oxygen could not be traced in the southern transects (8°N and 10°N) as the upwelling signatures are comparatively weak. The oxygen depletion in the inner shelf region showed an increasing trend from 8°N to 13°N (Fig. 4.5). A corresponding drop in the nitrate concentration was observed in the same region, where oxygen depletion occurred along 13°N transect indicating a possible denitrification in the region.

Even after the withdrawal of upwelling the shallow regions are often noticed with oxygen deficient waters. The surface layers which receive large amount of fresh water, may also prevent vertical mixing due to density stratification. As the upwelled waters advance through the bottom towards the coastal surface waters, it will be further depleted in oxygen due to utilization by plankton and oxidation of organic matter (Balachandran, 2001). Thus, the subsurface oxygen demand may be a causative factor for low oxygenated waters along the coastline during this season.

The offshore stations however showed a deepening of isotherms and nitracline down to ~ 50m depth, imparting an oligotropic nature to the surface waters. It is evident from the thermal structures that the surface waters along the western shelf between 10°N and 15°N were colder compared either to north or south of the region (Fig. 4.1). An upslope of nutrient contours towards the coastal surface layers off the southwest coast of India suggests the possible grip of upwelling even after southwest monsoon.

A general increase in the biological production was evident in the coastal region and a decrease in the open ocean region during intermonsoon fall. In October, when the summer monsoon has ended enhanced biological production appear in the upwelling zones in the Arabian Sea (Banzon *et. al.*, 2004). The depth integrated PP and chlorophyll *a* along the open ocean were 316 mg $Cm^{-2}d^{-1}$ and 24 mg m^{-2} respectively (Table. 4.1). However, in the coastal region it increased in an order of 550 mg $Cm^{-2}d^{-1}$ and 84 mg m^{-2}. On approaching the coast the surface nutrient concentrations enhance and a relatively high biological production was encountered near the coast, with 820 mg C $m^{-2}d^{-1}$ at 8°N and 935 mg C $m^{-2}d^{-1}$ at 10°N.

4.3. Intermonsoon spring

4.3.1 Surface layers

During the intermonsoon spring winds along the north west coast of India are relatively weak and are predominantly northwesterly (Maheswaran, 2004). The SST decreased towards the northern latitudes, and the lowest value (27.5°C) was observed in the open ocean region along 22°N. SST showed an increasing trend towards south. Comparatively deeper MLDs were observed off the north west coast. North of 19°N MLDs deepened towards the open ocean (Fig. 4.6).

Distribution of nitrate at different surface layers has been depicted in Fig. 4.3b, to visualize its enrichment along the northern region during spring. The nitrate concentration ranged between 0.6μM to 2μM in the 30m water column. The nitrate concentration along the southern part of the study region was non-detectably low. The elevated nitrate concentration (1μM) coincided with the isotherm of 27.5°C. Waters with enhanced nitrate concentration, covered only a smaller part of the northern transects.

4.3.2. Hydrography of the vertical water column

4.3.2.a. Temperature

Figure 4.7 delineates the vertical distribution of temperature along 19°N, 21°N and 22°N during spring. Weak thermal gradients were observed in the mixed layer of all the transects. Surface temperatures gradually increased from coastal to open ocean waters. The 28°C isotherm observed at 25m near the coast, surfaced west of 67°E in the 22°N transect. The waters below 50m were strongly stratified. The surface waters along 19°N were warmer than the other two transects (Fig. 4.7). The deeper waters (below 150m) along the 22°N transect were warmer than 21°N and 22°N. The isotherm with 22°C bulge up at ~ 100m.

4.3.2.b Salinity

The existence of ASHSW was prominent along the northwest coast of India during spring. High saline waters (36 - 36.4psu) were wide spread in the surface and sub surface waters along the three transects (19°N, 21°N & 22°N). However sinking of salinity contours was evident (Fig. 4.7) in the offshore region (68°E). The coastal surface waters along 19°N and 21°N were characterized by comparatively low saline waters whereas the salinity was fairly high in the 22°N transect. The ASHSW mass was observed to flow down gradually towards south.

4.3.2.c. Density

The density contours in the upper 50m showed an upward tilt towards the open ocean (Fig. 4.7). The surface density increased towards north. The density of offshore surface waters along 22°N was 23.6 Kgm^{-3} while it was 23 Kgm^{-3} along 19°N. The isopycnals were clustered at the thermocline depth of the 22°N and 21°N transects (Fig. 4.7). Below the thermocline depth isopycnals showed a downwelling towards the open ocean. A doming of 25 Kgm^{-3} isopycnal was observed at ~ 100m depth along 22°N between 66.5°N and 67°N.

4.3.2.d. Dissolved Oxygen

The surface waters along 19°N, 21°N and 22°N were saturated with dissolved oxygen (DO > 200μM) upto ~50m. The 200μM contour of DO was observed to be slightly upsloped towards the open ocean at 22°N transect where it was running parallel to the transect at 21°N and 19°N (Fig.4.8). The waters below 50m were strongly stratified. An oxygen minimum (DO < 20μM) was observed between 150m and 200m, with its maximum spreading towards the shelf. During this season along the 22°N transect 80μM contour of DO showed a doming at ~100m depth (Fig. 4.8). At the core of the dome oxygen was found to deplete further. At 21°N transect a similar dooming was observed with 20μM contour of DO further down (~ 150m). Nevertheless, such a condition could not be identified along 19° N.

4.3.2.e. Nitrate

Vertical distribution of nitrate along the northern transects during spring illustrates sloping of 2μM contour towards the open ocean surface waters. The

2μM contour observed at ~50m near the coast reached the surface waters along the open ocean region (Fig. 4.8). In the 19°N transect signals of surface overturning of nitrate were prominent, with 2μM nitrate reaching the surface. In the other two transects (21°N & 22°N) the 2μM contour could reach only up to the subsurface waters. Along 19° N transect, the deeper waters (100 - 200 m) also showed an upward movement of nitrate towards the open ocean. In contrast, a downward movement was observed among the nitrate contours within this depth range. The coastal surface waters along all the three transects (19°N, 21°N and 22°N) remained oligotrophic during the season. In the middle area of 22°N transect at about 100m, 14μM of nitrate showed a doming with a seaward tilt, as that of DO. The 16μM contour of nitrate was observed to be contained within the dome (Fig. 4.8). Along the 21°N transect a pocket of high nitrate (NO_3 > 22μM) was trapped at depth of ~150m (Fig. 4.8) between 67°E and 68°E. Such a trapping of high nitrate pocket was absent in 19°N.

4.3.2.f. Silicate

Silicate showed a homogeneous pattern in the surface waters of all the transects (19°N, 21°N & 22°N) towards the open ocean (Fig. 4.8). The surface 50m water column contained ~ 2μM of silicate in 21°N and 22°N transects. In 19°N and 22°N, 1μM contour of silicate dipped in to the surface waters to a depth of 25m. At the 21°N transect 3μM contour of silicate domed up to the surface (Fig. 4.8). In agreement with doming of low oxygen and high nitrate, the 8μM of silicate also showed an upward bulging at ~100m along 22°N (Fig. 4.8). At 21°N transect this bulging shifted down to ~150m with a concentration of 14μM silicate contour.

4.3.2.g. Phosphate

The values of phosphate in the 200m water column ranged between 0.4 to 3μM. Like silicate, phosphate distribution also has registered high values in the surface waters. The1μM contour of phosphate was found lifted up to the surface waters of the open ocean region along 19°N transect. Along 21°N transect 0.6μM contour of phosphate reached the surface waters near the coast (Fig. 4.8). Phosphate concentration also showed a similar doming of 2μM contour at ~100m along 22°N. At a depth of ~150m 2.2μM of phosphate bend up between 67°E and 68°E along 21°N transect (Fig. 4.8). Such a bending in the deeper waters was absent along 19°N.

4.3.3. Discussion

Intermonsoon spring represents the retreat of northeast monsoon. Even though it is the primary heating season of the year (Prasanna Kumar *et. al.*, 2000) as the solar radiation increases during this season (Hastenrath and Lamb, 1979), the surface distribution of temperature along the northern part of the study area was more representative of winter pattern, during this study. A combination of predominant northwesterly wind and the continued convective overturning eventually enhanced the nutrient loading to the surface layers along the offshore regions of the north west coast. Deepening of MLD and the thermocline with an increase in density towards the open ocean along the northern transects (19°N, 21°N & 22°N), substantiate the existing grip of winter cooling in the intermonsoon spring.

Vertical profiles of nutrients, especially nitrate, establish a sharp seaward sloping to the surface layers during the season. Among the three transects, 2μM nitrate surfaced at western end (68°E) of the 19°N transect. In the other transects it reaches the near surface waters (Fig. 4.8). The surface waters along the coastal belt off northwest India remained nitrate depleted and warm.

In 21°N and 22°N transects the distributional pattern of DO and nutrients suggest the formation of an eddy like structure within 100m and 150m depth. Along 22°N transect a convergence of 80μM DO, 14μM NO_3, 8μM SiO_4, and 2.2μM PO_4 contours were observed at 100m depth between 67°E &

67.5°E. In 21°N transect it was shifted down to 150m depth with the convergence of 20μM DO, 22μM NO_3, 14μM SiO_4, and 2.2μM PO_4 contours between 67°E & 68°E. With the onset of the southwest monsoon the currents in the Arabian Sea turns into a complex pattern leading to the formation of eddies (Bruce, 1974, 1979; Luther and O' Brien, 1985). These eddies are important component with a short-term variability in the region.

Silicate occupied a high concentration (~ 2μM) in the surface water of the open ocean region of the three transects. The concentration of phosphate in the surface waters along 68°E in the 19°N transect was found to be 1μM whereas it reduced to ~ 0.6μM along 21°N and 22°N. In contrast, during intermonsoon spring season, a shallow oxygen minimum was absent in the inner shelf region. In these northern transects oxygen depletion begins below 200m (discussed in chapter 5).

In general the column chlorophyll *a* and primary production in the eastern Arabian Sea varied from 4.6 to 41mgm^{-2} and 62 to 297mg C m^{-2}d^{-1} respectively during intermonsoon spring (Table.4.1). Phytoplankton biomass (chlorophyll *a*) and production in the euphotic water column did not show much variability in the eastern Arabian Sea. The average values column chlorophyll *a* and primary production seems to be more or less similar both in the southwest (19.4mg m^{-2} & 156 mg C m^{-2} d^{-1}) and northwest regions (17mg m^{-2} & 150 mg C m^{-2} d^{-1}) of the Indian EEZ.

The intermonsoon spring measurements showed the prevalence of winter conditions in the northeastern Arabian Sea. The effects of cooling due to evaporation are supported by the presence of relatively cool and saline waters along the northern region during spring (Morrison *et. al.,* 1998). Consequently, the SST was relatively low (< 28°C) with moderately deeper mixed layer (~ 40m). The convective process continues until the SST increases in late spring, with the commencement of winter cooling (Prasanna Kumar et. al., 2001). The availability of nutrients in the surface layers under improved light and weak wind conditions favours the formation of spring blooms in the open ocean region, which are short lived (McCreary *et. al.,* 2001). The winter scenario changes when the atmosphere starts warming up under the increased solar radiation during the late spring. The sea surface was warmer (>29°C) with thinner mixed layer (< 30m) and increased stratification that restricted the input of nutrients to the surface layers (Madhupratap *et. al.,* 1996 b; de Souza *et. al.,* 1996). This in turn could reduce the primary production in the region.

Season	Primary productivity ($mgC\ m^{-2}\ d^{-1}$)			Chlorophyll *a* ($mg\ m^{-2}$)		
	Range	Station observed maximum	Physical processes	Range	Maximum	Physical processes
Spring	62-297	21°N: 69°E	Winter cooling	4.6-41.2	13°N: 70°E	Winter cooling
Fall	149-820	8°N: 77°E	Upwelling	8.8-39.1	19°N: 70°E	Upwelling

Table 4.1. Biological production (primary) in the eastern Arabian Sea during different seasons

4.4. Conclusion

Upwelling along the southwest coast of India, with surfacing of isotherms, sharpening of MLD, increase in nutrients concentrations and comparatively high biological production during intermonsoon fall is concordant with observation of Banse, 1959; 1968. The upwelling in the southwest coast of India begins with the onset of the southwest monsoon and reaches its maximum intensity during July - August, and ends by mid October. In the upwelling region, the upward transport of nutrients is triggered seasonally, replenishing the surface waters with nutrients (Spencer, 1975). The upwelling signatures last throughout the southwest coast of India until October (Johannessen *et. al.,* 1987). The seasonal signals in the transition periods (intermonsoon fall and spring) are distinguishable to understand the strong bearing of summer and winter characteristics.

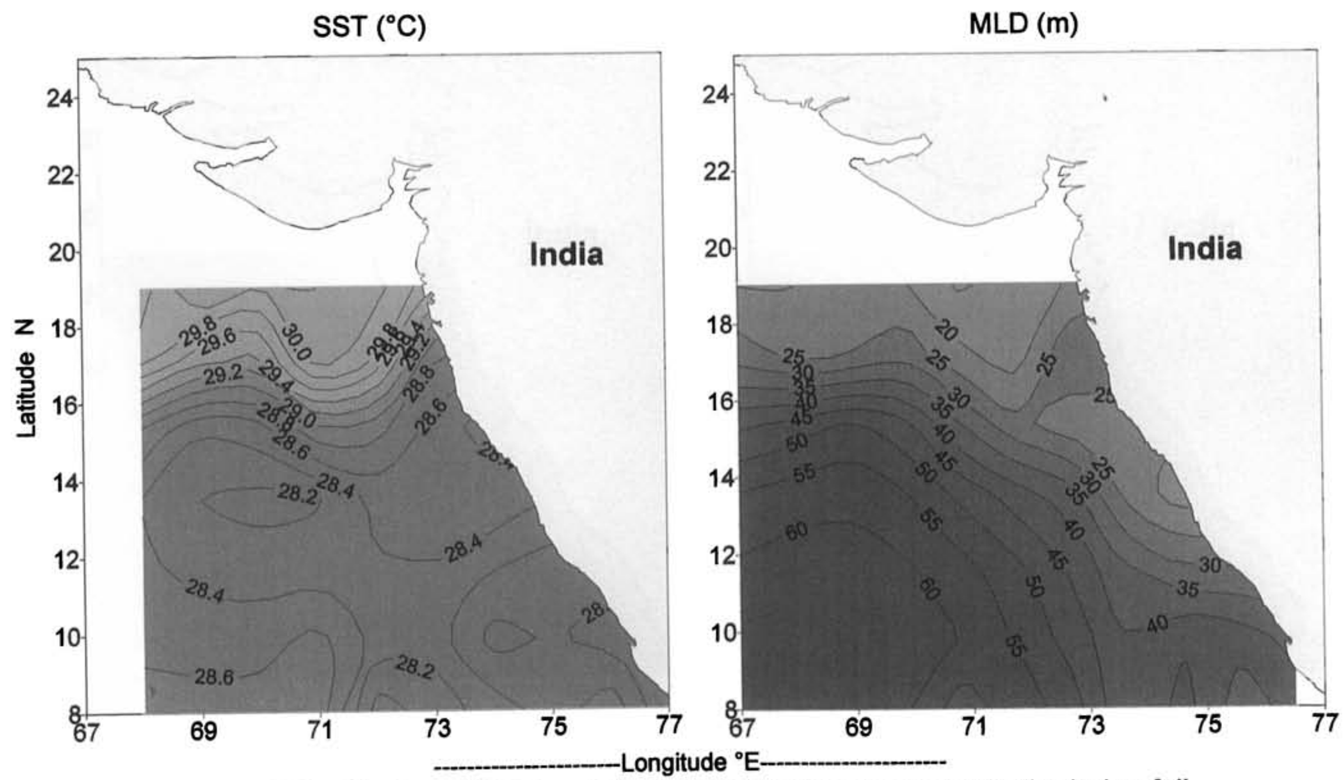

Figure 4.1 Distribution of SST and MLD along the west coast of India during fall

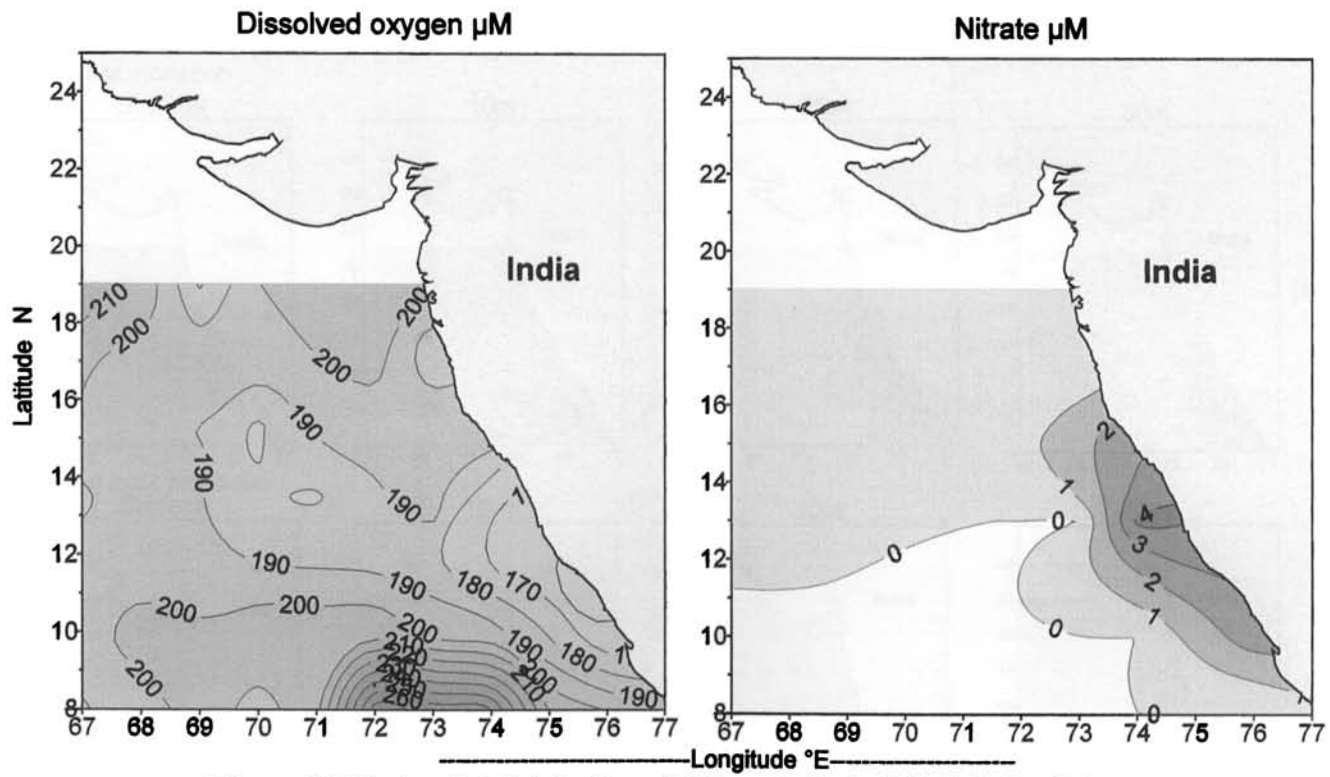

Figure 4.2 Horizontal distribution of DO and nitrate (20m) during fall

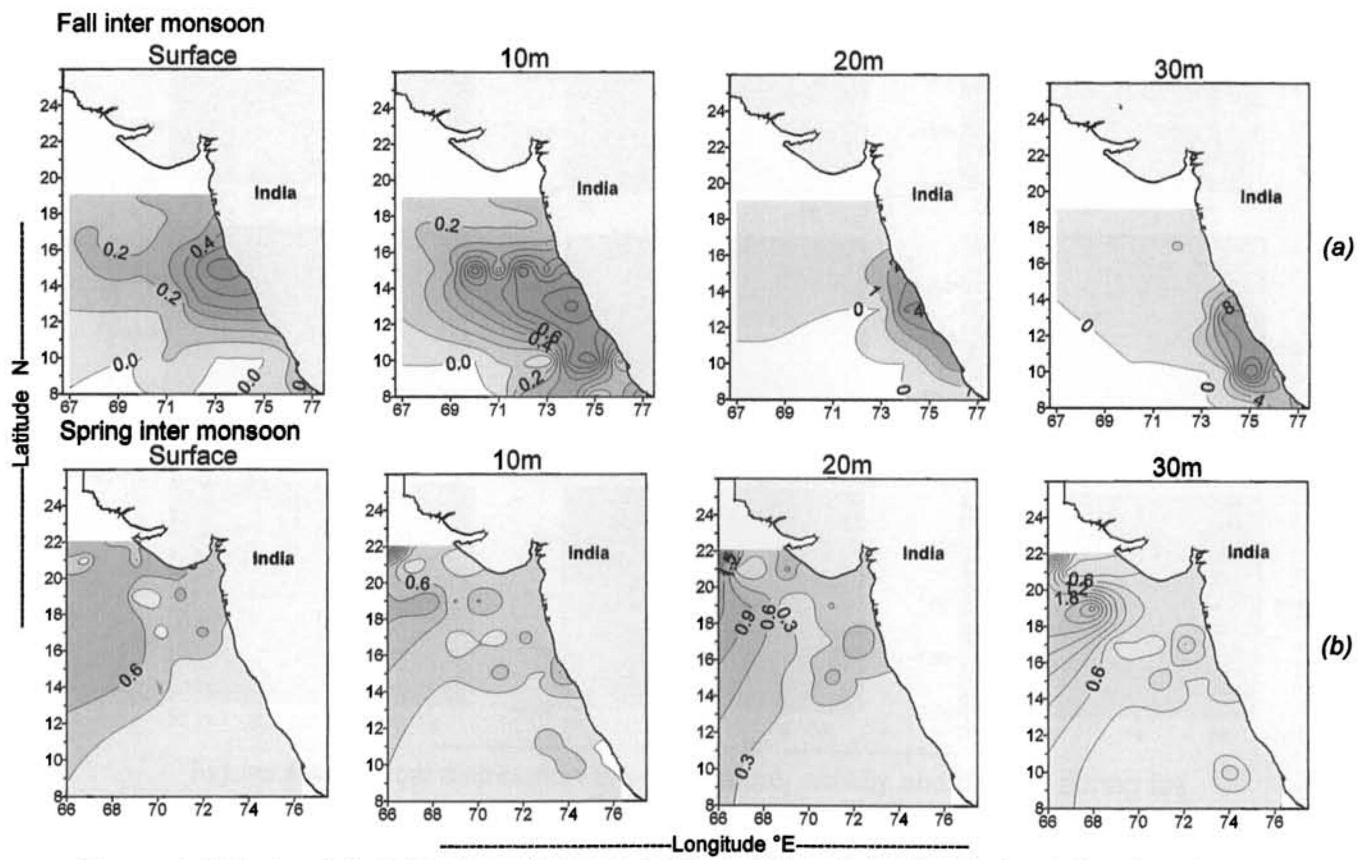

Figure 4.3 Horizontal distribution of nitrate (μM) at different depths during fall and spring

