Chapter Three

The Northeastern Arabian Sea

3.1 Introduction

The northern Indian Ocean is divided into two major ocean basins by the Indian Peninsula: The Arabian Sea in the west and the Bay of Bengal in the east. The Arabian Sea has a unique geographical setting: it is surrounded by the Arabian and African continents in the north and west and by the Indian peninsula in the east. The presence of a huge landmass in the form of Indian peninsula, Eurasian continent and Arabia makes the oceanic and atmospheric circulation of the northern Indian Ocean different from the other two major oceans *i.e.*, the Atlantic and the Pacific. Unlike the other two major oceans upwelling does not occur along the equator in the Indian Ocean, but rather in the northern hemisphere off Somalia, Oman and the western coast of India, and that too is limited to the boreal summer (Schott et al., 2002). The Arabian Sea constitutes the northwestern part of the Indian Ocean. It is comparatively small in its aerial extent: assuming equator as its lower boundary it encompasses an area of about $6.2*10^6$ km^2. It is one of the most biologically productive regions of the world ocean (Madhupratap et al., 1996; Smith, 2001) and is characterized by a range of biogeochemical provinces such as eutrophic, oligotrophic and oxygen deficient zones, based on atmospheric forcing due to the seasonally reversing monsoons: Southwest (summer) and Northeast (winter) monsoons (Bange et al., 2000; Wiggert et al., 2000; Prasanna Kumar et al., 2001a; Wiggert et al., 2002) and thus is an ideal laboratory for the oceanographic studies. Both the monsoons trigger high biological production but the underlying mechanisms are different. Fig 3.1 shows wind stress field over the Arabian Sea during different seasons. During the southwest monsoon, from May to September, strong south-westerly wind causes strong upwelling off Somalia and Oman and also along the western Indian coast, which enhances nutrients in the upper layers and causes high primary production. During the winter monsoon, cool dry air from the Himalaya enhances evaporation in the northern Arabian Sea causing surface cooling and convective mixing; this deepens the upper mixed layer causing entrainment of nutrients from the deeper to the upper layers triggering high primary production (Prasanna Kumar et al., 2001b), sometimes leading to the initiation of phytoplankton bloom.

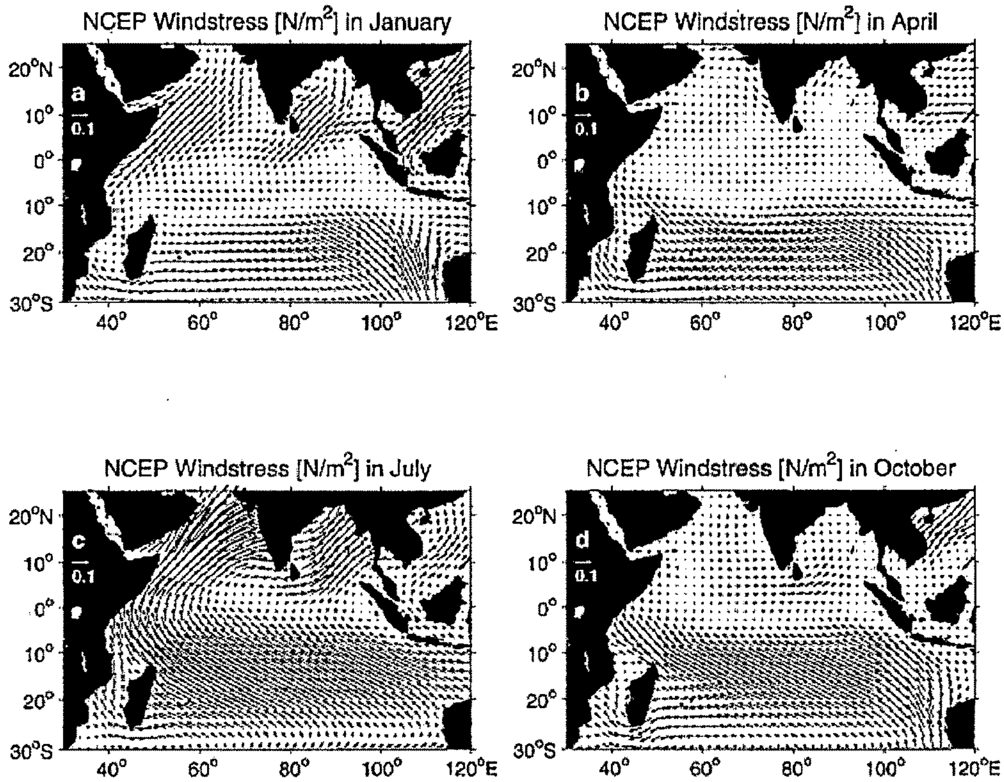


Fig 3.1 Monsoon wind stress field from the NCEP climatology for a) January, b) April, c) July and d) November (Source: Schott and McCreary 2001)

The total production during the bloom can reach up to ~ 2 $gCm^{-2}d^{-1}$ (Sanjeev Kumar et al., 2008). The spring and fall intermonsoon seasons are characterized by weak winds and surface heating, which results in oligotrophy. These monsoonal circulations have also established a permanent gradient in terms of biological productivity in the Arabian Sea, from highly productive Oman coast to the oligotrophic central Arabian Sea (Pfannkuche and Lochte 2000). Because of the above reasons the Arabian Sea has always been a centre of attraction for the oceanographers and has been studied in detail during the past few decades. During the US and Indian JGOFS a detailed study of the Arabian Sea was carried out. Most work was concentrated on studies of nutrients (De Souza et al., 1996), chlorophyll and productivity (Bhattathiri et al., 1996), denitrification (Bange et al., 2000) and physical forcing responsible (Madhupratap et al., 1996; Prasanna Kumar and Prasad, 1996). The main aims of JGOFS were as under:

1. To understand different physical processes controlling the biogeochemistry of the Arabian Sea.
2. To asses the variation in the primary production and the flux of carbon through the water column during different seasons
3. To asses the role of Arabian Sea in CO_2 air-sea exchanges. Does it act as a source or sink for the atmospheric carbon?
4. What is role of zooplankton in the overall transport of carbon to the deeper ocean?

Despite past major oceanographic programmes, limited data is available for the winter monsoon, especially for rates of primary and new production, as compared to the data available for the southwest monsoon in the Arabian Sea. As mentioned earlier the entrainment of nutrients into the surface layer during the winter monsoon leads to initiation of bloom in the northern Arabian Sea. The bloom during late winter monsoon is dominated by *Noctiluca scintillans*, a large and conspicuous dinoflagellate. This species is common in coastal areas worldwide and its most widely spread form is completely heterotrophic, survives on a wide range of prey such as phytoplankton and micro-zooplankton (Hansen et al., 2004). Heterotrophic red *Noctiluca scintillans* had been reported from the eastern Arabian in the month of September i.e., during the late summer/early winter monsoon (Sahayak et al., 2005). In the tropical and subtropical areas of the Southeast Asia, particularly in the northeastern Arabian Sea during late winter monsoon, a green form of *Noctiluca scintillans* is also found which can do photosynthesis and survive on itself under light for at least a month (c.f Sweeney 1971). The appearance of *Noctiluca* bloom in the northeast Arabian Sea is well documented in the literature (Dwivedi et. al., 2006, Parab et al., 2006) but data available on the nitrogen uptake and *f*-ratios is limited (e.g. Sanjeev Kumar et al., 2008). The present study is mainly concentrated on the estimation of total and new productivity in the northeastern Arabian Sea during the winter monsoon. The measurements carried out during the late winter monsoon also include productivity measurement in the *Noctiluca* dominated bloom areas.

Two different methodologies are used for the present study: 1) remote sensing study and 2) measurement of total and new productivity using the ^{15}N tracer technique over a large area in the eastern Arabian Sea.

3.2 Remote sensing studies

As discussed in the earlier section, the only possible way to monitor the variation in the biological properties of the ocean on a larger spatial scale is by remote sensing. Gregg et al. (2005) were the first to report an increase in the primary production of northern Indian Ocean using ocean color remote sensing data. They analyzed a 6 years time series of remotely-sensed global ocean chlorophyll data and reported an increase of 37.2% in the chlorophyll concentration in the western Indian Ocean (Somalian shelf) and 20.1% and 16.7% decrease in central Indian gyre and Bay of Bengal respectively. Goes et al. (2005) also reported an increasing trend in the chlorophyll concentration, and hence in the productivity, in the western Arabian Sea (47°E to 55°E & 5°S to 10°N and 52°E to 57°E & 5°S to 10°N). They attributed the cause to be the warming of the Eurasian landmass: the melting of the Himalayan snow cover in the recent past due to global warming apparently resulted in the enhancement of the land-sea contrast in summer temperature, thus enhancing monsoon winds. Though Gregg et al., 2005 also reported an increase in the chlorophyll concentration along the Somalian shelf, they did not attribute the cause to global warming. It is now well established through literature on palaeo-monsoon (Dupelssy, 1982; Sarkar et al., 1990) that whenever the southwest monsoon weakened (e.g. during the last glacial maximum circa 21,000 years ago), the northeast monsoon strengthened and *vice versa.* If this is taken in conjunction with Goes et. al., (2005) result one would expect a decreasing trend in the winter productivity in the north-eastern Indian Ocean. To verify this we have analysed the chlorophyll data over a period of eight years (1997 to 2005), obtained from SeaWiFS to characterize the interannual variation in the north eastern Arabian Sea, where winter cooling in the north and upwelling in the south are very prominent, causing an increase in the primary production. Our analysis of 8 years record of satellite ocean colour data over north-eastern Arabian Sea (Fig. 3.2.), from September 1997 to June 2005, suggests that chlorophyll concentration has not changed significantly with time but two seasonal peaks can be seen clearly; one during the winter monsoon (Feb/March) and other during summer monsoon (September). There is no monotonic increase in the chlorophyll-a concentration as reported for the southwest Arabian Sea. On the other hand the southwest Arabian Sea, where the chlorophyll distribution is not bimodal.

In zone 1, 1997-2005, the chlorophyll concentration has remained more or less similar during October to December (Fig. 3.2.). In most years there is a seasonal increase from January to March. This is because of the input of nutrients from the deeper level to the surface layer due to the deepening of the mixed layer caused by the winter cooling and convective overturning. Also, wind blowing from the continent to the ocean supplies nutrients and iron dust. According to a pervious study (Bange et al., 2000) the NH_4^+ input was the highest (0.69 ± 0.31 $\mu g/m^3$) during the declining phase of NE monsoon (March). The increased input of nutrients into the photic zone through convective mixing and atmospheric input causes the increase in the productivity in Feb/March sometimes leading to blooms. The average Chl-a concentration in March over the last 8 years is 1.45 mg Chl/m^3, the maximum being 1.96 mg Chl/m^3 in 2002 and the minimum 0.92 mg Chl/m^3 in 2004. After March again Chl-a concentration starts decreasing till the onset of the summer monsoon. Because of dense cloud cover very little data is available for the months of June, July and August. From September onwards as the cloud cover decreases it is easier to obtain remotely sensed Chl-a data. In September the chlorophyll concentration is fairly high (but less relative to Feb/March) because of the input of nutrients due to upwelling in the southwest Arabian Sea and possible lateral advection (Prassana Kumar et al., 2001a).

The sea surface temperature, an indicator of vertical mixing, has remained almost the same (Fig. 3.3.) over past eight years. Thus the SST data do not show a significant reduction in the winter cooling. In this zone, during winter a significant fall in the SST can be seen (3-4°C). The decrease in SST is due to the mixing of the deeper water with the surface water. This causes increase in the productivity. The decrease in SST can also be seen during SW monsoon when moderate upwelling takes place although it is not that prominent in this zone. During summer too the SST falls but the magnitude of decrease is less (1-2°C). This clearly suggests that winter cooling has more control on the productivity than upwelling in this zone.

