Chapter 3
The Northeastern Arabian Sea

3.1 Introduction

The Arabian Sea constitutes the northwestern part of the Indian Ocean. It is surrounded by the Asian and African continents to the north and west and the Indian subcontinent to the east. Assuming equator as its southern boundary, it encompasses an area of about $6.2*10^6$ km^2 (Burkill et al. 1993). Although the Arabian Sea is one of the smaller ocean basins, its unique geographical setting transforms it into a perfect biogeochemical laboratory that contains different biogeochemical provinces such as eutrophic, oligotrophic and oxygen deficient environments. The uniqueness of the Arabian Sea is that it comes under the influence of seasonally reversing monsoonal wind forcing. The winds have the greatest influence in the biogeochemical cycling in the Arabian Sea. The winds over Arabian Sea blow from northeast (NE) during December to February (NE monsoon) and reverse direction during May and start blowing from the southwest (SW) direction (SW monsoon) persisting till August. The transition periods, October-November and March-May are known as Fall and Spring intermonsoons (Schott et al. 1990).

The monsoonal coupling between ocean and atmosphere is so intense that the seasonal shift in wind pattern causes semi-annual reversal of surface currents in the Arabian Sea basin (Figure 3.1). These changes lead to the greatest seasonal variability of biological productivity observed in any ocean basin in the world (Smith et al.1998). In general, the most important characteristics of the Arabian Sea seasonal cycle of physical conditions are as follows (Barber et at. 2001):

1. Strong wind stress during the SW monsoon resulting in widespread upwelling and mixing.
2. Moderate strength, relatively cool and dry winds during the NE monsoon leading to evaporative cooling and subsequent convective mixing.
3. Weak winds and strong stratification due to surface layer heating during the spring and fall intermonsoons.

Apart from witnessing changes in physical and biogeochemical conditions in time, the Arabian Sea also exhibits considerable spatial variation that is not seen in any other ocean (Smith and Bottero 1977). Asymmetric monsoonal effect creates strong gradient in biogeochemical processes within the basin (Burkill et al. 1993). During the SW monsoon, a narrow, low level, atmospheric jet with exceptionally strong winds known

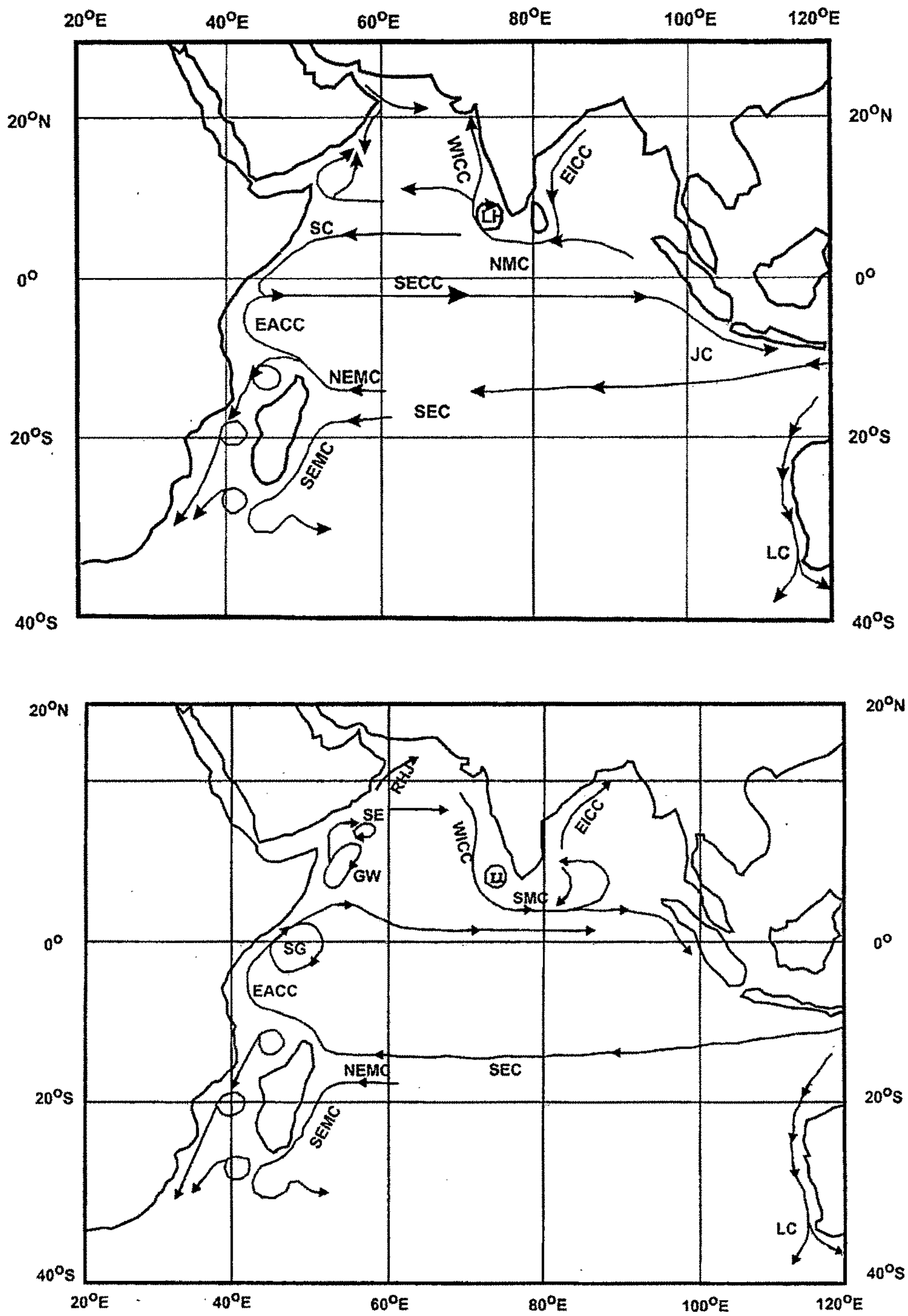

Figure 3.1 A schematic representation of identified current branches during Northeast (top) and southwest (bottom) monsoon taken from Schott and McCreary Jr. (2001). Current branches indicated are the South Equatorial Current (SEC), South Equatorial Counter Current (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), East African Coast Current (EACC), Somali Current (SC), Southern Gyre (SG), Great Whirl (GW), Socotra Eddy (SE); Ras al Hadd Jet (RHJ); West and East India Coastal Current (WICC and EICC), Laccadive High and Low (LH and LL), Southwest and Northeast Monsoon current (SMC and NMC); South Java current (JC) and Leeuwin Current (LC).

as the Findlater Jet (Findlater, 1974) causes strong gradients in the wind stress curl field (Figure 3.2). A positive wind stress curl drives open ocean upwelling (at the rate of about $1\text{-}2*10^{-3}$ cm s^{-1}) due to upward Ekman pumping to the NW of the Findlater Jet axis extending as far as 400km offshore (Smith and Bottero 1977). To the SE of the jet axis decreasing southwesterly wind causes negative wind stress curl (Hastenrath and Lamb 1979) that drives the surface water downward by Ekman pumping resulting into considerable deepening of mixed layer (Brock et al. 1991; Brock and McClain 1992;

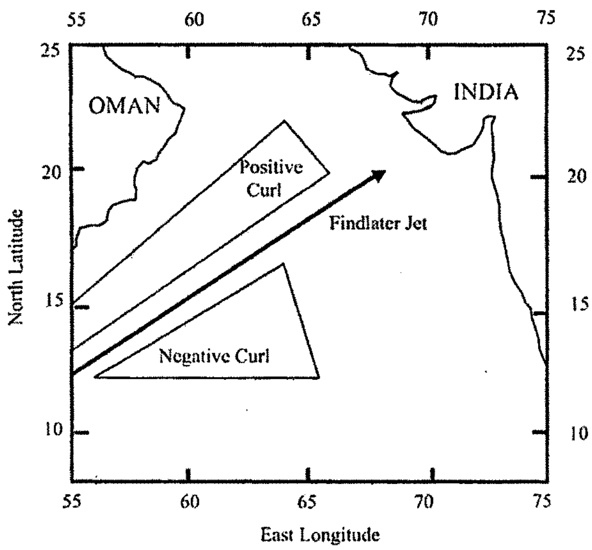

Figure 3.2 Findlater jet along with region assumed to have positive and negative wind stress curl (Brock et al. 1991).

McCreary et al. 1996). Apart from the open ocean upwelling in the Arabian Sea, coastal upwelling driven by offshore Ekman divergence of surface water under the influence of winds parallel to the coast is also known (Smith and Bottero 1977). Coastal upwelling (at the rate of about $3*10^{-3}$ cm s^{-1}) is more pronounced off the coast of Oman and Somalia (Smith and Bottero 1977; Lee et al. 2000) however, a weaker upwelling is known to occur off southwest India (Wyrtki 1973). Upwelling is replaced by the convective mixing during NE monsoon in the Arabian Sea. The phenomena of upwelling and convective mixing bring enormous amount of nutrient rich deep water into the surface ocean, leading to increase in productivity and subsequently the cycling of nitrogen in the Arabian Sea.

Even before JGOFS, the Arabian Sea had been widely studied for its physical, chemical, geological and biological characteristics. However, the collective and thorough exploration of the Arabian Sea with well-defined objectives was performed during the JGOFS period (1994-96). The main purpose of the JGOFS was to answer the following questions (Smith 2001):

1. Is the Arabian Sea a source or sink of carbon dioxide?
2. Is the Arabian Sea Mother Nature's iron experiment?
3. Do grazing zooplankton control carbon flux to the seabed?
4. Does the paleoceanographic record help us predict the ocean's response to climate change? and
5. What are the predominant physical processes of the Arabian Sea?

The present study concentrates mainly on the measurement of total and new production using ^{15}N tracer technique along with natural nitrogen isotopic studies in the northeastern Arabian Sea. The following two subsections briefly discuss the productivity measurements carried out earlier in the region using ^{14}C and ^{15}N techniques followed by the work carried out during the present study.

3.2 ^{14}C based Productivity in the Arabian Sea

Several observations for the total primary productivity in the Arabian Sea have been made (Ryther et al. 1966; Kabanova 1968; Krey 1973; Qasim 1977; Qasim 1982; Banse 1987), but in majority of the cases data have been averaged over coarse spatial and temporal domains, which is a serious limitation for a detailed process study. After the advent of satellite oceanography, greater insight into the annual changes in the phytoplankton productivity regimes have been observed, particularly using Coastal Zone Colour Scanner (CZCS) data (Banse and McClain 1986; Brock et al. 1991, 1993, 1994; Brock and McClain 1992). In addition to the JGOFS study (Savidge and Gilpin 1999 and Barber et al. 2001), earlier ship based studies include Owens et al. (1993) and Jochem et al. (1993).

Savidge and Gilpin (1999) have studied the size fractionated ^{14}C based productivity in the Arabian Sea during two UK "ARABESQUE" cruises during the late SW Monsoon and autumn intermonsoon of 1994. During the late SW monsoon season, maximum productivity of 3800 mgC m^{-2} d^{-1} (dominated by > 18μM fraction), distributed patchily, was observed in the coastal upwelling zone, whereas an average productivity of 1500 mgC m^{-2} d^{-1} was observed elsewhere with the dominance of 0.2-2μM fraction. During the autumn intermonsoon the productivity averaged around 750 mgC m^{-2} $d^{-1}$with dominance of 0.2-2μM size fraction. Ryther et al. (1966) have reported a mean productivity of 2230 mgC m^{-2} d^{-1} (ranging from 840-6580 mgC m^{-2} d^{-1}; n =18) for the Oman coastal upwelling zone (north of 18°N) compared to 3080 mgC m^{-2} d^{-1} reported for the same region by Savidge and Gilpin (1999). A decrease in the mean productivity to 1550 mgC m^{-2} d^{-1} by Ryther et al., (1966) and 2050 mgC m^{-2} d^{-1} by Savidge and Gilpin (1999) have been reported for region between 16 and 18°N. For the region between 9 and 16° N the average productivity of 910mgC m^{-2} d^{-1} by Savidge and Gilpin (1999) and 1060 mgC m^{-2} d^{-1} by Ryther et al. (1966) have been reported.

Owens et al. (1993) have reported primary productivity variations from approximately 500 mgC m^{-2} d^{-1} at the equator to 300 mgC m^{-2} d^{-1} in the oligotrophic gyre in the central Arabian Sea, and > 2500 mgC m^{-2} d^{-1} in the upwelling region off the coast of Oman during September-October, 1986. They observed higher production in the regions where chlorophyll was more but could not find any significant statistical relationship to conclude that higher productivity was due to the presence of subsurface chlorophyll maximum at a number of stations.

Jochem et al. (1993) have studied the productivity regime and size structure of the phytoplankton during the spring intermonsoon of 1987, in the Arabian Sea. They found the integrated productivity to vary from 1000 to less than 600 mgC m^{-2} d^{-1} near the coast of Oman with a maximum contribution from picoplankton (<2μM). The mean productivity was around 700 mgC m^{-2} d^{-1} for the central Arabian Sea with picoplankton as the dominant contributing fraction. Primary productivity of 200-400 mgC m^{-2} d^{-1} was observed near the shelf off Pakistan.

The monsoon-driven variability in primary productivity and its regulation in the Arabian Sea were studied by Barber et al. (2001) in year 1995 as a part of the US JGOFS using the ^{14}C technique. The study was carried out from the coast of Oman to the central Arabian Sea (65°E). According to this study, the SW Monsoon was the most productive season with an average value of 1476±108 mgC m^{-2} d^{-1} followed by an unexpectedly high average productivity of 1344±84mgC $m^{-2}d^{-1}$ during the NE Monsoon. However, the Barber et al. (2001) argue that high productivity observed during the SW Monsoon was less than that expected for a coastal upwelling region because of efficient grazing of diatoms by mesozooplankton. During the spring intermonsoon season, the Arabian Sea is considered to be oligotrophic; however, the observed productivity during this season by Barber et al. (2001) was much higher (1032±72 mgC m^{-2} d^{-1}) than in other oligotrophic regions of the world such as the tropical Pacific (348±24 mgC m^{-2} d^{-1}) and the North Pacific gyre (384±96 mgC m^{-2} d^{-1}). Overall, the annual mean productivity in the Arabian Sea in the year 1995 was observed to be 1332 ±132 mgC m^{-2} d^{-1} that is roughly equal to that during the spring bloom of the North Atlantic (1284±276 mgC m^{-2} d^{-1}). No gradient in productivity was observed from the coast to the open ocean. There was no evidence of light limitation, as expected, during NE Monsoon convective mixing or deep wind mixing during the SW monsoon.

Qasim (1982) has reported a very wide range of primary productivity for the northern Arabian Sea (north of 15°N) varying from 13.0 to 6010 mgC $m^{-2}d^{-1}$ with an average value of 835 mgC $m^{-2}d^{-1}$. He has also found the coastal areas to be more productive (average 1329 mgC $m^{-2}d^{-1}$) than the offshore areas (626 mgC $m^{-2}d^{-1}$) and concluded that coastal water sustained more than 50% of the total production of the northern Arabian Sea. Qasim (1982) found that the Arabian Sea was most productive during the SW monsoon (average 921±1140 mgC m^{-2} d^{-1}); the productivity during NE monsoon (919±1030 mgC $m^{-2}d^{-1}$) was less and during premonsoon (733±947 mgC $m^{-2}d^{-1}$) was lesser. Qasim (1982) emphasised that northern Arabian Sea (~ $1.7*10^6$ km^2 ~ 25% of total area) supports 50% ($518*10^6$ tonnes C y^{-1}) of the total primary production of the Arabian Sea. However, Radhakrishna et al. (1978) have reported lower estimates of productivity from the same region.

The primary productivity study closest to the present study area (the northeastern Arabian Sea) was performed during the intermonsoon, NE monsoon and SW monsoon by Bhattathiri et al. (1996) as a part of the Indian JGOFS. The integrated production rates reported by Bhattathiri et al. (1996) varied between 193-199, 337-643 and 770 mgC $m^{-2}d^{-1}$ in the open ocean (along 64°E) for the three seasons respectively whereas for the near coastal stations these values were 281-306, 200-807 and 440-1760 mgC $m^{-2}d^{-1}$. The seasonal variation in productivity was found to be consistent with the circulation patterns and associated nutrient levels.

Overall, available literature points towards the seasonal and geographical variation in the productivity regime of the Arabian Sea. In general, the SW monsoon has been found to be the most productive season followed by NE monsoon and intermonsoon. The reason cited for the SW monsoon and NE monsoon to be the productive seasons is the availability of nutrients in the surface layer due to vertical wind mixing during SW monsoon and convective mixing due to winter cooling during

NE monsoon. Geographically, the coastal locations such as off Oman are more productive than open ocean locations. The average productivity values reported for the Arabian Sea have been indexed in Table 3.1.

Table 3.1 ^{14}C based average total productivity values reported for different seasons and locations in the Arabian Sea.