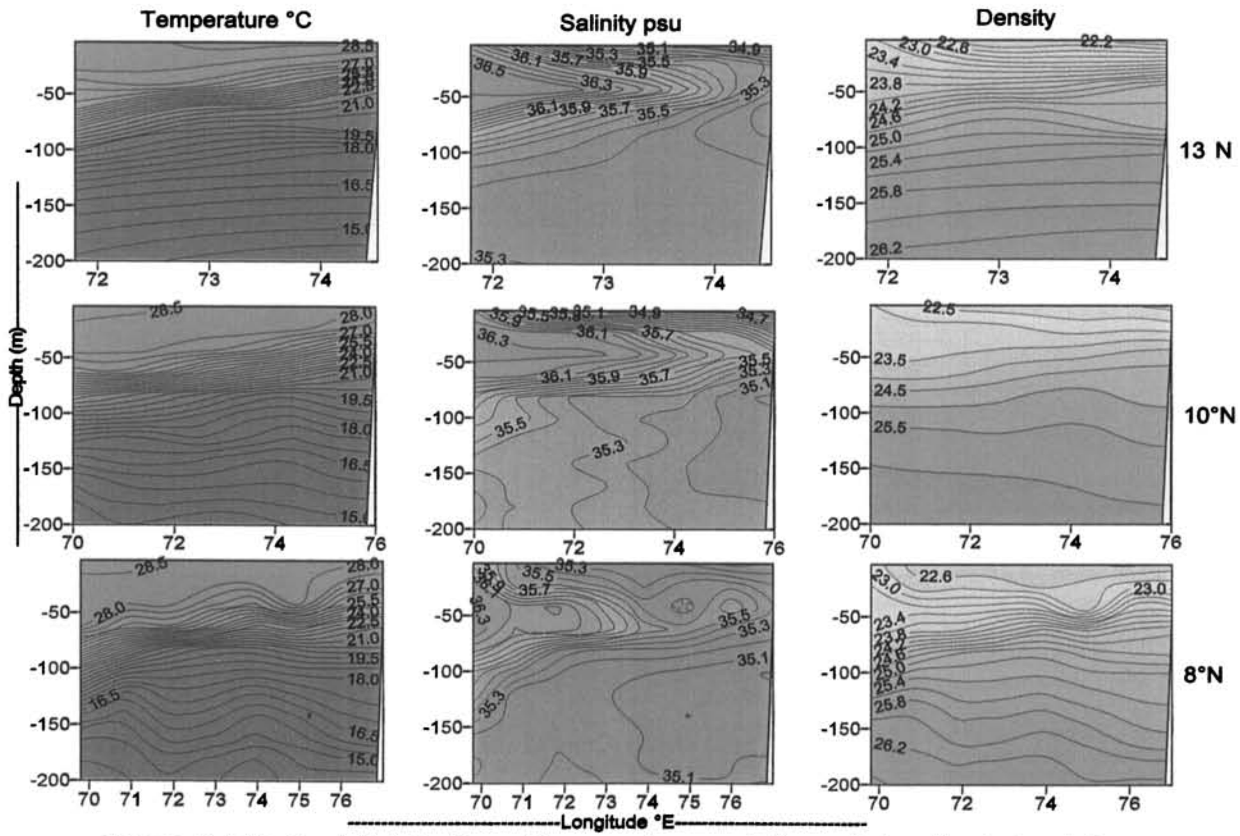

Figure 4.4 Vertical distribution of temperature, salinity and density during fall

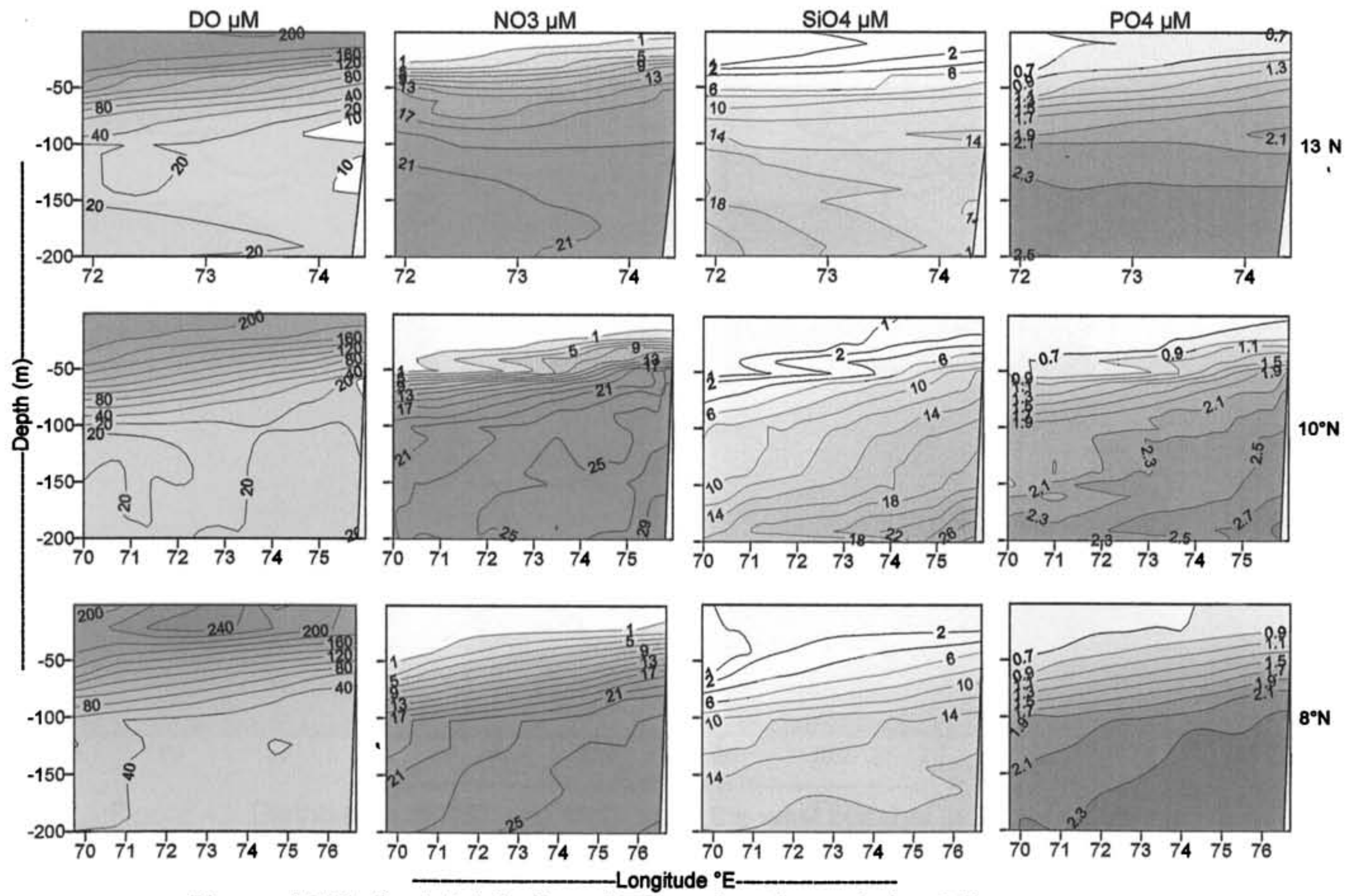

Figure 4.5 Vertical distribution of DO and nutrients during fall

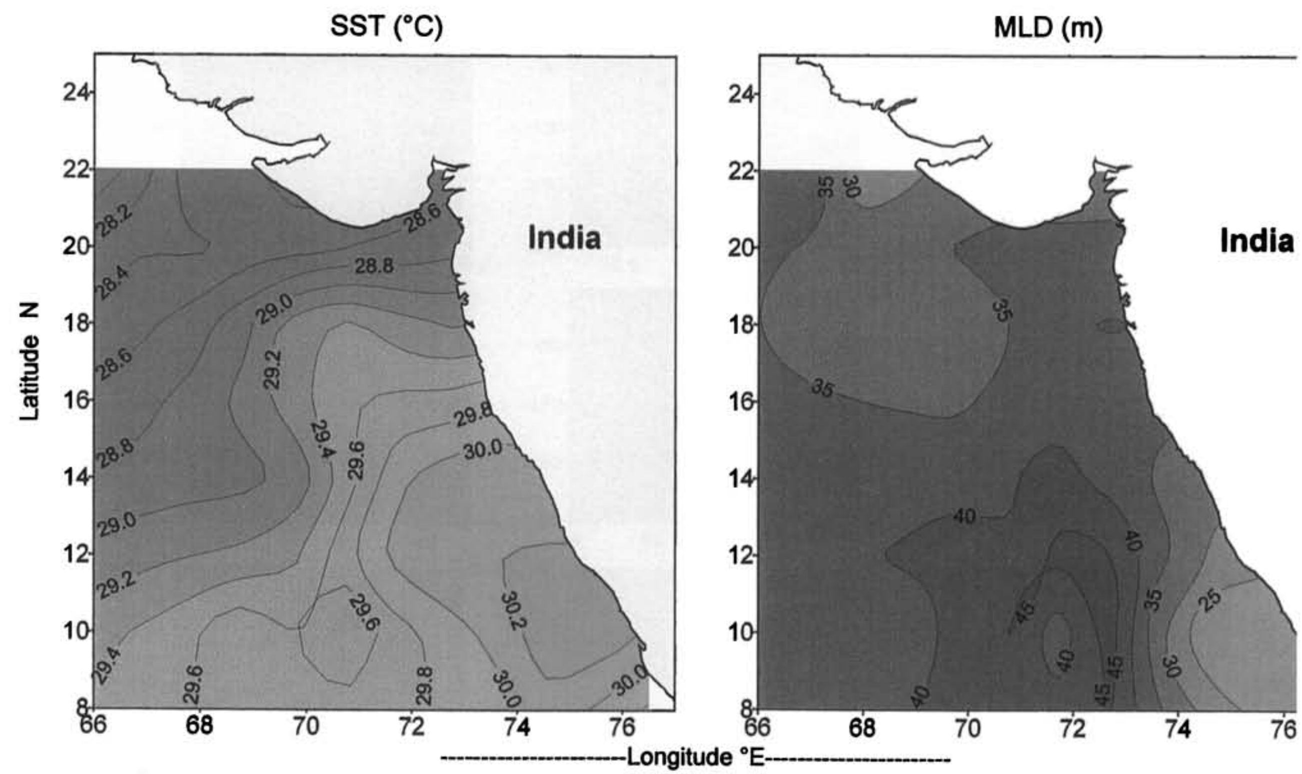

Figure 4.6 Distribution of SST and MLD along the west coast of India during spring

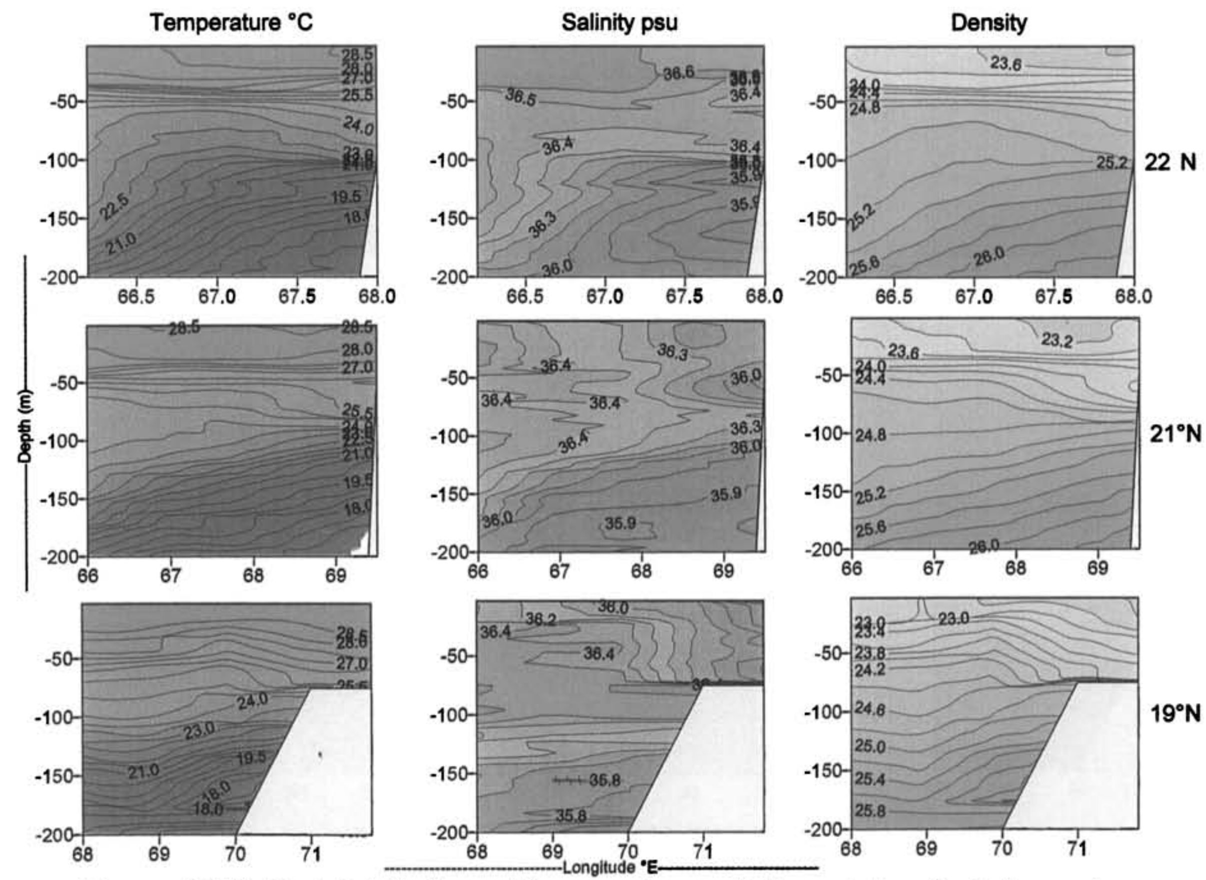

Figure 4.7 Vertical distributions of temperature, salinity and density during spring

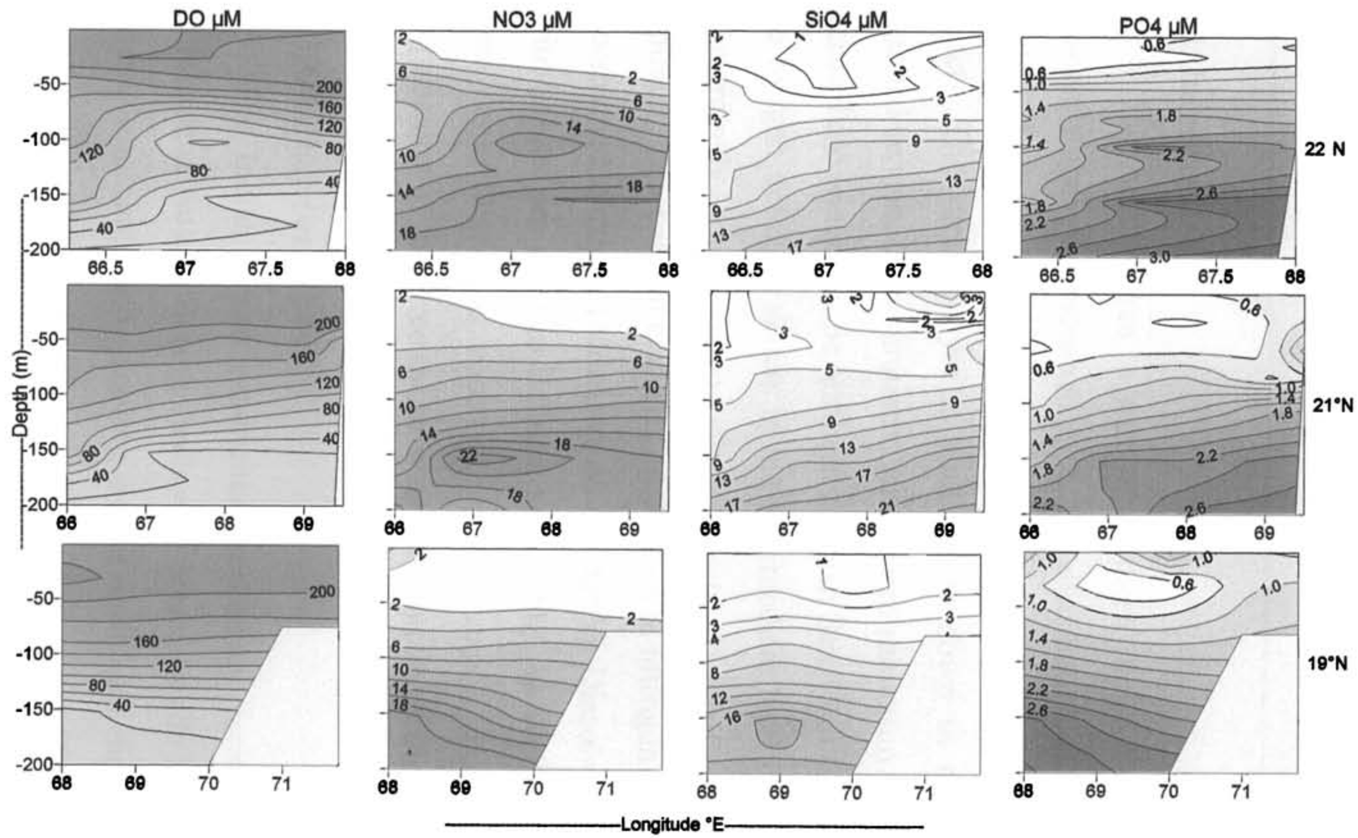

Figure 4.8 Vertical distributions of DO and nutrients during spring

Chapter 5

Oxygen Minimum Zone and Denitrification in the EEZ of the west coast of India

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5. 1. Introduction

The Arabian Sea, a part of northern Indian Ocean, comes under the seasonally changing monsoon gyre. The distribution of dissolved oxygen in the northern Indian Ocean is different from the other areas of the ocean in certain aspects. The surface layer is well mixed down to the thermocline having saturated oxygen concentrations. An oxygen minimum zone is observed in the intermediate waters of the northern Arabian Sea. (Sen Gupta and Naqvi, 1984). The oxygen deficient waters in the intermediate layers are important, because in extremely low oxygen environments, denitrification is a prominent respiratory process that converts nitrate to free nitrogen through different forms of combined nitrogen (Morrison *et. al.,* 1999). Dissolved oxygen, nitrate, and nitrite values are used to delineate the OMZ, as well as to identify regions where denitrification is observed. The suboxic zones in the Arabian Sea comprise one of the three major water column denitrification sites in the world ocean having an annual denitrification rate of 10 - 30 Tg N yr^{-1} (Mantoura *et. al.*, 1993; Naqvi *et. al.*, 1992)

The Indian Ocean experiences seasonally variable surface circulation and related upwelling during south west monsoon (de Sousa *et. al.*, 1996) and convective mixing due to cooling during north east monsoon (Prasannakumar *et. al.*, 2001; Madhupratap *et. al.,* 1996a), resulting in high biological production in the Arabian Sea (Qasim,1977; Jyothibabu *et. al.*, 2004). High biological production and subsequent sinking of organic matter leads to high oxygen demand in the intermediate waters and hence a sharp fall in dissolved oxygen occurs within the thermocline. The strong density gradients prevent any significant exchange of dissolved oxygen from the euphotic zone to layers below the thermocline. The poor horizontal advection due to the semi - enclosed nature of the region prevents the renewal of intermediate waters, making the intermediate layer severely depleted in dissolved oxygen. (Sen Gupta and Naqvi, 1984)

Associated with these suboxic intermediate waters, there occurs a secondary nitrite maximum below the thermocline and within the upper part of the oxygen minimum zone (Joel, 1972). This feature is called secondary nitrite maxima because they normally occur fairly deeper in the water column while the primary nitrite maxima in the oxygen saturated photic zone arise from nitrification (Wada and Hattori, 1971,1972; Codispoti and Christenser, 1985).

The objective of this work has been to relate the distribution of, temperature, salinity, components of nitrogen and nitrate deficit in the OMZ, to assess the geographical extent of denitrification zone in the EEZ of India along the west coast during different seasons.

5. 2. Winter Monsoon

5. 2. 1. Hydrography of the vertical water column

5. 2. 1.a. Temperature

During winter the open ocean and coastal region in the EEZ of the north west coast of India appeared cooler. The permanent thermocline deepened up to approximately 70m (Fig.5. 1 & 2) and the mixed layer to 50 -70m thick. Convective mixing and a deep mixed layer were observed along the northern latitudes (figure in chapter 3). Surface Temperature was below 27.5°C along 18°N decreasing drastically below 26.5°C further north (Fig.5.1 & 2). Below the thermocline, the isotherms showed a downward sloping towards north to about 1000m depth.

5. 2. 1.b. Salinity

During this season surface layers were characterized by Arabian Sea high salinity watermass (ASHSW). The salinity range within the upper 100m along the northwest coast was between 35.7 and 36.5 psu. The high saline (> 35.7) water mass originating in the north could be traced up to 8°N through a subsurface layer (~ 50m) above the coastal transect (Fig.5.1). In the intermediate waters between 200 and 700m a salinity maxima was identified, (35.5 psu), near the continental shelf (Fig.5.1). Along 8°N a lens of low saline (< 34.7) waters were identified indicating the intrusion of low saline Bay of Bengal (BOB) waters during winter (Prasanna Kumar *et. al.*, 2004).

The open ocean transect was also characterized by high saline (35.7 – 36.5 psu) waters in the upper 75m layer (Fig.5.2). Intrusion of high saline waters (> 35.5psu) was observed to about 15°N through the intermediate layer. The core of the deeper salinity maximum was observed at ~ 300m, with a maximum value of 36.0 psu. The intermediate waters along the southern latitudes were of uniform salinity distribution.