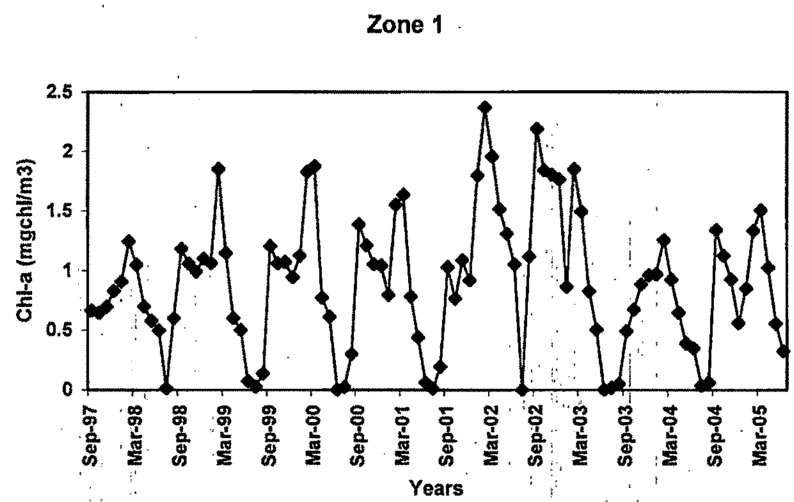


Fig. 3.2. Satellite derived Chl-*a* over zone 1.

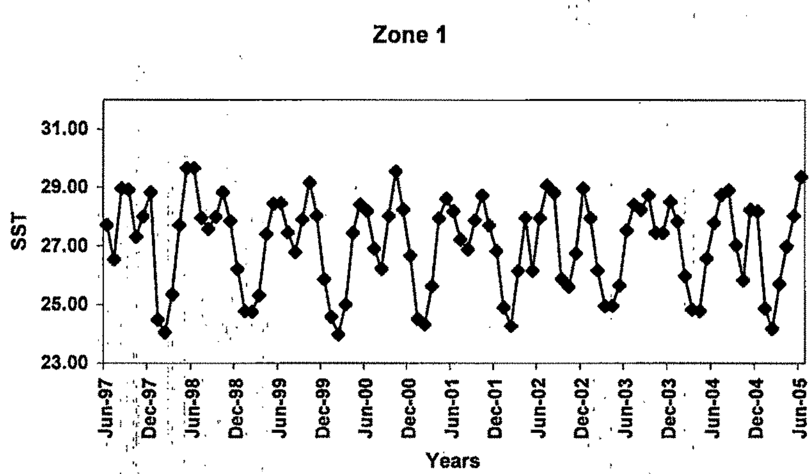


Fig. 3.3. Satellite derived SST over zone 1

In zone 2 the chlorophyll concentration remains low compared to zone 1, throughout the year. However, two prominent peaks can be seen every year (Fig. 3.4); one in the month of September when upwelling/vertical mixing takes place and the other, in the months of Feb/March, when winter cooling in the north triggers high production. Chlorophyll concentration is the highest in the month of September. The average value during 1997-2005 in September is 0.52 mg Chl/m^3, the maximum being 0.69 mg Chl/m^3(2004) and the minimum being 0.33 mg Chl/m^3 (1997). The chlorophyll concentration is also high during October to March, being the highest in March. The average chlorophyll concentration in March is 0.33 mg Chl/m^3. In this part of Arabian Sea the satellite derived sea surface temperature shows a bimodal temperature cycle with lows during SW (2-3°C) and NE (1-2°C) monsoons (Fig. 3.5.). This change in temperature has a profound effect on the mixed layer through change in water density. The increase in the mixed layer depth causes the transport of nutrients rich colder water from the deeper level to the surface and supply of nutrients for production. This enhances the Chl-a value in this region during these months.

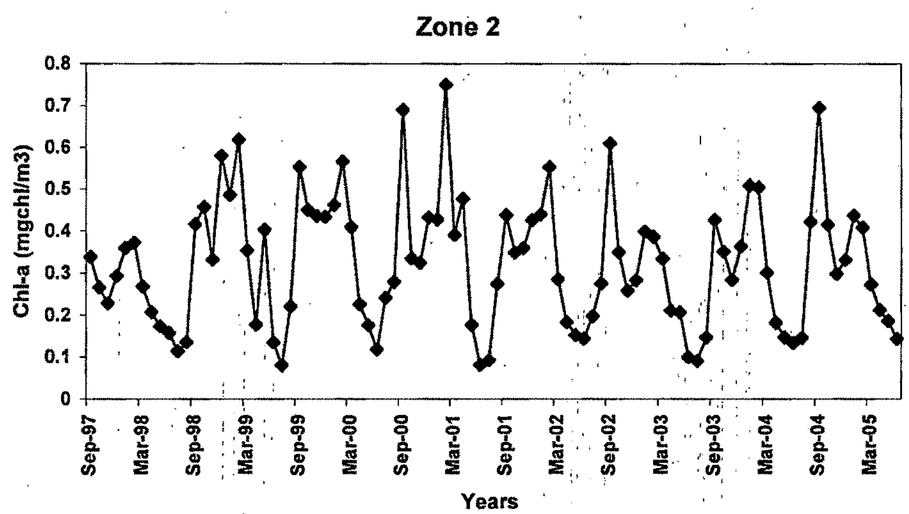


Fig. 3.4. Satellite derived Chl-*a* over zone 2

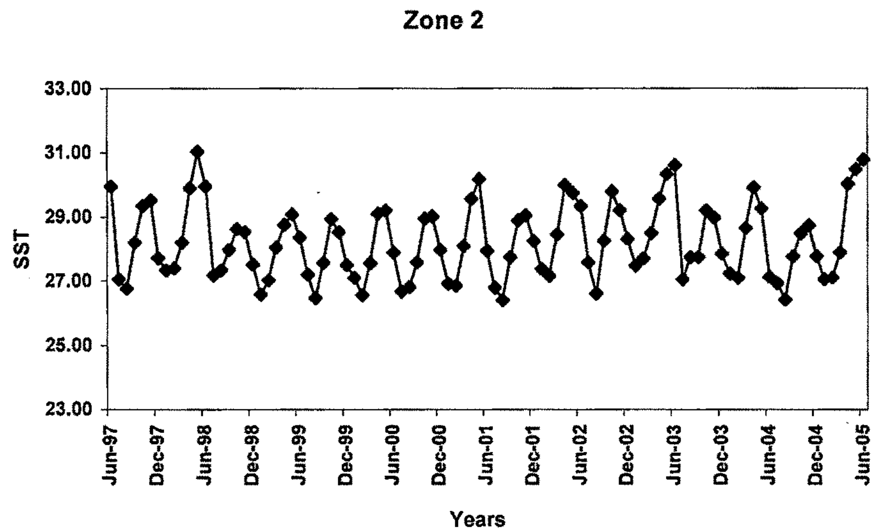


Fig. 3.5. Satellite derived SST over zone 2

Goes et. al., 2005 have argued, on the basis of the correlation between SST and satellite derived chlorophyll (Fig. 3.6, $R^2 = 0.70$), that the summer productivity has increased over the years due to increasing monsoon winds.

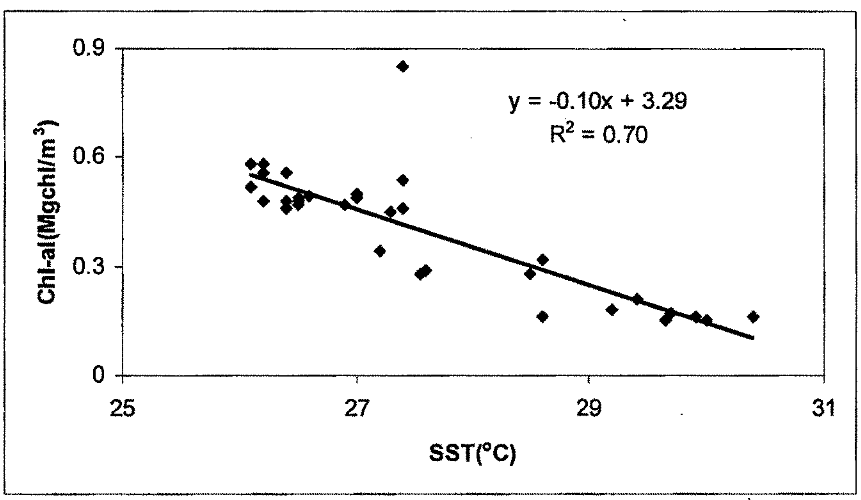


Fig. 3.6. Satellite derived Chl-*a* data and SSTs from May to September from the region 52°E to 57°E and 5°S to 10°N (Source: Goes et. al., 2005)

We also analysed the correlation between SSTs and Chl-a over Zone 1 and Zone 2 for the boreal winter i.e. October to March for the same time period and have observed that the slopes of the regressions are similar (~ -0.10) for all the three regions. Our analysis of sea surface wind data also does not show any significant change in the wind speed over north-eastern Arabian Sea (Fig. 3.7 and 3.8). In zone 2 we do not find any change in the wind strength. Wind speed pattern, over this region, has remained more or less constant during 1999-2005. Some small variations in wind speed can be seen in zone 1 but certainly there is no significant secular trend. These small changes can not be attributed to global warming because had it been due to temperature contrast between Eurasian plate and Arabian Sea, it should have affected both the zones. It is also difficult to relate these changes to decadal-scale oscillatory events using these data sets.

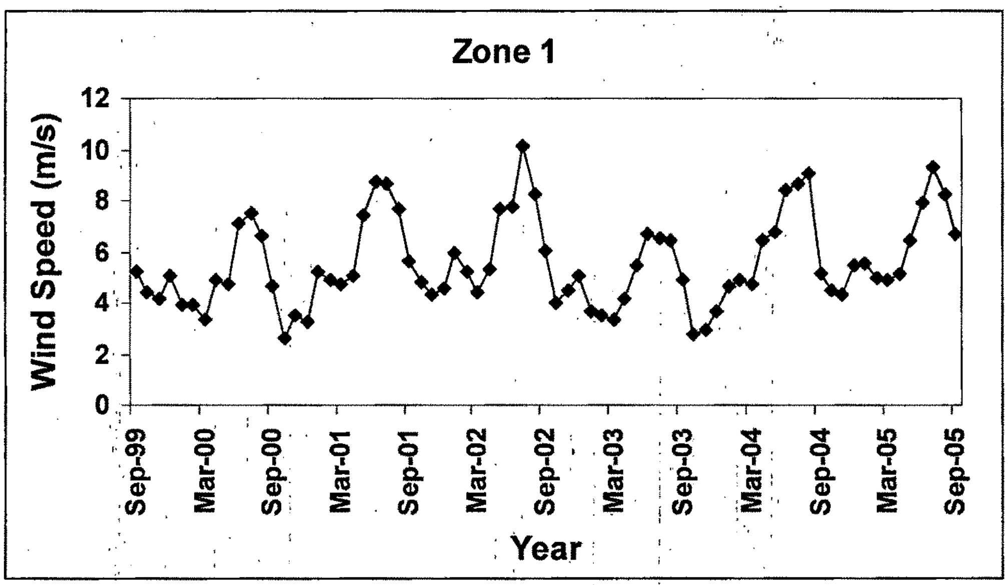


Fig. 3.7. Satellite derived wind speed over zone 1

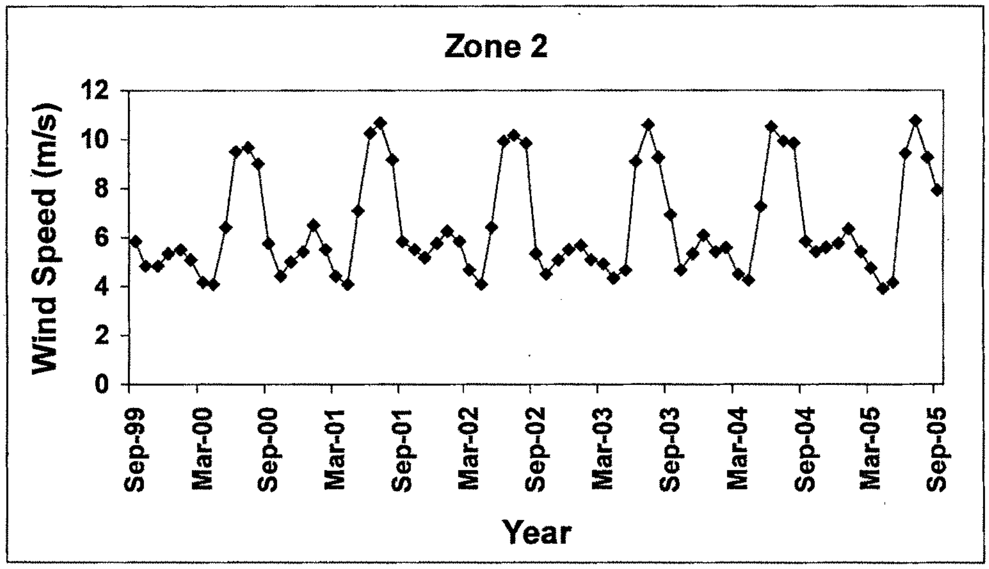


Fig. 3.8. Satellite derived wind speed over zone 2

The satellite derived chlorophyll and SST do not show significant correlation in winter in zone 1 (Fig. 3.9, $R^2 = 0.18$) but a significant correlation in zone 2 (Fig. 3.10, $R^2 = 0.44$).