	Season	Region	Total Productivity ($mgC\ m^{-2}\ d^{-1}$)
Ryther al. (1966)	Late September- Early November	North of 18°N 16 and 18°N 9 and 16°N	2230 1550 1060
Qasim (1982)	Premonsoon SW monsoon NE monsoon	Northern Arabian Sea	733 921 919
Owens et al. (1993)	September-October	Equator Central Northern Indian Ocean Off Coast of Oman	500 <300 >2500
Jochem et al. (1993)	Spring Intermonsoon	Coast of Oman Central Arabian Sea Shelf off Pakistan	1000-300 700 200-400
Bhattathiri et al. (1996)	Premonsoon NE monsoon SW monsoon Premonsoon NE monsoon SW monsoon	Central and Eastern Arabian Sea Open Ocean Locations Coastal Locations	193-199 337-643 770 281-306 200-807 440-1760
Savidge and Gilpin (1999)	Late SW monsoon Autumn Intermonsoon	NW Indian Ocean	1500 750
Barber et al. (2001)	NE monsoon- January NE monsoon- December Intermonsoon- Spring SW monsoon-Mid SW monsoon-Late Annual Mean	Coast of Oman to 1000km offshore in Central Arabian Sea	1644 1056 1032 1620 1320 1332

3.3 ^{15}N based productivity in the Northwestern and the Central Arabian Sea

Results for ^{15}N based productivity (new and regenerated production) or nitrogenous nutrient uptake in the northwestern and central Arabian Sea have been reported by Owens et al. (1993), McCarthy et al. (1999), Watts and Owens (1999) and Sambrotto (2001). *No data for nitrogen based productivity has been reported from the eastern Arabian Sea till the present study.*

Owens et al. (1993) observed almost five-fold variation in the potential total nitrogen (Nitrate + Ammonium) assimilation (23.1 mmolN $m^{-2}d^{-1}$ for central Arabian Sea to 96.7 mmol N $m^{-2}d^{-1}$ for off Oman coast) during September-October 1986 and found that the assimilation rates varied with primary production. The f-ratio varied from 0.09 in the oligotrophic region to as high as 0.92 in the upwelling region and showed a marked switch from a system dominated by ammonium assimilation in the oligotrophic region to nitrate-dominated in the upwelling region. Based on the high f-ratio Owens et al. (1993) concluded that a significant portion of the productivity would be available for higher trophic levels or sedimentation.

McCarthy et al. (1999) studied the nitrogen dynamics of the Arabian Sea during early and late NE monsoon of 1995. They found the higher abundance of all nitrogenous nutrients in the late phase of NE monsoon. McCarthy et al. (1999) have also reported the widespread suppressing effect of NH_4^+ on NO_3^- uptake that was found to be 2-3 times more extreme during night than during day. They have reported low f-ratios, 0.15 (s.d. = 0.07, n= 15) and 0.13 (s.d. = 0.08, n=17) for early and late NE monsoon respectively and argued that the combined effect of high affinity for low concentration of NH_4^+ and effect of NH_4^+ concentration on NO_3^- uptake may be the possible reasons. McCarthy et al. (1999) also studied the effect of light on uptake of NO_3^- and NH_4^+ in the Arabian Sea and concluded that NO_3^- utilization was more strongly influenced by light than NH_4^+ utilization (only 20% of NO_3^- uptake occurred during night relative to 35% in the case of $NH4^+$). The higher uptake for $NH4^+$ relative to NO_3^- reflects either a higher contribution of heterotrophic activity to the aggregate rate of NH_4^+ uptake or greater autotrophic potential to use NH_4^+ in the absence of light. For the whole study area, the total nitrogen uptake during the late NE monsoon (~26mmolN $m^{-2}d^{-1}$) was higher than during the early NE monsoon (11mmol N $m^{-2}d^{-1}$).

Watts and Owens (1999) reported nitrogen assimilation by phytoplankton that varied from 1.1 to 23.6 mmol N $m^{-2}d^{-1}$ in the northwestern Indian Ocean during an intermonsoon period of 1994. They also reported ammonium to be the most preferred substrate.

Sambrotto (2001) reported nitrogen productivity and regeneration during the Spring Intermonsoon and the SW monsoon for the northern Arabian Sea. Overall, the new (nitrate) production varied from 0.1 to 13mmolN $m^{-2}d^{-1}$, whereas the f-ratio varied from 0.03 to 0.4. As expected, the onset of SW monsoon results in an increase in the nitrate uptake by an order of magnitude compared to the spring intermonsoon.

3.4 Chlorophyll *a*, nutrients and physical parameters during January 2003 in the Northeastern Arabian Sea

3.4.1 Chlorophyll *a*

Chlorophyll *a* concentrations were measured at six out of seven stations. The measurement could not be performed at PP7 due to sampling problems. During the study period the maximum integrated Chl *a* concentration of 68.5 mg m^{-2} was found at PP2 (an open ocean station). For all other stations it varied within a range of 26.4 to 31.8 mg m^{-2} (Figure 3.3-left panel). The surface Chl *a* was also maximum at PP2 where it was 1.15mg m^{-3}. At all other stations it varied from 0.42 at PP4 (an open ocean station) to 0.7 mg m^{-3} at PP6 (a coastal station). The vertical profiles of Chl *a* at different stations are shown in Figure 3.3-right panel. At PP1 there is decrease in Chl *a* from surface to 40m that increases again to show Chl *a* maximum at 55m, slightly more than that of the surface value (0.56 compared to surface value of 0.52 mg m^{-3}). At PP2 the Chl *a* is slightly more than or around 1 mg m^{-3} at most of the depths and decreases sharply after 50m to reach a lowest value of 0.39 mg m^{-3} at 65m. There is no distinct Chl *a* max at PP2. Profile at PP3 shows a small subsurface Chl *a* minimum at 20m and again peaks up to remain almost uniform throughout the water column with a typical concentration of ~0.42 mg m^{-3}. The range of variation at PP4 is between 0.41 to 0.52 mg m^{-3} with a maximum at 50m. The Chl *a* concentration at PP5 shows a general increase with depth with a minimum value at the surface and a maximum at 65m (base of euphotic depth) whereas PP6 shows the trend opposite to PP5 with a general decrease with depth in Chl *a* concentration.

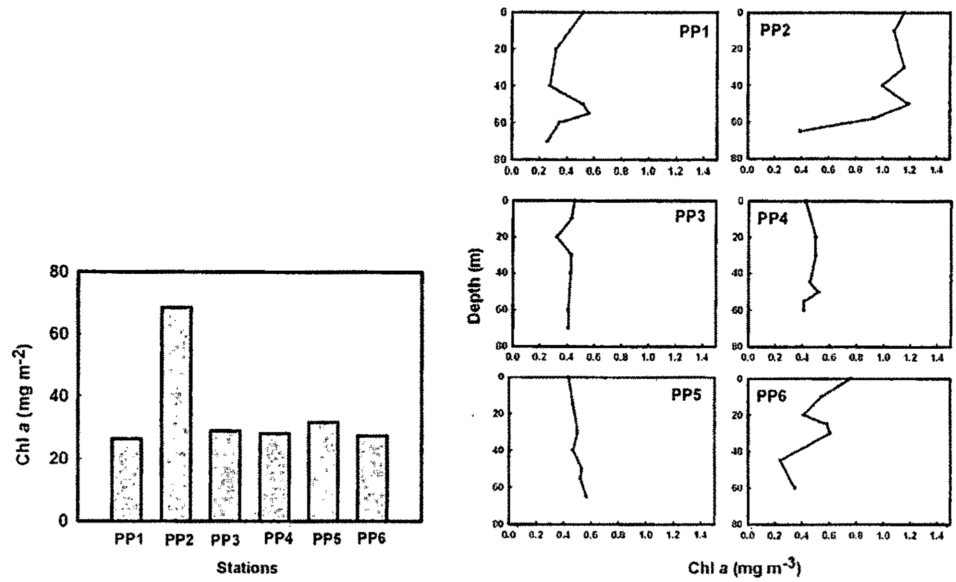

Figure 3.3 Euphotic zone integrated concentration (left panel) and vertical profile (right panel) of Chlorophyll *a* at productivity stations during January 2003.

3.4.2 Nutrients

Samples from different stations were analysed for nitrate and ammonium concentrations using an autoanalyser. The integrated nitrate varied from as low as 5.2mmol m^{-2} at coastal station (PP7) to as high as 254mmol m^{-2} at open ocean station (PP4). Most of the stations had integrated nitrate around or more than 100 mmol m^{-2}

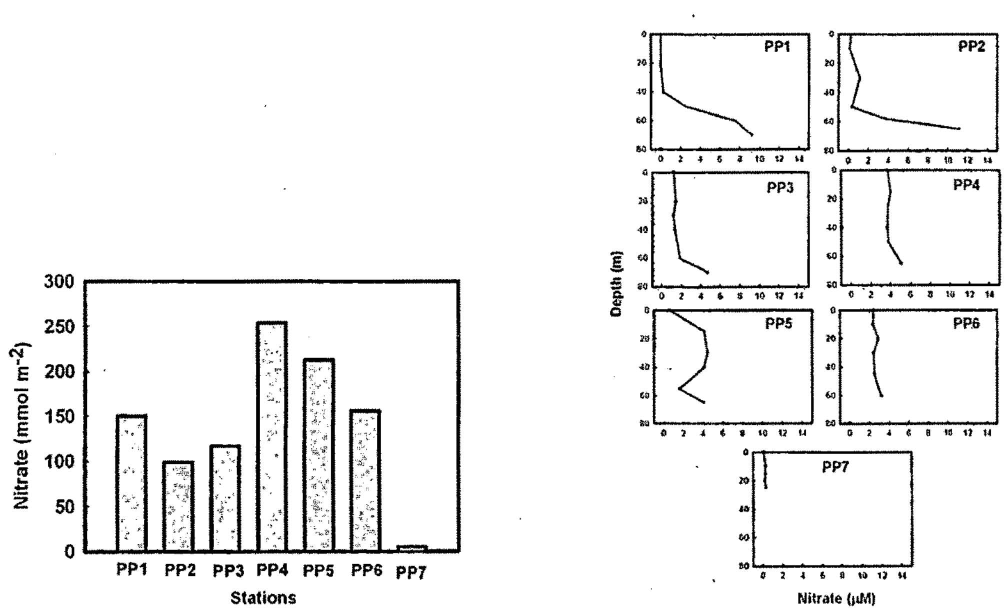

Figure 3.4 The euphotic zone integrated (left panel) and vertical profile (right panel) of ambient nitrate at different stations during January 2003.

(Figure 3.4-left panel). The vertical profiles of nitrate at different stations are shown in Figure 3.4-right panel. PP1 and PP2 do not have much nitrate in the upper 50m of water column (<0.4μM), but it increases to around 7 and 11μM respectively around 65m. PP3 has nitrate more than 1μM throughout the water column, it increases to 3μM throughout at PP4. PP5 and PP6 also have almost uniform nitrate concentrations with 4 and ~2μM respectively at each depth. Again at the coastal station PP7, nitrate decreases significantly to around 0.1μM (measurement was made only up to 25m, euphotic depth). The increased nitrate concentration at open ocean stations indicates the effect of winter cooling leading to deeper mixed layer depth and consequent enrichment of nitrate in the water column.

The integrated ammonium concentration during January in the northeastern Arabian Sea varied within a narrow range of 0.5 (PP7) to 8.4mmol m^{-2} (PP4). The integrated ammonium concentration at different stations is shown in Figure 3.5 (left panel). The ammonium concentration during the study period was never more than 0.3 μM for any station within the euphotic zone and it was found below detection limit (0.01μM) at several depths. At PP7 ammonium was almost absent through the top 20m of water column to reach 0.05μM at bottom of euphotic zone. The depth profile of ammonium is shown in Figure 3.5 (right panel).

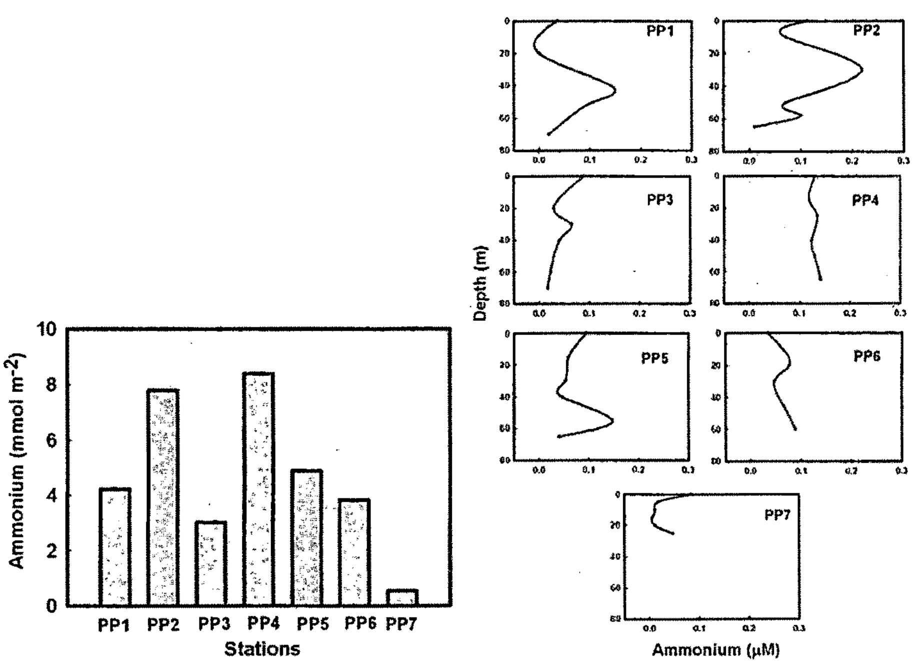

Figure 3.5 The euphotic zone integrated (left panel) and vertical profile (right panel) of ambient ammonium at different stations during January 2003.

3.4.3 Hydrographic and meteorological conditions

The present study was conducted during the Asian winter monsoon. This period in the Arabian Sea witnesses a temperature difference of almost 5-6°C from the south to the north. The long-term average temperature during the month of January in the Arabian Sea is shown in Figure 3.6 (left-panel). During the study period sea surface temperature showed a general decrease from south to north, with maximum temperature of 28.6°C at one of the southernmost stations (PP1) and minimum of 23.9 °C at one of the northernmost stations i.e., Stn.11 (Figure 3.6-right panel). Decrease in temperature from the south to the north during winter is characteristic of the region and has been found to decrease at a rate of 0.5°C per degree latitude (Madhupratap et al. 1996).

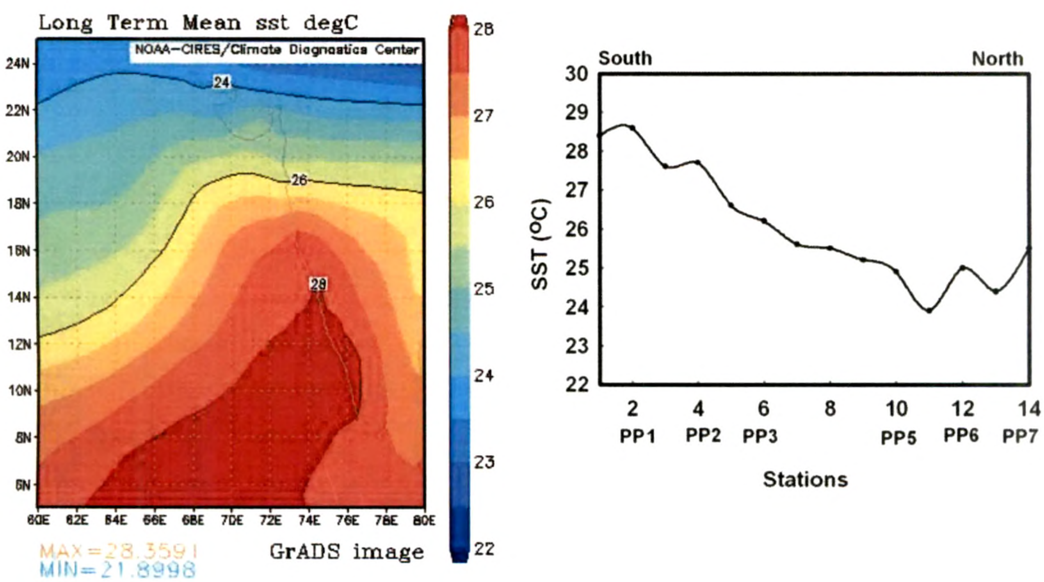

Figure 3.6 The long-term average Sea surface Temperature (SST) of the Arabian Sea during January (left panel, Source: Climate Diagnostic Center, National Center for Environmental Prediction, USA) and SST at different stations at the time of sampling (right panel) during January 2003.