5. 2. 1.c. Dissolved oxygen

A vertical profile of dissolved oxygen during North East monsoon (winter) along the coastal transect (figure in chapter 2) is shown in figure 5.1. Exceedingly low oxygen concentrations were found within a large body of intermediate water. The area of oxygen depleted intermediate waters (Defined by DO < 10µM) is referred to as the Oxygen Minimum Zone (OMZ). A rapid increase in thickness of OMZ occurs from 12°N to 18°N between ~ 200 and 750m. This is accompanied by a steady northward decrease in oxygen concentrations reaching below 5µM towards the northern most latitude in the transect investigated. The 5µM "suboxic" layer is an important biological boundary where the oxygen apparently becomes physiologically limiting to many bacteria causing a shift from oxygen respiration to nitrate reduction and denitrification (Devol, 1978). The severe oxygen depletion (DO < 5µM) was found to occupy a large portion of the intermediate layer in the northern Arabian Sea. The oxygen deficient waters < 20µM was observed along the entire transect between 100 and 1000m depth during this season. The thickness of the 20µM patch along 22°N transect increased to more than 900m. The top 100 m layers were highly stratified, except a well-mixed homogenous patch along the northern latitudes, in the upper 50m due to convective mixing (discussed in chapter 3).

In figure 5.2, a similar distribution of DO along the open ocean transect (figure in chapter 2) far from the coast is depicted. It was observed that the lob of 10µM contours extends only up to 14°N transect. This intermediate waters, sinks to 300m, which was at 150 m along coastal transect. A corresponding sinking for the depth limit of the low oxygen (20µM) patch along the northern latitudes also was evident (Fig.5.2). This may be due to the winter cooling effect when the water mass is replenished by convective process in the northern Arabian Sea (Morrison *et. al.*, 1998). Thus, the OMZ gets re-oxygenated as a consequence of evaporative cooling and convective mixing during NE monsoon (Morrison *et. al.*, 1999). In the open ocean the depletion of oxygen below 5µM was restricted to the northern latitudes. A wide band of 5µM contours in the coastal transect near the continental shelf, may be due to the sedimentary action. The organic degradation in the sediment lower the level of dissolved oxygen in the waters overlaying the sediment and the diffusion level of oxygen within the sediments determines the extent to which the redox levels are altered by microbial process (Stanley, 1976)

5. 2. 1.d. Nitrate

Figure 5.1 & 2 shows distribution of nitrate in the upper 1000m water column along the coastal and open ocean transect. The surface distribution of nitrate showed typical winter conditions in the northern latitudes (North of 15°N). The surface waters were rich in nitrate (1-3µM), leaving the southern region nitrate depleted. Below the thermocline depth concentration of nitrate increase with depth reaching > 37μM at about ~ 1000m. In the intermediate waters between 250m and 400m, a downward decrease of nitrate was evident (Fig.5.1) along the northern Arabian Sea, indicating a nitrate loss from the system. Thus, the 31μM nitrate observed at 300m along 8°N was lowered to a depth of ~ 550m along 18°N near the continental slope.

Distribution of nitrate along the open ocean transect (Fig.5.2) was also similar to the coastal transect. The surface waters north of 15°N had high nitrate (1-3μM) with an increasing gradient towards the north. A loss of the intermediate nitrate was also evident in this transect. The 20μM contour of nitrate was trapped between 150m and 300m in the northern region (18°E & 22°E) whereas at the southern region at the same depth registered ~ 22μM nitrate (Fig.5.2). In the deeper waters (below 750m) nitrate showed a northward upsloping with a maximum concentration of 37μM at 1000m.

5. 2. 1.e. Nitrite

During the northeast monsoon, a tongue of secondary nitrite was observed in the intermediate waters (200 - 500m) along the northern latitudes (Fig.5.1 & 2). Secondary nitrate maxima usually below the thermocline is associated with low oxygen concentrations and is believed to result from the reduction of nitrate during the oxidation of sinking organic matter. NO_2^- ion is an intermediate product in the over all process leading to free nitrogen called denitrification (Joel and Fracies, 1972)

Secondary nitrite maxima, with concentration in excess of 0.5μM observed between 200m and 800m with an increase in the width of nitrite patch towards north. During northeast monsoon nitrite concentration of ~ 4μM was observed along the northern latitudes at depth of ~ 400m accompanied with a zone of nitrite removal (Fig.5.1 & 2). An increase in secondary nitrite maxima in the coastal transect may be due to denitrification incorporated in the sediments. The secondary nitrite concentration gradually decreased to the south and at the southern extremity it got reduced to 0.5μM. An interesting feature observed in the distribution of secondary nitrite in the vertical section is the limited vertical mixing and an extensive horizontal transport (Fig.5.1 & 2).

5. 2. 1.f. Nitrate Deficit

In the intermediate waters (100 – 400m) along the coastal transect relatively high nitrate deficit was observed. The highest δN values were centered along the northern latitudes near the continental shelf. During winter, a maximum of 6μM was recorded along this coastal transect. The nitrate deficit was wide spread little above the denitrifying layer (Fig.5.1). In the waters of the open ocean transect, considerable nitrate deficit was encountered (Fig.5.2). The δN values in the area ranged between 1 - 6μM and the maximum was along the northern latitudes (15°N - 22°N). The core of this δN maxima along the open ocean transect was at ~ 500m depth where the secondary nitrite maxima also was observed, and it was shifted up to 150m in the coastal transect.

5.2.2. Horizontal distribution of Oxygen Minimum Zone and Denitrifying layer

Figure 5.8 shows the horizontal extent of OMZ along the west coast of India at different depth strata during winter. From the figure, it is clear that the OMZ (< 10μM) was observed between 100m and 750m. Below this depth the extent of the OMZ was further reduced and got shifted more towards northern region.

Figure 5.9 gives the horizontal extend of secondary nitrite maximum during winter (Defined by > 1μM Nitrite). A zone of denitrification was identified in the three depth layers at 200m, 300m,and 500m. The maximum spreading of denitrifying zone was in 300m layers where it extended up to ~ 10°N along the open ocean region. At 200 m depth layer it got shifted towards north and at 500m it was restricted to a limited area between 17 to 18°N.

5. 2. 3. Discussion

Winter monsoon season is characterized by cold (< 26.5°C) surface waters along the north (North of 20°N). Towards south the sea surface temperature gradually increases (> 28°C). The surface waters upto about 50m along the northern end of the transect (Open ocean and coastal) were homogenously cold, as indicated by the sharp peak of isotherm to the surface (Fig.5.1 & 2). Below the thermocline depth the isotherm showed a latitudinal down sloping towards the north imparting a spatial difference in temperature between the south and north transects. Vertical water column structure of salinity images two salinity maxima during winter. The ASHSW originating from the north penetrates to south reaching far beyond 10°N, through the subsurface layers within upper 100m. Another salinity maxima (35.6 - 35.0 psu) associated with the OMZ was found trapped between 250 and 600m

During winter a severe depletion of oxygen (> 5μM) was found wide spread in the intermediate waters with a maximum southward extend to ~ 12°N (Fig.5.1). From the horizontal and vertical distribution of DO at different depth strata, it was obvious that the OMZ during winter lies between 100 and 750m, with a maximum spreading at 300m depth layer (Fig.5.8). Formation of secondary nitrite maxima was high and the thickness of the denitrifying zone during this season was ~ 500m. It was observed to be most intense among the four seasons considered, with its southern boundary at ~8°N, indicating the active denitrification, leading to nitrate deficits (Naqvi, 1994). During this season, the core of denitrifying layer was projected at about 300m.

Along the open ocean transect, a considerable loss in nitrate concentration was evident especially between 300 and 500m, the depth range where secondary nitrite maxima occurred. The 31μM contour of nitrate observed at 300m along the southern latitudes sinks to 500m along the northern latitudes in the coastal transect. Reduction of nitrate to nitrite would be the main process to occur when organic substrate levels are high (Anderson *et. al.*, 1982). Similar down sloping was observed in deeper depths also. Above 300 m nitrate concentration was almost horizontal except surface 50m of northern transects where the convective mixing prevailed.

5. 3. Spring Inter monsoon

5. 3. 1. Hydrography of the vertical water column

5. 3. 1.a. Temperature

Along the coastal transect the surface temperature depicted a general northward increase (Fig.5.3). The surface waters south of 14°N were warmer (> 30°C) whereas the surface waters north of 19°N were comparatively cold with temperatures < 28.5°C. The isotherm of 28.5°C traced at ~ 30m depth along 8°N reached the surface along 19°N. Between 100 and 150m the isotherm are thickly clustered offering an increased gradient within this depth strata. Below 200m the isotherms were observed bending down towards north, with a marked shift between 200 and 400m.

Towards the north of 19°N, along the open ocean transect the SST was relatively lower than the coastal transect (Fig.5.4). The 27.5°C isotherm observed at 75m along 8°N reached the near surface waters along 21°N. The surface water between 8°N to 12°N remained warmer (~ 30°C), but the depth zone 100 - 150m were highly stratified especially along the southern region. A considerable northward down sloping of isotherms were observed between 200 and 300m.The 15°C contour of temperature at 200m along 8°N dipped down to 350m along 22°N.

5. 3. 1.b. Salinity

During spring inter monsoon the surface waters along the northern region of the coastal transect showed a similar salinity structure as that of winter. The high saline waters (35.7 - 36.7 psu) in the upper 150m got diluted towards south and reached up to 10°N at 100m. The core of this ASHSW lies at about 75m between 14°N and 18°N with a maximum salinity of 36.7 psu. At the surface between 8°N and 14°N a 25m thick lens of low saline Bay of

Bengal (BOB) waters was evident (Fig.5.3) and the effect of dilution with BOB waters was observed up to 18°N through the surface. The salinity structures in the intermediate waters during spring also showed a southward doming of 35.5 psu isohaline to about 16°N. The core of this intermediate high saline water patch was at ~ 300m with a maximum salinity of 36.1 psu. Waters below 150m along the southern transects exhibited homogeneous salinity.

Along the open ocean transect the intrusion of high saline (> 35.7 psu) waters through the sub surface layer reached up to 8°N at 100m depth (Fig.5.4). The surface waters upto 175m depth along the northern transects were highly saline (> 36.4 psu). The intermediate salinity maximum (> 35.5 psu) did not exceed southwards beyond 16°N. The core of this salinity maximum was at 300m with a maximum value of 36.0 psu. The salinity of the intermediate water in the coastal areas was found to be uniform along the southern latitudes.

5. 3. 1.c. Dissolved Oxygen

The surface layers along the coastal transects were saturated with oxygen (DO > 200μM). In the northern region, the surface saturated layer extended down to ~ 60m. At the thermocline depth oxygen contour were strongly stratified (Fig.5.3). Below the thermocline depth oxygen concentration diminished considerably to < 10μM. This oxygen depleted zone was observed in the intermediate waters between 150 and 800m. The thickness of the OMZ was high (600m) along the northern transect (22°N), which gradually decreased (50m) towards south (10°N). The oxygen concentration in the intermediate waters (150 - 400m) was ~ 20μM along 8°N. In the deeper waters oxygen concentrations increased.

During this period, the open ocean surface waters (~ 50m) were saturated with oxygen (DO > 200μM). Below 50m the DO contour were densely packed upto ~150m. Drastic depletion in oxygen content was evident in the intermediate waters (200 – 1000m) especially along the northern region of the transect (Fig.5.4). Waters with oxygen > 10μM occupied a larger part of a water column at the intermediate depths. Thickness of the OMZ (DO < 10μM) was considerably low (~ 25 m) along the southern latitudes (10°N), whereas it widened to about 800m towards the north (22°N). Intense depletion of oxygen observed as a patch of < 5μM was trapped within the intermediate waters at about 250m between 16°N and 20°N.

5. 3. 1.d. Nitrate

The surface waters along the coastal transect recorded very low nitrate except at some stations where nitrate ~ 1μM was present in the surface along the northern region. A sinking of nitrate contour was observed in the middle of the transect (Fig.5.3). Thus, 17μM of contour of nitrate observed at 150m along 8°N went down to 200m along 14°N and then recovered again to 150m along 22°N. Below 200m the nitrate contour run almost parallel to the transect. Nitrate concentration increased with depth reaching 34μM at 1000m.

In the open ocean transect, the surface waters along the northern end (22°N) were observed to be rich in nitrate (>1μM). The surface waters along southern transects remained oligotropic with non-detectable level of nitrate (Fig.5.4). The 1μM contour at ~ 75m along 8°N, peak up to the surface between 20°N and 22°N. A sinking tendency of nitrate was evident between 100m and 200m along 10°N to 14°N latitudes. In the intermediate waters (200 - 400m) along the northern latitudes (19°N - 22°N) a sharp down welling of nitrate contours was identified. The 17μM contour of nitrate at 200m depth running parallel to the transect, was found to fall down to ~ 350m at 19°N (Fig.5.4). Consequently a marked loss in nitrate concentration was observed between 19°N and 22°N, within the intermediate waters. Below 400m nitrate showed an increasing trend up to 1000m without any north south gradients. The maximum concentration observed was 34μM.

5. 3. 1.e. Nitrite

A tongue shaped secondary nitrite concentration (> 1μM) was observed far north of the coastal transect, within the intermediate waters (150 - 500m). During this season secondary nitrite ranged between 1μM and 4μM. Along this coastal transect the contours with high nitrite was concentrated between 250 and 350m (Fig.5.3). The southern limit of the secondary patch extended up to ~ 11°N. Along 22°N, near the continental shelf, nitrite value got reduced to1.5μM. In the deeper waters (below 500m) ~ 0.5μM nitrite concentration was recorded. In the surface waters nitrite concentration was below detectable level.

In the open ocean transect during spring the nitrite concentrations ranged between 1μM - 4μM and occupied the intermediate layers (150 - 500m). The core of the secondary nitrite patch remained between 250 and 350m in the coastal transect. The southern limit of this patch slightly shifted south to 10°N at 400m. Detectable level of secondary nitrite concentrations were recorded below 100m depth (Fig.5.4)

5. 3. 1.f. Nitrate Deficit

The vertical section of the nitrate deficit computed during spring inter monsoon along the coastal transect is shown in the figure 5.3. The highest value computed was 7μM in the intermediate waters of the northern transects. The core of nitrate deficit patch was between 300 and 400m. The nitrate deficit in the open ocean transect was observed high in magnitude, ranging between 1 - 11μM. The core of the patch was observed between 250 and 400m where the secondary nitrate maxima were identified (Fig.5.4). In this transect a larger part of the intermediate waters suffered relatively high nitrate loss.

5. 3. 2. Horizontal distribution of the OMZ and denitrifying zone

Figure 5.10 shows the horizontal distribution of DO at different depth strata. The OMZ is marked by 10μM contour. Maximum spreading of oxygen depleted waters were at 200m extending up to 10°N. From the distribution pattern it is evident that the OMZ was between 200 and 1000m. Figure 5.11 portrays the lateral extend of denitrification in the west coast of India during spring. Patches of secondary nitrite, marked by 1µM contour were observed at 150m, 200m, 300m and 500m. The denitrifying zone got concentrated to the northern part off the west coast except in 150m, where it was concentrated between 18°N and 14°N (Fig.5.11). The maximum southward extension of denitrifying zone was noticed at 300m depth, where it extended up to 10°N along the open ocean region. At 500m denitrifying zone got shrunk between 22°N and 18°N.

5. 3. 3. Discussion

Spring inter monsoon, being a period of transition is expected to be the heating season (Prasanna Kumar *et. al.*, 2001). The surface distribution of temperature along the coastal and open ocean transects indicated a northward up sloping of isotherms in the surface layers, suggesting the existence of relatively cool surface waters in the north during the study period. From the temperature pattern, it is clear that along the northern region the open ocean waters are cooler than coastal waters (Fig.5.3 & 4). Salinity distributions showed the existence of two salinity maximum within the 1000m water column. One in the upper 150m (ASHSW) and the other between 200 and 400m. The deep salinity maxima (> 35.5 psu) was associated with the OMZ and denitrifying layer. Salinity increased steadily towards north at any given depth in the Arabian Sea (Wyrtki, 1971).

The vertical span of the OMZ is largest during spring where O_2 concentrations are < 10µM between ~ 150 and 800m. During this season isolated pockets of oxygen concentrations < 10µM were observed spreading in a large part of the 200m strata (Fig.5.10). Reduction in nitrate concentrations and elevated nitrite concentrations in the oxygen-depleted waters suggest significant denitrification during spring (Morrison et. al, 1999). The peak value in δN (> 9µM) were observed in the open ocean during this season. The highest deficit observed during this period was 11.3 μM at the northern region. Along the coastal transect the nitrate deficit ranged between 1 - 9 μM. During this season the secondary nitrite patch was of ~ 350m thick with its core at 300m. It was widely spread in a larger area of the northern part of the study region. The core of this patch usually occurred at ~ 300m (Somayajalu *et. al.*, 1996). Denitrification explains lack of equivalently high nitrate (Fig.5.4) during this season. Nitrate concentration was found decreasing in the OMZ along the open ocean region. As discussed above the co - occurrence of sub oxic conditions and nitrite maxima are signals of denitrification, which is dominant respiratory path way and fixed nitrogen is being reduced to free nitrogen gas (Olson, 1981).

5. 4. Summer monsoon

5. 4. 1. Hydrography of the vertical water column

5. 4. 1.a. Temperature

The vertical distribution of temperature along the coastal transect is given in figure 5.5. The upliftment of isotherm along the southern side of the section reveals the presence of the upwelling phenomenon. Surface waters were generally cool with an average temperature of 28.5°C. The sub surface (~ 30m) waters from the northern region (10 - 18°N) was observed at the surface of the southern latitudes (South of 10°N). The isotherms between 50 and 100m were highly stratified. Below 100m the isotherms showed a general down sloping towards north.

5. 4. 1.b. Salinity

During summer the existence of ASHSW was restricted to ~ 70m depth along the northern transects (Fig.5.5). The southward intrusion of this high saline water mass at a depth of 50m was checked at about 13°N. An intrusion of high saline waters through the intermediate layers was restricted to north of 16°N. The core of this high saline patch was observed at 400m with a maximum value of 35.6 psu. These surface waters along the southern transects also had comparatively high salinity (> 35.0 psu). The salinity distributions of the intermediate waters along the southern transects were uniform up to 1000m.

5. 4. 1.c. Dissolved Oxygen

During summer only one transect nearer to the coast is considered because of the lack of sufficient observations in the oceanic region for comparison. The surface waters exhibited a general decrease in oxygen saturation, with DO concentrations not exceeding 200μM. However the surface waters along the southern region were comparatively less oxygenated (DO < 190μM). The surface oxygen contours showed an upsloping towards south. The 190μM contour of DO at ~ 50m along the northern side of the transect bend up to the surface at ~ 11°N (Fig.5.5). This is because of the upwelling mechanism prevailing over the southern regions of the west coast. Along the transect investigated, OMZ (DO < 10μM) shifted to the northern side of the transect and was associated with the continental shelf (Fig.5.5). This zone is observed between 200 and 350m. Waters with DO < 20μM was found to spread southward to about 15°N. The width of this water body was maximum at the northern end between 100 to 950m. Along the southern latitudes, the intermediate waters had DO concentration above 20μM.

5. 4. 1.d. Nitrate

The vertical distribution of nitrate up to1000m along the coastal transect, during a typical summer monsoon period is illustrated in figure 5.5. The surface waters between 8°N and 10°N were enriched in nitrate (> 1μM). The 1μM contour of nitrate at a depth of ~ 30m along 17°N, surfaced near 8°N latitude due to upwelling. Upsloping of nitrate contour was observed up to ~ 60m.

Surface waters in the northern side of the transect were devoid of nitrate. In the intermediate waters of the transect, distribution of nitrate showed a considerable down sloping, where an oxygen depletion has been observed (Fig.5.5). The 27μM contour of nitrate observed at a depth of 250m along 8°N transect shifted down to 350m along 17°N transect. In the deeper waters (below 500m) nitrate concentrations increased gradually and reached a maximum of 37μM without any north - south gradients.

5. 4. 1.e. Nitrite

Secondary nitrite concentrations during summer ranged between 1 - 3μM. The thickness (250m thick) and magnitude of secondary nitrite patch was high along northern regions. The thickness of the high nitrite tongue sharpened towards the south (Fig.5.5). During this season the secondary nitrite patch along the coastal transect reached up to 8°N between 300 and 400m. The core of the patch was observed between 350 and 400m depth. A slight enrichment in nitrite concentration was observed (> 0.5μM) within the shallow depths along the southern transects.

5. 4. 1.f. Nitrate Deficit

The pattern of distribution of δN in the EEZ of the west coast of India during summer monsoon along the coastal transect is shown in figure 5.5 The δN values ranged between 1 - 4μM in summer. From the figure it is evident that the nitrate deficit was concentrated only in the northern region of the transect. The core of the nitrate deficit patch (3 - 4 μM) was trapped between 250 and 400m. Traces of nitrate deficit was located at 11°N (Fig.5.5).

5. 4. 2. Discussion

During summer, the surface temperature contours was found to slope up towards south and sloped down in the intermediate waters towards north. The surfacing of contours of temperature, DO and nitrate clearly indicated an upwelling along the southwest coast of India. The ASHSW originating from north intrude south through the subsurface layers. The 35.6 psu salinity contour in the ASHSW mass reached up to 9°N during this season at about 50m depth. In summer, the bulging of 35.5 psu contour was restricted to 16°N in the intermediate waters.

The oxygen depletion was located below the thermocline. The OMZ, marked by 10μM contour of DO, occupied only a smaller water body in the intermediate waters of the northern region 200 - 350m (Fig.5.5). The oxygen content of the intermediate waters along the southern side was comparatively higher than the other seasons (~ 40 - 30μM). The reduction in nitrate levels towards north and the nitrite maximum occur at approximately the same depth, but the two do not coincide laterally. The core of the secondary nitrite patch was seen towards the northern transects, which gets diluted towards south. The secondary patch penetrated through the intermediate waters reached up to 8°N. In the shallow waters along the southern region a thin layer of considerable nitrate with concentration ~ 0.5μM was observed within a narrow depth range (Fig.5.5). Brendhorst (1959) attributed the high nitrite concentrations in thermocline waters of the ocean to the activities of the nitrifying bacteria, whereas Vaccaro and Ryther (1960) felt that excretion of nitrite by phytoplankton was mainly responsible for the high concentrations. Olson (1981) suggested photo inhibition as a possible mechanism, which allows accumulation of nitrite in the narrow band in the euphotic zone.

The δN maximum was associated with secondary nitrite patch where the nitrate concentration showed a decrease in the intermediate waters (Fig.5.5). The δN patch shifted more to the north. The horizontal extend of nitrate deficit to the south was 11°N. The maximum value of δN computed during summer monsoon did not exceed 5μM.

5. 5. Inter monsoon Fall

5. 5. 1. Hydrography of the vertical water column

5. 5. 1.a. Temperature

The temperature distribution during fall inter monsoon along the coastal transect is shown in figure 5.6. The surface waters along the northern latitudes were observed to be warmer (~ 30°C) than the southern latitudes (< 29°). The isotherms between 50 and 100m were thickly stratified. The isotherms below 100m were observed to be down sloping towards the north, making the intermediate waters along the northern region warmer than the south (Fig.5.6).