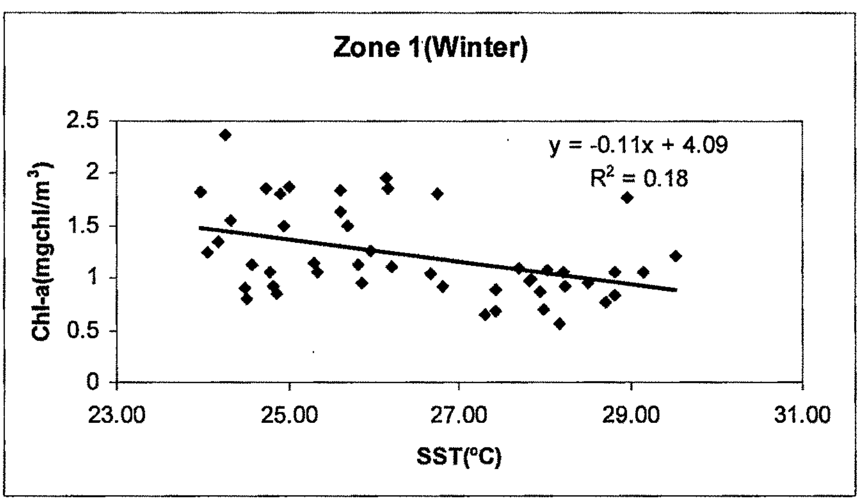


Fig. 3.9. Satellite derived Chl-*a* data and SSTs over Zone 1 in winter (October to March)

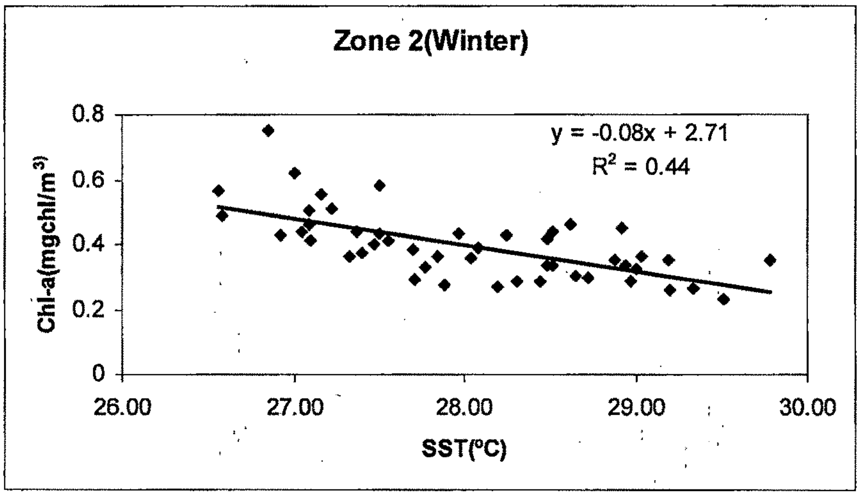


Fig. 3.10. Satellite derived Chl-*a* data and SSTs over Zone 2 in winter (October to March)

This suggests that both upwelling (SW monsoon) and convective mixing (NE monsoon) are responsible for a seasonal high productivity in this zone. Transportation of the deeper, colder, nutrient rich water to the surface triggers high production in the Western as well as in the Northern Arabian Sea. The average chlorophyll concentration in zone 1 is thrice the average concentration in zone 2 suggesting a greater control of winter cooling for the observed high production in this area. Although winter cooling has greater control on the production in the northeast Arabian Sea, it is not the only factor.

In summary, the interannual, remotely sensed, monthly composite chlorophyll data suggest high chlorophyll concentrations in the eastern Arabian Sea. The chlorophyll concentration in the north-eastern part of Arabian Sea is thrice that in the south-east. March is the most productive month due to winter cooling, while September is the most productive month during the summer monsoon. This is due to the difference in the physical forcing. The south-eastern Arabian Sea is equally productive in both summer and winter whereas the north-eastern part is more productive in winter than in summer. Overall, winter cooling has a more pronounced effect on the chlorophyll concentration and hence on the productivity in the eastern Arabian Sea compared to the summer monsoon. Although we see some seasonal variations in different parts of the Arabian Sea there is no significant secular trend.

Our analysis also shows that the trend reported by Goes et al., 2005 in the Western Arabian Sea is not observed in the eastern Arabian Sea. The increase in the chlorophyll reported by the Goes et al. 2005 is probably restricted to the west. Also their proposal that the intensification of southwest monsoon due to global warming has caused the increase in the productivity appears untenable, as we fail to observe any corresponding decreasing trend in the productivity of the north-eastern Arabian Sea. Any change in the monsoonal pattern because of land-sea temperature contrast should affect the north-eastern Arabian Sea in a bigger way because of its close proximity to the Himalaya as compared to the south-western Arabian Sea, which is not borne out by our analysis.

3.3 Chlorophyll-*a*, nutrients and physical parameters during February-March 2004 in the northwestern Arabian Sea

3.3.1 Chlorophyll-*a*

Chlorophyll concentration was measured at all the stations during this cruise. The surface waters at the stations in the south had less surface chlorophyll as compared to the stations in the north. It varied from 0.13 to 0.53 $mgChlm^{-3}$ at the stations in the south (non-bloom area) *i.e.*, PP1 to PP6 and PP8, where as in the north, where the *Noctiluca* bloom was present i.e., from PP7 and PP9 to PP11, surface chlorophyll concentration was very high; it varied from 0.96 to 2.74 $mgChlm^{-3}$. The vertical profiles of Chl-*a* at different stations are shown in Fig. 3.11. In non-bloom areas, most of the station had a deep chlorophyll maximum. At PP1 the surface chlorophyll concentration was 0.15 $mgChlm^{-3}$ which increased to 0.37 $mgChlm^{-3}$ at 57 m. PP2 and PP4 had similar chlorophyll profiles; at both stations the chlorophyll concentration decreased slightly at 3-4 m but again increased to a maximum at 45-50 m. At PP5 the chlorophyll concentration increased from 0.29 $mgChlm^{-3}$ at surface to 0.39 $mgChlm^{-3}$ at 55 m, which decreased with depth to a low of 0.029 at 115 m. PP6, being a shallow station (<20 m) because of the presence of a sub-surface bank, relatively high surface Chl (0.53 $mgChlm^{-3}$) but had low integrated chl concentration of 3.29 $mgChlm^{-3}$ because of less column depth. PP7 had high chl concentration (0.96 $mgChlm^{-3}$) at surface, which decreased rapidly at 1.5m to 0.27

mgChlm^{-3} but again increased to 0.69 mgChlm^{-3} at 40 m. PP8, despite being in the bloom zone this area was away from the actual bloom patch. The surface chlorophyll concentration, here, was significantly less (0.24 mgChlm^{-3}) compared to PP7. The deep chlorophyll maximum was at 35 m and had concentration of 0.43 mgChlm^{-3}. Station PP9, 10 and 11 was in the northeast Arabian Sea. These stations had high surface chlorophyll concentrations (> 1 mgChlm^{-3}). The dominant species was *Noctiluca*. The concentration of *Noctiluca* was so high (1.2-2.7 mglm^{-3}) that a significant amount of light (~ 22 %) got absorbed near the surface. As a result of this the depth of photic zone in this area decreased (mean photic depth ~ 50 m).

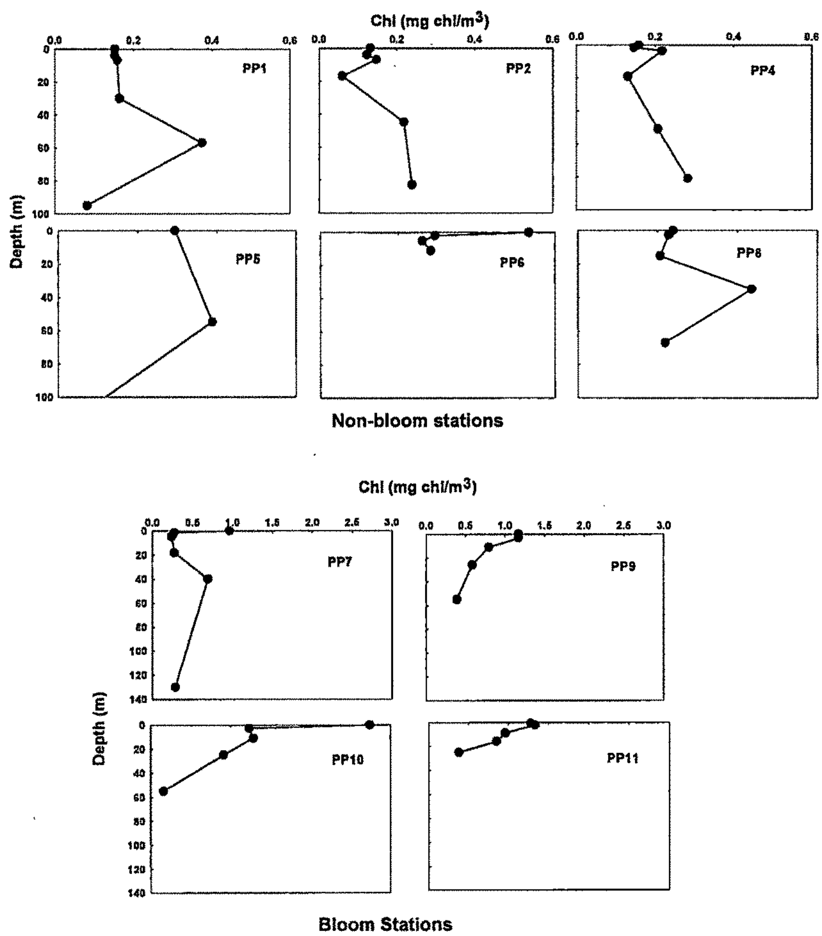


Fig 3.11. Vertical profiles of Chl-*a* at different stations in the eastern Arabian Sea during late winter monsoon (Feb.-March 2004)

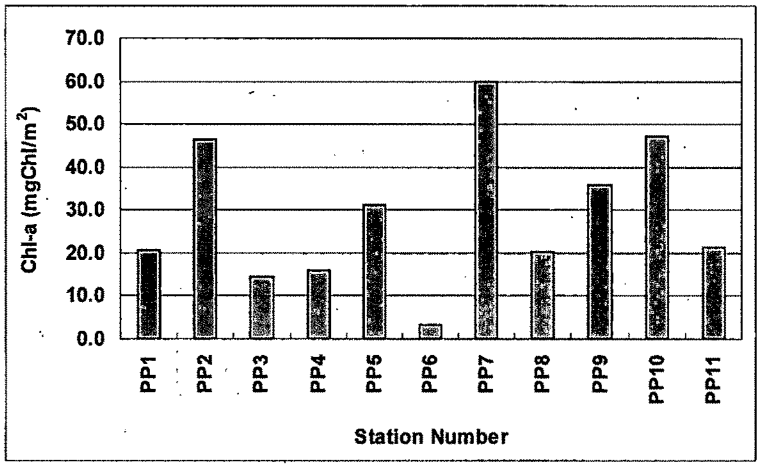


Fig. 3.12 Euphotic zone integrated chl-*a* concentration at all the stations during Feb.-March 2004.