Similarly, the air temperature over the Arabian Sea also dropped from 29.2°C in the south to 24°C in the north during the study period (Figure 3.7-left panel). Long term average of air temperature during January is shown in Figure 3.7 (right panel). At most of the stations SST was higher than the air temperature by 0.6°C or more. Wind during January was north/northeasterly with an average speed of around $4ms^{-1}$. The average wind direction and speed during January is shown in Figure 3.8 (left-panel) and the wind speed during sampling is shown in Figure 3.8 (right-panel). The surface pressure was the lowest at the start of the cruise (1012.5mb at Stn 1) and increased

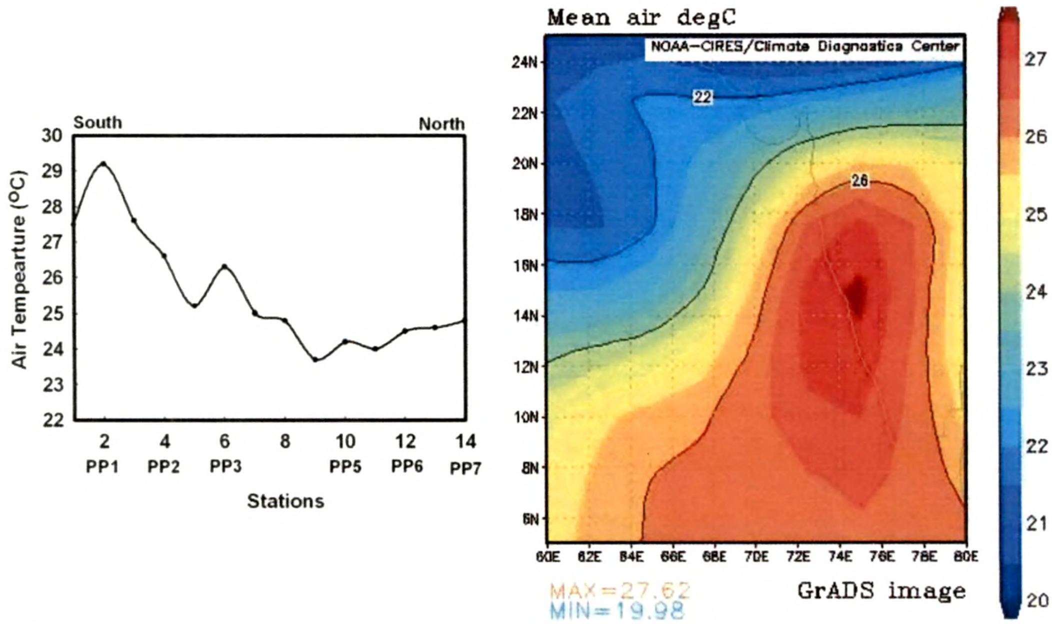

Figure 3.7 Air temperature at different stations at the time of sampling (right panel) during January 2003 and the long-term average air temperature over the Arabian Sea during January (left panel, Source: Climate Diagnostic Center, National Center for Environmental Prediction, USA).

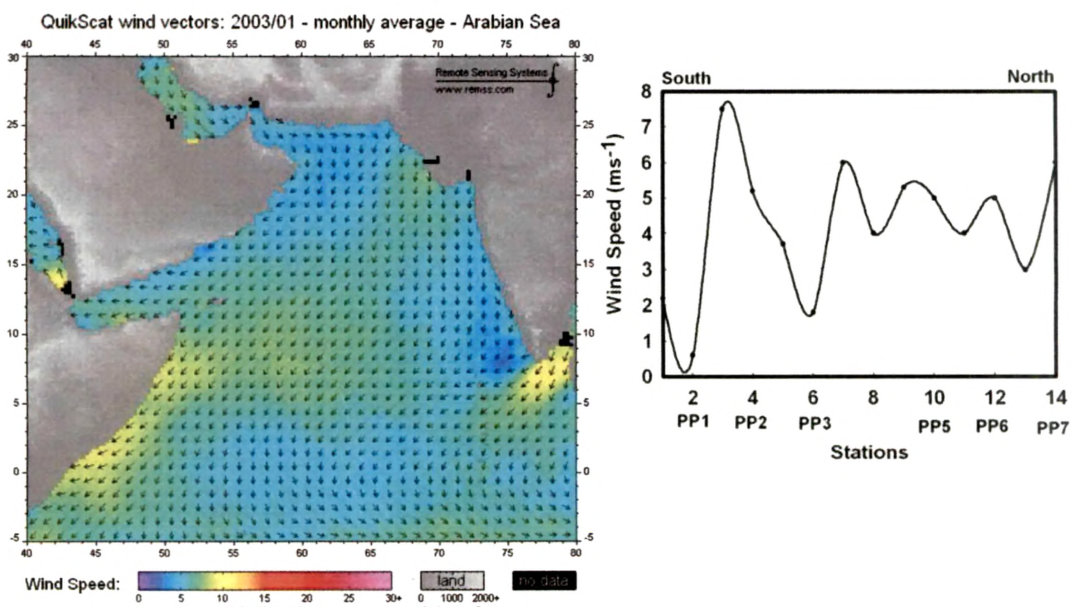

Figure 3.8 The monthly average of wind speed and direction over Arabian Sea (left panel, Source: Quikscat) and wind speed measured at the time of sampling during January 2003.

gradually to reach a maximum of 1019mb at PP5 (Stn. 12). A sharp drop in atmospheric pressure was observed from Stn. 10 to Stn. 11 (1014.5 mb) to peak up again at stn. 12 (Figure 3.9). General increase in surface layer depth with uniform

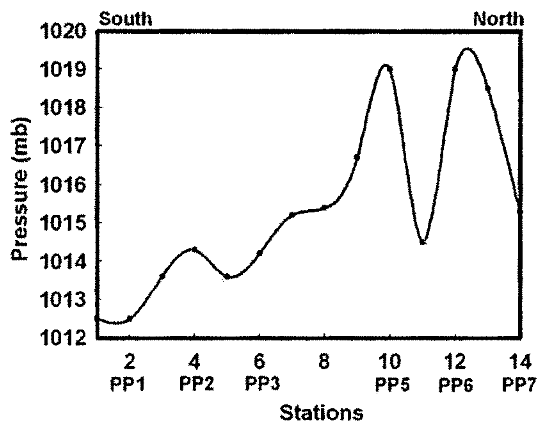

Figure 3.9 Air pressure at the time of sampling during January 2003.

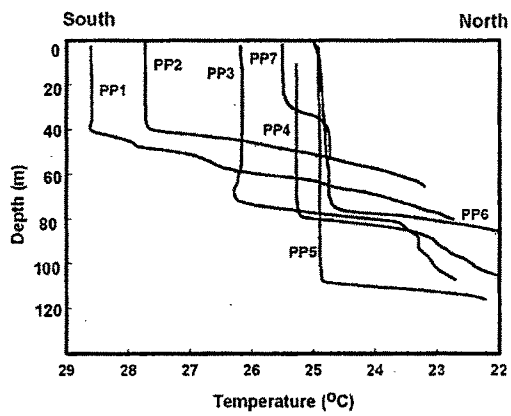

Figure 3.10 Temperature profile at different stations obtained with Satlantic Radiometer during January 2003.

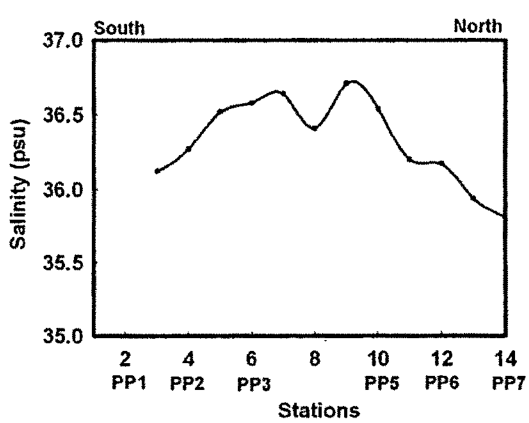

Figure 3.11 Salinity variation from south to north at sampling time during January 2003.

temperature (henceforth as temperature based mixed layer or MLD) was observed from south to north with southern station PP1 at around 40m to 107m for one of northernmost (PP5~ stn.10) stations (Figure 3.10). The most dramatic increase in MLD was observed from PP2 (40m) to PP3 (70m). The average euphotic depth in the open ocean was 60m (maximum 70m at Stn.1 to minimum 53m at stn.10~PP5) that reduced to 25m at coastal station PP7 (stn. 14). Slight variation in surface salinity from south to north was observed during study period (Figure 3.11). The maximum salinity of 36.71 was observed at an open ocean station (stn. 9) whereas minimum was observed at coastal stn.14. (PP7).

3.5 ^{15}N based productivity study during January 2003

3.5.1 Total Production

The present study concentrated mainly in the open ocean, where five out of seven were open ocean stations (PP1 to PP5) and two (PP6 and PP7) were coastal stations (off Gujarat). The rates of total N-uptake, integrated over the water column from the surface upto 1% light level (photic depth) span an order of magnitude over the study area and range from 6.17 mmolN m^{-2} d^{-1} to 65.4 mmolN m^{-2} d^{-1} (Figure 3.12). The highest rate has been measured at the second station (PP2), which is 65.4mmolN m^{-2} d^{-1} (~ 5000mgC m^{-2} d^{-1}), one of the highest observed so far for the northeastern Arabian Sea.

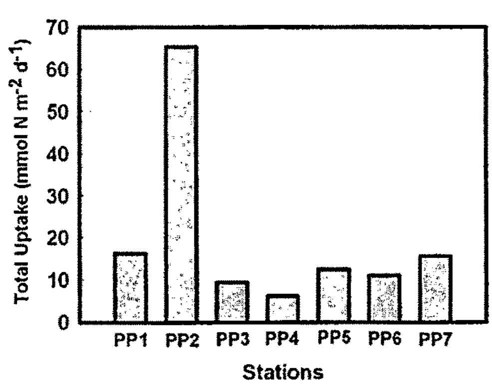

Figure 3.12 ^{15}N based total productivity (estimated as sum of nitrate, ammonium and urea uptakes) observed during present study.

However, total productivity as high as 6010 mgC m^{-2} d^{-1} has been reported for coastal waters of the northern Indian Ocean during the premonsoon season (Qasim, 1982). Ryther et al. (1966) have also reported the productivity value as high as 6580 mgC m^{-2} d^{-1} from the coastal area off Oman. The minimum rate of 6.17 mmolN m^{-2} d^{-1} was observed in the station PP4, also an open ocean station. No systematic spatial variability from south to north has been observed in the total uptake rates. Except PP2, uptake rates range from ~6 to 16mmolN m^{-2} d^{-1} for the region. Total productivity during present study averages around 20 (±20)* mmolN m^{-2} d^{-1} (~ 1590 mgC m^{-2} d^{-1}), which reduces to 12 (±3.8) mmolN m^{-2} d^{-1} (954 mgC m^{-2} d^{-1}) when PP2 is excluded. The average rate of total N-uptake for open ocean station is around 22(±24) mmolN m^{-2} d^{-1} (~1750 mgC m^{-2} d^{-1}) and comes down to 11 (±4.4) mmol N m^{-2} d^{-1} (~ 874 mgC m^{-2} d-1) after excluding PP2. Two coastal stations studied off Gujarat averaged around 13.4(±3.2) mmol N m^{-2} d^{-1} (~1065 mgC m^{-2} d^{-1}). For the same region, Bhattathiri et al., (1996) have reported ^{14}C based total productivity varying from 337-643mgC m^{-2} d^{-1} for the open ocean and upto 807 mgC m^{-2} d^{-1} (~ 10.1 mmol N m^{-2} d^{-1}) for the coastal locations during the same season. The average values reported here (excluding station PP2) are similar to the values reported by Bhattathiri et al. (1996). Since the PP2 has anomalously high value compared to other stations, the average value excluding PP2 will be considered as the representative value for the study region and the same will be used for comparison with other studies. Average total nitrogen uptake of 26 mmolN $m^{-2}d^{-1}$ (ranging from 9.2 - 40 mmolN $m^{-2}d^{-1}$) and 11 mmolN $m^{-2}d^{-1}$ (ranging from 3.9-24mmolN $m^{-2}d^{-1}$) has been reported for the northwestern and central Arabian Sea during the month of January (same season as present study) and November respectively (McCarthy et al. 1999). Although of the same month, the value reported by McCarthy et al. (1999) for January is significantly higher than reported during the present study probably indicating higher nutrient availability due to convective mixing by winter cooling and effective utilization of the available nutrients by the phytoplankton in the northwestern and central Arabian Sea than the northeastern Arabian Sea. However, the average value reported by McCarthy et al. (1999) for the month of November is comparable with the average values of the present study. Highest value of productivity (40mmolN $m^{-2}d^{-1}$) reported by McCarthy et al. (1999) for a central Arabian Sea station is considerably lower than the highest value for open ocean station of the present study. Watts and Owens (1999) have reported the average integrated assimilation rate of 8.3 mmolN $m^{-2}d^{-1}$ for northwestern Arabian Sea during intermonsoon, which is significantly lower than the average values reported during present study. This shows that the northeastern Arabian Sea during NE monsoon is definitely more productive

* Numbers in parentheses are geographical variabilities and not experimental uncertainties.

than the otherwise highly productive northwestern Arabian Sea during intermonsoon season. The values reported here are comparable to nitrogen uptake rates in the northeast Atlantic during July 1996 (Donald et al. 2001) but higher than the total productivity reported for equatorial Pacific Ocean along meridional section at 150°W during February-March (Dugdale et. al. 1992). The 'productivity normalised to Chlorophyll *a*' during the present study (spatially) averaged around 2.3 (± 2.3) h^{-1} which is well within the observed oceanic range.

3.5.2 New Production

As mentioned in the earlier chapter, nitrate uptake has been considered as new production during the present study. Barring station PP2, where new production has been found to be quite high (34.8 mmolN $m^{-2}d^{-1}$ ~ 2766 mgC $m^{-2}d^{-1}$), it ranges from 1 (~ 80mgC $m^{-2}d^{-1}$) to 4.3mmolN m^{-2} d^{-1} (~342 mgC $m^{-2}d^{-1}$) (Figure 3.13). Overall new production for the region averages around 2.3(±1.1) mmolN m^{-2} d^{-1} (~183 mgC $m^{-2}d^{-1}$), but it increases to ~7(±12.3) mmolN m^{-2} d^{-1} (~ 557 mgC $m^{-2}d^{-1}$) when PP2 is taken into consideration. Open ocean locations average around 1.7(±0.61) mmolN m^{-2} d^{-1} (~ 135 mgC $m^{-2}d^{-1}$) whereas at two coastal stations average new production (3.4±1.2 mmolN m^{-2} d^{-1} ~ 270 mgC$m^{-2}d^{-1}$) has been found to be twice that of open ocean average. The highest new production among the stations other than PP2, was observed at a coastal location closest to the coast (PP7).

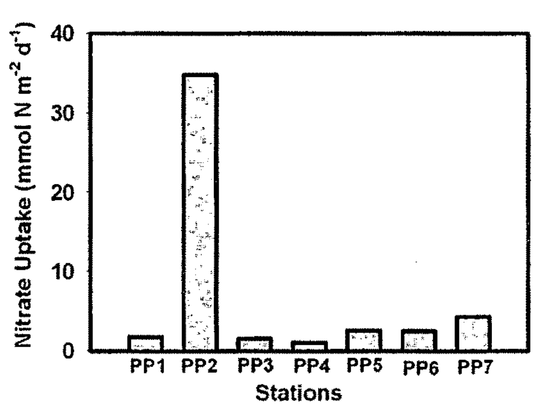

Figure 3.13 New production observed at different locations during January 2003.

The average new production measured during the present study is less by ~1mmol Nm^{-2} d^{-1} from the average value reported by McCarthy et al. (1999) for nitrate uptake during January (3.2mmolN m^{-2} d^{-1}) but is more than average value reported for November (1.5

mmolN m^{-2} d^{-1}) for the northwestern and the central Arabian Sea. However, the average values reported by McCarthy et al. (1999) can be considered similar in magnitude to the present study as they fall within 1 standard deviation (1σ) of the present average value. The average nitrate uptake values reported by Sambrotto (2001) for different transects (coastal upwelling, Findlater Jet, Off India) during the SW monsoon and spring intermonsoon for the northern Arabian Sea are more (>3.1 mmolN m^{-2} d^{-1}) than the average new production reported during present study. But the average value for southeastern Arabian Sea (0.4 mmol N m^{-2} d^{-1}) is significantly less than the present average value. Watts and Owens (1999) have reported the average nitrate assimilation rate of 1.8 mmolN m^{-2} d^{-1} for the intermonsoon season of the northwestern Arabian Sea, which is comparable within 1σ of the present average value. The nitrate uptake in the NE Atlantic measured along a transect from 58°N to 37°N during July 1996 (Donald et al. 2001) is also within the upper limit (~3.5mmol $Nm^{-2}d^{-1}$) of the present study. However, the new production during the present study is higher than that reported for equatorial Pacific Ocean during February-March (Dugdale et al. 1992) and eastern Alboran Sea (L'Helguen et al. 2002). Total average nitrate uptake of 5.6 mmol N m^{-2} d^{-1} has been observed during Lagrangian experiments in the Iberian upwelling region by Joint et al. (2001) which is significantly higher than the present average value, but is comparable to off India (5.2 mmol N m^{-2} d^{-1}) nitrate uptake value, during spring intermonsoon and SW monsoon reported by Sambrotto (2001). One of

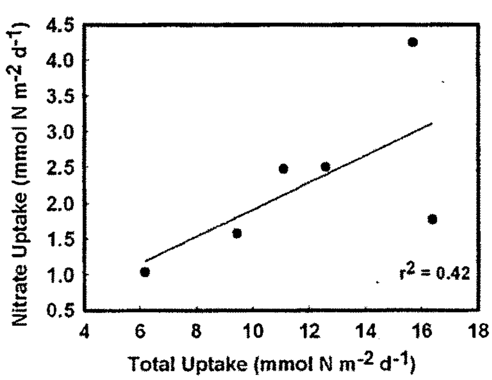

Figure 3.14 Relationship between new and total production (excluding PP2) observed during January 2003 in the Arabian Sea.

the most important aspects of the new production result during present study is a general trend of spatial increase from south to north (i.e., from Goa to Gujarat). Also, excluding PP2, there exists a fair correlation (r^2 =0.42; significant at 0.10 level) between new and total production during January (Figure3.14). However, this correlation becomes very significant (r^2 = 0.98) when PP2 is included. This is mainly due to very high total and new production at PP2 which falls far away from the rest of the stations basically transforming the regression into a two point regression, one being PP2 and second, the cluster of rest. Overall, it appears that new production during January 2003 in the northeastern Arabian Sea is well within the range for nitrate uptake obtained by other workers for northwestern and central Arabian Sea.