The open ocean surface waters during this season were generally warm (~ 30°C). The isotherms between 50 and 100m were thickly clustered indicating the existence of a strong thermocline (Fig.5.7). The temperature contours between 200 and 400m showed a drastic down sloping towards north. The 14°C contour observed at 200m along 8°N was traced at 400m along 19°N. The deeper waters also showed a down sloping tendency towards north.

5. 5. 1.b. Salinity

The salinity distribution along the coastal transect resembles that of summer (Fig.5.6). The upper 50m waters were highly saline (35.7psu - 36.6 psu). Like in summer this high saline water mass was traced up to 10°N. The existence of low saline BOB waters was absent in the surface layers along 8°N. The southward pushing of the high saline (> 35.5 psu) water was evident up to 15°N. The core of this high saline patch was shifted down to 400m during fall inter monsoon.

In the open ocean transect a thick layer (~ 200m) of ASHSW was observed along the northern latitudes (Fig.5.7), with its core nearer to the surface. This high saline patch penetrates towards south reaching beyond 8°N at 50m. The deeper salinity maximum (> 35.5 psu) was observed between 200 and 800m. The southern boundary of this high saline patch extends up to 15°N.

The intermediate waters along the southern latitudes were uniformly distributed in salinity up to 100m.

5. 5. 1.c. Dissolved Oxygen

A north south distribution of dissolved oxygen upto 1000m depth along the coastal transect is shown in figure 5.6. The surface layers up to ~ 25m was saturated with ~ 200μM of oxygen along the entire transect. Between 50 and 100m the oxygen contours were thickly stratified. Below 100m, the oxygen content reduced considerably. A severe depletion of oxygen (DO < 5μM) was observed along a smaller part of the northern region between a depth of 200 and 800m. The 10μM contour of dissolved oxygen observed between 150 and 850m extended up to 16°N. The intermediate waters along the southern part of the transect was comparatively rich in oxygen. It is clear from the figure that the oxygen content in the intermediate water was > 20μM to the south of 14°N.

The surface waters along the open ocean transect were oxygenated (DO > 200μM). Like the coastal transect thick clustering of oxygen contours were also evident between 50 and 100m (Fig.5.7). Along the open ocean transect intermediate waters with DO < 10μM was observed only in a smaller body of water column (150 - 400m) at the northern end of the transect. Intermediate waters with DO < 20μM was observed between 100 and 150m along 8°N, whereas the thickness of this water parcel increases towards north between 200 and 1000m. A small patch of low oxygenated water with DO < 5μM was identified between 100 and 150m in the northern side of the transect (16°N - 18°N).

5. 5. 1.d. Nitrate

Along the coastal transect the surface waters (~ 25m) were devoid of nitrate. The nitrate contours below 50m showed a down sloping towards north up to 400m (Fig.5.6). The 25μM contour observed above 200m along 8°N deepened to ~ 400m along 18°N. A pool of 25μM contour was evident between

200 and 300m indicating a nitrate loss in the intermediate layers along the north. Below 400m nitrate concentration increased gradually without any north - south gradients. The maximum concentration observed was 33µM at 1000m.

Even though the surface waters are depleted in nitrate along the open ocean transect, a minor peak of 1 µM contour was evident as shown in figure 5.7. The waters between 50 and 100m were highly stratified with nitrate contours running parallel to the transect. Below 100m the nitrate contours down welled sharply towards the northern side of the transect up to 350m. The 21µM contour of nitrate running straight at about 100m took a sharp bend at 16°N to reach 250m at 19°N (Fig.5.7). From 400m down, nitrate concentration increased to 34µM at 1000m.

5. 5. 1.e. Nitrite

The low oxygenated intermediate waters of the Indian EEZ contain considerable quantities of nitrite, which could vary between different seasons. During this season, a patch of secondary nitrite was observed in the intermediate waters between 200 and 500m. The concentration of nitrite ranged between 0.5 - 2.5µM. The thickness of the secondary nitrite layer increased towards the north, with a maximum thickness along 19°N (~ 300m thick). The core of the secondary nitrite patch was observed at ~ 300m depth. The 2µM contour of nitrite was observed along the northern end of the transect which is concomitant with oxygen depleted water body (Fig.5.6). The southern limit of the secondary nitrite patch reaches almost closer to 8°N along the costal transect. It is evident from the figure 5.6 that the nitrite maximum is clearly associated with the nitrate minimum.

In the open ocean transect the thickness and magnitude of secondary nitrite patch was found to increase (Fig.5.7). The upper limit of the secondary nitrite patch shifted up to 100m in this transect and the value reached 3µM along the northern region of the transect. The southern limit of the secondary layer extends up to 10°N. Secondary nitrite maxima was observed between 100 and 400m along 18°N. The core of the secondary nitrite maximum was shifted up to 200m along this open ocean transect.

5. 5. 1.f. Nitrate deficit

Figure 5.6 demonstrates the vertical distribution of δN along the coastal transect during fall inter monsoon. The values ranged between 1 - 7μM. Like the other seasons the δN concentration was prominent along the northern part of the study region. The δN patch in the intermediate waters were observed between 200 and 600m. In the open ocean transect the core of the δN patch was located at 200m with a maximum concentration of 7μM along 19°N (Fig.5.7). In terms of magnitude, nitrate deficit was rather high in the open ocean than the coastal waters.

5. 5. 2. Horizontal Distribution of the OMZ and denitrifying zone

During fall inter monsoon the OMZ was extended only up to ~ 14°N (Fig.5.12). The maximum spreading of the oxygen minimum zone was observed at 500m depth. OMZ was not observed in the 1000m depth strata. The secondary nitrite patch (defined by 1μM) extents upto ~ 14°N except in the 500m layer where it extended beyond 10°N in the open ocean region (Fig.5.13). Secondary nitrite patch was observed only between 150 and 500m depths.

5. 5. 3. Discussion

Fall inter monsoon season is a transition season between summer and winter. This season is characterized by warm waters at the surface. However there was a difference in temperature between the southern side and the northern side of the study region. The surface waters of the northern side the open ocean and coastal transect were warmer (> 30°C) than the southern side (< 29°C). The observed decrease in temperature along south can be attributed to the after effect of southwest monsoon. Similar to the other seasons the isotherms in the intermediate waters during fall inter monsoon sloped down to the northern latitudes (Fig.5.6 & 7). During this season the 35.7 psu salinity contour of the ASHSW intrudes upto 9°N in the coastal transect. In the open ocean transect the intrusion was beyond 8°N towards south. The southward intrusion of the intermediate salinity maximum (> 35.5 psu) varies between the open ocean and the coastal waters. In the coastal transect investigated the intrusion was restricted to 15°N whereas it could reach only up to 14°N in the open ocean transect.

During this season the water mass up to 100m were highly stratified. Below this depth a substantial depletion of oxygen was evident. The depletion of oxygen was more towards north. The intermediate waters south of 14°N had an oxygen concentration > 20μM. Waters with oxygen content < 10μM was observed along the northern part of the study region. A severe depletion of oxygen (< 5μM) along the northern side of the coastal transect was associated with the interaction processes of the continental shelf region (Fig.5.6). Sediments along the Indian and Pakistan coasts are expected to experience vigorous denitrification due to high biological productivity of the overlying waters (Bange *et. al.,* 2005). Though weak in magnitude a patch of secondary nitrite was found in the intermediate waters concomitant with the oxygen minima and an intermediate salinity maximum. Deuser *et. al.*, 1978 stated that the secondary nitrite associated with low oxygen encountered within the layer of maximum salinity, which has its origin in the Persian Gulf and occur at a depth range of 200 to 400m.The thickness and magnitude of the secondary nitrite patch varied between the coastal and open ocean waters. A nitrate loss was evident associated with the depth range where the secondary nitrite occurred. The maximum value for δN was located within the denitrifying zone. The OMZ was observed between 100 and 750m during fall inter monsoon. During this season the lateral shift of the OMZ was restricted to ~ 14°N (Fig.5.12). The denitrifying zone was identified between 150 and 500m (Fig.5.13).

5. 6. AOU - Nutrient Relationship

The evidence for denitrification is best visualized by a plot of calculated Apparent Oxygen Utilization (AOU) versus the sum of nitrate and nitrite (Deuser *et. al.*, 1978). Such plots obtained during different seasons are shown in figure 5.14. The secondary nitrite zone is clearly separated in the plots (top clustering). The points representing secondary nitrite maximum are clustered to the left of the mean positions of points. During winter (r^2 = 0.86) and spring (r^2 = 0.82), a pronounced change in slope can be recognized in the AOU - Nitrate plot, indicating an apparent removal of nitrate. In summer monsoon (r^2 = 0.9) and fall inter monsoon (r^2 = 0.83) the change in slope was not so pronounced indicating a reduction in the denitrifying intensity.

The plot showing the relationship between AOU - Phosphate also depicts recognizable signals of denitrification intensity (Deuser *et. al.*, 1978) (Fig.5.15). During winter (r^2 = 0.78) and spring (r^2 = 0.82) when intense denitrification occurs, a bulging in phosphate points to the left from the mean positions, was evident. Whereas in summer monsoon (r^2 = 0.94) and fall inter monsoon (r^2 = 0.73) the scatter plots of AOU versus Phosphate did not show any marked deviation from the mean positions.

5. 7. Conclusion

A depletion in oxygen in the intermediate waters, which is a prerequisite to denitrification, was observed in almost all the seasons (Winter, Summer, Spring intermonsoon and Fall intermonsoon). The northern part of the Arabian Sea contains one of the most pronounced oxygen minimum zones found anywhere in the world oceans. Except summer monsoon in all other seasons oxygen depletion drops below 5µM along the northern part of the EEZ of the west coast of India. The OMZ occupied a larger geographical extend in the EEZ during winter, indicating the maximum horizontal shift. During north east monsoon the renewal of these oxygen deficient waters are sluggish because of the restricted trans equatorial transport of high oxygenated waters in the western Indian Ocean (Swallow 1984) and the absence of northward subsurface current (Shetye *et. al.*, 1994). In accordance with these physical conditions an increased supply of organic carbon (Ittekkot *et. al.*, 1987 ; Nair *et. al.*, 1989) could probably trigger an intense reducing condition in this region. The vertical and horizontal extend of the OMZ shrinks considerably during summer monsoon. Only a 150m thick band of OMZ could be traced during this season with its southern limits at 17°N, since the renewal of oxygen deficient waters is rapid during southwest monsoon (Naqvi, 1990).

Irrespective of the seasons, two salinity maxima have been identified in the vertical structure along the study area: One within the upper 150m and other in the intermediate waters (200 - 800m). A high salinity core of the ASHSW is normally noticed within the top 200m depth (Prasanna Kumar and G Prasad, 1999). In the northern Arabian sea the Persian Gulf waters spreads southeastward at depths of 200 to 400m (Premchand *et. al.*, 1986).

On a geographical scale (both vertical and horizontal) the denitrifying intensity varies with seasons. Somayajulu *et. al.*, 1996 has identified seasonal variations in intensity of denitrification with maximum being observed during winter. In the present study, a wider coverage in the EEZ of the west coast of India during different seasons inferred a significant seasonality in the denitrification propelled by, changes in primary productivity in the overlying waters. The horizontal extend of denitrification zone also changes with time in the eastern Arabian sea, where the southern boundary extended up to 8°N during winter. The seasonal variability in denitrification in the Arabian Sea has the potential to alter the oceanic nitrogen inventory (Naqvi *et. al.,* 1990; Morrison *et. al.,* 1998; Bange *et. al.*, 2005).

The nitrate deficit (δN) was maximum at 300m in almost all the seasons except during winter where it was around 500m in the open ocean and 150m in the coastal region. However, noticeable discontinuity in the δN distribution was observed in some seasons, which could be attributed to the deep vertical movement of eddies and the advection of subantarctic waters in to the northern

Arabian Sea (Naqvi and Sen Gupta, 1985; Kesava Das *et. al.*, 1980). The maxima in δN occurred where minima in nitrate observed. In winter, the peak values of δN occurred slightly up at the coastal belt in the EEZ. However in most other seasons the extrema in various properties were generally located at the same depth level. Consequently, the principal maximum in nitrate deficit usually occurs in conjunction with the intermediate salinity maxima. The absolute value of δN are not always correlated with the concentration of secondary nitrate, in conformity with the results of Naqvi *et. al.,* (1982). Among the four seasons the highest value observed for nitrate deficit (> 10μM) was in the spring inter monsoon.

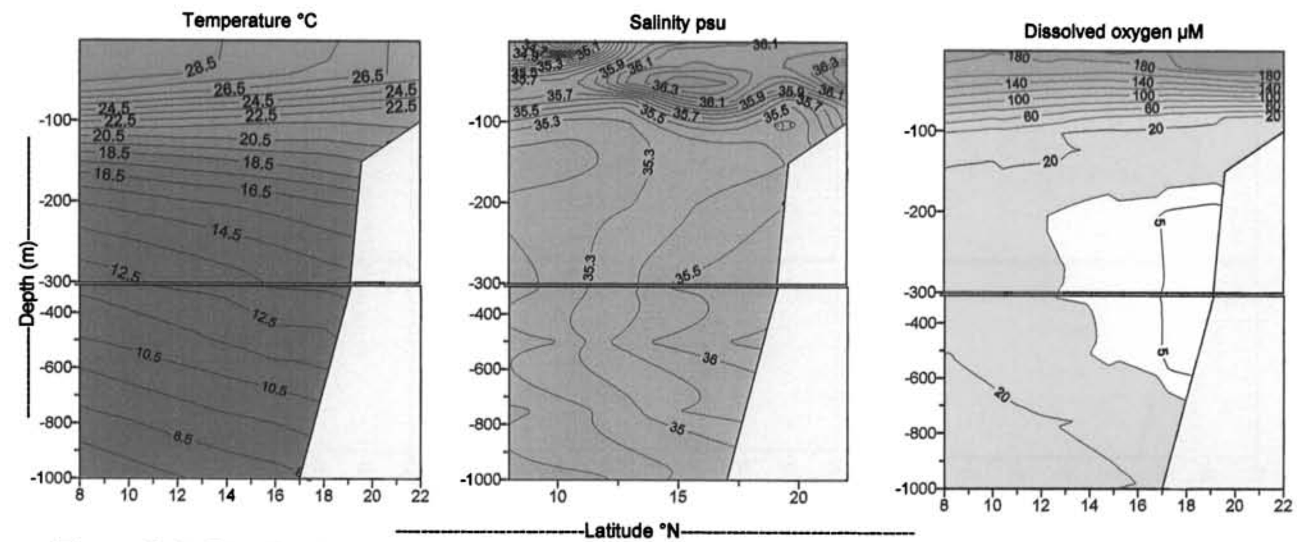
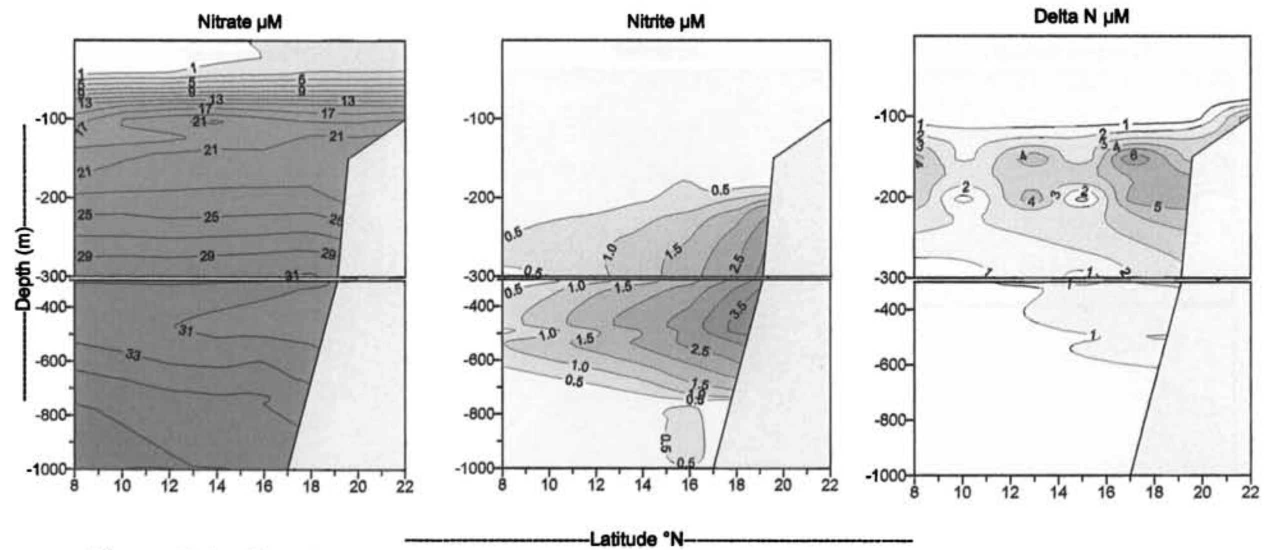


Figure 5.1. Distribution of physicochemical parameters along the coastal transect during winter



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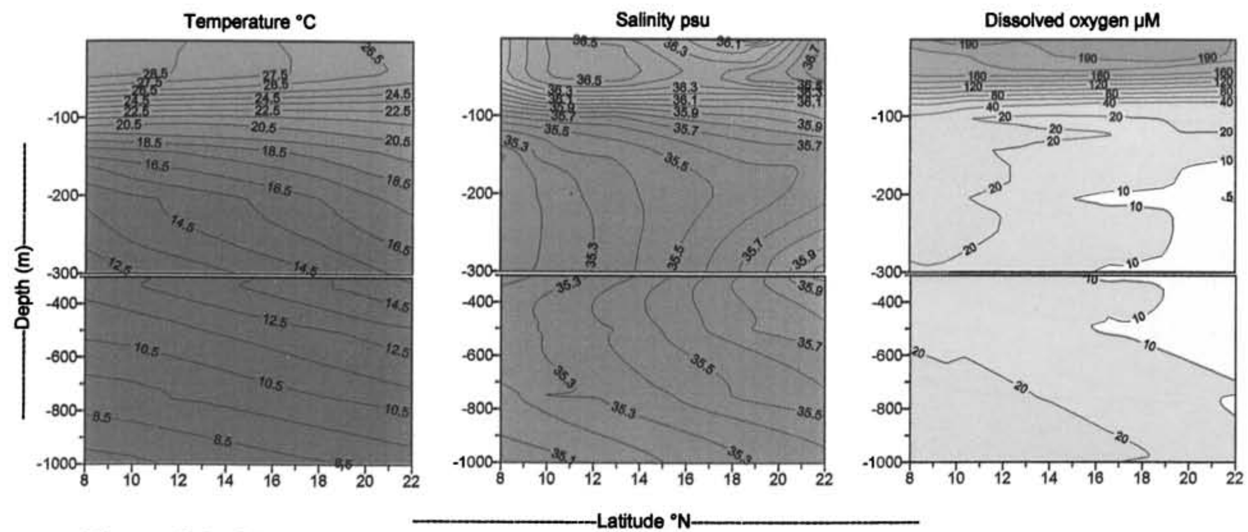
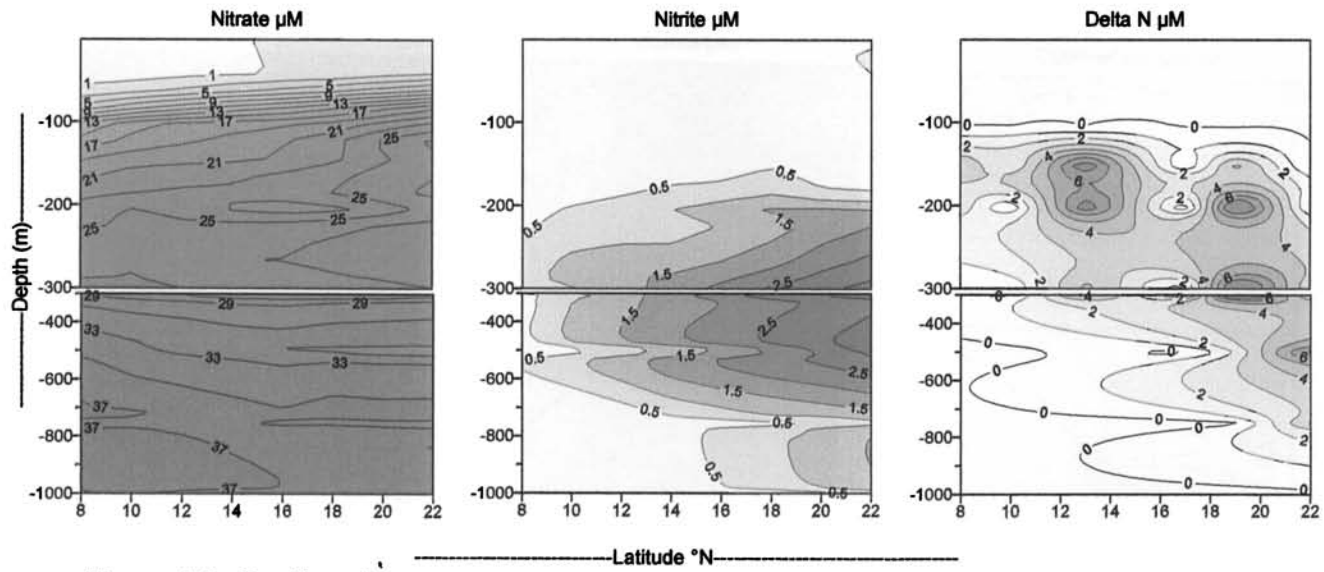


Figure 5.2. Distribution of physicochemical parameters along the open ocean transect during winter