The average column integrated Chl-*a* concentration during the study period was 27.04 $mgChlm^{-2}$; the maximum column integrated Chl-*a* concentration of 59.72 $mgChlm^{-2}$ was found at PP7 and a minimum of 14.53 $mgChlm^{-2}$ at PP2 (Fig 3.12).

3.3.2 Nutrients

Samples from all stations and all depths were analyzed for ambient nitrate concentration using an autoanalyzer. The surface layer had almost no nitrate at the southern stations i.e., from PP1 to PP6. The vertical profiles of nitrate are shown in Fig.3.13. At PP1 the water column was devoid of nitrate up to a depth of 57 m. Its concentration started increasing downwards. At PP 2 nitrate was not present up to 17 m. Downwards it increased slightly to 2.17 μM at 45 m but again decreased further below. PP3, 4 and 5 had similar characteristics as PP1. The nitrate concentration in the surface layer was near zero but increased downwards from depths of 27, 50 and 55m respectively. Though PP6 was a shallow station it showed heterogeneity in terms of nitrate concentration. The surface water at this station had nitrate concentration 0.47 μM which decreased to near zero between 2-5 m but increased again to 0.50 μM at 11 m.

PP7 was a bloom station with high chlorophyll in its surface waters but very little nitrate (~0.01-0.07 μM) in the surface waters. It increased slightly to 0.47 μM at ~5 m. There was again a decrease in nitrate at around 18 m. Downwards it increased to a maximum of 10.65 μM at 130 m. Though station PP8 was in a general area dominated by *Noctiluca* bloom, this station was out side the actual *Noctiluca* patch and this is reflected on the nitrate concentration here as well.

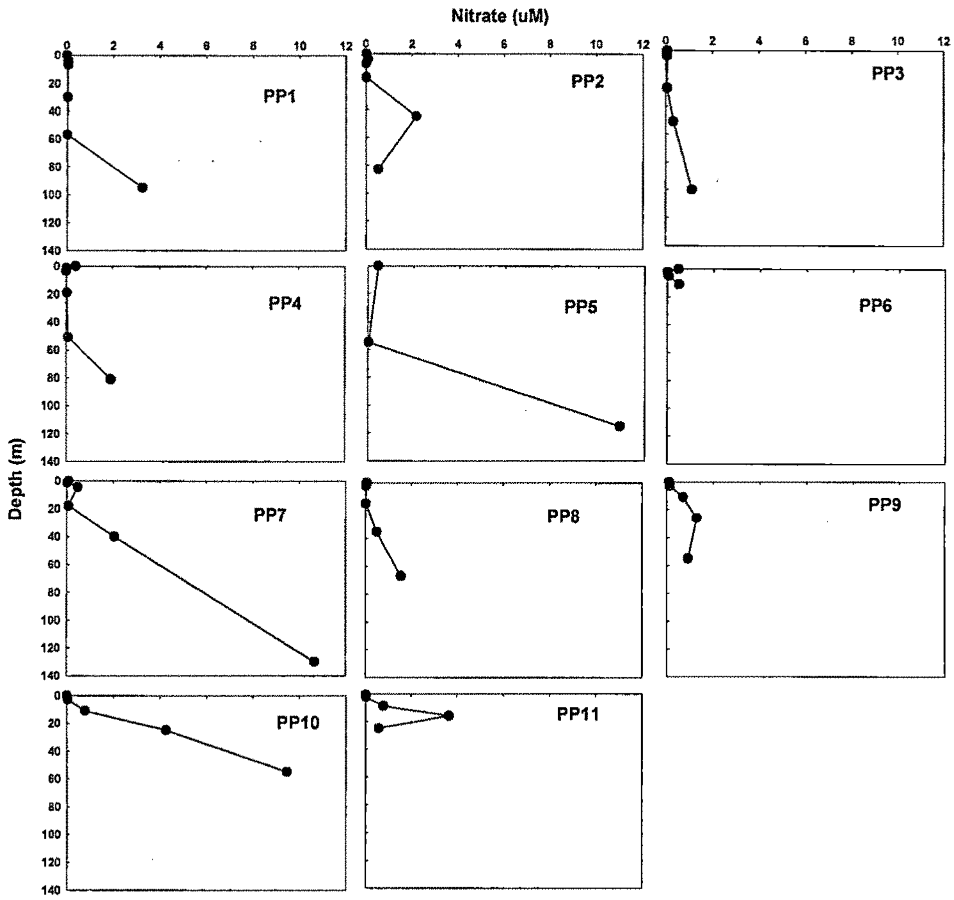


Fig 3.13 Vertical profiles of nutrients at different stations during the present study (cruise SS#222)

The nitrate concentration was low throughout the photic zone with almost no nitrate in the surface layer. Its concentration started increasing below 27 m but this increase was less compared to the other bloom stations. These three stations had high concentrations of Chl-*a* and were characterized by the presence of bloom dominated by green *Noctiluca scintillans*. During this period of the year these areas are influenced by convective mixing which brings ample nutrients, mainly nitrate, to the surface triggering high primary production often resulting in blooms. Though the bloom was present, high nitrate concentrations in surface waters were not observed. An earlier study in this area (Sanjeev Kumar 2004) had reported a large concentration of nitrate (~100 mmolm^{-2}) in the surface waters. The lesser concentration of nitrate suggests that most of the upwelled nitrate was utilized efficiently to trigger the high production and hence the bloom.

3.3.3 Hydrographic conditions

The present study was carried out during the months of February-March when this part of the world is under influence of the winter monsoon. During this period the Sea Surface Temperature (SST) of the Arabian Sea decreases upto 5-6°C on a south-north transect. Madhupratap et al., (1996) has reported a northward decrease in SST at a rate of 0.5°C per degree latitude during the winter in the Arabian Sea. During the present study the maximum SST of 28.9°C was recorded at one of the southernmost station (PP2) and a minimum of 25.2°C was recorded at PP10, a station in the north. The rate of decrease was low in the south i.e., from 10°N to 17°N, where SST decreased from 28.8°C to 28.2°C but in the north the rate of decrease was high; it decreased from 28.2°C to 25.2°C between 17°N to 22°N (Fig 3.14). The rate was decrease was more (~0.65°C per latitude) than that reported by Madhupratap et al., (1996). The lowering of sea surface temperature was associated with the increase in salinity of the surface waters. Salinity was low in the south and increased gradually towards the north. The minimum salinity of 33.8 psu was recorded at the southernmost station PP1 and a maximum of 36.6 psu was recorded at PP10, a station in the north. Unlike SST which showed a rapid decrease over a comparatively small area in the north, salinity showed a gradual increase over the whole study region.

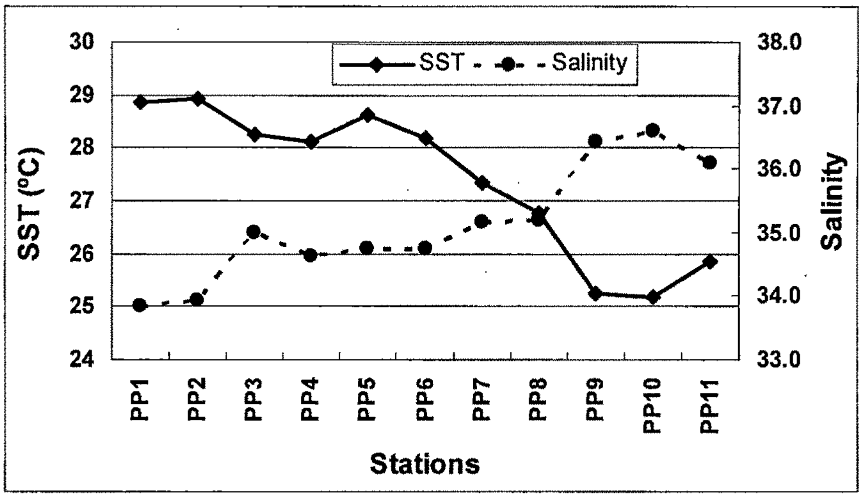


Fig 3.14 SST and salinity at different stations in the eastern Arabian Sea during Feb-March 2004.

During the winter land looses temperature much faster than the ocean. This results in wind from the land towards the ocean. As this wind is cool and dry, it absorbs moisture and in this process it causes evaporation of the surface water in the northern Arabian Sea. Excess evaporation over precipitation causes an increase in salinity of the surface waters. This dense surface water tends to sink and causes convective mixing. This transports nutrient rich deeper cold water to the surface and lowers SST. Figure 3.14 shows anti-correlation between SST and salinity: decrease in SST is associated with an increase in salinity. Higher rate of decrease in SST suggests more intense winter cooling and this has also been reflected in the column N-uptake rates and *f*-ratios, which will be discussed later in this chapter. Though the effect of winter cooling could be observed in SST and salinity, the same could not be observed in temperature based mixed layer depth or MLD (Fig 3.15). The deepest MLD was at PP1, a station in the south. MLD at this station was 37m. Rest of the stations did not show a well defined MLD. Temperature profiles of all other stations showed lots of undulation. As the sampling was done towards the end of the winter monsoon, undulations in temperature profiles suggest the dying phase of the winter cooling phenomenon.

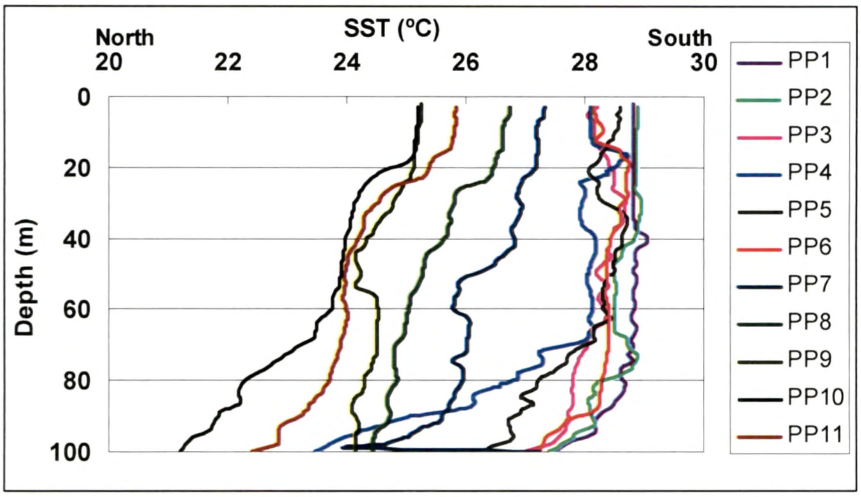


Fig 3.15 Temperature-depth profiles at different stations obtained using CTD data during Feb.-March 2004

3.4 ^{15}N based Productivity in the late winter monsoon (Feb.-March 2004)

3.4.1 Total Production

The rates of nitrogen uptake, integrated over euphotic zone, varied from 2.7 $mmolNm^{-2}d^{-1}$ to 23.4 $mmolNm^{-2}d^{-1}$ over the study area. The higher rates were measured at the stations in the north (PP9, 10 and 11), whilst the lower rates were associated with the southern stations (Fig.3.16). The same spatial variability in the nitrogen uptake was also reported by Owens et al., (1993) i.e., the lower uptake in the south and the higher in the north with an overall increasing trend from south to north, in the north-western Arabian Sea.