3.5.3 Regenerated production

The sum of NH_4 and urea uptake has been considered as regenerated production. As in the case of new and total production, regenerated production was also the highest at PP2. The NH_4 uptake at this station was found to be 23.3mmolN m^{-2} d^{-1}. Regenerated production at all the stations except PP2 is more than the new production. However, at PP2 new production (34.8 mmolN m^{-2} d^{-2}) is significantly higher than the regenerated production indicating the more significant role played by nitrate than ammonium at this station. Except at PP2, NH_4 uptake rate varied from 3.8 to 10mmolN m^{-2} d^{-1}, with an overall average of 6.4(±2.2)mmolN m^{-2} d^{-1} (8.8±6.7 mmolN m^{-2} d^{-1} including PP2). There is not much difference between the overall average NH_4 uptake and the average NH_4 uptake at open (6.7±2.7 mmolN m^{-2} d^{-1}; 10±7.7mmolN m^{-2} d^{-1} after including PP2) and coastal (5.8±0.5 mmolN m^{-2} d^{-1}) locations. The lowest NH_4 uptake was observed at PP4, where nitrate uptake was also the lowest, whereas the second highest (PP2 being the first) NH_4 uptake was observed at PP1. The values of regenerated production reported here are significantly lower than the average ammonium uptake rate (21.5 mmol N m^{-2} d^{-1}) reported by McCarthy et al. (1999) for January of the northwestern Arabian Sea. The latter is comparable to the highest ammonium uptake rate (at PP2) reported during the present study. Except one station of McCarthy et al. (1999), where ammonium uptake is 5.4mmolN m^{-2} d^{-1}, all other stations have ammonium uptake more than that observed for any station of the present study (except anomalous PP2). Ammonium uptake during November for northwestern Arabian Sea averages around 8.6mmolN$m^{-2}d^{-1}$ (McCarthy et al. 1999), which is comparable within the upper limit of the present study. Overall comparison of present study with McCarthy et al. (1999) suggests that the ammonium uptake and role of ammonium as a nutrient is more prevalent in the northwestern Arabian Sea than the northeastern Arabian Sea during peak NE monsoon. However, the average ammonium uptake reported here is more than the average ammonium assimilation rate of 3.7mmolN $m^{-2}d^{-1}$ reported by Watts and Owens (1999) for intermonsoon period in the northwestern Arabian Sea and the ammonium uptake rate (3.2 mmolN$m^{-2}d^{-1}$) reported by Joint et al. (2001) for the Iberian upwelling during August.

Urea uptake during the present study is a conservative estimate and hence the minimum contribution of urea to the total production. Urea uptake obtained for the study period varied from 1.3 to 7.3mmolN m^{-2} d^{-1}. The overall average was found to be 3.8mmolN m^{-2} d^{-1} (including PP2) with an open ocean average of 3.63 and a coastal average of 4.2mmolN m^{-2} d^{-1} respectively. The average urea uptake observed by Watts and Owens (1999) for the northwestern Arabian Sea averages (1.6 mmolN m^{-2} d^{-1}) less than half of that observed during the present study, with a minimum of 0.5 mmolN m^{-2} d^{-1} near the Oman coast to a maximum of 5.5 mmolN m^{-2} d^{-1} off India. The nitrate, NH_4 and urea uptakes observed at different stations are shown in Figure 3.15.

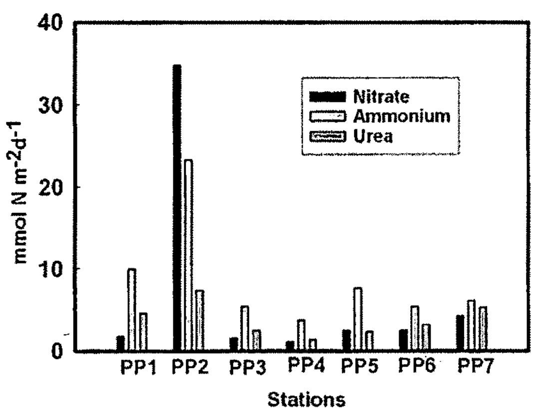

Figure 3.15 New (nitrate uptake) and Regenerated (ammonium + urea uptake) production observed in the Arabian Sea during present study.

3.5.4 Rationale for the preference of ammonium over nitrate

At almost all stations during the present study NH_4 was assimilated in preference to urea and NO_3, which is in agreement with the observations for the northwestern and the central Arabian Sea. This similarity in the relative preferences for different nitrogenous nutrients in the northwestern and the northeastern Arabian Sea indicates more or less the same nitrogen dynamics for both parts of the basin. The preference for reduced (recycled) forms of nitrogen such as NH_4 (if available) relative to nitrate is well known in marine and freshwater environments (Dugdale and Goering 1967; McCarthy and Eppley 1972; McCarthy et al. 1977; Glibert et al. 1982b; Paasche and Kristjiansen 1982; Smith and Nelson 1990; Owens et al. 1991; Rees et al. 1995). The physiological reason for the preference of NH_4 over NO_3 is given in terms of higher enery requirement during assimilation of NO_3, as nitrate has to be transported and reduced before being consumed by the phytoplankton (McCarthy and Carpenter 1983). It is also known that large part of reduced nitrogen pool is consumed by the phytoplankton of size less than 20µm. Size fraction study of productivity was not the aim of the present study and therefore estimation of phytoplankton in different size ranges was not carried out. However, high picoplankton densities, ranging upto $45*10^6$ cells l^{-1} has been observed during February near the present study area (Ramaiah et al. 1996) but their contribution in total productivity is not known. The nano- (2-18µm diameter) and Pico- (<2µm diameter) planktons fraction are known to constitute >75% of productivity in the northwestern Arabian Sea (Watts and Owens 1999). Jochem et al. (1993) have found picophytoplankton dominating the phytoplankton productivity (48-76%) in the central Arabian Sea and off the Oman Coast. Owens et al. (1993) have also found in their study that phytoplankton less than 5µm size were responsible for more than 75% of the phytoplankton production. Heterotrophic bacteria are also known to assimilate dissolved ammonium (Laws et al. 1985; Kirchman 1994) and if these bacteria form a significant portion of the total biomass, they could pose serious implications to new and regenerated production estimation by ^{15}N tracer technique (Watts and Owens 1999). Pomroy and Joint (1999) have found a 10-30% contribution by heterotrophic bacteria during their study in northwestern Arabian Sea. The present study cannot estimate the effect of heterotrophic bacteria on ammonium uptake data for the same reason cited by Watts and Owens (1999) i.e., unknown fraction of bacterial abundance on the GF/F filter paper (pore size 0.7µm) used for present study and also the extent of dissolved inorganic nitrogen as an alternative source of nitrogen, if present. However, Ramaiah et al. (1996) have found higher bacterial densities (of about $1*10^9$ cell l^{-1}) during the intermonsoon period than the southwest and winter monsoons. Therefore, the effect of bacteria may not be very prominent in ammonium assimilation during the present study or it would be less than that during the intermonsoon. However, it is necessary to study phytoplankton abundance in different size ranges and bacterial abundance during the same cruise in order to ascertain their roles in the uptake of different nitrogen sources.

3.5.5 Vertical profiles of Nitrate and Ammonium Uptake

The vertical profiles of nitrate and ammonium uptake obtained by ^{15}N technique are a function of light and nutrient concentrations at different depths. The vertical profile of nitrate uptake at different stations during January 2003 is shown in Figure 3.16. The nitrate uptake profile at almost all the stations suggests a subsurface uptake maximum varying between 5 and 40m from the surface. The general euphotic depth during the

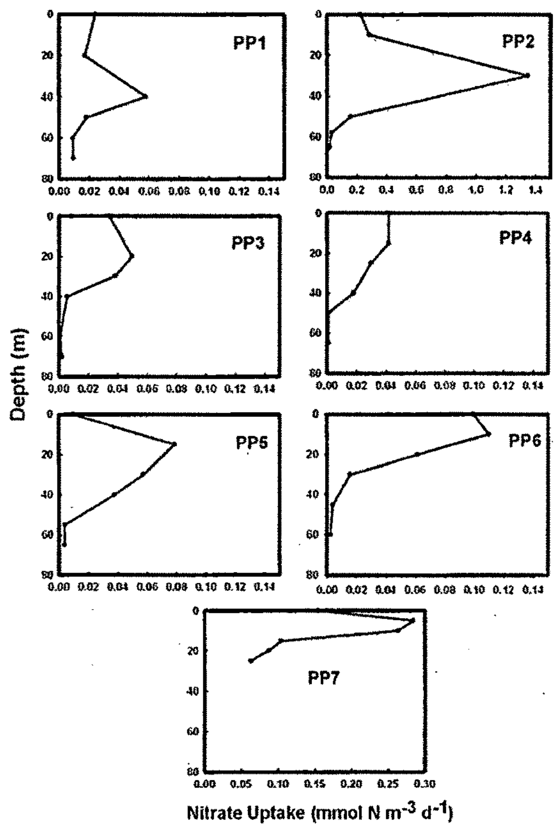

Figure 3.16 Vertical profiles of nitrate uptake rates at discrete depths at different locations. The uptake profile is limited upto the measured euphotic depths.

study period was between 60-70m, except at PP7 where it was just 25m. So the uptake maxima in general fell within the 90 and 5% of surface light. At PP1 the maximum was at 40m with an uptake value of around 0.06mmolN $m^{-3}d^{-1}$. This was the zone in the water column from where there was sharp increase in the nitrate concentration. The nitrate uptake did not stop at 1% light level (0.01 mmolN $m^{-3}d^{-1}$) at this station. The nitrate uptakes for all depths were highest at PP2 with surface uptake around 0.2mmolN $m^{-3}d^{-1}$ and a maximum uptake of around 1.4mmolN $m^{-3}d^{-1}$ at 30m. However, the nitrate profile of the station does not show very high values (<1.2μM in top 50m of water column). The reason may be the rapid utilisation of nitrate in the water column by the phytoplankton as this station, characterised by very high biomass (Chl *a* varying between 1-1.2mg m^{-3} with euphotic zone integrated value of 68.5mg m^{-2}). PP3 to PP6 show the uptake maxima in the top 20m of water column with the maximum uptake rate varying from 0.04 to 0.11mmolN $m^{-3}d^{-1}$. All these stations are characterised by higher uniform nitrate in the water column. The uptake profile of the coastal station PP7 shows relatively higher uptake rates at discrete depths than the open ocean stations with maximum at 5m with an uptake value of around 0.28 mmolN m^{-3} d^{-1}. The uptake at the base of euphotic depth is also high (around 0.06mmolN $m^{-3}d^{-1}$). However, the nitrate profile of the station does not suggest very high value (maximum 0.28 μM at base of euphotic zone).

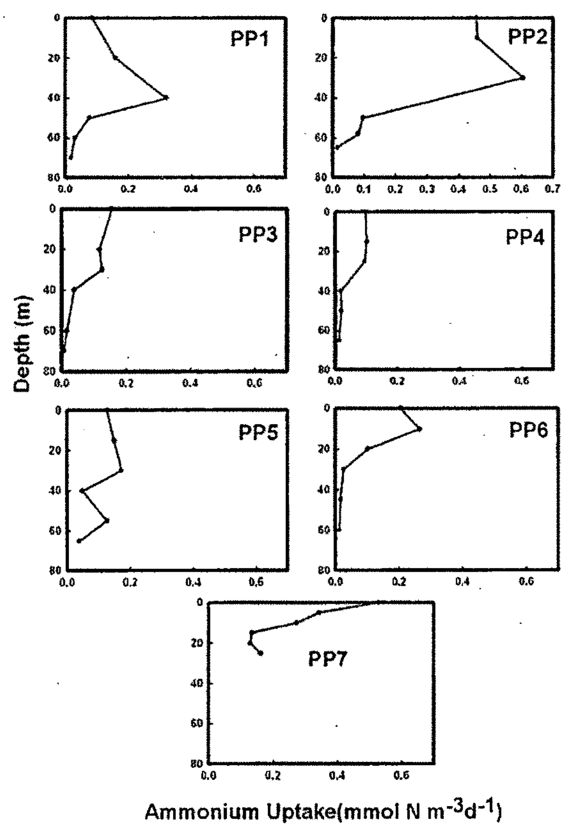

Figure 3.17 Vertical profile of ammonium uptake rates at different depths at various locations. The uptake profile is limited upto measured euphotic depths as in the case of nitrate.

The vertical profile of ammonium uptake at different stations during January is shown in Figure 3.17. The ammonium uptake profiles do not show the subsurface maximum at all the stations as was the case in the nitrate uptake. PP1 shows subsurface maximum at 40m as in the case of nitrate uptake but with higher values (0.32mmolN $m^{-3}d^{-1}$). The ammonium concentration in the water column was also maximum (0.14μM) at that depth. PP2 also has the subsurface maximum (0.61mmolN m^{-3} d^{-1}) at 30m, similar to nitrate uptake at this station. However, the maximum ammonium uptake at PP2 is only twice that of PP1 maximum value, whereas in the case of nitrate uptake, maximum at PP2 was around 23 times higher than maximum at PP1. The ammonium concentration at the depth of maximum ammonium uptake at PP2 was also found to be highest (0.22μM) for the study region. PP3 and PP7 show maximum ammonium uptake at the surface with values 0.15 and 0.52 mmolN m^{-3} d^{-1} respectively and decrease with depth. PP5 shows two distinct maxima for ammonium uptake at 30 and 55m respectively, the second peak coinciding with the maximum ammonium concentration in the water column (0.14μM). PP4 and PP6 show the maximum uptake at 15 and 10m respectively but these maxima do not coincide with maximum ammonium concentration in the water column as in other cases. The uptake of ammonium has not ceased completely at the base of the euphotic zone probably indicating the dark uptake of ammonium.

3.5.6 f-ratio during January 2003

The f-ratio during the present study has been calculated as integrated nitrate uptake/ total integrated (nitrate + ammonium + urea) uptake, where integration has been performed over the entire photic zone. f-ratio has been presented here in two different ways: first estimate does not include urea uptake and second estimate includes it (Figure 3.18). This has been done to estimate the effect of urea uptake on f-ratio as in most of the earlier studies f-ratio was expressed as nitrate uptake/(nitrate + ammonium) uptake, particularly because of lack of urea uptake measurements. Since the second estimate includes urea uptake that has been calculated assuming the absence of urea in the water column, it depicts the upper bound of f-ratio possible during the study period. When urea has not been taken into consideration, the overall variation in the f ratio is from 0.15 at PP1 to 0.60 at PP2 (0.11 and 0.53 respectively, after incorporating urea in the calculation). While discussing the average values of f-ratio for the region the PP2 has been excluded, due to its anomalously high value, as has been done in the case of nitrate. Without urea, f-ratio during the month of January for the region averages around 0.26(±0.09) [0.31(±0.15) after including PP2]. With urea, the f -ratio averages around 0.19(±0.06) [0.24(±0.14) after taking PP2 into consideration]. Inclusion of urea leads to decrease in the overall average f-ratio. Without urea, the open ocean stations averages around 0.21(±0.04) [0.29(±0.18) with PP2], whereas two coastal stations average around 0.36(±0.07). The inclusion of urea leads to decrease in open ocean [0.16(±0.03)] as well as coastal stations [0.25±0.03)] f-ratio. However, except PP2 and PP6, the f-ratios for all the stations are less than 0.32, indicating the relative importance of regenerated production over new production during this period. PP2, an open ocean location and PP6, a coastal location have f-ratios more than 0.4, implying that the new production is relatively more important at these two locations. The new, regenerated and total production along with f-ratio during the present study have been presented in Table 3.2.

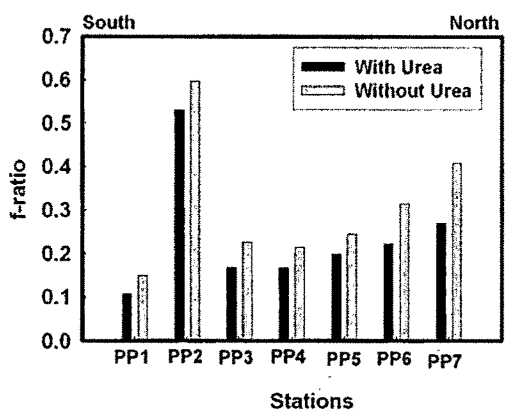

Figure 3.18 f-ratio observed (with and without urea) during January 2003.

Table 3.2 ^{15}N based productivity and f-ratio estimates during January 2003 in the Arabian Sea.