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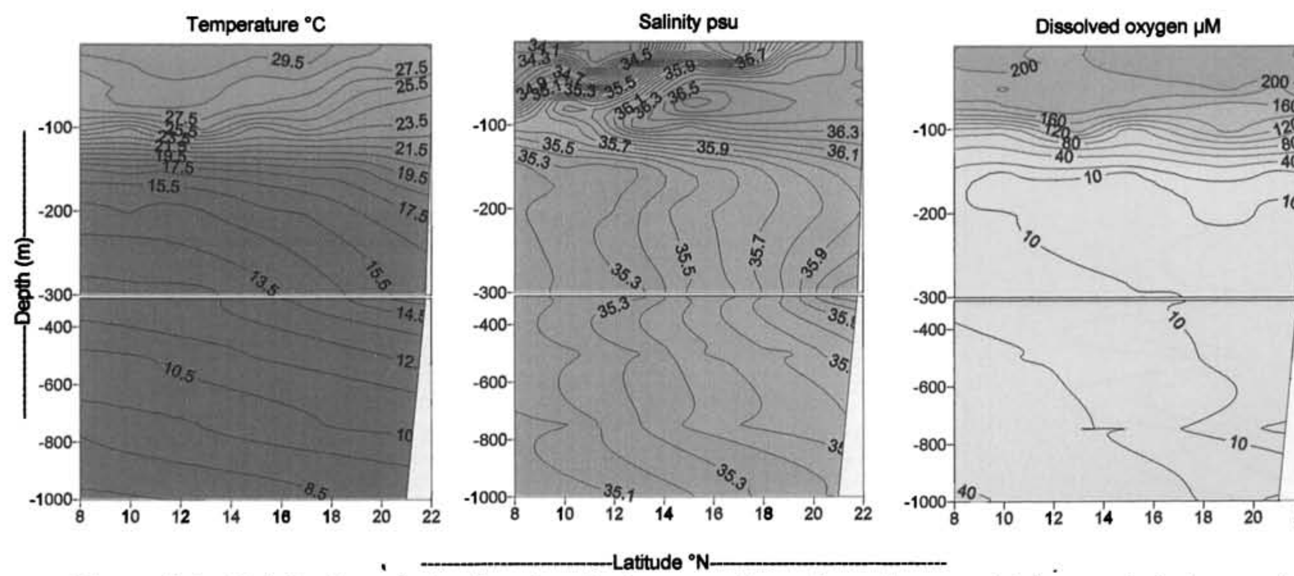
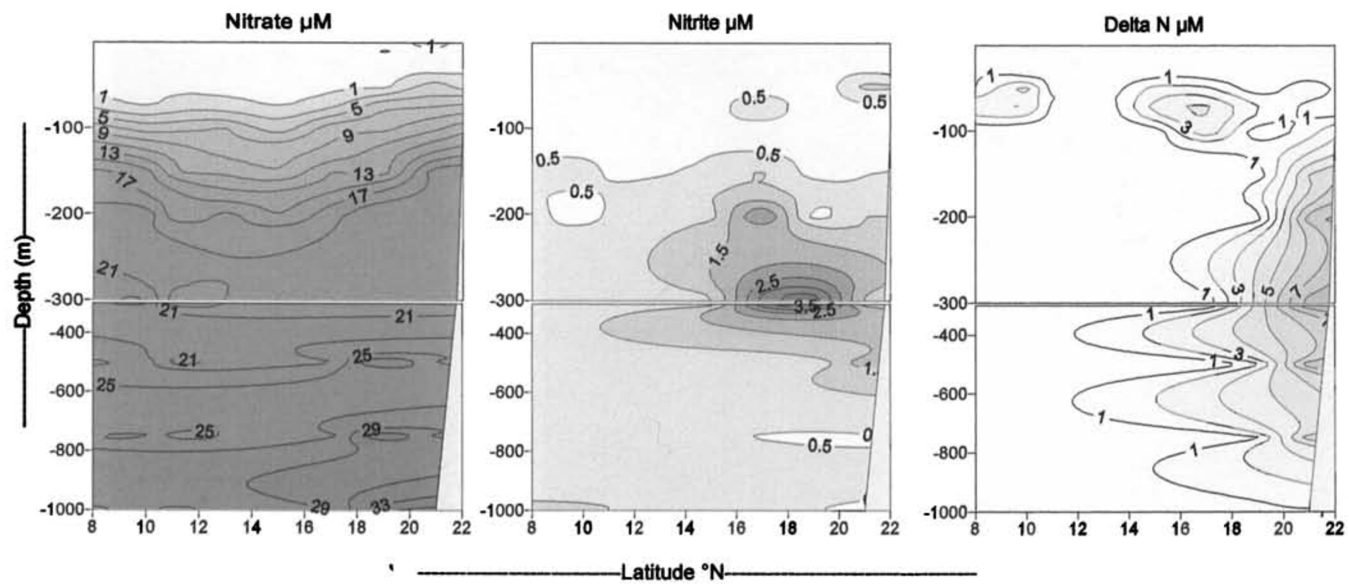


Figure 5.3. Distribution of physicochemical parameters along the coastal transect during spring



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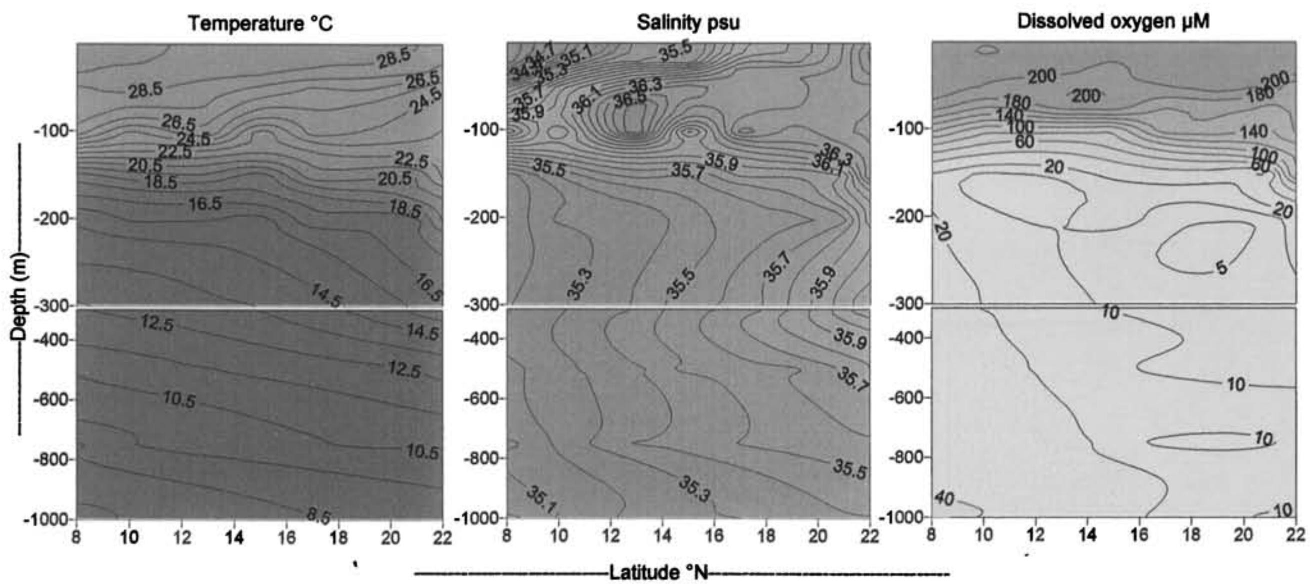
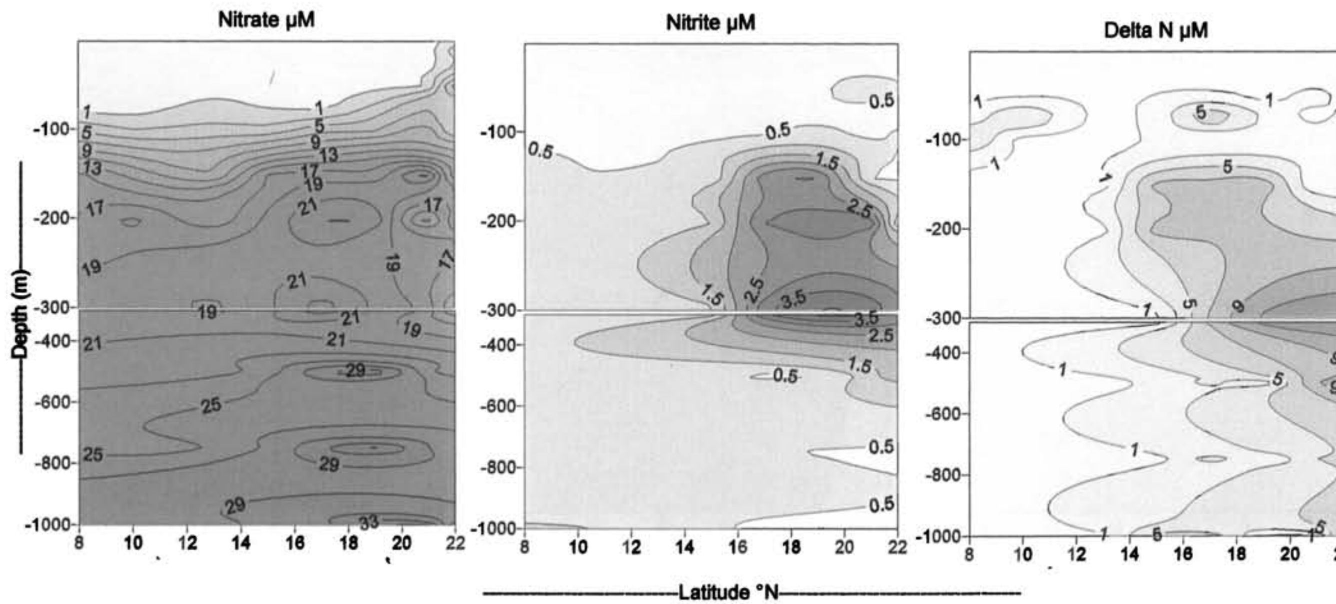


Figure 5.4. Distribution of physicochemical parameters along the open ocean transect during spring



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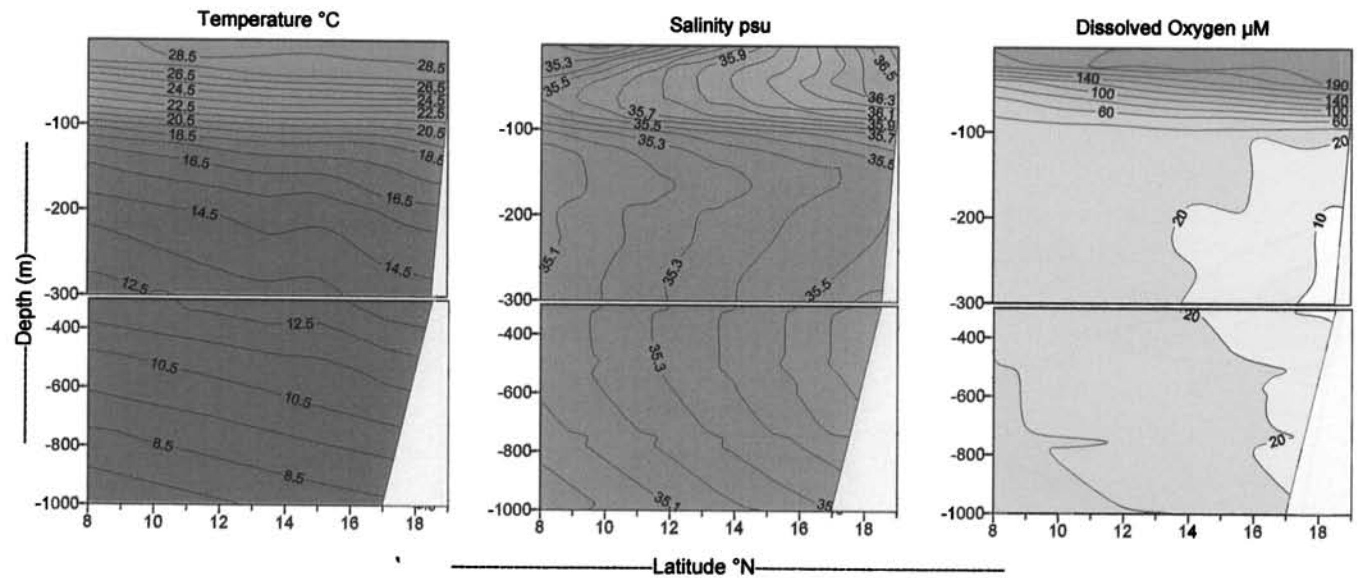
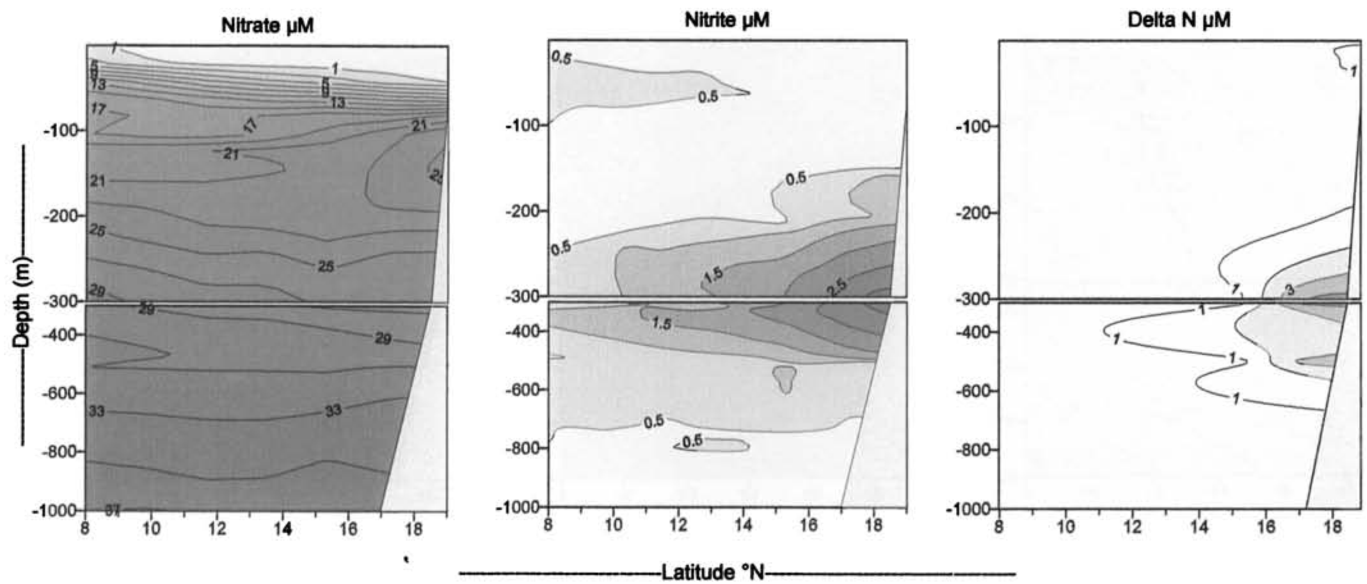


Figure 5.5. Distribution of physicochemical parameters along the coastal transect during summer



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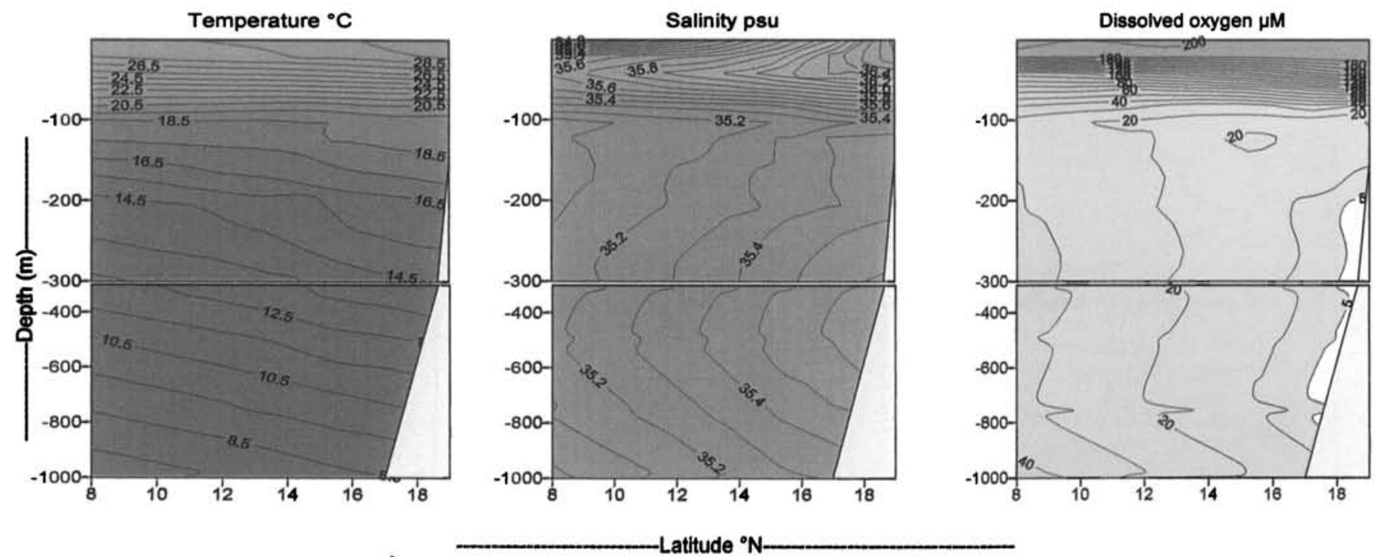
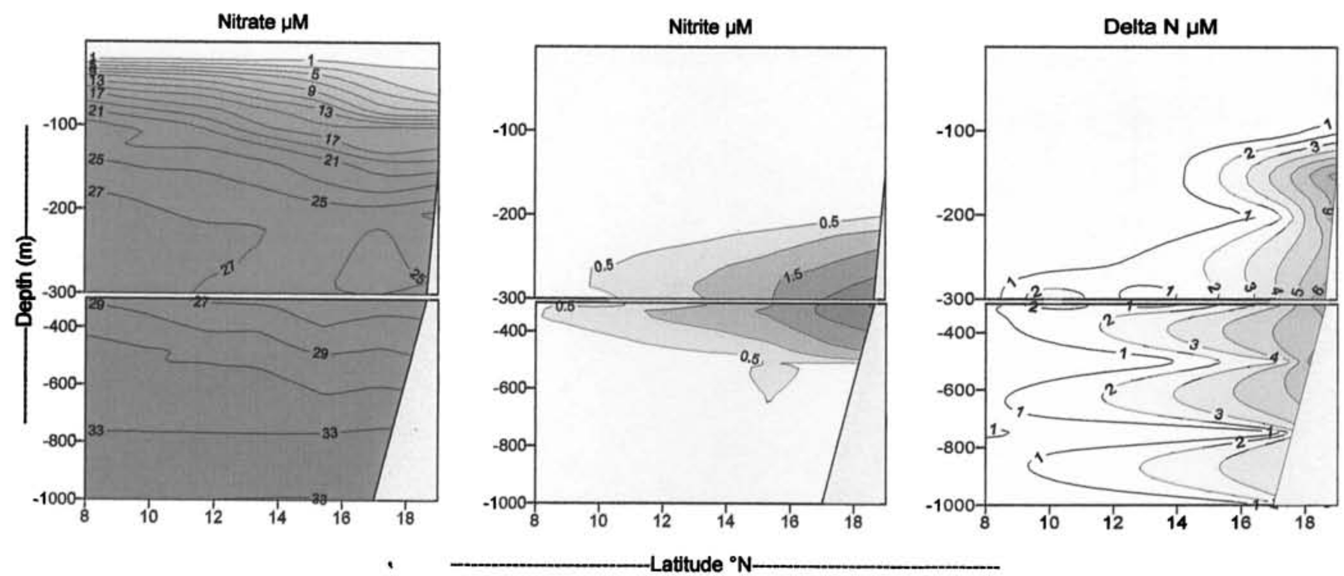


Figure 5.6. Distribution of physicochemical parameters along the coastal transect during fall



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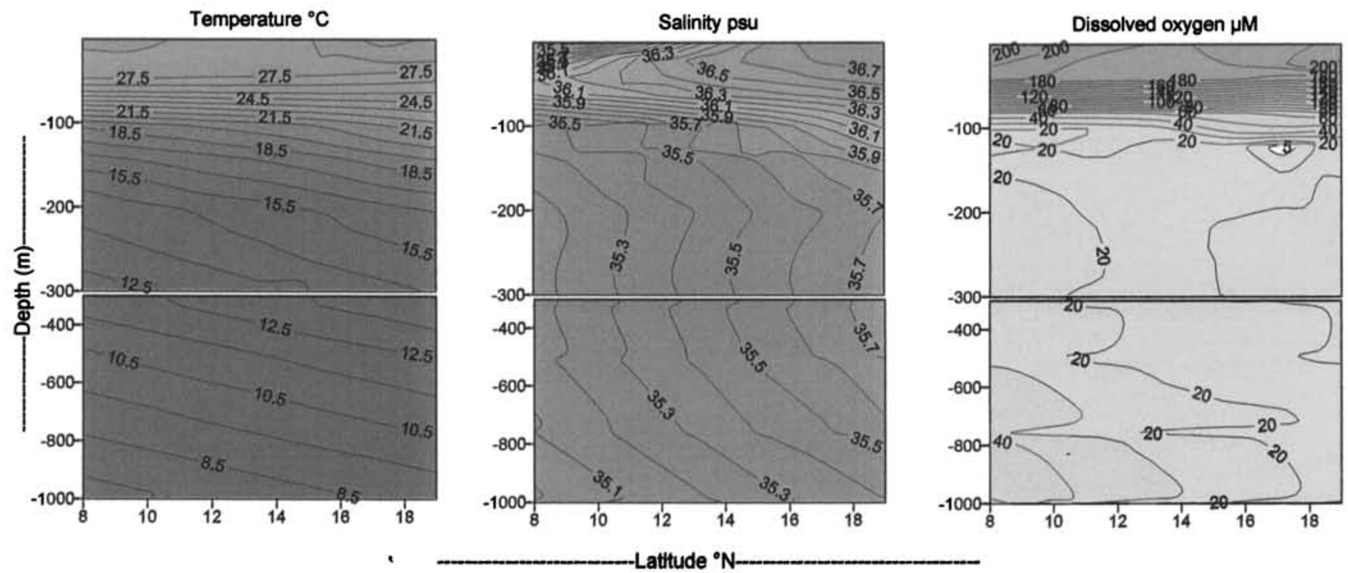
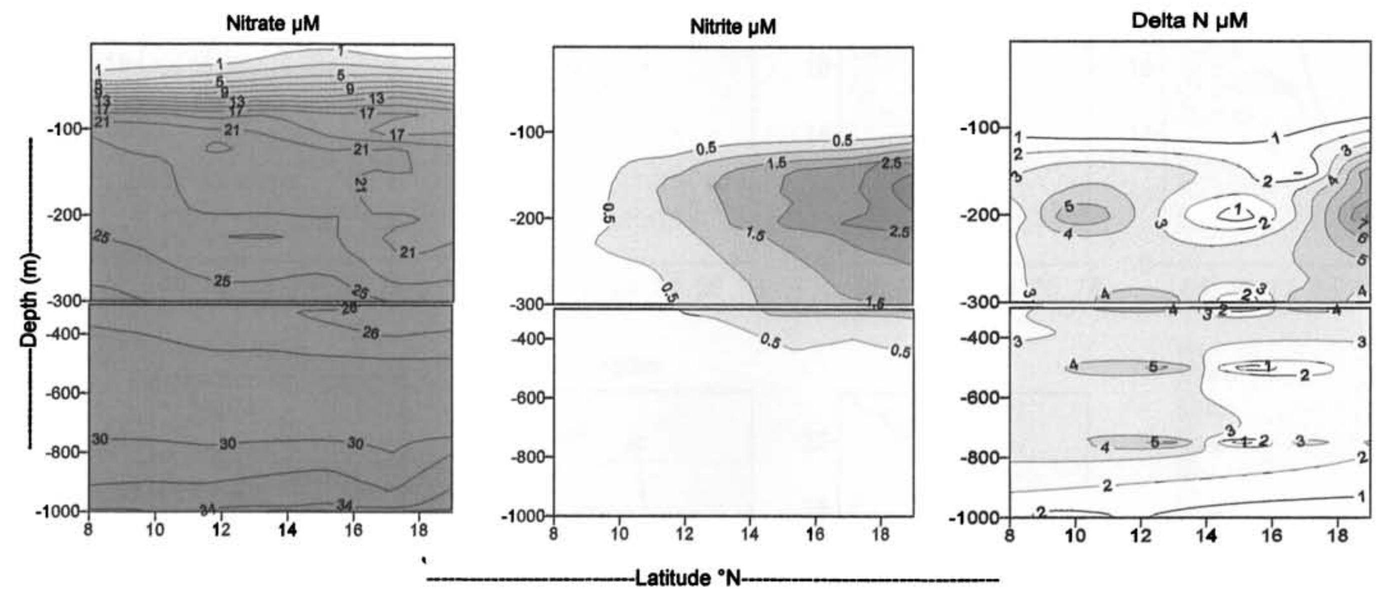