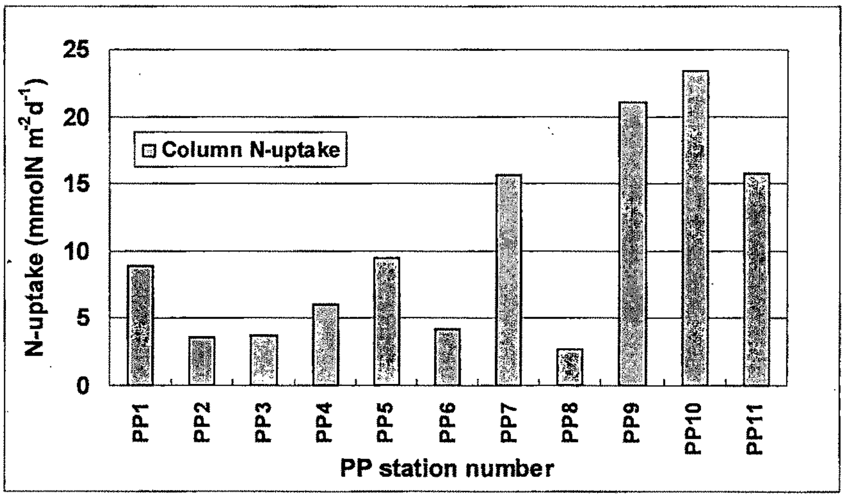


Fig. 3.16. Station-wise column-integrated total N-uptake for eastern Arabian Sea during the present study (total N-uptake rate is a sum of nitrate, ammonium and urea uptake rates)

At the southern stations (PP1 to PP 4 i.e., 10°N to 14°N) the mean depth of the euphotic zone was more, ~95 m. Column-integrated total N-uptake varied from 3.6 to 8.8 mmolNm^{-2}d^{-1}. At PP5 samples were collected from only three depths, from 100%, 5% and 1% light levels. Therefore the column production could have been somewhat underestimated. PP6 was a shallow station (<20 m) because of the presence of a sub-surface bank, sea bed was visible at this station, only 4 depths could be sampled here. The column production (integrated only up to 20% light level) is relatively high, 4.2 mmolNm^{-2}d^{-1}. We have sampled 4 stations (PP7, and PP9 to PP11) in the northeastern part of Arabian Sea during a phytoplankton bloom (defined as surface Chl-*a* $\geq$ 1 mg Chl m^{-3}) dominated by *Noctiluca scintillans* (green autotrophic variety). At PP7 the concentration of *Noctiluca scintillans* was less despite having relatively high nitrate in the surface waters. As this station was the southernmost among other bloom stations we suspect that the bloom had not yet initiated at the time of sampling. The column integrated total N-uptake rate of 15.6 mmolNm^{-2}d^{-1} was the lowest compared to other bloom stations, of which the nitrate uptake rate was 3-fold higher than the combined ammonium and urea uptake rates. Though PP8 was located north of PP7, it was outside the bloom patch and therefore was not considered as a bloom station for the present analysis. Here the column N-uptake was 2.7 $mmolNm^{-2}d^{-1}$. From PP9 to PP11, the concentration of *Noctiluca* (1.2-2.7 mgm^{-3}) was so high that a significant amount of light (~ 22 %) got absorbed near the surface. The depth of photic zone also decreased (mean photic depth ~ 50 m). Though the mean column N-uptake was very high (~19 $mmolNm^{-2}d^{-1}$) it was comparable to those reported by Owens et al., (1993) (23.1 $mmolNm^{-2}d^{-1}$) from the central Arabian Sea during the late summer monsoon. McCarthy et al., (1999) has also reported N-uptake rates varying from 9.2 $mmolNm^{-2}d^{-1}$ to 40 $mmolNm^{-2}d^{-1}$ during winter monsoon for the central Arabian Sea. Watts and Owens (1999) reported N-uptake rates varying from 1.1 $mmolNm^{-2}d^{-1}$ to 23.6 $mmolNm^{-2}d^{-1}$ for the northwestern Arabian Sea during an intermonsoon period. A large variation in the N-uptake rate, ranging from 0.1 $mmolNm^{-2}d^{-1}$ to 13 $mmolNm^{-2}d^{-1}$ had also been reported by Sambrotto (2001) during the spring intermonsoon and the summer monsoon for the northern Arabian Sea.

3.4.2 New Production

For the present study, as mentioned in earlier chapter, nitrate uptake is considered as new production. Euphotic zone integrated nitrate uptake rate or new production during the late winter monsoon in the eastern Arabian Sea showed significant variation in new production; it varied from 0.63 $mmolNm^{-2}d^{-1}$ to 20.91 $mmolNm^{-2}d^{-1}$. It was low in the southern sector of the sampling area but was significantly higher in the northern sector. The mean new production in the southern sector or the non bloom area was 2.1 $mmolNm^{-2}d^{-1}$ whereas in the bloom area it was 15.7 $mmolNm^{-2}d^{-1}$, almost eight fold higher. Station-wise nitrate uptake rate is shown in figure (3.17). Lowest new production of 0.63 $mmolNm^{-2}d^{-1}$ (~50.4 $mgCm^{-2}d^{-1}$) was measured at PP2, located in the southern part. Nitrate uptake rate increased northward, from 0.63 $mmolNm^{-2}d^{-1}$ at a station in the southernmost part to 20.91 $mmolNm^{-2}d^{-1}$ at one of the northernmost station. This is due to the unavailability of nitrate in the surface layer of the southern stations. At these stations plankton depended on other sources for their nitrogen needs.

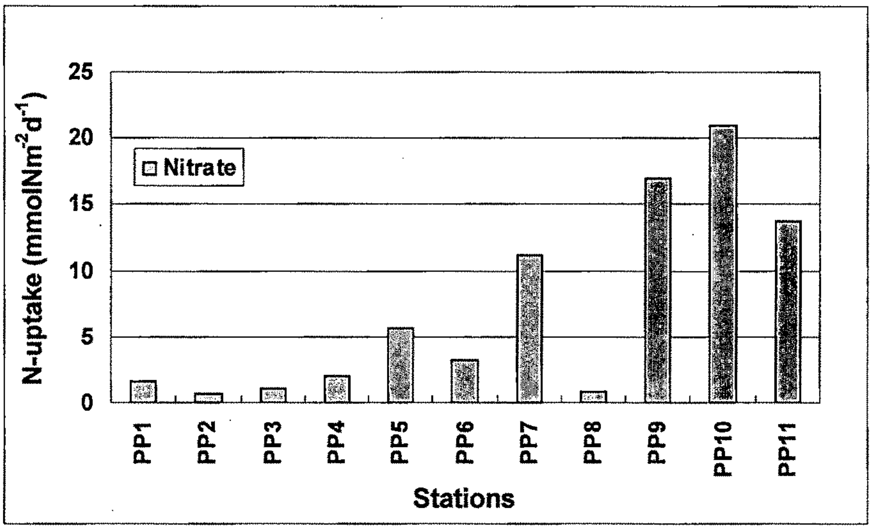


Fig 3.17 New production at different stations in the eastern Arabian Sea during the late winter monsoon.

At the northern stations where the winter cooling is more effective and bring ample nitrate in the surface layer due to convective mixing and thus the deepening of the mixed layer, nitrate uptake by the plankton increases. The average new production measured during the present study in the non-bloom area is less by ~1 $mmolNm^{-2}d^{-1}$ from the average value reported by McCarthy et al., (1999) for January-February (3.21 $mmolNm^{-2}d^{-1}$) during the winter monsoon for the central Arabian Sea but is less than those for the month of October (1.54 $mmolNm^{-2}d^{-1}$). Watts and Owens (1999) have reported mean nitrate uptake rates of 2.38 $mmolNm^{-2}d^{-1}$ for the northwestern Arabian Sea during an intermonsoon period. New production estimates reported by Watts and Owens (1999) are comparable with those of the present study.

The present study indicates the presence of two different biogeochemical provinces in the eastern Arabian Sea during the late winter monsoon: less productive southern and more productive northern regions. The southern sector was characterized by low column N-uptake and thus low new production. The column integrated total N-uptake rates, although low, increased progressively towards north. This increase may be the effect of more intense winter cooling towards the north. The northern part was a highly productive zone, with very high N-uptake and new production. The process of convective mixing is also seen in the temperate and polar areas but increase in productivity or development of bloom has not been reported. In the northeastern Arabian Sea, the presence of ample light, coupled with nitrate input triggers the bloom. Nitrate based phytoplankton community during development of bloom (Bienfang et. al., 1990) and ammonium based community during later periods (Rees et. al. 2002) have been reported. The column integrated total production (x) and new production (y), show a significant correlation (Fig.3.18): for non-bloom stations: $y = (0.44 \pm 0.23)\,x - (0.30 \pm 1.38)$; (coefficient of determination, $r^2 = 0.43$) and for bloom stations, $y = (1.08 \pm 0.23)\,x - (4.68 \pm 4.46)$; ($r^2 = 0.91$).

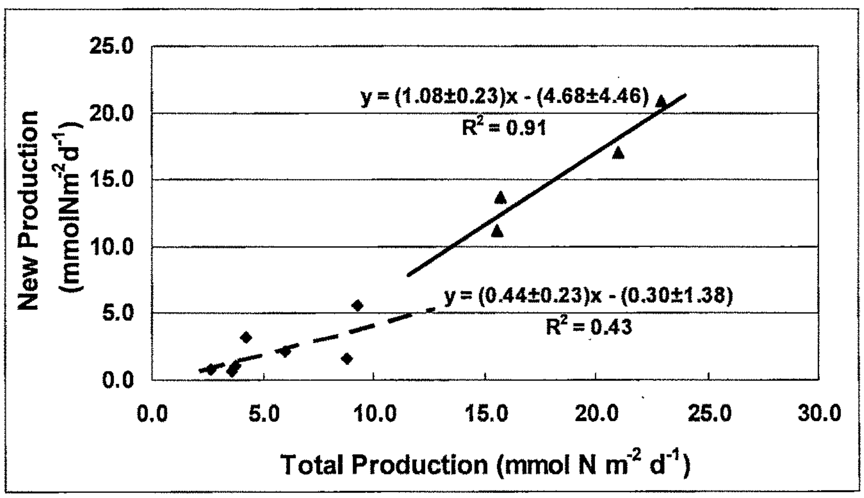


Fig 3.18 Relationship between total N uptake rate and nitrate uptake rate in the eastern Arabian Sea during the late winter monsoon.

The slope of regression (i.e., 0.44 and 1.0 for non-bloom and bloom stations respectively) is the maximum possible value of the *f*-ratio and can be used to estimate new production over a large area using ocean color remotely-sensed data. The present study suggests that though there is significant variation in the total N-uptake in the eastern Arabian Sea, the new production can be more than 90% of the total production, particularly in the northern part during *Noctiluca* bloom. Thus this area plays a significant role in the atmospheric carbon sequestration and hence in the global carbon cycle.

3.4.3 Regenerated Production

The sum of ammonium and urea uptake rates is considered as regenerated production for the present study. The ammonium uptake rates varied from a low of 0.36 $mmolNm^{-2}d^{-1}$ to a high of 3.28 $mmolNm^{-2}d^{-1}$, the highest was at the southern most station *i.e.*, PP1 (Fig 3.19). The ammonium uptake decreased northward to a low of 0.36 $mmolNm^{-2}d^{-1}$ at station PP6. At PP7 it again increased to 1.89 $mmolNm^{-2}d^{-1}$. This may be because of the increase in the depth of photic zone at this column; the photic zone depth of 130 m was the maximum at PP7.

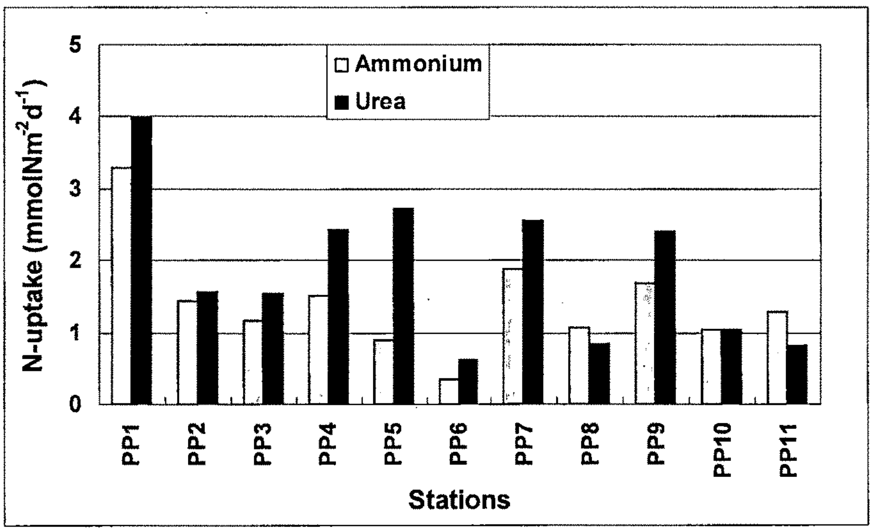


Fig 3.19 Ammonium and urea uptake rates at different stations in the eastern Arabian Sea during the late winter monsoon.