Stn.	New Production	Regenerated Production		Total	f-ratio	
	Nitrate Uptake (mmol N m^{-2} d^{-1})	Ammonium Uptake (mmol N m^{-2} d^{-1})	Urea Uptake (mmol N m^{-2} d^{-1})	Production (mmol N m^{-2} d^{-1})	(With Urea)	(Without urea)
PP1	1.77	10.00	4.61	16.38	0.11	0.15
PP2	34.78	23.30	7.34	65.43	0.53	0.60
PP3	1.58	5.39	2.47	9.44	0.17	0.23
PP4	1.03	3.78	1.36	6.17	0.17	0.21
PP5	2.51	7.72	2.36	12.58	0.20	0.25
PP6	2.48	5.39	3.22	11.09	0.22	0.31
PP7	4.25	6.14	5.31	15.69	0.27	0.41

3.5.7 Effect of winter cooling on the f-ratio

Except at PP2, f-ratio in general shows an increasing trend from the south to the north (PP1 ~0.15 being the southernmost and PP6 ~0.31, the northernmost). This can be explained in terms of the spatial variation in the sea surface temperature, air temperature, wind speed (atmospheric forcings) and mixed layer depth. During the study period winds were predominantly north/northeasterlies with an average speed of ~4ms^{-1}. However, the wind speed is too weak to induce significant offshore Ekman transport. Madhupratap et al. (1996) overrules Ekman transport due to the existence of a deep mixed layer in the region. Also, the suggested positive wind stress curl (< $1 * 10^{-8}$ dyne cm^{-3}) by the climate atlas over the region is too small to support the existence of deep MLD and higher nutrient in the surface layer together. Madhupratap et al. (1996) have shown through the computation of heat and freshwater (Evaporation-Precipitation) fluxes along 64°E that the northern Arabian Sea (north of 10°N) experiences a net heat (~30Wm^{-2}) and freshwater losses (~125mm per month) during the winter season. Further, a comparison of specific humidity during different months (Climate Atlas) suggests the prevalence of dry air (specific humidity ~10g kg^{-1}) during winter over the northeastern Arabian Sea. Based on these observations Madhupratap et al. (1996) advocated that the northeast trade winds prevalent in the region during this season brings the cool, dry continental air causing an increase in the evaporation. During this period the evaporation in the region exceeds the precipitation and also the heat loss exceeds heat gain. This intensified evaporation leads to the cooling of surface water as a result of which the surface water of the northeastern Arabian Sea becomes denser. The increase in density causes the water to sink resulting in convective mixing. This whole process leads to a deepening of the mixed layer as observed, and consequent transport of nutrients from the base of the mixed layer and upper thermocline to the surface layer. The general increase in the nitrate concentration, new production and consequently the f-ratio from south to north observed during the present study suggests the influence of above mechanism. The increased mixed layer depth (MLD) also suggests a strong coupling between the surface and the subsurface layers. An examination of the column integrated nitrate reveals that the nitrate varies from as low as 5.2mmol m^{-2} for PP7 (coastal station) to as high as 254mmol m^{-2} for PP4 (open ocean station) with temperature based mixed layer of around 80m. If it is assumed that the vertical upward flux of nitrate from below the photic zone is the dominant component of newly available nitrate (Eppley et al. 1977), then the degree of coupling can also be deciphered by the f-ratio. Platt et al. (1992) have observed that the area where surface layers are strongly coupled with sub-surface layers will experience new production as a large fraction of the total production. Therefore the observed increase in new production and f-ratio from the south to the north clearly indicates the effect of winter cooling during January and may be interpreted as the biological response to the prevailing physical forcings.

3.5.8 Low f-ratio despite presence of nutrients in the water column

Excluding PP2 which has a anomalously high f -ratio, the relationship between f-ratio and the ambient euphotic zone integrated nitrate concentration levels reveals that the stations fall into two distinct groups (Figure3.19-left panel): First group where stations are characterised by relatively low column integrated nitrate concentration (<150 mmol m^{-2}) which includes two southern stations PP1 and PP3 and one northern coastal station PP8. The second group includes the three northern stations that have column integrated nitrate more than 150mmol m^{-2}. The regression analysis of both the groups yields r^2 = 0.99. This figure suggests very clear negative relationship of f-ratio and integrated nitrate indicating that even at higher column nitrate the f-ratio can be low. The relationship observed is regardless of inclusion of urea uptake in the f-ratio calculation. The same negative relationship with r^2= 0.61 has been found between new production (excluding PP2) and euphotic zone integrated nitrate (Figure3.19-right panel). This leads to the situation where nitrate is available in the water column but is

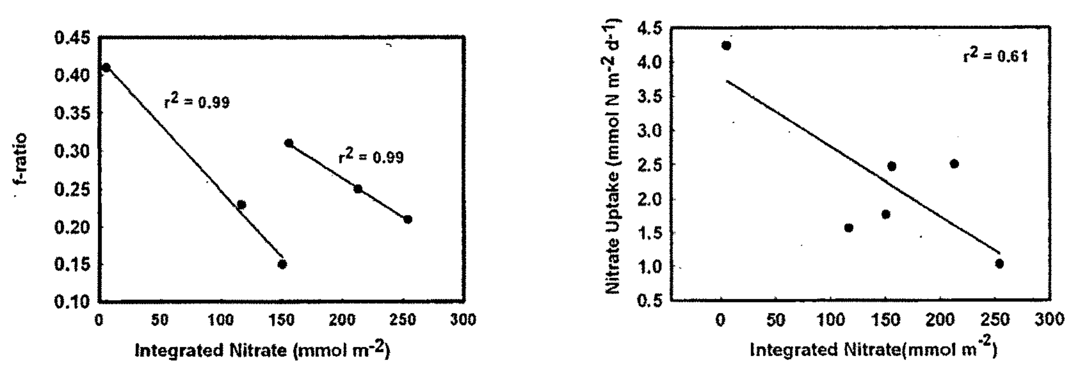

Figure 3.19 The observed negative relationship between f-ratio and euphotic zone integated nitrate (left panel) and new production-integrated nitrate (right panel) during present study.

not being utilized. Watts and Owens (1999) suggest two possible explanations for this kind of situation: First, the suppression of nitrate uptake in presence of ammonium that has been very commonly observed in the world oceans (Glibert et al. 1982b; Harrison et al. 1987; Jacques 1991; Owens et al. 1991; Rees et al. 1995, McCarthy et al. 1999). McCarthy et al. (1999) have observed that the effect of NH_4 addition is most sensitive at NO_3 concentrations less than 1.0 μmol kg^{-1} and also relatively higher rates of NO_3 uptake persisted at higher concentrations of ammonium. The second reason for nitrate being not utilized is the higher addition of $^{15}NH_4$ tracer than required. Ideally, the concentration of enriched tracers added should be less than 10% of ambient concentaration. Higher concentration of tracer added may artificially stimulate ammonium uptake in the presence of nitrate. However, during the present study, at times the addition was made more than 10% of ambient ammonium concentration but it was not large enough to stimulate the artificial uptake of ammonium. This is suggested by the very low correlation (r^2~0.006) found when regression was performed between the percentage of NH_4 addition relative to ambient and ammonium uptake rates at different depths at different stations. The third possibility could be the deterioration of light conditions due to deep mixed layer (Sambrotto 2001) and relative preference for ammonium in light limited conditions (McCarthy et al. 1999).

3.6 Chlorophyll *a*, nitrate and physical parameters during late February- early March 2003 in the Northeastern Arabian Sea

Late February and early March in the Arabian Sea witnessed a phytoplankton bloom particularly at the three open ocean stations PP3, PP4 and PP5 (between 19-21°N and 66-68°E). The genus of phytoplankton during the bloom was *noctiluca.*

3.6.1 Chlorophyll *a*

In general, the euphotic zone integrated Chlorophyll *a* during late February-early March in the Arabian Sea was more than that observed during January, despite the fact that the euphotic depth, in general, was shallower than that of January. This is due to higher concentration of Chl *a* at different depths. The stations during this period can be divided into two categories: one with Chl *a* concentration less than 40 mg m^{-2} which includes three out of six stations (PP1: 36.6, PP2: 38.8 and PP6: 29.3 mg m^{-2}) and other with Chl *a* more than 40 mg m^{-2}. The second category includes stations (PP3: 45.1, PP4: 52.5 and PP5: 45.3 mgm^{-2}) that were typical bloom stations. Seawater at these stations was virtually green (Figure3.20-left panel). Even though these were bloom stations the Chl *a* concentrations at these stations were not of the same magnitude that was observed at PP2 during January (68.5 mg m^{-2}).

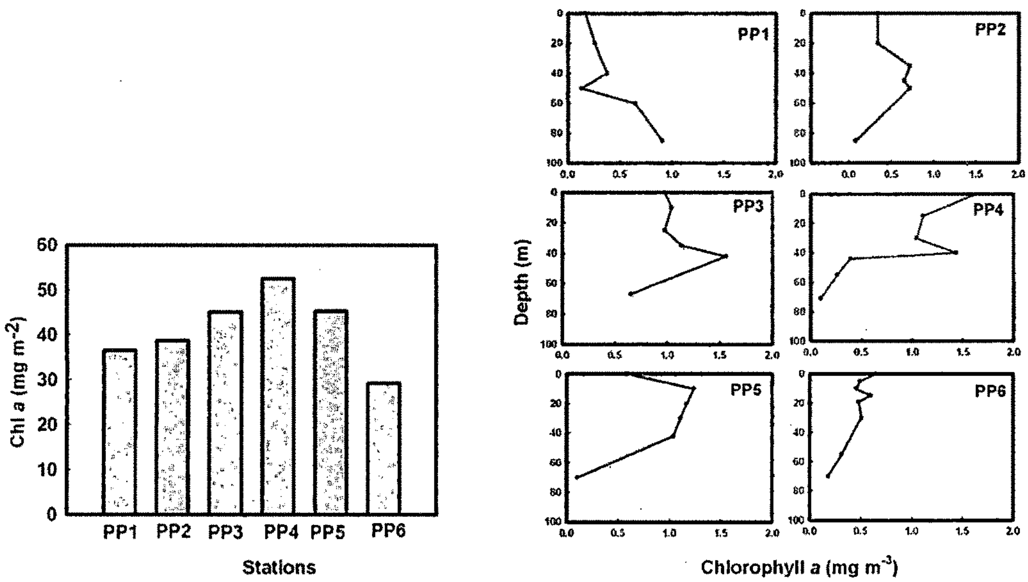

Figure 3.20 Euphotic zone integrated (left panel) and vertical profiles (right panel) of Chlorophyll *a* at productivity stations during late February-early March 2003. The euphotic depth at three stations PP3, PP4 and PP5 were only 42m.

Vertical profiles of Chl *a* suggest varying patterns at different stations (Figure 3.20-right panel). The profile at PP1 shows a subsurface minimum at 50m (0.13mg m^{-3}). The maximum value has been observed at the base of the euphotic zone (0.91mg m^{-3}). PP2 shows a plateau of Chl *a* maximum between 35 and 50m with concentration around 0.70 mg m^{-3}. PP3 shows higher Chl *a* throughout the photic zone (> 0.9mg m^{-3}) with a maximum at the base of photic zone i.e., 42m (1.5mg m^{-3}) whereas PP4 shows maximum Chl *a* at the surface (1.6 mg m^{-3}) with another peak at 40m (1.4mg m^{-3}) and decreases to near zero at 70m. PP5 shows more than 1.0 mg m^{-3} Chl *a* at the subsurface depths between 10 and 42m (euphotic depth) and decreases thereafter. PP6 has Chl *a* around 0.5mg m^{-3} in first 30m of water column to decrease to 0.18mg m^{-3} at base of euphotic zone (70m). The profiles of Chl *a* at bloom stations PP3-PP5 suggest the existence of chlorophyll well beyond the euphotic depth which is around 42m.

3.6.2 Nitrate

Among the nutrients, only nitrate could be measured during late February-early March. On an average, euphotic zone integrated nitrate was less than that observed during January (Figure3.21-left panel). However, the maximum euphotic zone integrated nitrate during the present study (both January and late February-early March) has been observed at PP2 (537 mmol m^{-2}) of late February-early March. It is noteworthy that the integrated nitrate at bloom sustaining stations PP3, PP4 and PP5 were 22, 53 and 132 mmol m^{-2} respectively, which is very less compared to non bloom sustaining stations PP1 (174 mmol m^{-2}) and PP2 (537 mmol m^{-2}). This is because of shallower euphotic depths at bloom stations. However, one non bloom station (PP6) also shows very low integrated nitrate (24.9 mmol m^{-2}). The vertical profile of nitrate does not show much change in nitrate concentaration within the euphotic zone at most of the stations (Figure 3.21-right panel). The nitrate at PP1 is below detection limit in the top 12m of water column and increases to 2μM around 40m and with a sharp increase from 60 to 85m (8μM). At PP2 also the water is almost devoid of nitrate in the first 20m but nitrate increases sharply downwards to reach to 12μM at the base of the euphotic zone at 85m. PP3 and PP4 show almost uniform nitrate in the euphotic zone with concentrations below 1 and 2.2μM respectively. PP5 shows the highest nitrate concentration in the top 20m (~3.5μM) which goes down to 2.1 μM at 40m. PP6 is characterized by a nitrate concentration of less than 0.7 μM throughout the euphotic zone.

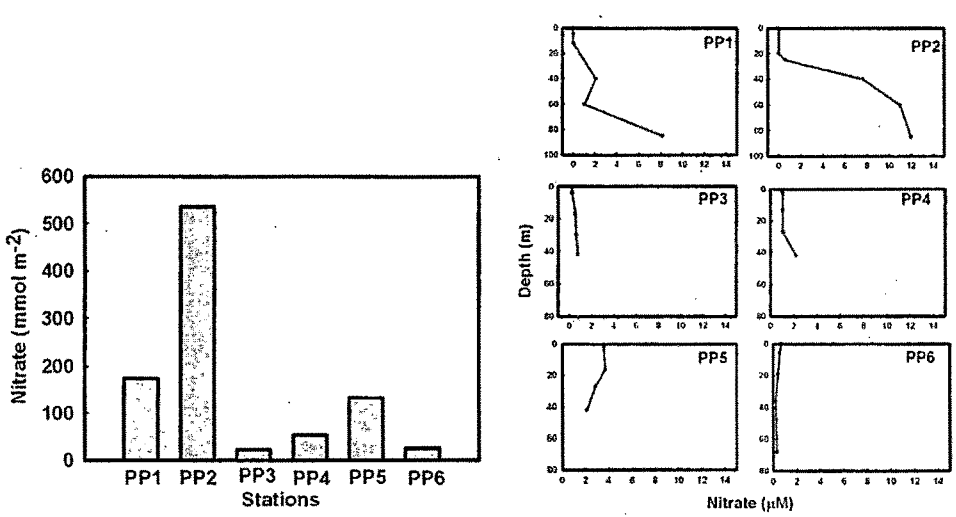

Figure 3.21 The euphotic zone integrated (left panel) and vertical profiles (right panel) of ambient nitrate at different stations during late February-early March 2003.

One important difference between bloom and non bloom stations is the existence of nitrate in the top surface layer at bloom stations; non bloom stations are almost devoid of it in the top layer, where light is available in plenty for photosynthesis.

3.6.3 Hydrographic and meteorological conditions

The sea surface temperature pattern during the study period (late February-early March) was almost the same as in January i.e., decreasing SST from the south to the north as indicated by the long-term average temperature profile (Figure3.22-left panel). However, a slight decrease in temperature (< 0.5°C) for a particular location from January to late February-early March can be observed by the long-term average SST data. SST measured during the sampling indicates the temperature variation between 27.8°C at the southernmost station (PP1) to 24.7°C at the northernmost station (PP5) (Figure 3.22-right panel). Air temperature over the study region also showed a

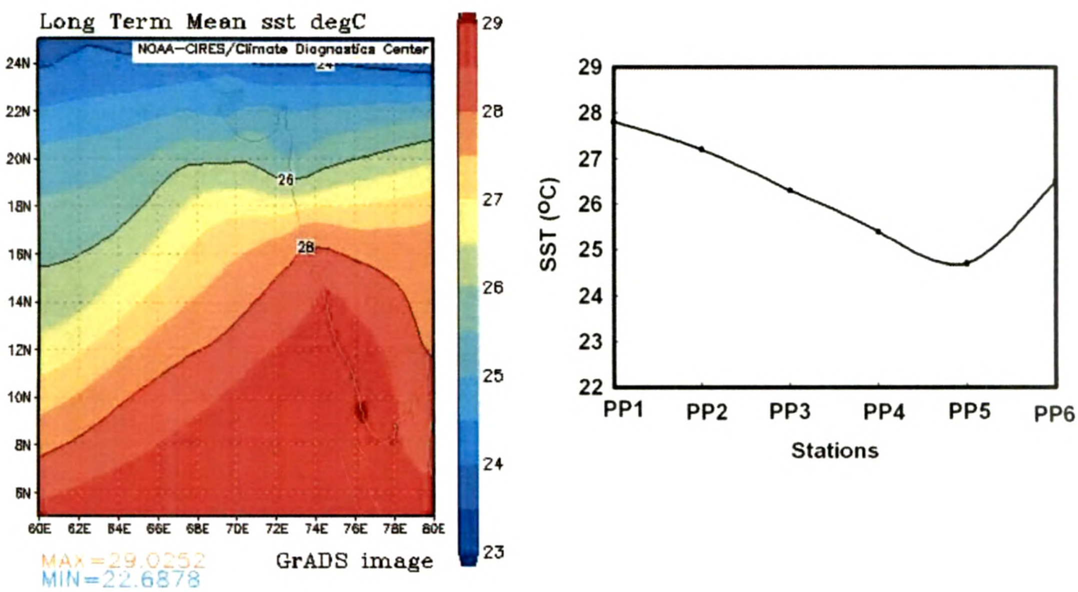

Figure 3-22 The long-term average Sea Surface Temperature (SST) of the northeastern Arabian Sea for the study period (1-10 March) (left panel, Source: Climate Diagnostic Center, National Center for Environmental Prediction, USA) and SST at different stations at the time of sampling (right panel) during late February-early March 2003.

similar pattern of spatial variability from the south to the north (Figure 3.23). It varied from 27.2°C to southernmost station (PP1) to 22.8°C at northernmost station (PP5). Air temperature at all stations was less than that SST of that particular station. This difference was less for the southern stations (<0.5) than the northern stations, where the

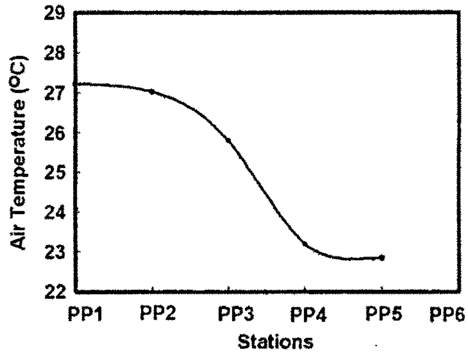

Figure 3-23 Air temperature measured over the northeastern Arabian Sea during sampling. Data for PP6 is not available.

difference was around 2°C.Wind speed at the first two stations were around 4.01 and 2.74ms^{-1}, typically in the range observed during January.(Figure 3.24). Sea was also calm at these two sites. However, the wind speeds of more than 8ms^{-1} were encountered at the rest of the stations and the sea was very choppy with sea state 4-5. The surface pressure increased from 1013mb at PP1 to a maximum of 1017mb at PP4

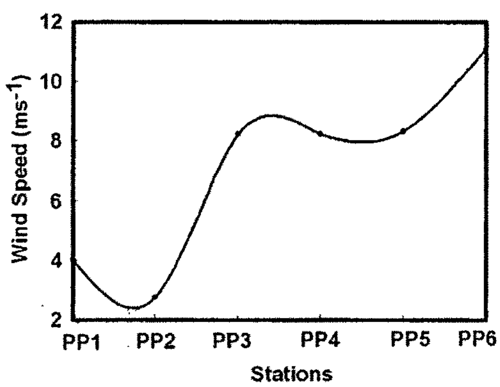

Figure 3.24 Wind speed over the Arabian Sea during Late February-early March.