Figure 5.7. Distribution of physicochemical parameters along the open ocean transect during fall



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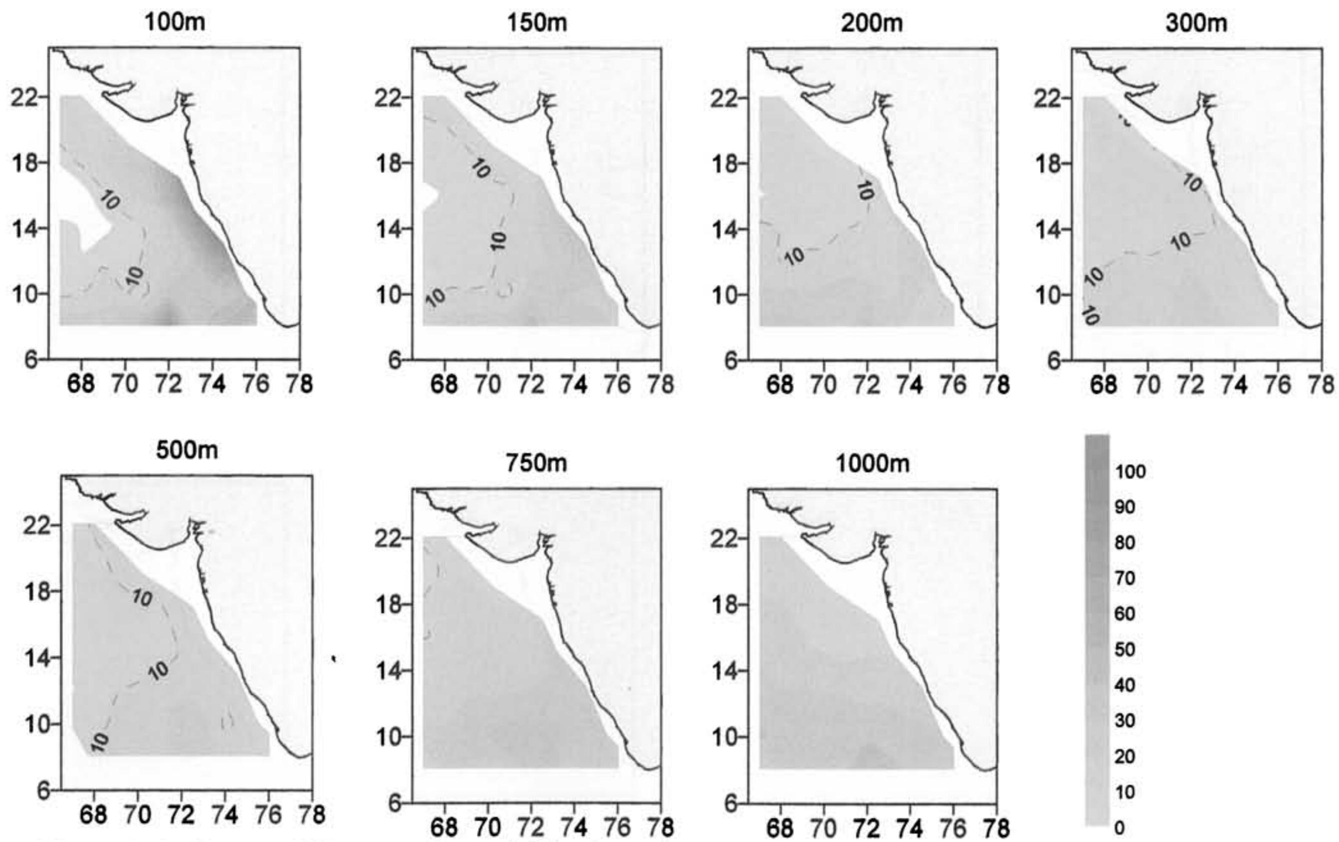

Figure 5.8. Oxygen Minimum Zone (μM) along the west cost of India during winter

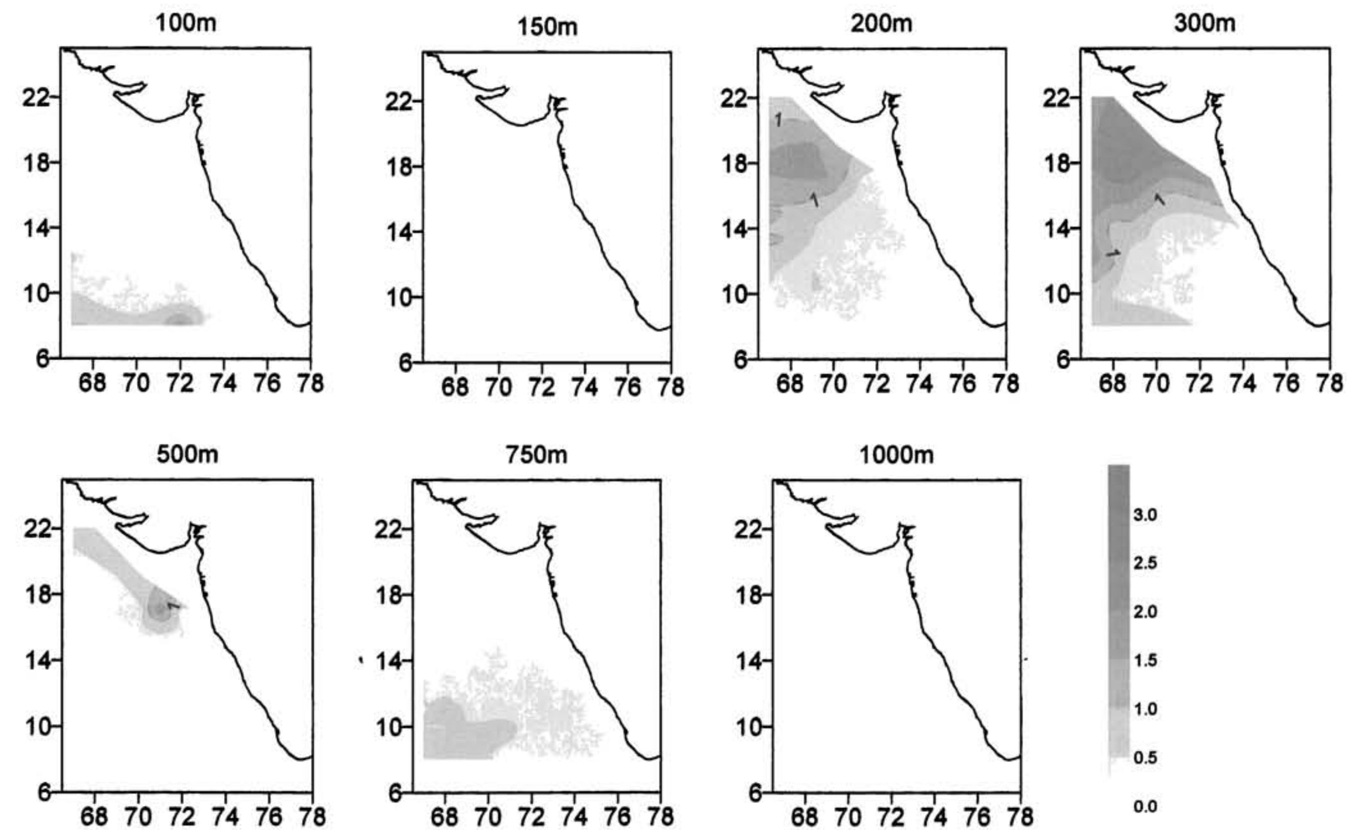

Figure 5.9. Zone of denitrification (μM) along the west coast of India during winter

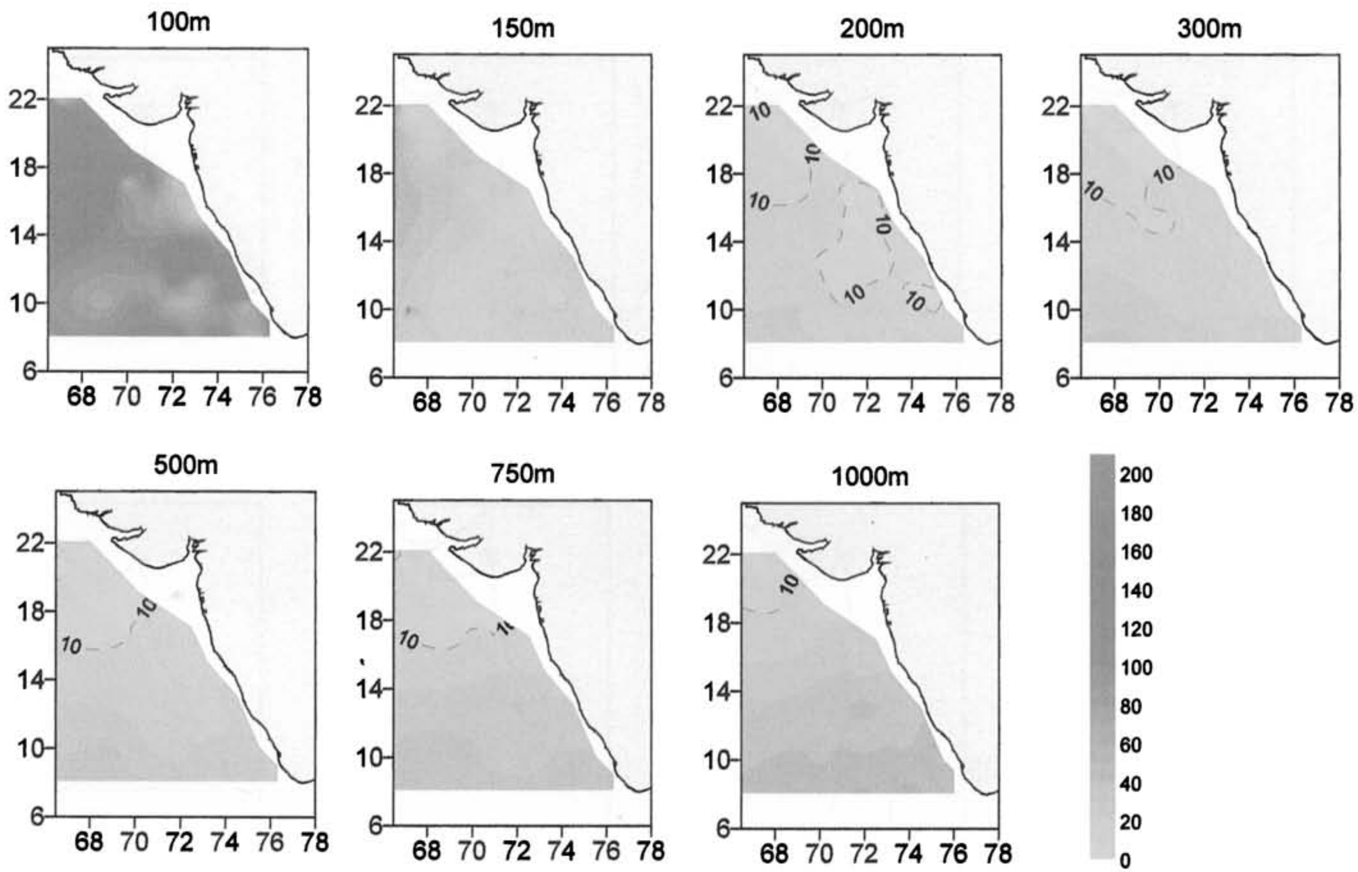

Figure 5.10. Oxygen Minimum Zone (μM) along the west coast of India during winter

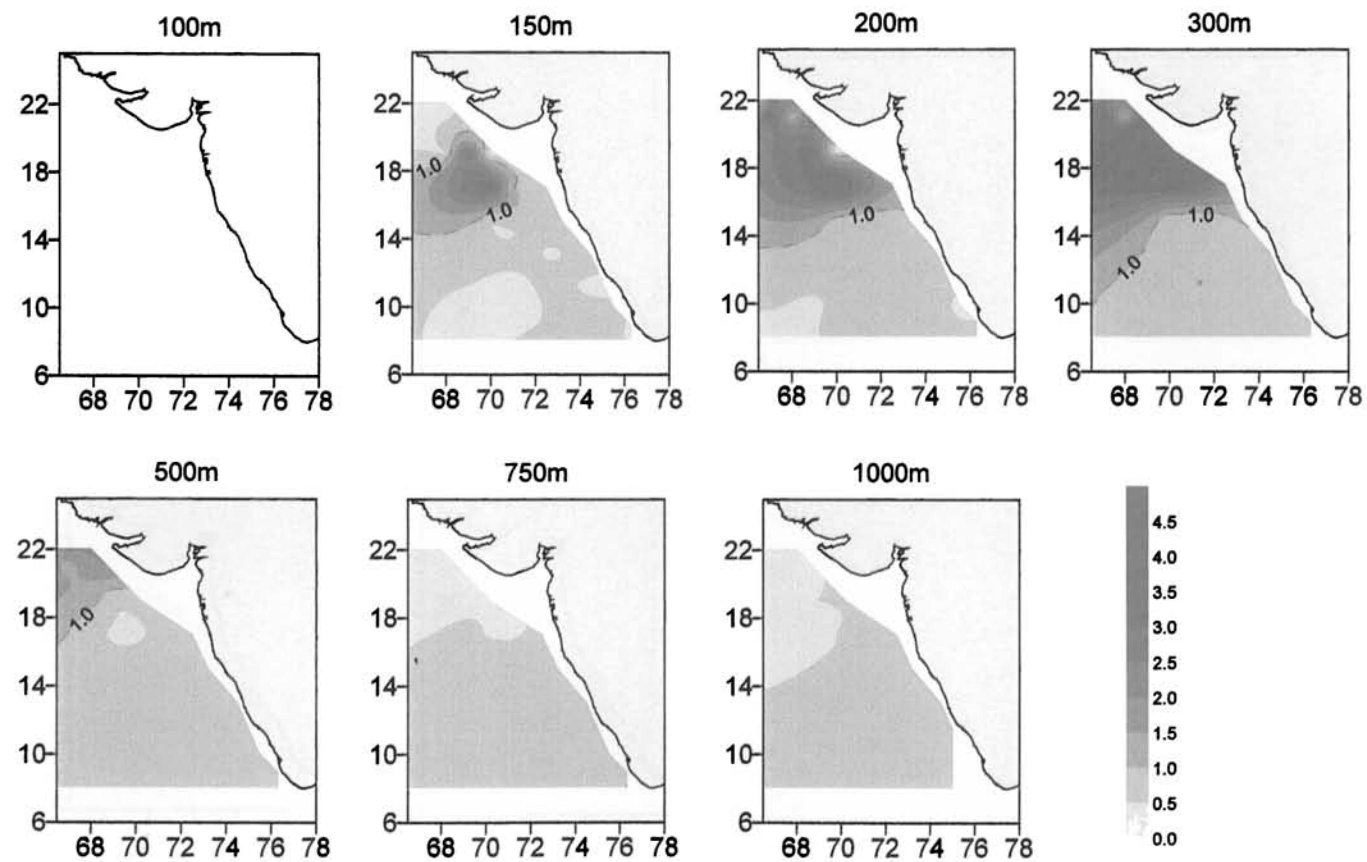

Figure 5.11. Zone of denitrification (µM) along the west coast of India during spring

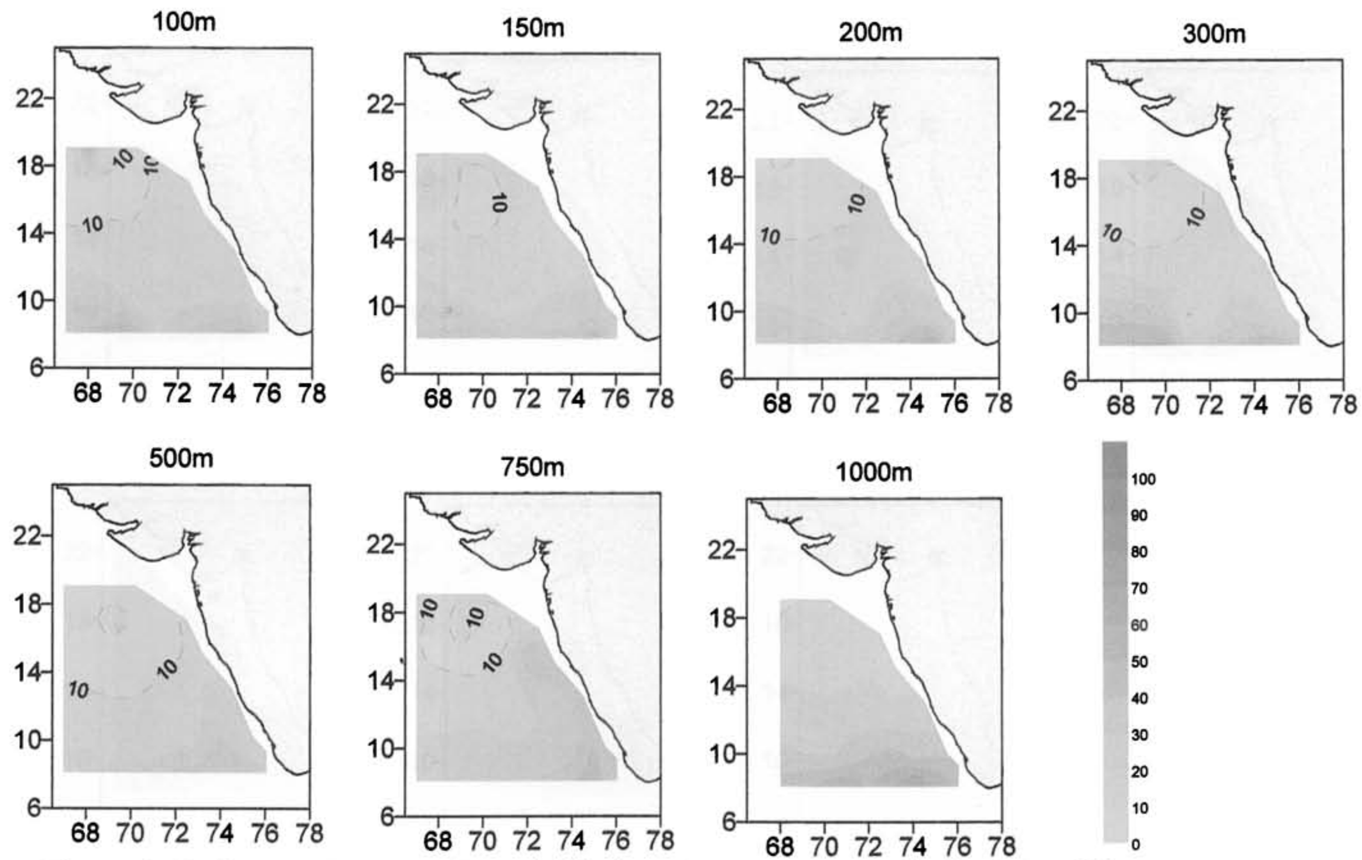

Figure 5.12. Oxygen Minimum Zone (μM) along the west coast of India during fall

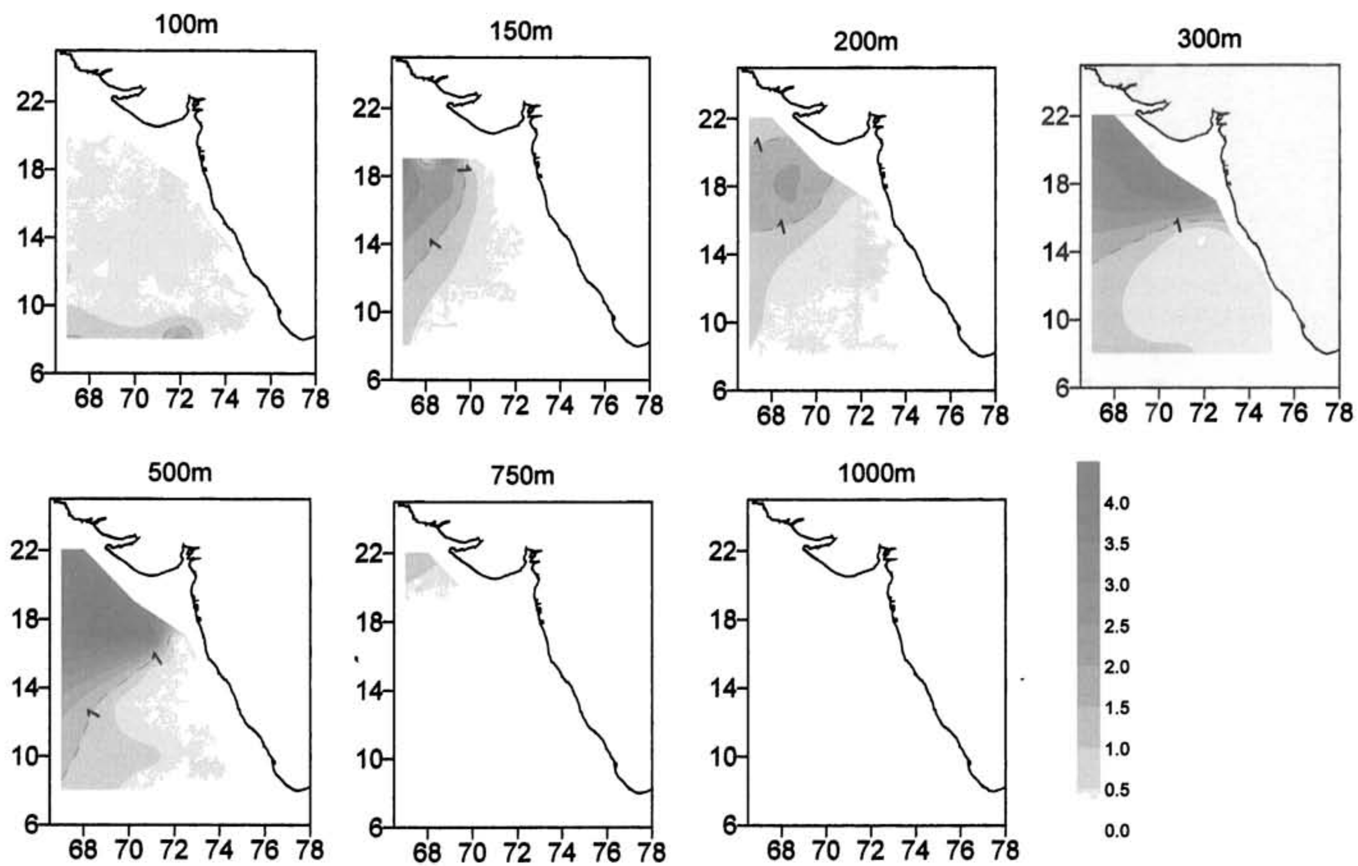

Figure 5.13. Zone of denitrification (μM) along the west coast of India during fall