The ammonium uptake rates at bloom and non-bloom stations varied between 1.03 $mmolNm^{-2}d^{-1}$ to 1.89 $mmolNm^{-2}d^{-1}$ and 0.36 $mmolNm^{-2}d^{-1}$ to 3.28 $mmolNm^{-2}d^{-1}$ respectively. The mean ammonium uptake rates at the non-bloom and bloom stations were 1.39 $mmolNm^{-2}d^{-1}$ and 1.47 $mmolNm^{-2}d^{-1}$ respectively. Urea uptake rates were more than ammonium uptake rates at almost all the stations except at PP8, PP10 and PP11. At PP10 both ammonium and urea uptakes rates were almost equal and at PP8 and PP11 ammonium uptake rates were more than urea uptake rates. These three station lie in the *Noctiluca* bloom patch and thus they suggest that ammonium was preferred more than urea during the *Noctiluca* bloom. Urea uptake rates varied from 0.36 $mmolNm^{-2}d^{-1}$ to 3.99 $mmolNm^{-2}d^{-1}$ over the study area. At the bloom and non-bloom stations it varied between 0.82 $mmolNm^{-2}d^{-1}$ to 2.55 $mmolNm^{-2}d^{-1}$ and 0.63 $mmolNm^{-2}d^{-1}$ to 3.99 $mmolNm^{-2}d^{-1}$ respectively. The mean urea uptake rates at bloom and non-bloom stations were 1.70 $mmolNm^{-2}d^{-1}$ and 1.96 $mmolNm^{-2}d^{-1}$ respectively.

3.4.4 *f*-ratios in the eastern Arabian Sea during Feb.-March 2004

The *f*-ratios also showed significant spatial variation in the eastern Arabian Sea during the late winter monsoon (Fig 3.20); it was low in the southern sector (0.17 at PP2) whereas was very high in the north (0.91 at PP10) where the *Noctiluca* bloom was present (Table 3.1). In the south (non-bloom area) the *f*-ratio was in general low; it varied from 0.18 to 0.34. Also, the *f*-ratio increased progressively towards the north, 0.18 at PP1 to 0.34 at PP4. Similar trend in *f*-ratio were also reported by Sanjeev Kumar et al. (2008) for the eastern Arabian Sea during Feb.-March 2003. At the incomplete station *i.e.,* PP5 and PP6 the *f*-ratio was 0.61 and 0.77 respectively. Since at PP5 samples were collected from only three depths, the *f*-ratio could have been somewhat overestimated. At PP6, being a shallow station (<20 m) because of the presence of a sub-surface bank, only 4 depths could be sampled. The *f*-ratio is also high here, 0.77, suggesting presence of nitrate based phytoplankton community.

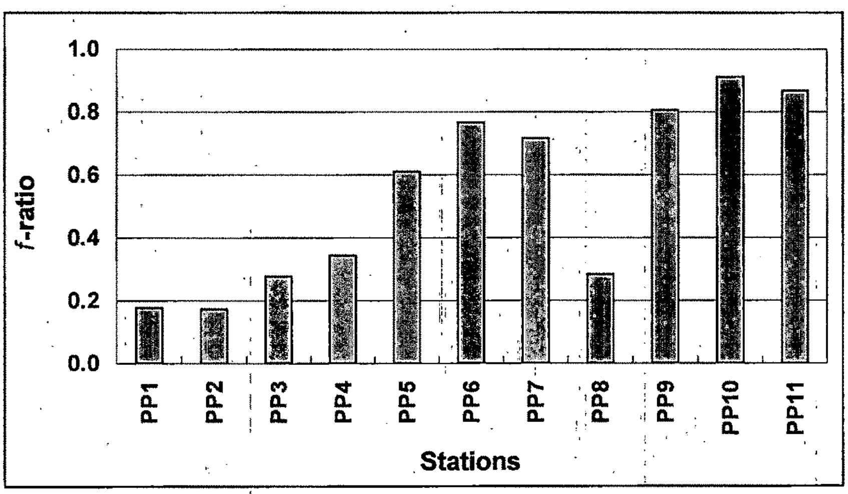


Fig. 3.20 *f*-ratios at different stations in the Eastern Arabian Sea during the late winter monsoon.

Stations	New Production	Regenerated Production		Total* Production	f-ratio
	ρNO_3*	ρNH_4*	ρNH_2*		
PP 1	1.56	3.28	3.99	8.8	0.18
PP 2	0.63	1.43	1.56	3.6	0.17
PP 3	1.04	1.16	1.55	3.7	0.28
PP 4	2.06	1.52	2.43	6.0	0.34
PP 5	5.64	0.89	2.73	9.3	0.61
PP 6	3.25	0.36	0.63	4.2	0.77
PP 7	11.19	1.89	2.55	15.6	0.72
PP 8	0.75	1.07	0.85	2.7	0.28
PP 9	16.97	1.67	2.40	21.0	0.81
PP 10	20.91	1.03	1.04	23.0	0.91
PP 11	13.66	1.27	0.82	15.8	0.87

* all uptake rates are in $mmolNm^{-2}d^{-1}$

Table 3.1 ^{15}N based productivity and f-ratios during Feb.-March 2004 (late winter monsoon) in the eastern Arabian Sea

3.5 Chlorophyll-*a*, nutrients and physical parameters during December-2004 in the northwestern Arabian Sea

3.5.1 Chlorophyll-*a*

Chlorophyll concentrations were measured at all the 11 stations during the early winter monsoon cruise as well. As almost all the stations were in the northern Arabian Sea, zonation in south-north transect could not be seen. Chlorophyll concentration was, in general, low at all the stations. The mean surface chlorophyll concentration over the study area during the present season was 0.33 $mgChlm^{-3}$ but varied significantly over the study area; it varied from a low of 0.19 $mgChlm^{-3}$ to 0.51 $mgChlm^{-3}$, the maximum was at PP3 and the minimum was at PP8. The mean column integrated Chl-*a* was 22.42 $mgChlm^{-2}$. It varied from 18.38 $mgChlm^{-2}$ to 27.26 $mgChlm^{-2}$, the maximum was at PP10 and the minimum was at PP5. Station-wise integrated chlorophyll values and chlorophyll-depth profiles are shown in Fig 3.21 and Fig 3.22.

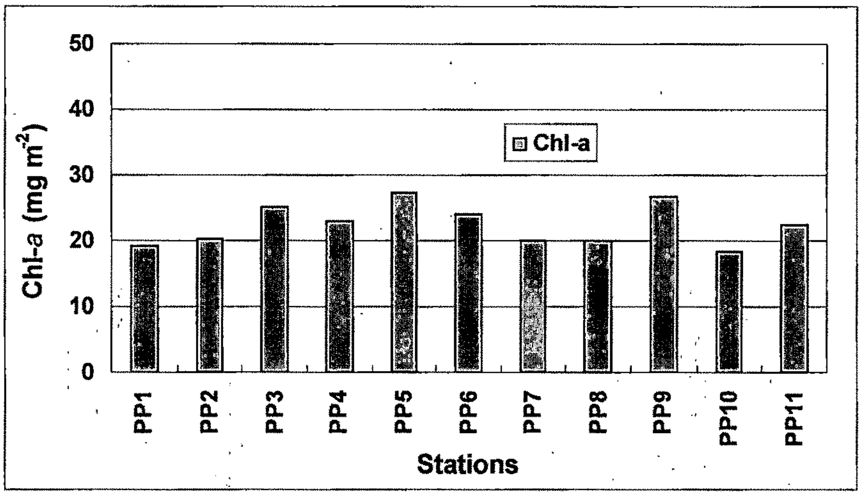
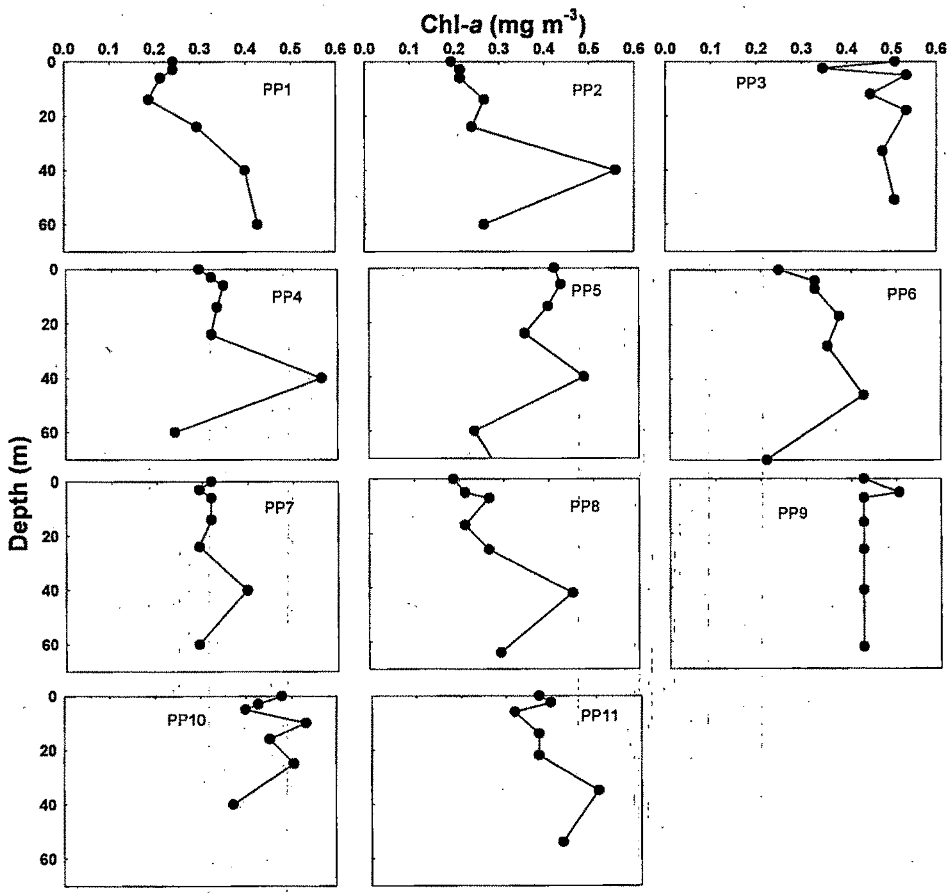


Fig 3.21 Station-wise column integrated chlorophyll concentration during Dec-2004

During the early winter monsoon most of the stations had irregular chlorophyll-depth profiles with more than one deep chlorophyll maximum (DCM), one immediately below the surface and other at a depth of 40-50 m; the deeper peak being more prominent than the upper ones. At PP1, the chlorophyll concentration decreased at 14 m depth as compared to the surface but again increased gradually to reach a maximum of 0.42 $mgChlm^{-3}$ at a depth of 60 m. PP2, PP4, PP8 and PP11 had similar profiles with prominent DCM at around 40m. PP3 has very irregular profiles as compared to the other stations; chlorophyll varied between 0.3 to 0.5 $mgChlm^{-3}$ in the upper layer. PP5 and PP7 had two chlorophyll peaks, one at 6 m and another at 40 m but the peak at 40 m was more prominent than that at 6 m depth. Chlorophyll decreased below 40 m. At PP6 chlorophyll increased downwards to reach a maximum of 0.42 $mgChlm^{-3}$ at a depth of 46 m which again decreased with increasing depth. At PP9 chlorophyll was the same throughout the column except one undulation in the upper 7 m; chlorophyll value increased to 0.51 $mgChlm^{-3}$ at a depth of 5 m but again decreased to 0.43 $mgChlm^{-3}$ at 7m and remained almost the same in the column. At PP10 chlorophyll varied between 0.39 $mgChlm^{-3}$ to 0.53 $mgChlm^{-3}$ in the upper water column. Though the chlorophyll-depth profiles at different stations showed some undulations at most of the stations, the variation was very small and varied between 0.1-0.2 $mgChlm^{-3}$.