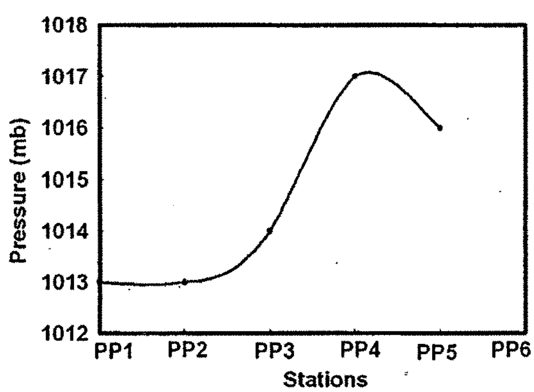

Figure 3.25 Air Pressure during sampling time in the Arabian Sea. Measurement at PP6 could not be performed.

to decrease to 1016mb at PP5 (Figure3.25). Euphotic depth at the first two stations (PP1 and PP2) was 85m that reduced to less than half (42m) at all three bloom stations (PP3-PP5) and again increased to 68m at the non bloom station PP6. The drastic decrease in euphotic depth at bloom stations was probably due to faster attenuation of light because of increased biomass. This perhaps led to an increase in the attenuation coefficient to $0.1m^{-1}$.

The most important feature of this cruise, which was strikingly different from January, was the temperature based mixed layer depth (MLD). The MLD for the first three stations (PP1-PP3) was not clearly defined and temp-depth profile shows a continuous decrease in temperature with slight undulations (Figure 3.26). This might

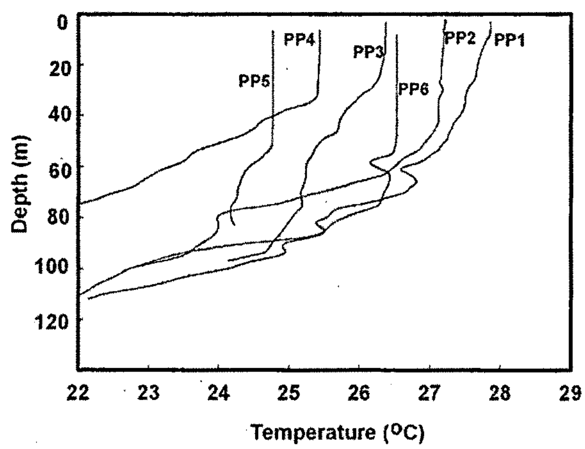

Figure 3.26 Temperature profiles at different stations obtained with Satlantic Radiometer during Late February-Early March 2003.

be an indication of the varying degree of mixing with depth between cooler water and relatively warmer surface water. The cooler water might have been supplied from deeper sources or due to horizontal advection from a nearby region. Interestingly, depth-temperature profiles of stations PP4-PP6 is marked by relatively sharper decrease in temperature with depth, probably indicating a shallow mixed layer for these stations varying between 33-55m. Although SST at these locations is not drastically different from January, the MLD is markedly shallower compared to January (it was near 80m in the same region). The relatively shallow mixed layer at these locations persisted despite higher wind speed ($8ms^{-1}$) indicating the limited role played by wind in the deepening of MLD in this period. Prasanna Kumar et al. (2001) in their study of physical forcing of biological productivity in Arabian Sea during NE monsoon have also observed that the formation of deep mixed layer during winter is not due to wind mixing but is a result of winter cooling. Therefore, the shallowness in MLD from January to early March indicates the decrease in effectiveness of winter cooling in the region (cooling starts in December and persists till the end of February, Madhupratap et al. 1996).

One important source of nutrients to the study region could be the surface currents. However, the current known to flow from the southern to the northern Arabian Sea during winter is WICC (West India Coastal Current) whose strength decreases at it moves northward (400km wide at 10°N to 100 km wide near 22°N; Shetye et al. 1990). Moreover, WICC is a coastal current and is unlikely to supply nutrients at 19°N-68°E.

3.7 ^{15}N based productivity study during late February-early March 2003

3.7.1 Total Production

^{15}N based total productivity has been calculated as the sum total of nitrate uptake and conservative estimates of ammonium and urea uptakes (Figure 3.27). The total productivity varied from a minimum of 17mmolN m^{-2} d^{-1} (~ 1353mgC $m^{-2}d^{-1}$) at PP6 (a non bloom station) to maximum of 37.8mmolN m^{-2} d^{-1} (~ 3006mgC $m^{-2}d^{-1}$) at PP4 (a bloom station). Overall, the average total productivity during the study period was 26.3(±8.6)mmolN $m^{-2}d^{-1}$ (~2090±687 mgC $m^{-2}d^{-1}$). The average total productivity at non-bloom stations was 22.3±4.7mmolN $m^{-2}d^{-1}$ whereas at bloom stations it was 30.2±10.9mmolN $m^{-2}d^{-1}$. The high spatial variability for bloom stations was because of relatively low total productivity at PP5 (17.8mmolN m^{-2} d^{-1}) compared to the other two stations, where it was 35.1 (PP3) and 37.8mmolN m^{-2} d^{-1} (PP4) respectively. The average total productivity reported here is more than twice of the average total productivity reported for the month of January (11.9mmol $Nm^{-2}d^{-1}$) during the same study. However, it is comparable to the average value (25.8mmolN $m^{-2}d^{-1}$) reported by McCarthy et al. (1999) for the northwestern Arabian Sea during the NE monsoon (January) and is thrice higher than the average value (8.3mmolN $m^{-2}d^{-1}$) reported by Watts and Owens (1999) for intermonsoon season in the northwestern Arabian Sea. McCarthy et al. (1999) values are based on nitrate and ammonium uptake only and urea uptake was not considered in their total productivity estimation. Inclusion of uptake by urea would lead to a higher total productivity than reported and hence the actual total productivity during the experiments of McCarthy et al. (1999) may be higher than reported. One major difference between McCarthy et al. (1999) and present study is the contribution of nitrate and ammonium uptakes to total productivity. The maximum contribution to the total productivity budget during present study is due to nitrate uptake whereas McCarthy et al. (1999) have found the maximum contribution by the ammonium component. This difference is clearly evident in the f-ratios of the respective studies. One possible reason could be species composition.

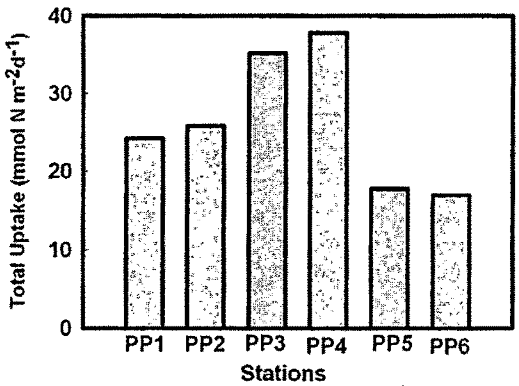

Figure 3.27 ^{15}N based total productivity during late February-early March 2003 expressed as the sum of nitrate uptake and conservative estimates of ammonium and urea uptakes.

3.7.2 Regenerated Production

Due to lack of ambient ammonium and urea concentrations, a conservative estimate of regenerated production was made during late February-early March, assuming the absence of ammonium and urea in the water column (Figure 3.28). Ammonium uptake varied within a narrow range of 6.2 at PP5 to 9mmolN m^{-2} d^{-1} at PP3 with an average

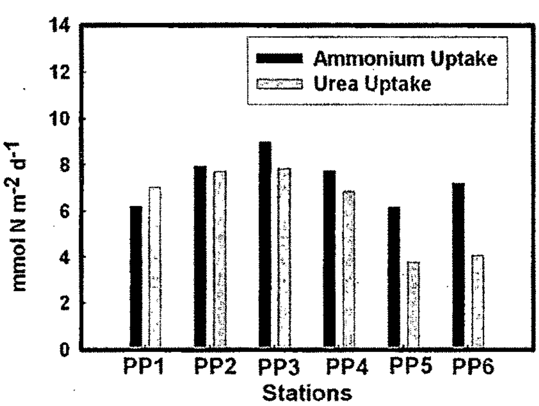

Figure 3.28 Components of regenerated production (ammonium and urea uptake). Both ammonium and urea uptake estimates are conservative.

value of 7.4 (±1) mmolN m^{-2} d^{-1} for the region. There is not much difference between the average values of ammonium uptakes at bloom (7.6mmolN $m^{-2}d^{-1}$) and non bloom (7.1 mmolN $m^{-2}d^{-1}$) sustaining stations. Since the assumption for ambient nutrient is same for all the stations, it can be inferred from the ammonium uptake estimates that there was no major relative difference in ammonium uptake from one station to another. However, the ammonium uptake observed by McCarthy et al. (1999) in the northwestern Arabian Sea during late NE monsoon showed a wide variation with a minimum value of 5.4mmolN $m^{-2}d^{-1}$ in the central part to 37mmolN m^{-2} d^{-1} at the northern part. Watts and Owens (1999) have also reported ammonium uptake variation ranging from 0.1 to 11.8mmolN $m^{-2}d^{-1}$ for the northwestern Arabian Sea.

Conservative estimates for urea uptake varied from a minimum of 3.8mmolN m^{-2} d^{-1} at PP5 to a maximum 7.8mmolN m^{-2} d^{-1} at PP3, both being bloom stations. The average urea uptake for the region worked out to be 6.2 (±1.8) mmolN m^{-2} d^{-1}. There is no difference between the average urea uptake of bloom (6.2 mmolN m^{-2} d^{-1}) and non bloom (6.2mmolN m^{-2} d^{-1}) stations. However, urea uptake estimates from the northwestern Arabian Sea show variations from 0 to a maximum of 5.6mmolN $m^{-2}d^{-1}$ (Watts and Owens 1999).

3.7.3 New production

Euphotic zone integrated new production during late February-early March (Figure 3.29) in the northeastern Arabian Sea ranges from 5.7mmolN m^{-2} d^{-1} (454 mgC $m^{-2}d^{-1}$) at a non-bloom station (PP6) to 23.2mmolN $m^{-2}d^{-1}$ (1846 mgC $m^{-2}d^{-1}$) at a bloom station (PP4). The average column new production was found to be 12.7(± 6.7)mmolN m^{-2} d^{-1} (~1009 mgC $m^{-2}d^{-1}$) that is more than five times the new

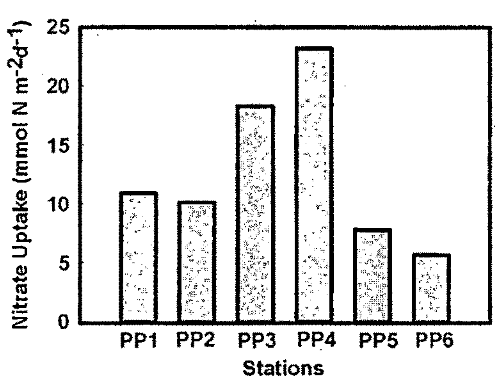

Figure 3.29 New production observed at different locations during late February-early March in the northeastern Arabian Sea.

production observed during January (2.3 mmolN $m^{-2}d^{-1}$, excluding PP2). The average new production at bloom stations is 16.4 (±7.8)mmolN $m^{-2}d^{-1}$ (~1307 mgC m^{-2} d^{-1}) that is almost twice the average new production at non bloom stations (8.9 mmolN $m^{-2}d^{-1}$ ~710mgC $m^{-2}d^{-1}$). There is no systematic spatial trend in the new production as was the case during January. At PP5 the euphotic zone integrated chlorophyll *a* concentration was one of the highest (45mg m^{-2}) with a typical (bloom station) euphotic depth of 42m but surprisingly the new production (7.8mmolN $m^{-2}d^{-1}$) is far below the other two bloom stations where it was 18.3 (PP3) and 23.2 mmolN m^{-2} d^{-1} (PP4) respectively. On the basis of integrated column new production the stations during late February-early March could be divided into three different groups: PP1 and PP2 with new production around 10mmolN$m^{-2}d^{-1}$; PP3 and PP4 with new production more than 18mmolN m^{-2} d^{-1}, representative of bloom condition in the

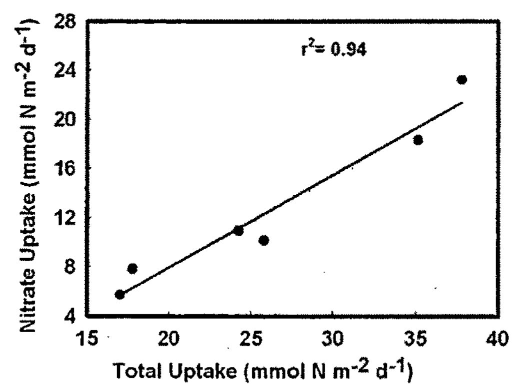

Figure 3.30 Observed relationship between new and total production in the Arabian Sea during late February and early March 2003.

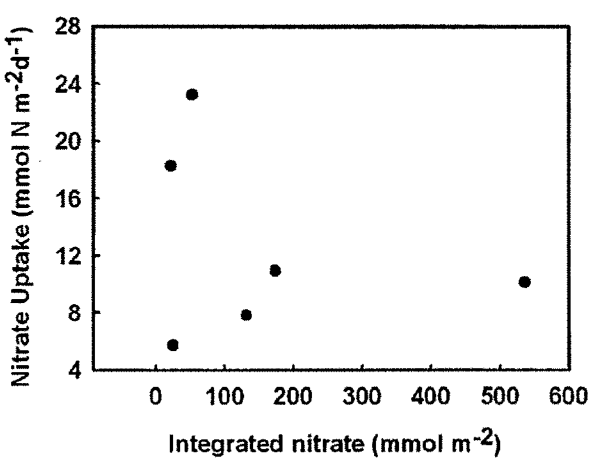

Figure 3-31 Relationship between new production and euphotic zone integrated nitrate observed in the Arabian Sea during late February and early March 2003.

region and PP5 and PP6 with new production less than 8mmolN m^{-2} d^{-1}. The values reported here are the highest estimates of new production reported for the region so far. Watts and Owens (1999) reported a maximum nitrate uptake of 9.8mmolN m^{-2} d^{-1} off India during the intermonsoon. McCarthy et al. (1999) reported a maximum nitrate uptake of 7.2mmol N m^{-2} d^{-1} off Oman followed by 6.8 and 5.6 mmol N m^{-2} d^{-1} in the central Arabian Sea (along 65°E) during NE monsoon. No earlier data exists for comparison in the northeastern Arabian Sea. However, based on the higher values observed by Watts and Owens (1999) off India and McCarthy et al. (1999) in the central Arabian Sea, it can be speculated that the eastern Arabian Sea also has a potential for high new production, as evident during the present study. There is a very strong correlation (r^2 = 0.94) between the new and total production during late February-early March (Figure 3.30) and is significantly better than that observed during January. This significant relationship may be because of a very high dependence of total production on the new production. During January the contribution of regenerated production to the total production was significant leading to poor new-total production relationship. However, no particular relationship is observed between the euphotic zone integrated column nitrate and new production (Figure 3.31) indicating the former to be a poor indicator of new production. It also signifies that the availability of nitrate in the water column is not the only criterion for high new production. Significant nitrification could also be taking place, but this needs to be verified.