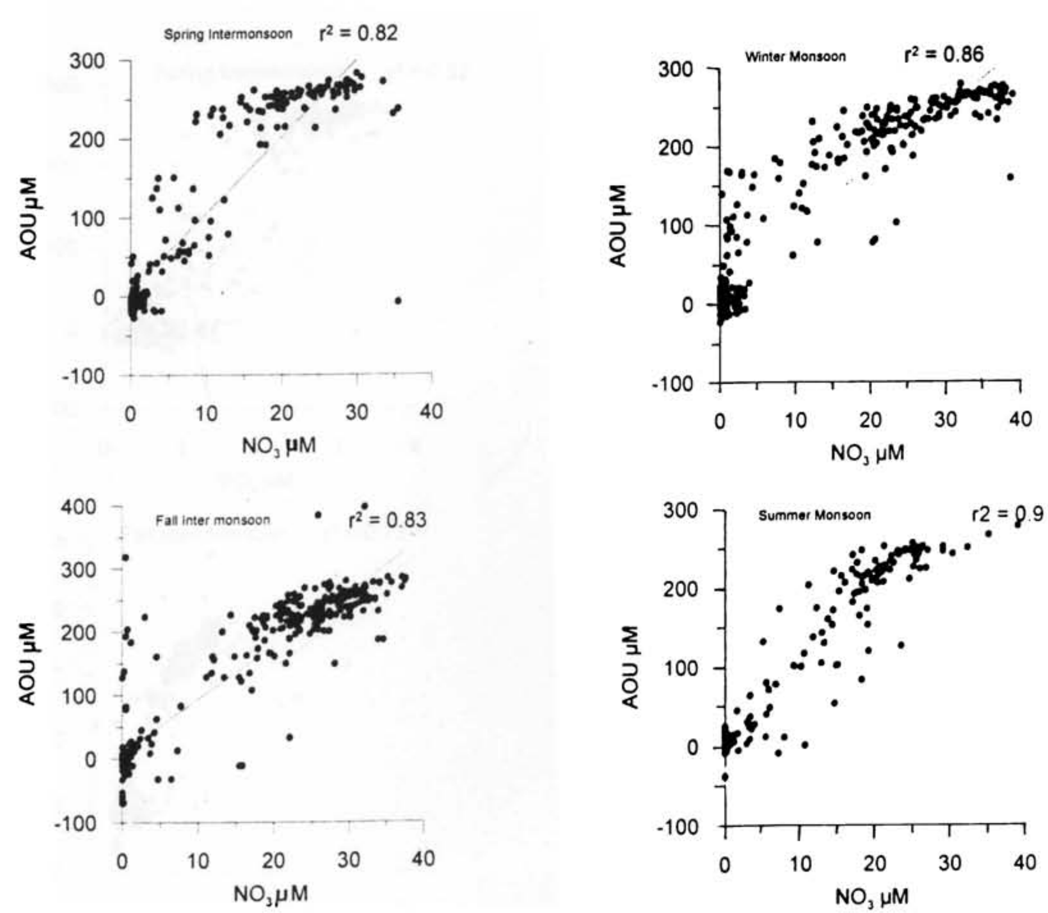

Figure 5.14. AOU vs NO_3 plot during different seasons

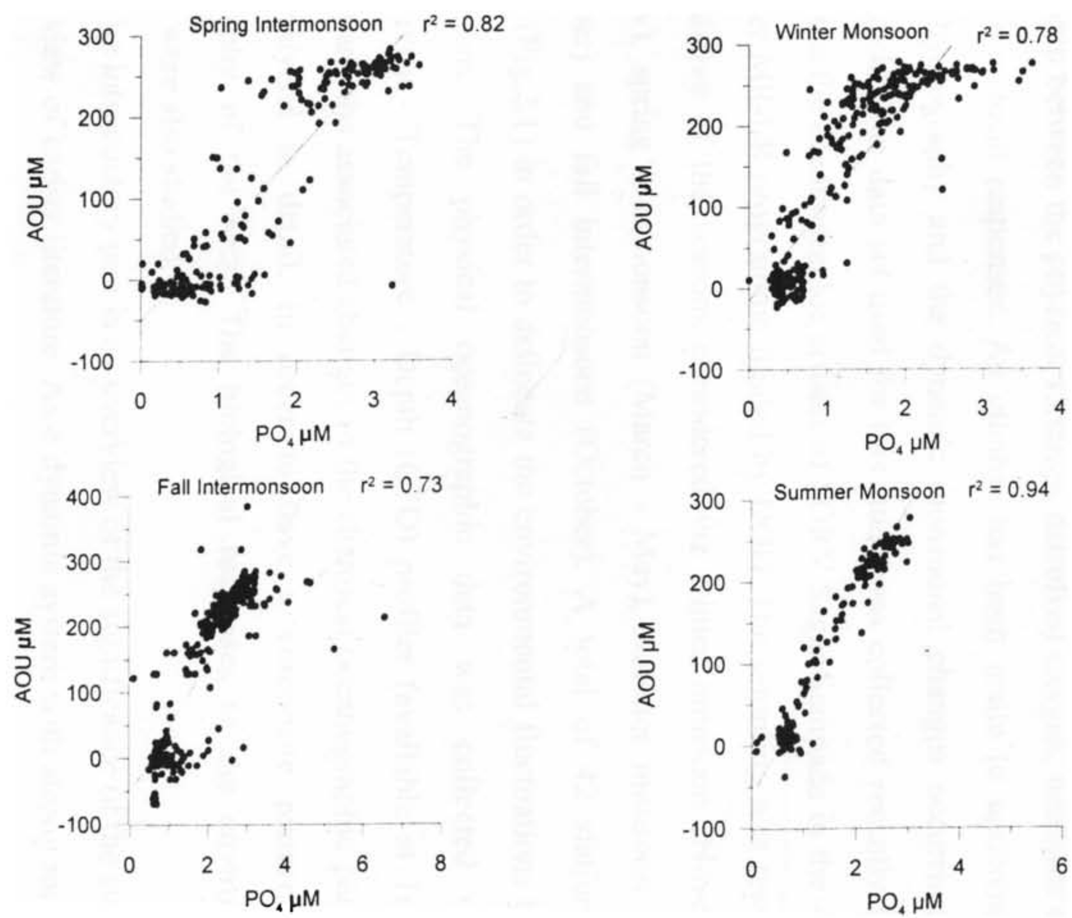

Figure 5.15. AOU vs PO_4 plot during different seasons

Chapter 6

Summary and conclusions

The thesis is an almost exhaustive environmental study covering almost the entire EEZ of the west coast of India (eastern Arabian Sea). As outlined in the introductory chapter, the investigation was designed to trace out the relationship between the physical forcings, dissolved oxygen, nutrients and the relative biological responses. An attempt has been made to understand the general hydrography and the dynamic monsoonal changes occurring in an annual cycle. The data set used for this study was collected recently (1999 - 2004) from the oceanographic cruises of FORV Sagar Sampada in the Arabian Sea under MR-LR programme funded by DOD. The sampling was reasonably representative of the seasons considered viz winter monsoon (November - February), spring intermonsoon (March - May), summer monsoon (June - September) and fall intermonsoon (October). A total of 42 stations were covered (Fig.2.1) in order to delineate the environmental fluctuations between the seasons. The physical oceanographic data was collected using a Conductivity - Temperature - Depth (CTD) profiler (available at 1m depth interval) and the associated changes in the chemical oceanographic parameters were analyzed in detail, in order to have a composite picture of the hydrography of the EEZ. The biological responses to the environmental changes were also studied.

The introductory part is an overview of the significance of the study area and a review of earlier literature. As a dynamic system with strong monsoonal character and oceanic circulations, the eastern Arabian Sea has certain significant features, which could be attributed to its geographical settings. The monsoon winds over the study area offer a strong coupling between the atmosphere and the ocean. However the seasonal shift in the wind pattern causes a complete semi annual reversal of surface currents in the eastern

Arabian Sea resulting in seasonal variations in the surface water characteristics. During summer, the wind driven Ekman drift dominates over most of the Arabian Sea, overwhelming the geostrophic flow at the surface and leading to a more complex vertical structure in the summer monsoon current (SMC). In winter, geostrophy dominates since the northeast winds in the northern Arabian Sea are too weak to produce off shore Ekman transport.

Appearance of high nutrient concentration in the surface layers during summer and winter monsoons and the development of oxygen depleted intermediate waters makes Arabian Sea different from the other oceanic regions of the world. The study area further derives its significance in the context of the denitrification and subsequent reduction in nitrate resulting in nitrate deficits (δN) that occurs in the intermediate waters along the EEZ of the west coast of India. The unique biological conditions in the eastern Arabian Sea makes it one of earth's biologically rich bodies of water. In spite of its relatively small geographic area, the EEZ of the west coast of India comprises a variety of biogeochemical zones such as highly productive, oligotrophic, upwelling and oxygen depleted areas. The present approach of the study focusing this EEZ exclusively assumes added relevance as very few studies have been carried out in this area covering the entire seasonal cycle covering inter annual variability.

The analytical methods used in this study are the latest and have enabled the generation of precise and accurate data. A detailed description of the methods used is given in Chapter 2. Sampling was done from various pre-determined stations in the EEZ, from standard depths up to 1000m wherever depth permitted. Sampling was performed between 1 degree longitudinal grid and 2 degree latitudinal grid. The sampling depths chosen (0, 10, 20, 30, 50, 75, 100, 150, 200, 300, 500, 750 and 1000m) are representative of the entire water column. A much closer sampling in the first 200m was done since this was the layer where seasonal changes were predominant. Physical oceanographic parameters like temperature, salinity and density were obtained from the CTD probe. The concentrations of the essential micronutrients like nitrate, nitrite, silicate and phosphate were measured using standard analytical techniques. The analysis was carried out using Segmented Flow Auto Analyzer (SKALAR) fitted on board FORV Sagar Sampada. The titrimetric Winkler method was used for the measurement of dissolved oxygen.

The primary data on nutrients, DO, temperature, and salinity were used to generate secondary inputs like Apparent Oxygen Utilization (AOU) and nitrate deficit (δN). Estimation of nitrate deficit was performed using 'nitrate tracer' (NO) tool as proposed by Naqvi *et. al.,* 1990. Two different equations were used to calculate the expected 'NO' for different temperature ranges, $10.39 \leq \theta \leq 27$ and $\theta \leq 10.39$.

The two distinct hydrographic features on the west coast of India- the wind driven coastal upwelling along the southwest coast during summer monsoon and the convective overturning of the surface waters along the northwest coast during winter monsoon- are discussed in detail. The semi annual reversing monsoons in the Arabian Sea make the study area one of the most productive regions among the world oceans. An upwelling area gets developed in the coastal region off southwest India, characterized by low sea surface temperature (< 27°C) and high surface nutrients (NO_3 > 2μM, SiO_4 > 2μM and PO_4 > 0.6μM) during summer. During this season the process of upwelling enhances the chlorophyll *a* (44.7 mg m^{-2}) and primary productivity (1629 mg C m^{-2} d^{-1}) on the southwest coast of India, leaving the open ocean region oligotrophic with depleted nutrients. The seaward extent of the upwelling observed along the southwest India was getting restricted to ~ 150 km off shore. Existence of deep MLDs (~ 70m) with weakly stratified surface layers were characteristics of the northwest coast of India during winter. Cooling and subsequent overturning of surface layers during this season injects nutrients to the surface layers in the open ocean region. The effect of winter cooling was weak towards the coastal region. A northward increase in the magnitude of convective mixing was evident from the pattern of distribution of DO and nutrients.

The differential behavior in the hydrographic characters of the EEZ during the transition seasons (spring intermonsoon and fall intermonsoon) is also addressed. Even though the process of upwelling ceases by September, its effect persists in October (fall intermonsoon) also. The upwelling observed off the southwest tip of Indian peninsula during summer appears to move towards north intensifying along the coastal region between 10°N and 13°N during fall. During this season the physicochemical parameters were observed to be under the influence of the upwelling processes with relatively colder (< 28°C) and nutrient rich (NO_3 > 1µM, SiO_4 > 1µM and PO_4 > 0.7µM) waters advected to the surface layers. A 2°C difference in the surface temperature between the open ocean and coastal region was observed with a shallow MLD (20 – 30m) near the shore. The oxygen saturated (DO > 200µM) surface waters were pushed away from the coast during this season. A less intense cross shelf up sloping in the distribution of physicochemical parameters clearly indicates that the fall intermonsoon is a retreating phase of the summer monsoon. Along 13°N transect a severe depletion in oxygen persists in the sub surface waters near the continental shelf slope, indicating the existence of productive (820 mg C m^{-2} d^{-1}) surface waters near the coast due to the retention of upwelling characteristics during fall. It could be inferred from the summer and fall characteristics that the summer monsoon initiates from south and its retreat also begins from the southern part of the EEZ during fall.

Even though spring intermonsoon in the Arabian Sea is a heating season, the northwestern part of the study area is still under the grip of winter cooling. The open ocean waters of the northern transects (19°N, 21°N and 22°N) registered comparatively low temperatures (< 28°C). The surface waters in this region possessed considerable concentrations of nutrients especially nitrate (NO_3 > 2µM). Deepening of MLD (~ 40m) and thermocline with a relative enhancement in primary production (290 mg C m^{-2} d^{-1}) evidenced the retention of winter conditions in the region. After winter mixing, the oceanic regions stabilized much faster than the coastal region in spring. Consequently in the open ocean region under the improved light and weak wind conditions along with the availability of nutrients in the euphotic zone remained favourable for spring blooms. The highest primary productivity value (1845 $mgCm^{-2}d^{-1}$) observed along the northern region of the study area during winter is higher than the production (1629 $mgCm^{-2}d^{-1}$) along the southwest coast of India observed during southwest monsoon, suggesting that the winter production and the summer production in the northern Arabian Sea are roughly of the same magnitude. A varying seasonal cycle of nutrient supply, oscillating between high productive and moderately oligotrophic conditions was assumed to impart a temporal pattern that makes the study region unique among the oceans.

This investigation also deals with some consequences of the oxygen deficient conditions prevailing within a large body of intermediate water in the EEZ. The low levels of dissolved oxygen within the oxygen deficient layer recorded is in agreement with those reported earlier. A rapid northward increase in thickness of the oxygen deficient layer (DO < 10μM) with seasonal variations between 150 – 800m depth, accompanied by a steady decrease in oxygen concentrations within this layer was observed. The maximum lateral shift of these oxygen deficient waters towards south was noticed during spring when it got extended to ~ 9°N. In summer it was restricted to ~ 17°N owing to the northward intrusion of sub-Antarctic water. Because of the existence of low oxygen conditions below the thermocline, nitrate is utilized as a terminal electron acceptor (denitrification) by facultative bacteria in their respiratory process. In the oxygen poor waters of the EEZ, denitrifires occur abundantly which could produce molecular nitrogen through different forms of combined nitrogen ($NO_3 \rightarrow NO_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2$) during their respiratory process. During this study the existence of a secondary nitrite maxima was observed between 8°N – 22°N, with noticeable seasonal variations. The secondary nitrite patch was in conjunction with a pronounced minimum in nitrate and confined to the intermediate salinity maximum (PGW) in the northern latitudes. Intrusion of high saline water mass (> 35.5psu), which has its origin from the PGW, was identified irrespective of the season. This intrusion through the secondary nitrite patch was found not to extend to the south of 14°N.

The seasonal fluctuations in the nitrate deficit values in the study region are also addressed in the present investigation. A peak value of nitrate deficit (11µM) in the study region was recorded during spring. During spring, intense nitrite maxima (> 4µM) and severe oxygen depletion (DO < 10µM) was observed in a wide area of the intermediate water, which could be attributed to the increased post winter settling of the organic matter. The depth at which the nitrate deficit maximum occurred was ~ 300m during most of the season, where the maximum value for the remaining properties were generally noticed. Because of the unique geographical setting, high ambient salinity, reversal of monsoons, coastal upwelling and winter cooling, the eastern Arabian Sea behaves differently from the other tropical basins of the world.

References

Anderson, J.J., Okubo, A., Robbins, A.S and Richards F.A. (1982). A model for nitrite and nitrate distributions in oceanic oxygen minimum zones. *Deep-Sea Res.*, **29** : 1113-1140.

Balachandran, K.K. (2001). Chemical oceanographic studies of the coastal waters of Cochin. *Ph.D Thesis, Cochin University of Science and Technology.*

Bange, H. W., Wajih Naqvi, S.A., and Codispoti, L.A. (2005). Nitrogen cycle in the Arabian Sea. Progress in Oceanography., **65** : 145-158.

Banse, K. (1959). On upwelling and bottom-trawling off the southwest coast of India. *J. Mar. Biol. Assn. India.* **1** : 33-49.

Banse, K. (1987). Seasonality of phytoplankton chlorophyll in the central and southern Arabian Sea. *Deep-Sea Res.*, **34** : 713-723.

Banse. K. 1968. Hydrography of the Arabian sea shelf of India and Pakistan and effects on demersal fishes. *Deep-Sea Res.*, **15** : 45-79.

Banzon F. Viva., Robert E. Evans., Howard r. Gordon., Roman M. Chomko. (2004). SeaWiFS observation on the Arabian Sea southwest monsoon bloom for the year 2000. *Deep-Sea Res.*, II **51**: 189-208.

Barber, R. T and Smith R. l. (1981). Coastal upwelling ecosystems. In: Analyzis of Marine Ecosystems, A. R. Longhurst, ed., Academic Press, 31 – 68.

Basil, M. (1983). Studies on upwelling and sinking in the seas around India. *Ph.D. Thesis, Cochin University of Science and Technology.*

Bauer, S., Hitchcock, G. L., and Olson, D. B. (1991). Influence of monsoonally forced Ekman dynamics upon surface layer depth and plankton biomass distribution in the Arabian Sea. *Deep-Sea Res.*, **38** : 531-553.

Bearman, G. (1989). Coastal upwelling in eastern boundary currents, *Ocean Circulation* (Bearman, G., ed). Pergamon Press, Oxford. pp. 118.

Bendschneider, K., and Robinson, R. J. (1952). A new spectrophotometric method for the determination of nitrite in seawater. *J. Mar. Res.* **11**: 87-96.

Brendhorst, w. (1959). Nitrification and denitrification in the eastern tropical North Pacific. J. Cons. Int. Explor. Mer., **25** : 3-20.

Broecker, W. S.(1947). 'NO', a conservative water mass tracer. *Earth Planet. Sci. Lett.*, **23** : 100-107.

Bruce, J.G. (1974). Some details of upwelling off the Somali and Arabian coasts. *J. Mar. Res.*, **32** : 419-423.

Bruce, J.G. (1979). Eddies off Somali coast during the southwest monsoon. *J. Geophys. Res.*, **84** : 7742-7748.

Burkill. P. H. (1999). ARABESQUE: An overview. *Deep-Sea Res.*, II **46** : 529-547.

Carpenter, J. H. (1965). The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. *Limnol. Oceanogr.*, **10** : 141-143.

Carruthers, J. N., Gogate, S. S., Naidu, J. R., and Laevastu, T. (1959). Shoreward upslope of the layer of minimum oxygen off Bombay: Its influence on marine biology, especially fisheries. *Nature* **183** : 1084-1087.

Codispoti, L. A., and Christensen, J. C. (1985). Nitrification, denitrification and nitrous oxide cycling in the eastern tropical south Pacific Ocean. *Mar. Chem.* **16** : 277-300.

Colborn, J.G. (1975). The thermal structure of the Indian Ocean. Univer. Of Hawaii Press, Honolulu., pp 173.

Cooper, L. H. N. (1933). Chemical constituents of biological importance in the English Channel, November 1930 to January 1932. Part I. Phosphate, silicate, nitrite and ammonia. *J. Mar. Biol. Ass. U.K.*, **18** : 677-728.

Culter,A. N., and Swallow, S. C. (1984). Surface currents of the Indian Ocean (to 25°S, 100°E):Compiled from historical data archived by Meteorological Office, Bracknell, U. K., *Report.* **187**, 8 pp., Charts, INST. Of Oceanogr. Sci., Godalming, Egland.

David, K. Young., and John, C. Kindle. (1994). Physical processes affecting availability of dissolved silicate for diatom production in the Arabian Sea. *J. Geophys. Res.*, **99,** C 11 : 22619-22632.

De Souza, S. N., Kumar, M. D., Sardessai, S., Sarma, V. V. S. S., and Shirodkar,P. V. (1996)Seasonal variability in oxygen and nutrients in the central and eastern Arabian Sea. *Curr. Sci.*, **71** : 847-851.

de Souza, S. N., Singbal, S. Y. S. and Reddy, C. V. G. (1979). Dissolved inorganic phosphorus and nitrogenous compounds in the sediments off Bombay and Gulf of Kutch. Mahasagar- Bulletin of the National Institute of Oceanography, **12**(4) : 213-218.

Defant, A. (1963). *Das kaltwasserauftreisgebiet vor der kustensudwestafrikas*, Landerkundliche studien (Festchrift W. Krebs). Stultgart 52-56.

Deuser, W. G. (1975). *Reducing environments;* Chemical Oceanography (eds) J. P Riley and Skirrow, G. (Academic Press) **3** : 1-37.

Deuser, W. G., Ross, E. H., and Mlodzinska. (1978). Evidence for and rate of denitrification in the Arabian Sea. *Deep-Sea Res.*, **25** : 431-445.