3.22 Vertical profiles of Chl-*a* at different stations in the eastern Arabian Sea during the early winter monsoon (Dec - 2004)

3.5.2 Nutrients

Samples were collected from different depths for ambient nitrate measurement. The vertical profiles of nitrate at different stations are shown in Fig. 3.23. PP1 and PP3 have almost similar vertical profiles; nitrate concentration was very low (<0.2 µM) throughout the column. At PP2 and PP4 the ambient nitrate concentration was below 0.5 µM at the surface but increased to 6.2 µM at a depth of 60 m at PP2 and to 6.3 µM at 40 m which further increased to 8.4 µM at 80 m at station PP4. PP5 had no nitrate (nitrate concentration below detection limit i.e., 0.01 µM) in the column. PP6, PP7 and PP8 had similar profiles with very less nitrate concentration in the upper 40m but increased suddenly to 5.4 μM and 2.6 μM at depths of 70 m and 60 m depths at PP6 and PP7 respectively and to 1.5 μM at a depth of 64 m at PP8. Unlike other stations PP9 and PP10 had nitrate present in the water column but the concentration was not high, it varied from 0.24 μM to 0.56 μM at PP9 and from 0.31 μM to 0.75 μM at PP10. Surface water was again devoid of nitrate at PP11; it was below detection limit upto a depth of 35 m but increased thereafter to 0.46 μM at 54 m.

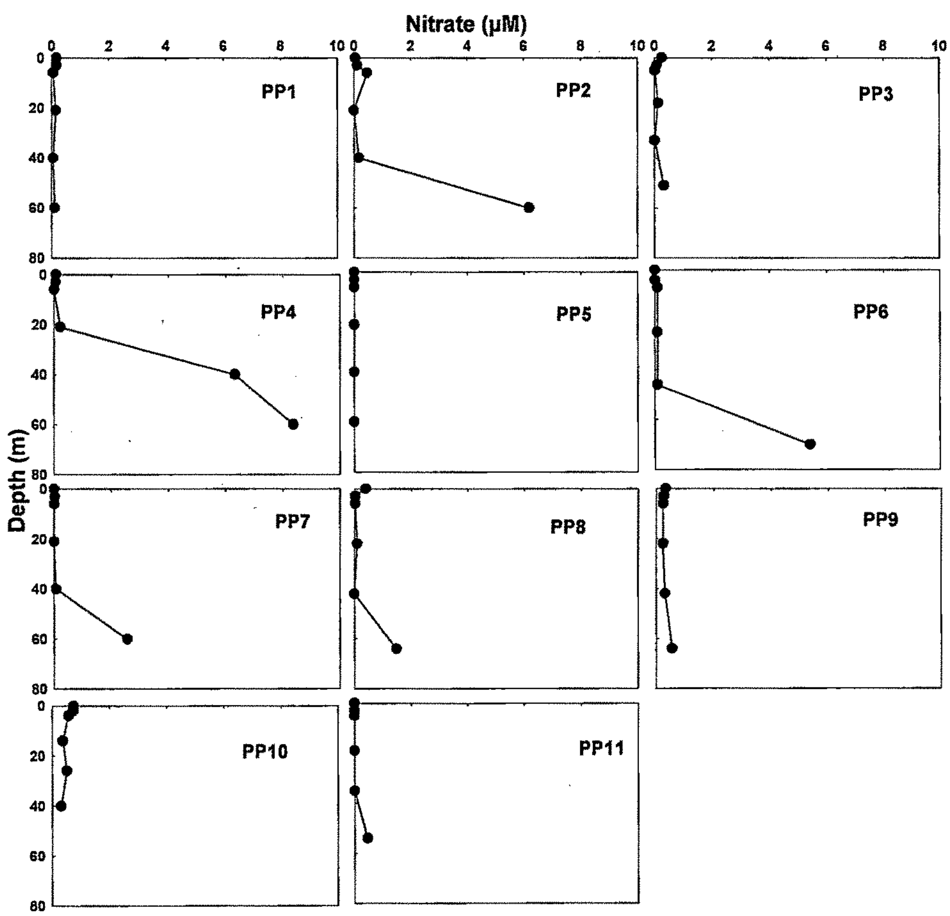


Fig 3.23 Vertical profiles of nitrate at different stations during December-2004

Integrated nitrate concentration during this period varied from a low of 4.4 mmol m^{-2} to a high of 210.7 mmol m^{-2}. The highest nitrate was at PP4 because of high nitrate concentration in the deeper waters (>6 μM). If PP4 is excluded then integrated nitrate varied from 4.4 μM to 70.1 μM which is significantly less than the integrated nitrate concentration (~100 mmol m^{-2}) reported by Sanjeev Kumar et al., (2008) for January 2003.

3.5.3 Hydrographic conditions

The eastern Arabian Sea was again studied during the month of December. This period of the year is characterized by the reversal of wind, from Himalaya to the ocean, and onset of winter monsoon. During this period also SST decreases on from south to north but the magnitude of the decrease is less as compared to that in the months of Feb.-March. SST decreased from 28.6°C to 26.3°C at an interval of 7° latitude, between 14°N to 21°N, during the present study (Fig 3.24). The maximum SST of 28.6°C was recorded at the southernmost station PP1 and a minimum of 26.3°C was recorded at a northernmost station PP9. The rate of SST decrease per latitude was ~0.3°C which is significantly less, almost half, than those during Feb.-March 2004.

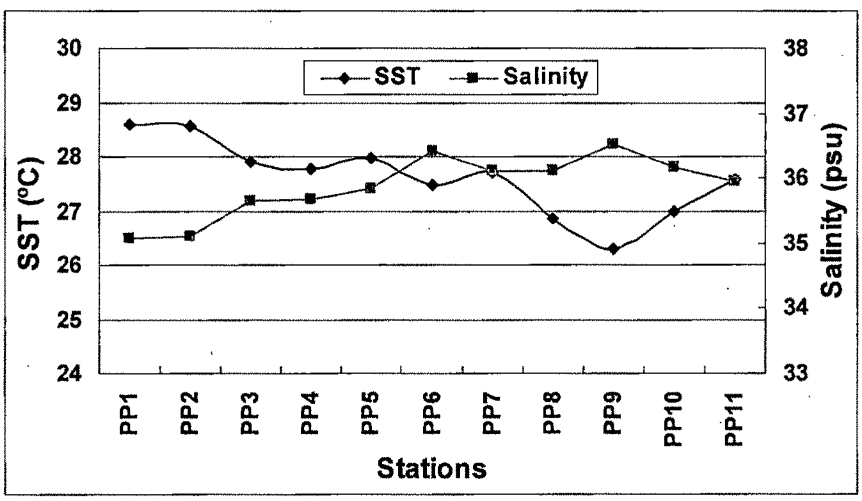


Fig 3.24 SST and salinity at different stations in the eastern Arabian Sea during early winter monsoon (Dec-2004)

Similar to the late winter monsoon, during the month of December also the decrease in SST was associated with an increase in salinity of the surface waters.

Salinity increased from 35.08 in the south at PP1 to 36.52 in the north at PP9. Though increase in salinity and decrease in SST was observed during present study also, its magnitude was less as compared to that observed during the late winter monsoon (Feb.-March 2004). Salinity increased by 2.8 during the late winter monsoon whereas during the early winter it increased by only 1.4. SST decreased by 2.32°C during the present study whereas the same had decreased by 3.6°C during the late winter monsoon. This suggests that the winter cooling effect was not much pronounced during the present study (December 2004) as it was during the late winter monsoon (Feb.-March 2004). Even though winter cooling was not much intense during the present study, the temperature based mixed layer depth was more than those during the late winter monsoon (Fig 3.25).

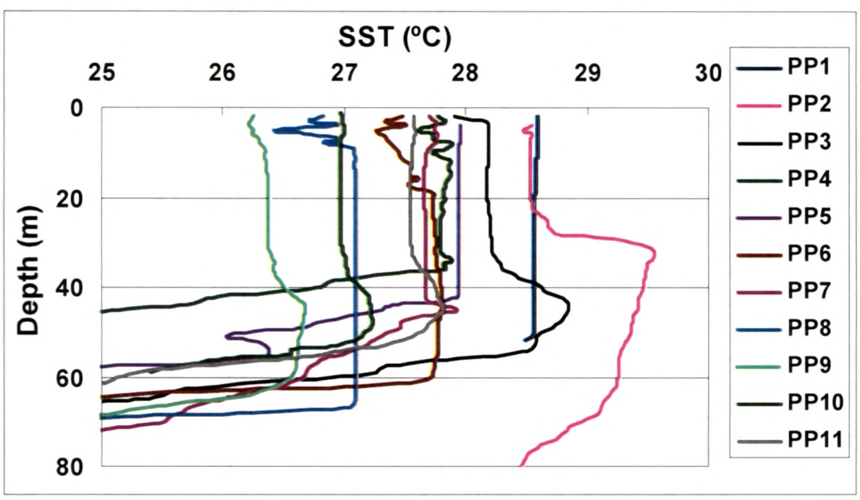


Fig 3.25 Temperature-depth profiles at different stations obtained using CTD data during December 2004

The mean MLD during the present study was found to be ~40 m; the maximum MLD (66 m) was observed PP8 (21.3°N) and a minimum (24 m) was observed at PP2 16°N. A clear trend in MLD from south to north could not be observed. At PP1 the mixed layer depth was almost 50 m which decreased to 24 m at a latitudinal interval of 1.5°. From PP2 northwards upto PP6 i.e., from 16°N to 19°N a general increase in MLD could be seen. MLD increased from 24 m at PP2 to 55 m at PP6.

PP7 and PP8 had mixed layer depths of 43 and 66 m respectively. PP9, 10 and 11 had almost the same mixed layer depth of 31 m. The presence of deep mixed layer during December may be due to the effect of winter cooling which starts in December and continues till the end of February (Madhupratap et al., 1996).

3.6 ^{15}N based Productivity study during the early winter monsoon (December 2004)

3.6.1 Total production

Total productivity for the present study has been calculated as a sum of nitrate uptake rates and conservative estimates of ammonium and urea uptake rates. The rates of nitrogen uptake, integrated over the photic zone, varied from 4.07 $mmolNm^{-2}d^{-1}$ to 23.31 $mmolNm^{-2}d^{-1}$ (Fig 3.26). Unlike the late winter monsoon when higher uptake rates were measured at stations in the southern part of the eastern Arabian Sea, during the early winter monsoon no such pattern was seen in the N-uptake rates at different stations in the same region (these PP stations are not the same stations described earlier). At PP1 total N-uptake rate was 10.51 $mmolNm^{-2}d^{-1}$ which increased anomalously to 23.31 $mmolNm^{-2}d^{-1}$ at PP2, 1°N of PP1.

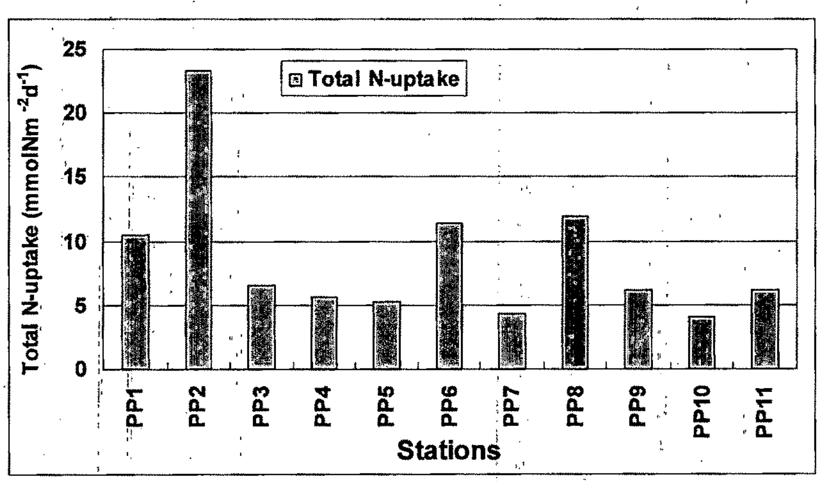


Fig. 3.26 Total N-uptake rate (new production) at different stations in the eastern Arabian Sea during December 2004.