3.7.4 Vertical profiles of nitrate uptake

The vertical profiles of nitrate uptake at different locations during late February-early March are shown in Figure 3.32. As expected, the uptake rates at different depths were quite high during late February-early March compared to January, which was less than 0.08 mmolN m^{-3} d^{-1} for most of the stations. The first three stations PP1, PP2 and PP3 show a typical subsurface uptake maximum. PP1 and PP2 show uptake maxima of 0.40 and 0.27 mmolN m^{-3} d^{-1} respectively at a depth of 40m that moves upward to 17m with a maximum value of 0.83 mmolN m^{-3} d^{-1} at PP3. A profile similar to that at PP3 has been observed at PP5 with an uptake maximum of 0.35 mmolN m^{-3} d^{-1} at 16m depth. The maximum uptake at PP4 has been observed at the surface (1.11 mmolN m^{-3} d^{-1} - this is also the maximum uptake at any particular depth during late February-early March) and is nearly the same till 13m, to decrease drastically to 0.05 mmolN m^{-3} d^{-1} at

27m. The upward shift in depths of maximum uptake rate at PP3, PP4 and PP5 compared to the two earlier stations may be because of light limitation at deeper

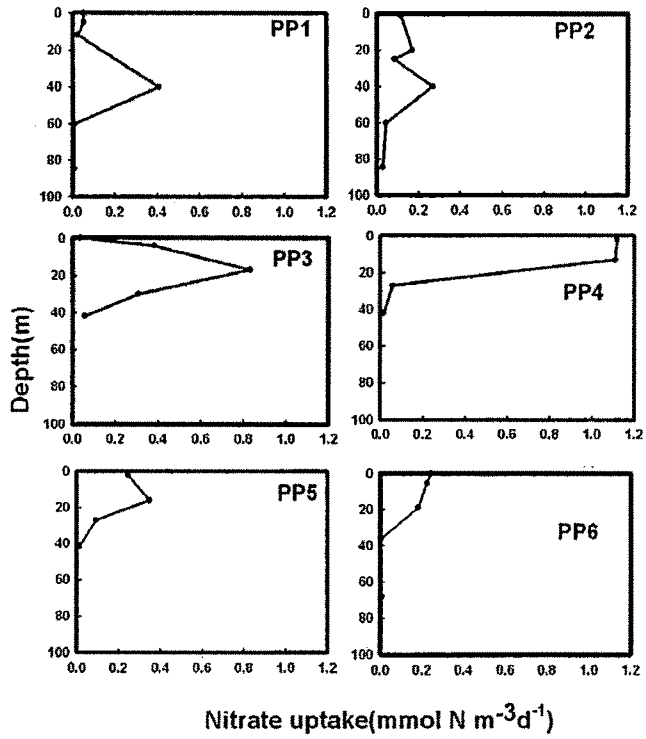

Figure 3.32 Vertical profiles of nitrate uptake rates at various locations in the northeastern Arabian Sea during late February-early March 2003. The uptake profile is limited upto the measured euphotic depths.

depths due to abundant biomass at the surface as they are bloom stations. However, the maximum uptake rate at surface has also been observed at PP6, a non-bloom station, but the rate of uptake is significantly less.

3.7.5 f-ratio

Since the f-ratio has been calculated using the conservative estimates of ammonium and urea uptakes, the values presented here represent the upper bound (Figure 3.33). The f-ratio averages around 0.60 (±0.10) without urea, which decreases by 25% (0.45±0.09) when urea is included into the calculation. These values are in sharp contrast to the average f-ratio (0.12 and 0.15) reported by McCarthy et al. (1999) during late and early NE monsoon and by Watts and Owens (1999) during intermonsoon (0.28) for the northwestern Arabian Sea. The average f-ratio of bloom sustaining stations is 0.65±0.10 without urea which decreases to 0.52±0.09 (by 20%) with urea. The average f-ratio of the three non-bloom stations is significantly lower

(0.54±0.09 without urea and 0.39±0.06 with urea; a decrease by 27%) than the average bloom station value. No particular relationship has been observed between f-ratio and the integrated nitrate and follows the same pattern as new production-integrated nitrate relationship. The new, regenerated and total production along with f-ratio observed during late February-early March is indexed in Table 3.3.

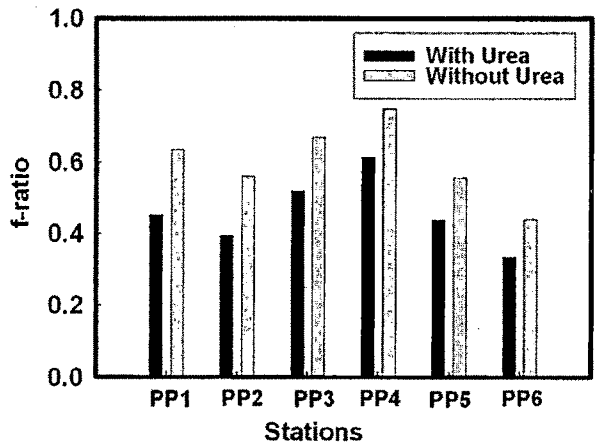

Figure 3.33 f-ratios observed (with and without urea) in the northeastern Arabian Sea during the present study.

Table 3.3 ^{15}N based productivity and f-ratio estimates during late February-early March 2003 in the Arabian Sea.

Stn.	New Production	Regenerated Production		Total	f-ratio	
	Nitrate Uptake (mmol N m^{-2} d^{-1})	Ammonium Uptake (mmol N m^{-2} d^{-1})	Urea Uptake (mmol N m^{-2} d^{-1})	Production (mmol N m^{-2} d^{-1})	(With Urea)	(Without urea)
PP1	10.94	6.22	7.04	24.21	0.45	0.63
PP2	10.13	7.92	7.72	25.78	0.39	0.56
PP3	18.30	8.99	7.84	35.14	0.52	0.67
PP4	23.22	7.73	6.85	37.81	0.61	0.75
PP5	7.81	6.19	3.78	17.80	0.43	0.55
PP6	5.71	7.22	4.08	17.02	0.33	0.44

3.7.6 Source of nutrients for the sustenance of the bloom

Compared to January, the average new and total productions during late February-early March were more than five and two fold respectively. The source of the nutrients during January was deeper nitrate due to convective mixing as indicated by deeper

MLD. However, there seems to be no such continuous supply of nitrate during late February-early March, as MLD has been observed to be shallow, particularly at the three bloom sustaining stations. The supply of nutrients due to advection from the first three stations (PP1-PP3) may be a potential source, as undulating MLD profile at these stations suggests supply of relatively cooler water. However, this supply does not seem to be strong enough to sustain a bloom as suggested by relatively low productivity at these stations. During January deeper nitrate is known to get entrained in the water column. Nitrate residence time in the water column was calculated from the January data of the region by dividing the column nitrate with the nitrate uptake rate. It was more than 50 days at most of the stations except at PP2 and PP7, where it was around 2 days (Figure 3.34). The residence time for nitrate reported here presents a minimum estimate as it ignores any additional nitrate supplied during the day. A residence time less than 1 day has been suggested to be indicative of nutrient limited productivity

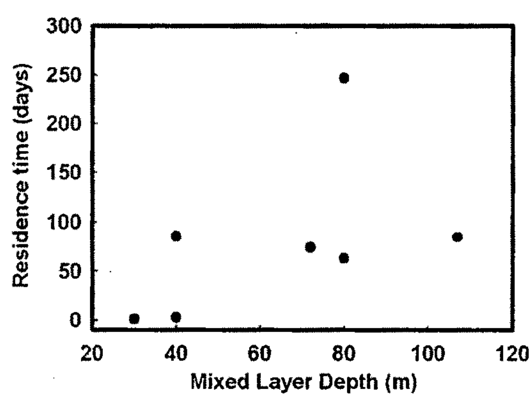

Figure 3.34 Relationship between the temperature based mixed layer depth and the residence time of nitrate in the water column estimated for January.

while a value significantly greater than one day indicates growth under nutrient replete conditions (Sambrotto 2001). Present data suggest nutrient replete conditions in the northeastern Arabian Sea during January at all stations. Residence time does not show any particular relationship with MLD and seems to be independent of it. The residence time suggests that if the same rate of removal due to nitrate uptake by phytoplankton continues the nitrate in the water column will remain at least for 50 days. However, the surface layer of ocean is not a closed system and nutrients will continuously be introduced as long as MLD is deeper and winter cooing is effective. Also the nitrate uptake by the phytoplankton may also increase as the effectiveness of winter cooling decreases. The nutrients introduced in the water column during January do not get efficiently consumed probably because of degraded light condition due to deeper mixing. However, the nutrients entrained in the water column have to be eventually consumed and is probably utilised during February-early March when the MLD becomes shallow due to the waning winter cooling. The available nitrate along with increased light conditions possibly leads to the development of a bloom. Hence, there seems to be a time lag between the nutrient entrainment and peak biomass development as has been reported by Banse and English (1993). This condition in the Arabian Sea is similar to high latitude spring blooms that do not deplete surface nitrate unless there is a sustained period where the mixed layer is less than half the critical depth (Sambrotto et al. 1986). Therefore, the nutrients entrained in the water column during January seem to be a more important source along with advected nutrients for the bloom development in the northeastern Arabian Sea.

3.8 Natural Isotopic Composition of Surface Suspended Matter

Particulate organic matter (POM), which mainly consists of phytoplankton in the euphotic zone of the open ocean, plays an important role in marine nitrogen and carbon cycles (Saino and Hattori 1980). Due to its significant vertical transport, it enables the ocean to remove carbon dioxide from the surface layer and, in turn, from the lower atmosphere, to the deeper parts of the ocean or settle permanently as sediment on the ocean floor. The study of the nitrogen isotope ratio $^{15}N/^{14}N$ of POM provides an insight into the availability and utilization of nutrients such as nitrate, ammonia and urea in the euphotic zone. Several studies in this regard have been done in different parts of the world ocean (Saino and Hattori 1980; Saino and Hattori 1987; Rau et al. 1991; Calvert et al. 1992; Altabet 1996). Similar studies in ocean sediments have been used for the reconstruction of past changes in surface ocean nutrient utilization (Altabet and Francois 1994, Farrell et al. 1995). In addition, sediment trap material has also been analysed in some cases (Schafer and Ittekkot 1995). To better understand the nitrogen isotope systematics in the ocean sediments and sediment trap material, it is essential to measure directly the nitrogen isotopes in surface POM to either verify whether surface $\delta^{15}N$ is faithfully transmitted down to the sediment column or to quantify the isotopic modification, if any (Altabet et al. 1991; Buesseler 1991).

The nitrogen isotopic composition ($\delta^{15}N$) of naturally occurring land derived particulate matter has been reported to have lower values (1.5-2.5‰; Miyake and Wada 1967), while the ^{15}N content in the marine realm has a strong dependence on source isotopic composition and has been reported to vary significantly (Saino and Hattori 1980; Altabet 1996; Wada and Hattori 1991; Rau et. al. 1998). The phytoplankton $\delta^{15}N$ averages around 7 ‰ while zooplankton and fishes, which are at higher trophic levels in the food web, have values around 10 ‰ and 15 ‰ respectively (Wada and Hattori 1976).

These variations in $\delta^{15}N$ of particulate organic nitrogen (PON) are caused by fractionation of isotopes during various biogeochemical transformations and biological processes. The processes mainly responsible for such variations are N_2 fixation, denitrification, nitrification and nitrate assimilation. Also, during the uptake of dissolved nitrogen in eutrophic waters, phytoplankton prefers ^{14}N to ^{15}N (Wada and Hattori 1978). Denitrification leads to ^{15}N enrichment of the remaining nitrate while nitrification causes enrichment of ^{15}N in the ammonia pool (Mariotti et al. 1984). Isotopic fractionation up to 20 ‰ has been found due to denitrification (Miyake and Wada 1971; Cline and Kaplan 1975; Liu and Kaplan 1989), nitrification (Miyake and Wada 1971) and nitrate assimilation (Wada et al. 1971). Fixation of atmospheric nitrogen is known to lower the $\delta^{15}N$ values of PON because of the depleted source (atmospheric nitrogen ~0 ‰); the areas with lower $\delta^{15}N$ may thus be attributed to N_2 fixation. However, a different view (Altabet 1988) is that lower $\delta^{15}N$ could also be caused by the preferential removal of ^{15}N enriched matter by sinking material, leading to a depletion of ^{15}N in the remaining suspended matter. In addition, $\delta^{15}N$ also depends on species, physiology and rate of growth of plankton (Montoya and McCarthy 1995).

One of the aims of the present study was to investigate the possible change in natural isotopic composition of nitrogen in particulate organic nitrogen (PON) of surface suspended matter from January to March. The aim was also to reconstruct the possible nutrient regime shift or change in utilisation behaviour of nutrients by the phytoplankton. For this purpose the Arabian Sea surface water was filtered to estimate the particulate organic nitrogen content in the suspended matter and its natural nitrogen isotopic composition ($\delta^{15}N$) during both January and late February-early March.

3.8.1 January

The samples were collected at 13 different locations, which included 9 open ocean location (Stn.2 to Stn.10) and 4 coastal locations (Stn. 11 to Stn. 14). Overall, the PON content varied widely ranging from 0.16 μM N at station 8, which was an open ocean station to 2.10μM N at station 13, a coastal station. Overall, PON averaged around 1.04 (±0.47)μM N. The PON at open ocean locations varied from 0.16 to 1.27μM N averaging around 0.90(±0.41) μM N, whereas at coastal stations variation was between 0.89 to 2.1μM N with relatively higher average value of 1.35 (±0.52)μM N. Among the open ocean stations, there is a clear demarcation in PON concentration, where the first four stations have PON more than 1μM N with an average of 1.23μM N. The rest of the open ocean locations have PON less than 1 μM N, averaging around 0.64μM N.

The nitrogen isotopic composition of PON also shows a wide variation in the region during this month with minimum of 1.7‰ at station 7, which is an open ocean location, to 7.5‰ at station 13, a coastal location. Interestingly, PON concentration at station 13 is also a maximum during the whole study period. No systematic spatial pattern was observed in $\delta^{15}N$. Overall, the $\delta^{15}N$ averaged around 4.7 (±1.7)‰. The average $\delta^{15}N$ for open ocean locations was around 4.4 (±1.5)‰ and no clear demarcation was observed as in the case of open ocean PON content. The $\delta^{15}N$ of coastal locations averaged around 5.3 (±2.2)‰. Barring three locations during the study period (Stations 3, 7 and 12) the $\delta^{15}N$ was around or more than 4‰ during January.

3.8.2 Late February- Early March

During this period, only five stations were sampled for natural isotopic variation study. All the five stations sampled were open ocean stations. The PON content during this period varied from 1.0 to 2.25 μM N with an average value of 1.6(±0.5)μM N. The $\delta^{15}N$ varied from 7 to 11‰ with an average of 9.4(±1.7)‰. The PON content and $\delta^{15}N$ for both the cruises is listed in Table 3.4.

A plot of $\delta^{15}N$ and PON content for the two cruises reveals a positive relationship between the two with r^2 = 0.41(Figure 3.35). No significant (r^2= 0.14) relationship has been observed between the surface nitrate and $\delta^{15}N$ (Figure 3.36) for both the months. In general, this relationship is expected to have a strong negative correlation, as the nitrate concentration increases $\delta^{15}N$ should decrease. Such a relationship is common in a region like the southern ocean where nitrate concentration is very high. The observed poor relationship may be because of low nitrate concentrations and limited number of nitrate measurements. The most

Table 3.4 PON content and nitrogen isotopic composition in surface suspended matter during January and late February-early March 2003. Cruise number given in bracket. In bold are the bloom stations.

Month	Stations	PON (μM N)	$\delta^{15}N$ (‰)
January (SK-186)	2	1.61	6.7
	3	1.06	2.7
	4	0.99	4.6
	5	1.27	5.8
	6	0.75	3.8
	7	0.79	1.7
	8	0.16	5.1
	9	0.65	4.7
	10	0.86	4.6
	11	1.20	5.7
	12	0.89	2.3
	13	2.10	7.5
	14	1.21	5.6
Late February-Early March (SS-212)	**2**	1.04	10.4
	3	2.25	10.6
	4	1.61	10.9
	5	2.00	8.1
	6	1.13	7.0

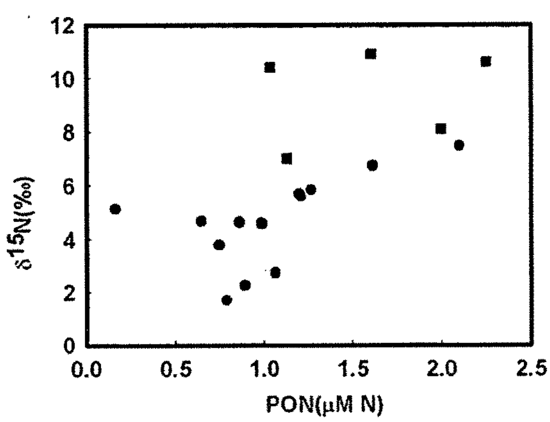

Figure 3.35 Relationship between $\delta^{15}N$ and PON during both cruises. Circles and squares represent January and late February-early March respectively.