Devol, A. H. (1978). Bacterial oxygen uptake kinetics as related to biological processes in oxygen deficient zones in the ocean. *Deep-Sea Res.*, **25** : 137-146.

Divakar Naidu P., Ramesh Kumar M. R., Ramesh Babu V. (1999). Time and space variations of monsoonal upwelling along the west and east coast of India. *Cont. Shelf. Res.*, **19** : 559-578.

Gopinathan, C. K., and Qasim, S. Z. (1974). Mud Banks of Kerala – Their formation and characteristics. *Indian J. Mar. Sci.* **3**: 105-114.

Grasshoff, K. (1983). *Methods of seawater analysis*. Edited by K. Grasshoff. M. Ehrhardt and K.Kremling. (2nd Edn.), Verlag Chemie, Weinheim. 419.

Green E. J and D. E Carritt (1967). New tables for oxygen saturation in sea water. *J. Mar. Res.*, **25**: 140-147.

Gruber, N. and Sarminto, J. L. (1997). Global patterns of marine nitrogen fixation and denitrification. *Glob. Biogeochem. Cycle.*, **11**: 235-266

Gunnar Kullenberg. (1999). The exclusive economic zone: some perspectives. *Ocean & Coastal Management.*, **42** : 849-855.

Haake, B., Ittekkot, V., Rixon, T., Ramaswami, V., Nair, R. R., Curry, W. B. (1993). Seasonality and inter-annual variability of particle fluxes to the deep Arabian Sea. *Deep-Sea Res.*, I **40** : 1323-1344.

Harish kumar, P.V., and Basil Mathew. (1997). Salinity distribution in the Arabian Sea. *Indian J. Mar. Sci.* **26** : 271-277.

Harvey, H. W. (1957). The chemistry and fertility of sea water (2nd Edn). *Cambridge University Press.*, pp. 234.

Hastenrath, S. and Lamb, P. (1979). Climatic Atlas of the Indian Ocean, Part 1: Surface climate and atmospheric circulation., pp. 273. Univ. of Wiisc. Press. Madison.

Hellerman, S. and Rosenstein, M. (1983). Normal wind stress over the world ocean with error estimates. J. Phys. Oceanogr., 13 : 1093-1104.

Ittekkot, V., Manganini, S. J., Guptha, M. V. S., Desai, B. N., Degens, E. T., and Hanjo, S. (1987). Particle fluxes in the Arabian Sea. *EOS.*, **68** : 1772.

Joel, D. Cline., and Francis, A. Rechard. (1972). Oxygen deficient conditions and nitrate reduction in the eastern tropical north Pacific Ocean. *Limno. Oceanogr.*, **17(6)** : 885-900.

Johannessen, O. M., Subbaraju, G. and Blindheim, J. (1987). Seasonal variations of the oceanographic conditions off the southwest coast of India during 1971-1975. *Fisk. Dir. Skr. Ser. Hav Unders.* **18**: 247- 261.

Jyothi Babu, R., Maheswaran, P. A., Madhu, N. V., Mohamed Asharaf, T. T., Vijay,J. G., Venugopal, P., Revichandran, C., Balasubramanian, T., Gopalakrishnan, T. C., and Nair, K. K. C.(2004). Defferencial response of winter cooling on biological production in the northeastern Arabian Sea and northwestern Bay of Bengal. Curr. Sci., **87 :** 783 - 791.

Kesava Das, V., Gouveia, A. D., and Varma, K. K. (1980). Circulation and water characteristics on isanosteric surfaces in the northern Arabian Sea during February-April. *Indian. J. Mar. Sci.*, **9** : 156-165.

Koroleff, F. (1983). Determination of phosphorus. In: *Methods of seawater analysis* (Grasshoff, K. (ed.)), Verlag Chemie, ISBN. 9: 125-139.

Lee, C. M., Jones, B. H., Brink, K. H., and Fischer, A. S. (2000). The upper ocean response to monsoonal forcing in the Arabian Sea: Seasonal and spatial variability. *Deep-Sea Res.*, II **47** : 1177-1226.

Livingstone, D. A. (1963). Chemical composition of rivers and lakes. *Proc. Pap. U.S. Geol. Surv.* **440** G. 64.

Luther, M. E., and O' Brien, J. J. (1985). A model of the seasonal circulation in the Arabian Sea forced by observed winds. *Prog. Oceanogr.,* **14** : 353-385.

Madhu, N. V. (2004). Seasonal studies on primary production and associated environmental parameters in the Indian EEZ. *Ph.D Thesis, Cochin University of Science and Technology.*

Madhupratap, M., Gauns, M., Ramaiah, N., Prasanna Kumar, S., Muraleedharan, P. M., de Souza, S. N., Sardesai, S., and Usha Muraleedharan. (2003). Biogeochemistry of Bay of Bengal: Physical, chemical and primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001. *Deep-Sea Res.,* II **50** : 881-886.

Madhupratap, M., Gopalakrishnan, T. C., Haridas, P., Nair, K. K. C., Aravindakshan, P. N., Padmavati, G. and Paul, S. (1996 b). Lack of seasonal and geographic variation in mesozooplankton biomass in the Arabian Sea and its structure in the mixed layer. *Curr. Sci.,* **71** : 863-868.

Madhupratap, M., Prasannakumar, S., Bhattathiri, P. M. A., Dileepkumar, M., Reghukumar, S., Nair, K. K. C. and Ramaiah, N. (1996 a). Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature.* **384** : 549-551.

Maheswaran, P. A. (2004). Mixed layer characteristics and hydrography off the west and east coast of India. *Ph.D Thesis. Cochin University of Science and Technology.*

Maheswaran, P. A., Rajesh, G., Revichandran, C., and Nair, K. K. C. (2000). Upwelling and associated hydrography along the west coast of India during southwest monsoon, 1999. *PORSEC 2000 Proceedings,* II, 873-876.

Mann, K. H., and Lazier, J. R. N., 1996, Vertical structure of the open ocean: Biology of the mixed layer. Chapter 3 in Mann KH & Lazier JRN: *Dynamics of marine ecosystems - Biological-physical interactions in the oceans.* 2nd ed Blackwell Science. pp.56-97.

Mantoura, R. F. C., Law, C. S., Owens, N. J. P., Burkill, P. H., Woodward, E. M. S., Howland, R. J. M. and Llewellyn, C. A. (1993). Nitrogen biogeochemical cycling in the NW Indian Ocean. *Deep-Sea Res.*, II **40** : 651-672.

Morris, A. W. and Riley, J. P. (1963) The determination of sea water. *Anal. Chim. Acta.*, **29** : 272-279.

Morrison, J.M., Codispoti, J. A., Gaurin, S., Jones, B., Manghnani, V., and Zheng, Z. (1998). Seasonal variation of hydrographic and nutrient fields during the US JGOFS Arabian Sea process study. *Deep-Sea Res.*, II **45** : 2053-2101.

Morrison, J.M., Codispoti, J. A., Sharon, L. Smith., Karen Wishner., Charls Flagg., Wilford, D. Gardner., Steve Gaurin., Naqvi, S. W. A., Vijayakumar Manghnani., Linda Prosperie., Jan, S. Gundersen. (1999). The oxygen minimum zone in the Arabian Sea during 1995. *Deep-Sea Res.*, II **46** : 1903-1931.

Muraleedharan, P. M. and Prasanna Kumar, S. (1996). Arabian Sea upwelling – A comparison between coastal and open ocean regions. *Curr. Sci.*, **71**, 842-846.

Muraleedharan, P. M., Ramesh kumar, M. R. and Gangadhara Rao, L. V. (1995). A note on poleward undercurrent along the southwest coast of India. *Continental Shelf Res.* **15**(2/3) : 165-184.

Murphy, J. and Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chim. Acta.* 27 : 31-36.

Naik,H. and Naqvi, S. W. A. (2002). Sedimentary nitrogen cycling over the western continental shelf of India. *EOS- Transactions of the American Geophysical Union.*, **84**, Abstract 05121-05.

Nair, P. V. R., Samuel, S., Joseph, K. J. and Balachandran, V. K. (1973). Primary production and potential fishery resources in the seas around India. In: *Proc. Symp. Living Resources of Seas around India*, 1960. ICAR Special publication, CMFRI, Cochin : 184-198.

Nair, R. R., Ittekkot, V., Manghanini, S. J., Ramaswamy, V., Haake, B., Degens, E. T., Desai, B. N. and Honjo, S. (1989). Monsoon related particle fluxes to the deep Arabian Sea. *Nature.*, **338** : 749-751.

Naqvi, S. W. A. (1991). Geographycal extent of denitrification in the Arabian Sea in relation to some physical processes. *Oceanolog. Acta.,* **14** : 281-290.

Naqvi, S. W. A. (1994). Denitrification processes in the Arabian Sea. *Proc. Indian Acad. Sci.* (Earth Planet. Sci.) **103** : 279-300.

Naqvi, S. W. A. and Jayakumar, D. A. (2000). Ocean biogeochemistry and atmospheric composition: Significance of the Arabian Sea. *Curr. Sci.* **78** (3): 289-299.

Naqvi, S. W. A. and Qasim, S. Z. (1983). Inorganic nitrogen & nitrogen reduction in the Arabian Sea. Indian. J. Mar. Sci., 12 : 21-26.

Naqvi, S. W. A. and Sen Gupta, R. (1985). 'NO', a useful tool for the estimation of nitrate deficits in the Arabian Sea. *Deep-Sea Res.* **32** : 665-674.

Naqvi, S. W. A., George, M. D., Narvekar, P. V., Jayakumar, D. A., Shailaja, M. S., Sardesai, S., Sarma, V. V. S. S., Shenoy, D. M., Hema Naik., Maheswaran, P. A., Sudheer., A. K. and Binu, M. S. (1998). Severe fish mortality associated with 'red tide' observed in the sea off Cochin. *Curr. Sci.* **75** (6) : 543-544.

Naqvi, S. W. A., Jayakumar, D. A., Narvekar, P. V., Naik, H., Sarma, V. V. S., D' Souza, W., Joseph, S. and George, M. D. (2000). Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature*, **408** : 346-349.

Naqvi, S. W. A., Noronha, R. J. and Reddy, C. V. G. (1982). Denitrification in the Arabian Sea. *Deep-Sea Res.*, **29**: 459-469.

Naqvi, S. W. A., Noronha, R. J., Shailaja, M. S., Somasundar, K. and Sen Gupta, R. (1992). Some aspects of nitrogen cycling in the Arabian Sea. In: *Oceanography of the Indian Ocean,* Desai (Ed). Oxford and IBH Publishing Co, New Delhi. pp. 285-311.

Naqvi, S. W. A., Noronha, R. J., Somasunder, K. and Sen Gupta, R. (1990). Seasonal changes in the denitrification regime of the Arabian Sea. *Deep-Sea Res.*, **37** : 593-611.

O' Neill, P. (1985). Minor elements and environmental problems. In: *Environmental Chemistry*, George Allen and Unwin (Publishers) Ltd., London. 181-214.

Olson, R. J. (1981). Differential photo-inhibition of marine nitrifying bacteria: a possible mechanism for the formation of the primary nitrite maximum. *J. Mar. Res.* **39** : 227-238.

Olson, R. J. (1981). Differential photo-inhibition of marine nitrifying bacteria: a possible mechanism for the formation of the primary nitrite maximum. *J. Mar. Res.* **39** : 227-238.

Pankajakshan Thadathil. and Aravind, K. Gosh. (1992). Surface layer Temperature Inversion in the Arabian Sea during winter. *J. Oceanography.* **48** : 293-304.

Pankajakshan, T. and Rama Raju, D. V. (1987). Intrusion of Bay of Bengal water into Arabian Sea along the west coast of India during northeast monsoon. In: *Contributions in Marine Sciences* – Dr. S.Z. Qasim felicitation volume. 237-244.

Payne, W. H. (1973). Reduction of nitrogenous oxide by micro-organisms. *Bacteriol. Rev.,* **37** : 409-452.

Plant, A. (1992). Primary productivity in coastal and offshore waters of India during two southwest monsoons, 1987 and 1989. In: Desai, B. N. (Ed), *Oceanography of the Indian Ocean.,* pp. 81-90.

Prasanna Kumar, S and Prasad, T. G. (1996). Winter cooling in the northern Arabian Sea. *Curr. Sci.,* **71** : 11

Prasanna Kumar, S and Prasad, T. G. (1999).Formation and spreading of Arabian Sea high-salinity water mass. *J. Geophys. Res.,* **104** : 1455-1464.

Prasanna Kumar, S., Gauns, M., Sarma, V. V. S. S., Muraleedharan, P. M., Raghukumar, S., Dileep Kumar, M. and Madhupratap, M. (2001). Physical forcing of biological productivity in the northern Arabian Sea during the northeast monsoon. *Deep-Sea Res.,* **48** : 1115-1126.

Prasanna Kumar, S., Jayu Narvekar., Ajoy Kumar., Shaji, C., Anand, P., Sabu, P., Rejomon, G., Josia, J., Jayaraj, K. A., Radhika, A. and Nair, K.K. C. (2004). Intrusion of the Bay of Bengal water into the Arabian Sea during winter monsoon and associated chemical and biological response. *Geophys. Res. Lett.,* **31** L15304, doi: 10. 1029/2004 GL020247,2004.

Prasannakumar, S., Madhupratap, M., Dileep Kumar, M., Gaune, M., Muraleedharan, P. M., Sarma, V. V. S. S. and de Souza, S. N. (2000).

Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea. *Proc. Indian. Acad, Sci.* (Earth Planet. Sci.) **109** (4) : 433-441.

Premchand, K., Sastry, J.S. and Murty, C. S. (1986). Water mass structure in the western Indian Ocean. *Ph.D Thesis, Andhra Univ., Vizakhapatnam.*

Qasim, S. Z. (1977). Biological productivity of the Indian Ocean. *Indian. J. Mar. Sci.,* **6** : 122-137.

Ramamritham, C. P. and Rao, D. S. (1973). On upwelling along the west coast of India. *J. M. Biol. Assn. India.* 15 : 411-417.

Richards, F. A. (1958). Dissolved silicate and related properties of some western north Atlantic and Caribbean waters. *J. Mar. Res.* 17: 449-465.

Richards, F. A. (1965). Anoxic basins and Fjords. In: *Chemical Oceanography.* (Riley, J. P. and Skirrow, G. (eds.). **Vol.1**. Academic Press, London. 611-645.

Rochford, D. J. (1975). Nutrient environment of Australian coastal waters. I. T. Lautieton upwelling. *Aust. J. Mar. Fresh. Res.,* **26**, 223-243.

Sarkar, A., Remesh, R., Somayajulu, B. L. K., Agnihotri, R., Jull, A. J. T. and Burr, G. S. (2000). High resolution. Holocene monsoon record from the eastern Arabian Sea. *Earth Planet. Sci. Lett.,* **177** : 209-218.

Sastry, J. S. and D' Souza, R.S. (1972). Upwelling & upward mixing in the Arabian Sea. *Indian J. Mar. Sci.***1** : 17-27.

Schott, F. (1983). Monsoon response of the Somali Current and associated upwelling. *Prog. Oceanogr.,* **12** : 357-381.

Sen Gupta, R. and Naqvi, S. W. A. (1984). Chemical oceanography of the Indian Ocean, north of the equator. *Deep-Sea Res.* **31** : 671-706.

Sen Gupta, R., Rajagopal, M. D. and Qasim, S. Z. (1976). Relationship between dissolved oxygen and nutrients in the north-west Indian Ocean. *Indian J. Mar. Sci.* **5**: 201-211.

Shankar, D. (2000). Seasonal cycles of sea level and currents along the coast of India. Curr. Sci., **78** : 279-288.

Shankar, D., Vinayachandran, P. N., Unnikrishnan, A. S. (2002). The monsoon currents in the north Indian Ocean. *Prog. Oceanogr.* **52** : 63-120.

Shetye, S. R. (1984). Seasonal variability of the temperature field off the south-west coast of India. Proc. Indian Acad. Sci. (Earth Planet. Sci.), 93 : 399-411.

Shetye, S. R. and Shenoi, S. S. C. (1988). The seasonal cycle of surface circulation in the coastal north Indian Ocean. Proce. Indian. Acad. Sci. (Earth and planetary Sciences), **97** : 53-62.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sunder, D., Michael, G. S., Almeida, A. M. and Santanan, K. (1990). Hydrography and circulation off the west coast of India during the southwest monsoon, 1987. *J. Mar. Res.* **48** : 359-378.

Shetye, S. R., Gouveia, A. D. and Shenoi, S. S. C. (1994). Circulation and water masses of the Arabian Sea. Biochemistry of the Arabian Sea: Present information and gaps. ed. by: Lal, D. [Proc. Indian Acad. Sci. (Earth Planet. Sci)]. Indian Acad. Sci; Bangalore; India., 103(2) : 107-123.

Smed, J. (1982). The oceanographic data base for the Cooperative Investigations of the Northern part of the Eastern Central Atlantic (CINECA) region. Rapport et process – Verbeaux des Renunions. Conseille International par L' Exploration de la Mer **180** : 11-22.

Smith, R. L. and Bottero, J. S. (1977). On upwelling in the Arabian Sea, pp. 291-304 in Angel, M. (Ed), *A Voyage of Discovery.*, Pergamon, New York.

Smith, S. L., Roman, M., Prusova, I., Wishner, K., Gowing, M., Codispoti, L. A., Barber, R. T., Marra, J. and Flagg, C. (1998). Seasonal responses of zooplankton to monsoonal reversals in the Arabian Sea. *Deep-Sea Res.,* II **45** : 2369-2404.

Somayajalu, B. L. K., Sarin, M. M. and Ramesh, R. (1996). Denitrification in the eastern Arabian Sea: Evaluation of the role of continental margins using Ra isotopes. *Deep-Sea Res.* II **43** : 111-117.

Spencer, C. P. (1975). The micronutrient elements. In: *Chemical Oceanography.* Riley, J. P. and Skirrow, W. (Eds), Academic Press, London. **2** : 245-300.

Stanley, S. O, (1976). Biodegradation of organic matter in marine sediments. In: *Biogeochemistry of estuarine sediments*. Proceedings of UNESCO/SCOR workshop, held in Melreux, Belgium: 222-223.

Steeman Nielsen, E (1952). The use of radio active carbon (^{14}C) for measuring organic production in the sea. *J. cons. int. Explor.Mer.*, 18(2).

Steeman Nielsen, E. (1952). The use of radioactive carbon (14C) for measuring organic production in the sea. *J. Cons. Int. Explor. Mer.*, **18** (2).

Strickland, J. D. H. and Parsons, T. R. (1972). In: *A practical handbook of seawater analysis*. Fish. Res. Bd. Can. Bull. (2nd ed.), Ottawa: 419.

Subramanian, V. (1993). Sediment load of Indian waters. *Curr. Sci.*, **64** : 928-930.

Swallow, J. C. and Bruce, J. G. (1966). Current measurements off the Somali coast during the southwest monsoon of 1964. *Deep-Sea Res.* **13** : 861-888.

Swallow, J.C. (1984). Some aspects of the physical oceanography of the Indian Ocean. *Deep-Sea Res.* **31** : 639-650.

UNESCO (1994), Protocols for the Joint Global Ocean Flux Studies (JGOFS), Core Measurements, IOC Manuals and Guides, **29**, UNESCO, Paris, pp170.

Vaccaro, R. and Ryther, J. H. (1960). Marine phytoplankton and the distribution of nitrite in the sea. *J. Cons. Int. Explor. Mer.* **25** : 260-271.

Vaccaro, R. F. (1965), Inorganic Nitrogen in Sea Water, in Riley, JP, and Skirrow,G.eds., Chemical Oceanography: New York, Academic Press, v. **1** : 365-408.

Wada, E. and Hattori, A. 1971. Nitrite metabolism in the euphotic layer of the central North Pacific Ocean. *Limnol. Oceanogr.* 16: 766-772.

Wafar, M.V. M., Wafar, S. and Devassy, V. P (1986). Nitrogenous nutrients and primary productivity in a tropical oceanic environment. Bull. Mar. Sci., **38**.

Warnke, D. A. (1970). Glacial erosion, ice rafting and glacial – marine sediments: Antartica and the Southern Ocean. *American Journal of Science*. **269** : 276-294.

Weiss, R. F. (1970). The solubility of nitrogen, oxygen and argon in water and seawater. *Deep-Sea Res.*. **17** : 721-735.

Wolery, T. J. and Sleep, N. H. (1976). Hydrothermal circulation and geochemical flux at mid-ocean ridges. *J. Geol.* **84** : 249-275.

Wyrtki, K (1973). Physical oceanography of the Indian Ocean. In: The Biology of the Indian Ocean, B. Zeitzschel, editor, Springer-Verlag, Berlin, pp. 18-36.

Wyrtki, K. (1971). Oceanographic Atlas of the International Indian Ocean Expedition. National Science Foundation, Washington. D.C., pp 531.

List of Papers published / Communicated

Vijay John Gerson., Mohamed Asharaf, T. T., Rejomon George., Madhu, N. V., Jyothibabu, R., Balachandran, K. K. Thresiamma Joseph., Mahesweri Nair., Venugopal, P. and Nair, K. K. C. Oscillating environmental responses in the eastern Arabian Sea. Estuarine Coastal and Shelf Science, (communicated)

Jyothi Babu, R., Maheswaran, P. A., Madhu, N. V., Mohamed Asharaf, T. T., **Vijay,J. G.**, Venugopal, P., Revichandran, C., Balasubramanian, T., Gopalakrishnan, T. C., and Nair, K. K. C.(2004). Differential response of winter cooling on biological production in the northeastern Arabian Sea and northwestern Bay of Bengal. Curr. Sci., **87** : 783 – 791.

Rejomon George., Joseph, P. S.,. and **Vijay John Gerson**. Trace metal concentration in zooplankton from the Bay of Bengal. Journal of Plankton Research. (communicated).

N. Ramaiah., Jane T. Paul., Veronica Fernandes., T. Raveendran,. O. Raveendran., D. Sundar., C. Revichandran., D. M. Shenoy., G. Mangesh., Siby kurian., **V. J. Gerson**., D. T. Shoji, N. V. Madhu., S. Sree kumar., P. A. Lokabharathi., and S. R. Shetye. (2005). The September 2004 stench off the southern Malabar coast – A consequence of holococcolithophore bloom. Curr. Sci., 88. No.4 : 25.

Laluraj, C. M., Kesavadas, V., Balachandran, K. K., **Vijay, J. G.**, Martin, G. D., Revichandran, C., Thresiamma Joseph. and Mahesweri Nair. Recovery of an estuarine system from tsunami impact- Southwest coast of India. Environmental monitoring and assessment (communicated).