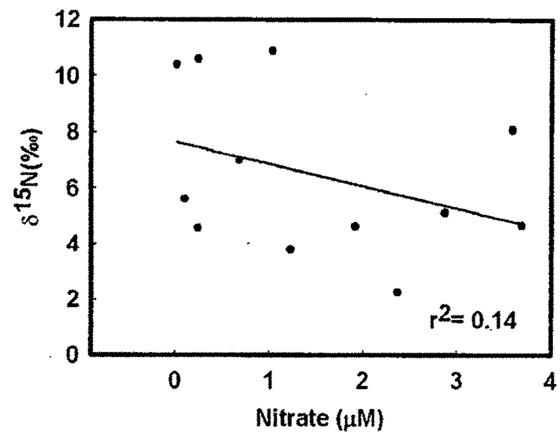

Figure 3.36 Relationship between $\delta^{15}N$ and NO_3 concentration during both cruises.

noticeable and significant result of the present study is the overall increase in $\delta^{15}N$ of the region during late February-early March. As stated earlier, during this period, study was undertaken for the open ocean only, a comparison of $\delta^{15}N$ of open ocean locations of January to Feb-March reveals an average increase of ~5‰, which is highly significant. A significant increase of 0.7μM N in PON content has also been observed from January to Feb-March.

3.8.3 Possible reasons for increased $\delta^{15}N$

This increase in $\delta^{15}N$ point towards the change in nutrient source or the fractionation pattern of the phytoplankton from one month to another. The significant increase in $\delta^{15}N$ of PON during late February-early March is possible under three circumstances: (A) the overall increase in the nitrogen isotopic composition of source ($\delta^{15}N$) nutrient taken up by the phytoplankton. (B) Change in the fractionation during uptake by the phytoplankton, while maintaining the same $\delta^{15}N$ of nutrient during both periods, and (C) a combination of both (A) and (B). However, the explanation for the mechanism of increased $\delta^{15}N$ of nutrient is dependent upon its source. Very high new production during early March suggests nitrate to be the principal source of nutrient. As mentioned in the previous section the source of nitrate during early March could be deeper nitrate or nitrate already present in the water column, which entrained during January due to the deeper mixed layer. However, the temperature based shallow mixed layer at the last three stations during early March suggests only a remote possibility of nitrate supply from deeper layers at these sites. However, the undulating and continuously sloping mixed layer at the first three stations suggests the supply of cooler water. This supply may be from deeper layers or due to advection from nearby region where the effect of winter cooling has not completely vanished and is still getting deeper nitrate. During the present discussion the contribution from both the above mentioned sources and consequent $\delta^{15}N$ enrichment of PON would be explored. If the nutrient source during both the months is deeper nitrate, the dramatic change in $\delta^{15}N$ of nitrate is possible only when there is intensification in denitrification process in the intermediate waters of the study region leading to an increase in the $\delta^{15}N$ of the supplied nitrate. However, if the nitrate already entrained in the surface layer is assumed to be the only source, the continuous use of available nitrate might probably leave the remaining pool enriched enough to explain the observed variation. The following subsections explore possible explanations based on both the above arguments.

A. Denitrification in the Arabian Sea

Although most part of the open Arabian Sea is well oxygenated, an acute depletion of oxygen occurs at intermediate depths (100-500m), particularly in the eastern and the central Arabian Sea. Reason for this depletion is the consumption of oxygen during the decomposition of organic matter sinking below the euphotic zone. This transition from 'oxic' to 'anoxic' condition at mid depths prompts the facultative bacteria, responsible for decomposition of organic matter, to switch over to nitrate ions that are the next most abundant source of free energy, for the decomposition of organic matter (Richards 1965; Naqvi 1994). The reduction of nitrate to molecular nitrogen with nitrite as one of the intermediate products is known as denitrification. The Arabian Sea is known for intense depletion of oxygen at intermediate depths with concentration often below the threshold value (1.2-3.85μM; Broenkow and Cline 1969) required for the initiation of denitrification (Devol 1978). Since, nitrite (NO_2^-) is one of the intermediate products in the denitrification process; its concentration within the water column provides the measure of denitrification. The distribution of NO_2 has been used to demarcate the geographical boundaries of denitrification zone; bounding the denitrification zone by 0.2μM contour, the total area affected by denitrification in the Arabian Sea has been estimated to be around $1.37*10^6$ km^2 (Naqvi 1991). The rate of denitrification ranges between 20-30 Tg N yr^{-1} when computed using physico-chemical and between 24-33 Tg N yr^{-1} using biochemical techniques respectively (Naqvi 1987; Naqvi and Shailaja 1993). The variation in the denitrification intensity based on seasonal scale has been observed (Naqvi et al 1990) in the Arabian Sea. During the southwest monsoon, a subsurface poleward undercurrent (Shetye et al. 1990) supplies oxygen and nitrate to the eastern Arabian Sea, suppressing the denitrification process. However, this feature is absent during the northeast monsoon i.e., the present study period.

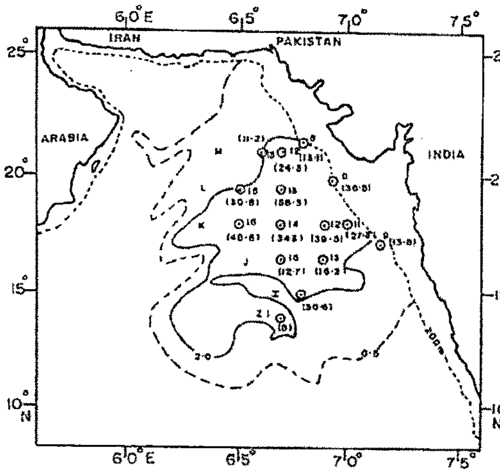

Figure 3.37 Geographical limits of the Arabian Sea denitrification zone delineated by Naqvi (1991). The area of present study falls within the zones of highest denitrification.

The area of present study undergoes intense denitrification (Figure 3.37) and modifies the isotopic composition of nitrate with a great deal which is the source nutrient for the phytoplankton.

Possible role of denitrification to explain the observed variation

During the process of denitrification $^{14}NO_3$ is used up faster than $^{15}NO_3$, resulting in the remaining nitrate getting enriched in $^{15}NO_3$. Thus, denitrification leaves a strong imprint upon the isotopic composition of the remaining nitrate (Cline and Kaplan 1975; Liu and Kaplan 1989). The fractionation for this process is given as $\alpha_{denitrification} = {}^{15}R/{}^{14}R$ where ^{15}R and ^{14}R are rates of denitrification for $^{15}NO_3$ and $^{14}NO_3$ respectively. This can also be represented as $\varepsilon_{denitrification} = (1-\alpha)*1000$. Brandes et al. (1998) have estimated $\varepsilon_{denitrification}$ in the central Arabian Sea using two different models and found it ranging from 22±3 (advection-diffusion model) to 25±4 (reaction-diffusion model) using an initial nitrate isotopic composition of 6‰.

It is well known from discussions earlier that denitrification leads to the enrichment of the remaining nitrate, which eventually acts as a source for phytoplankton. But why is there so much difference in $\delta^{15}N$ of PON from January to March? Are they signatures of intensification of denitrification at intermediate depths between these two months, which eventually have caused the nitrate $\delta^{15}N$ to get enriched from January to March? Banse (1984) have observed the suppression of denitrification during winter due to the supply of oxygen to the upper part of the oxygen minimum zone as a result of enhanced diffusion due to deepening of the mixed layer. The lowering of SST to 24°C and deepening of mixed layer up to 107m have been observed in the northern stations in the month of January during the present study. This might have helped in reducing the denitrification leading to lower $\delta^{15}N$ values of nitrate during January, which is reflected in the $\delta^{15}N$ of PON. Such situations were not as prolific as January during the study period in late February-early March as the effect of winter cooling was waning. The mixed layer during this period was also shallow at a few stations. These conditions suggest that the environment during late February-early March was not so supportive of convective mixing and hence the decrease in the aeration of deeper layers. This might have lead to increase in the intensity of denitrification and consequent increase in $\delta^{15}N$ of nitrate.

Intensification of denitrification

Brandes et al. (1998) have estimated the vertical profile of $\delta^{15}N$ of nitrate in the Central Arabian Sea for three different periods (September, January and April). The September and January profile exhibited the highest $\delta^{15}N$ value of 15‰ at 350m while April profile increased only upto 10.5‰ (Figure 3.38). However, they have observed a

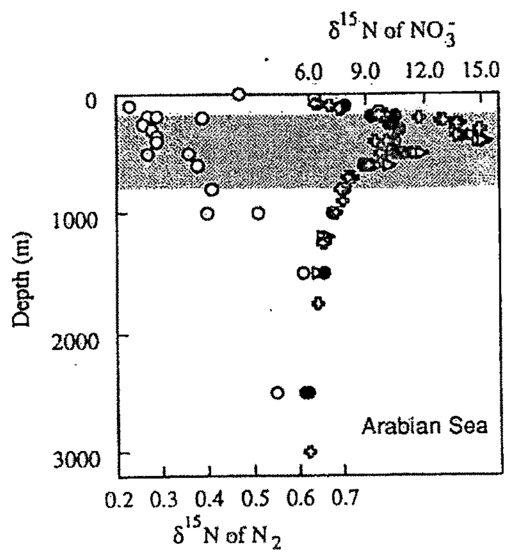

Figure 3.38 Isotopic composition of nitrate (filled circles, open triangles, and crosses) and nitrogen gas (open circles) with depth as observed by Brandes et al. (1998) for the central Arabian Sea.

decrease in $\delta^{15}N$ of nitrate (6‰) at 80m. The reason proposed by Brandes at al. (1998) for the reduced $\delta^{15}N$ observed at 80m is the dilution of heavy isotope signatures of nitrate supplied from subsurface layer through upwelling and vertical mixing in the Arabian Sea by lighter isotopes added due to nitrogen fixation. Going with the arguments of Brandes et al. (1998) and assuming that there is similar level of dilution of nitrate isotopic composition at around 80m by nitrogen fixation in the Arabian Sea, which is a potential nutrient source, and assuming the same fractionation factor for both months during uptake of nitrate by phytoplankton, the discussion point towards the potential increase in $\delta^{15}N$ of nitrate due to the intensification of denitrification from January to March.

Dilution of deeper nitrate

Another possible explanation could be the following. Assuming that there was no intensification in denitrification from January to March and the $\delta^{15}N$ of nitrate produced in the denitrification layer remains same (say 15‰) along with the fractionation behaviour of the planktons during the uptake of nitrate. If most nutrient input to the surface layer was from the suboxic layer; the observed $\delta^{15}N$ of PON points towards the requirement of surface light nitrate input for dilution as the deeper nitrate is significantly enriched. The resulting discrepancy of 5‰ in PON can be explained by the varying degree of dilution of enriched nitrate due to nitrogen fixation in the surface layer. The dilution during January will be more than that for late February-early March to explain the required level of $\delta^{15}N$ of nitrate. To estimate the level of dilution during both the months the highest value of $\delta^{15}N$ of PON of respective months would be considered as the $\delta^{15}N$ of ambient nitrate available for uptake assuming that these values of $\delta^{15}N$ are reflection of the $\delta^{15}N$ of nitrate consumed without fractionation. These values during January and late February-early March were 7.5 and 11‰ respectively, and represent the minimum values for nitrate during these two months assuming no significant spatial variation. The January value (7.5‰) is closer to the known $\delta^{15}N$ of nitrate in world ocean (~5‰; Miyake and Wada 1967). The dilution level required to obtain the 7 and 11‰ can be obtained by simple isotopic mass balance:

$$15x + (1-x)*5 = 7.5 \text{ (January) and } 15x + (1-x)*5 = 11 \text{ (March)}$$

Where x is the proportion of deeper nitrate and (1-x) is fraction of required dilution by lighter nitrate. 5 and 15‰ are the assumed isotopic composition of natural and deeper nitrate respectively. From this equation it is quite clear that the 75% of dilution would be required during January whereas only 30% required during late February-early March. The mechanism suggested for dilution is the nitrogen fixation.

Change in the fractionation behaviour of phytoplankton

Third scenario may be of a situation where there is same denitrification intensity and level of dilution with varying fractionation pattern. Assuming that the $\delta^{15}N$ of nitrate in the denitrification layer is 15‰ that undergoes similar dilution in the surface layer such that the isotopic composition changes to 11‰. This 11‰ nitrate will be acting as source during both months. The observed difference of 5‰ now can be explained by different degree of fractionation during uptake in January and March, to reach the observed isotopic composition from the same source. This depends upon the pool of available nitrate to the phytoplankton. If the pool is large, the phytoplankton can have the luxury of discriminating against ^{15}N to reach the desirable $\delta^{15}N$ level. However, such a scenario is not possible when there is a dearth of nitrate in the surface layer and the phytoplankton have to take up whatever is available and the nitrate isotopic composition is directly reflected in the PON. The nitrate concentration in surface water of the open Arabian Sea during these two months suggest the abundant nitrate (average ~ 1.8μM) during January whereas its dearth (average ~ 0.3 μM) during February except at one station where it was 3.5 μM. This high nitrate concentration during January and lower concentration during late February-early March indicate the flexibility for phytoplankton to fractionate during January, and not during March; consequently, reflecting lower and higher $\delta^{15}N$ values during January and late February-early March respectively. The $\delta^{15}N$ of PON is known to depend also on phytoplankton species, physiology and rate and phase of growth of phytoplankton (Montoya and McCarthy 1995).

However, all the above explanations are based on the assumption that the deeper nitrate is essentially the source. This is quite understandable during January when MLD is more than 80m and convective mixing due to winter cooling maintains the high nitrate concentration in the water column. However, this does not seem to hold good directly at all stations during late February-early March, when the MLD was found to be shallow (at three stations) despite high wind speeds in the region (>8 ms^{-1}). However, as mentioned earlier, supply due to advection from nearby regions with deeper MLD is a possible source during late February-early March. But surprisingly during late February-early March *noctiluca* bloom (>40mg Chl *a* m^{-2} in the euphotic zone) was observed during the study period. Where does the nutrient in the surface layer to support a bloom during late February-early March come from? Apart from nitrate due to advection, another possibility is the supply of nitrate due to turbulent diffusion across the thermocline; however, it is highly unlikely that the amount of nutrients required to sustain a bloom could be supplied due to diffusion.

B. Utilization of nitrate present in the surface layer

One important possibility of the nutrient availability during late February-early March is the inefficient utilization of the nitrate introduced in the water column during January. It is interesting to note that the euphotic zone integrated nitrate concentration in the water column at most of the stations during January was more than 150mmol m^{-2} but the average new production was only ~2.3mmolN $m^{-2}d^{-1}$. However, the integrated euphotic zone column nitrate during March was only around 80mmol m^{-2} but the average new production was as high as 13mmolN$m^{-2}d^{-1}$. These facts clearly indicate that the nutrients entrained in the water column due to convective mixing during January did not get consumed much and mostly remained there in the water column. Assuming the surface layer of the ocean as closed system and nitrate with initial isotopic composition (δ_o) of 7‰ as the source for phytoplankton during January, the isotopic composition of remaining nitrate (δ) will keep on changing with the consumption of the substrate pool (i e., fraction of substrate remaining, f) according to well known relationship:

$$\delta = \delta_o + \varepsilon * \ln(f) \quad \text{where, } \varepsilon = (\alpha-1)*1000; \alpha \text{ is fractionation factor.}$$

Assuming that the isotopic composition of nitrate available during late February-early March is 11‰ and taking ε = -5‰ (general value assumed for fractionation; Waser et al. 1998) the f from the above equation comes to be 0.4. It reveals that at the start of the uptake during late February-early March 60% of the nitrate introduced in the water column during January had already been consumed. If we take ε = -9‰ as in some cases (Rau et al. 1998) only 40% of the nitrate was consumed and rest 60% was available for further consumption (Figure 3.39).

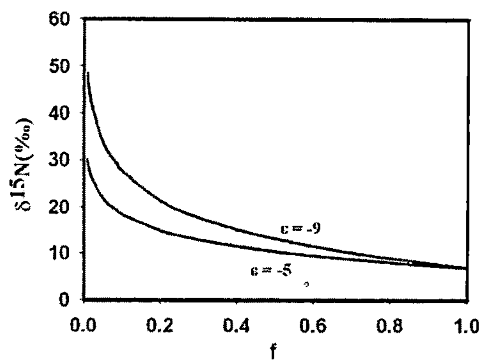

Figure3.39 Relationship between fraction of remaing nitrate (f) and its isotopic composition for different fractionation factors.

3.9 Conclusions

The present study was an attempt to understand and quantify the new production in the northeastern Arabian Sea during NE monsoon and compare it with the other, well explored, northwestern parts of the Arabian Sea. The effect of winter cooling on new production and on the natural nitrogen isotopic composition of suspended matter also formed a major part of the present study. The following are the most important findings of the present work:

- There exists a systematic dependence of new production on the winter cooling phenomenon in the northeastern Arabian Sea.
- The new production and f-ratio appear to increase from the south to the north.
- There appears to be a lag between the entrainment of nutrient in the water column and development of bloom in the northeastern Arabian Sea.
- The new production during bloom period in late February-early March was found to be five fold more than the new production in January.
- Ammonium was the preferred substrate during January whereas nitrate was during late February-early March.
- The inclusion of conservative urea uptake into the calculation reduces the f-ratio.
- The nitrogen isotopic composition of suspended particulate matter increases by ~5‰ from January to February indicating the shift in the nutrient regime.