N-uptake rate again decreased to 6.51 $mmolNm^{-2}d^{-1}$ at PP3. This station had also been sampled during the late winter monsoon (PP7 of SS222); column N-uptake was more than twice (15.6 $mmolNm^{-2}d^{-1}$) that of the early winter monsoon. PP4 and PP5 had almost the same column N-uptake rates, 5.68 $mmolNm^{-2}d^{-1}$ and 5.21 $mmolNm^{-2}d^{-1}$ respectively. PP6 and PP8 had higher N-uptake rates, 11.40 $mmolNm^{-2}d^{-1}$ and 11.95 $mmolNm^{-2}d^{-1}$ respectively, compared to other stations sampled during the present study. The sudden increase in the nitrogen uptake was mainly due to an increase in the nitrate uptake rates. PP9 to PP11 had column N-uptake rates varying between 4.07 $mmolNm^{-2}d^{-1}$ to 6.15 $mmolNm^{-2}d^{-1}$. The mean N-uptake rate during the present study was 8.65±5.61 $mmolNm^{-2}d^{-1}$. It was significantly lower, almost one-fourth, than the mean N-uptake rate reported for the month of Jan.-Feb. and similar to the N-uptake rates during the month of October by McCarthy et al., (1999) from the central Arabian Sea. Though the column N-uptake rate measured during the present study is on the higher side, a similar variation had also been reported by Watts and Owens (1999) for the northwestern Arabian Sea during an intermonsoon period. The uptake rates reported by Watts and Owens (1999) varied between 1.1 $mmolNm^{-2}d^{-1}$ to 23.6 $mmolNm^{-2}d^{-1}$. Sambrotto (2001) has also reported N-uptake rates varying from 0.1 $mmolNm^{-2}d^{-1}$ to 13 $mmolNm^{-2}d^{-1}$ for the spring intermonsoon and summer monsoon from the northern Arabian Sea.

3.6.2 New Production

Photic zone integrated nitrate uptake rate or new production during early winter monsoon 2004 varied from 1.95 $mmolNm^{-2}d^{-1}$ to 19.70 $mmolNm^{-2}d^{-1}$ (Fig 3.27) over the study area. New production was more at stations PP2, PP6 and PP7; nitrate uptake rates at these stations were 19.7, 9.02 and 8.69 $mmolNm^{-2}d^{-1}$ respectively. Excluding these three stations, the nitrate uptake varied from 1.95 $mmolNm^{-2}d^{-1}$ to 5.70 $mmolNm^{-2}d^{-1}$ at rest of the stations. At stations PP9, 10 and 11 also had moderately high new production; nitrate uptake rates at these stations were 4.70, 3.52 and 4.91 $mmolNm^{-2}d^{-1}$ respectively. Like total production, any significant spatial pattern in new production also could not be observed as was the case during the late winter monsoon 2004. The mean column new production over the study area was 6.12 mmolNm^{-2}d^{-1}, which reduced to 3.74 mmolNm^{-2}d^{-1} when three highly productive stations were excluded. The mean nitrate uptake rate was twice of the mean nitrate uptake (3.24 mmolNm^{-2}d^{-1}) reported by McCarthy et al., (1999) for the month of Jan-Feb and four-times of that in the month of October (1.54 mmolNm^{-2}d^{-1}).

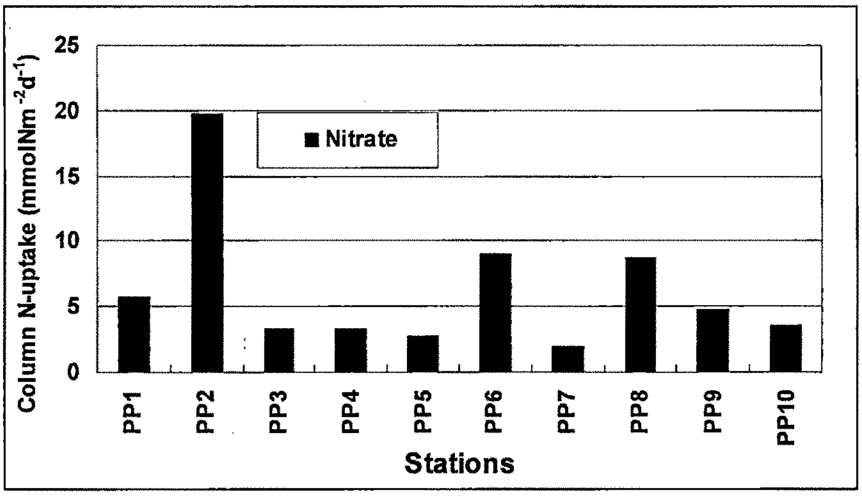


Fig. 3.27 Nitrate uptake rate (new production) at different stations in the eastern Arabian Sea during December 2004.

The nitrate uptake rate measured during the present study is almost half of the rate reported by Sanjeev Kumar et al., (2008) for the months of Feb.-March 2003 (12.7 mmolNm^{-2}d^{-1}) but is almost thrice of that reported for the month of January 2003 (2.3 mmolNm^{-2}d^{-1}). In comparison to the rates of nitrate uptake measured during the late winter monsoon, new production during December is thrice that of a non-bloom (2.1 mmolNm^{-2}d^{-1}) region but is less than half of that (15.7 mmolNm^{-2}d^{-1}) in the bloom area. Station PP7 and PP8 of SS-222 (late winter monsoon) were repeated during the present study as PP3 and PP6. Nitrate uptake increased almost five-fold, from 3.25 mmolNm^{-2}d^{-1} during early winter to 15.6 mmolNm^{-2}d^{-1} during the late winter monsoon in the presence of the *Noctiluca* bloom at station PP3 of the present study. At PP6 nitrate uptake decreased from 9.02 mmolNm^{-2}d^{-1} to 2.7 mmolNm^{-2}d^{-1}, again from the early winter monsoon to the late winter monsoon. These clearly suggests that the productivity pattern has significant heterogeneity over space and time in the eastern Arabian Sea but still this part of the world ocean has a potential of high new productivity. The strong correlation (r^2 = 0.96) between the column integrated nitrate uptake and total N-uptake (Fig 3.28) also supports this argument. The slope of the regression (0.88) gives the fraction of the total production that can be exported out of the photic zone. High slope suggests higher ability of this part of the ocean to produce which can be exported to the deep. High slope (>0.9) was also evident in this part during the late winter monsoon during the bloom, though it was low (0.44) during the same season in the southern part where the winter cooling was not that effective.

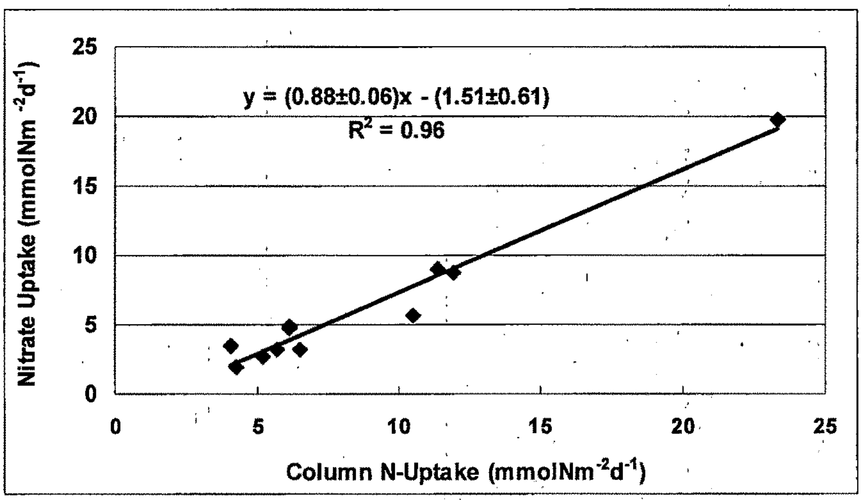


Fig 3.28 Relationship between total N-uptake during the early winter monsoon (December) in the eastern Arabian Sea.

3.6.3 Regenerated production

Ambient ammonium and urea concentration could not be measured during the present study and hence a conservative estimate of their uptake rates was made. Ammonium uptake rate varied from 0.47 $mmolNm^{-2}d^{-1}$ to 2.79 $mmolNm^{-2}d^{-1}$ (Fig 3.29) and urea uptake rates varied from 0.08 $mmolNm^{-2}d^{-1}$ to 2.02 $mmolNm^{-2}d^{-1}$. The mean ammonium and urea uptake rates were 1.81 $mmolNm^{-2}d^{-1}$ and 0.79 $mmolNm^{-2}d^{-1}$ respectively. The mean ammonium uptake rate during December was more than that during the Feb.-March but urea uptake was almost half. An interesting observation is that while urea uptake was more than ammonium at most stations during the late winter monsoon, during the present study ammonium uptake was more than urea uptake rate at all the stations. Also, urea uptake decreased from south to north while no such trend could be seen in the ammonium uptake. During the late winter monsoon also no such trend was observed.

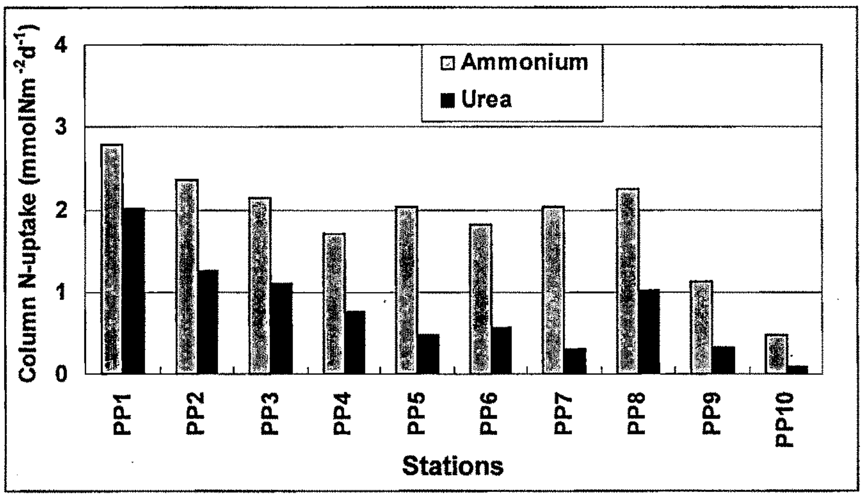


Fig 3.29 Ammonium and urea uptake rates at different stations in the Eastern Arabian Sea during early winter monsoon.

3.6.4 *f*-ratio during December-2004

The *f*-ratio was calculated as a ratio of nitrate uptake to total N-uptake (a sum of nitrate, ammonium and urea uptakes). As the ammonium and urea uptake rates are conservative estimates, here a ratio of new to total production represents the upper bound of the *f*-ratio. Figure 3.30 shows the station-wise *f*-ratio measured during this study. Estimated *f*-ratio during early winter monsoon varied from a minimum of 0.46 at PP7 to a maximum of 0.87 at PP10 (Table 3.2). This suggests that at most 46 to 87% of the total production can be exported to the deep under steady state. The mean *f*-ratio during the present study was estimated to be 0.67; significantly higher than the average *f*-ratio estimated in the non-bloom region (0.38) during the late winter monsoon and slightly less than the same in the *Noctiluca* bloom (0.82) region. The *f*-ratio estimated here is so far the highest observed in this region for the early winter monsoon period. Sanjeev Kumar et al., (2008) have reported *f*-ratio varying from

0.11 to 0.53 (mean = 0.24) for January-2003 and from 0.45 to 0.61 (mean = 0.46) for Feb-March 2003 from the eastern Arabian Sea.

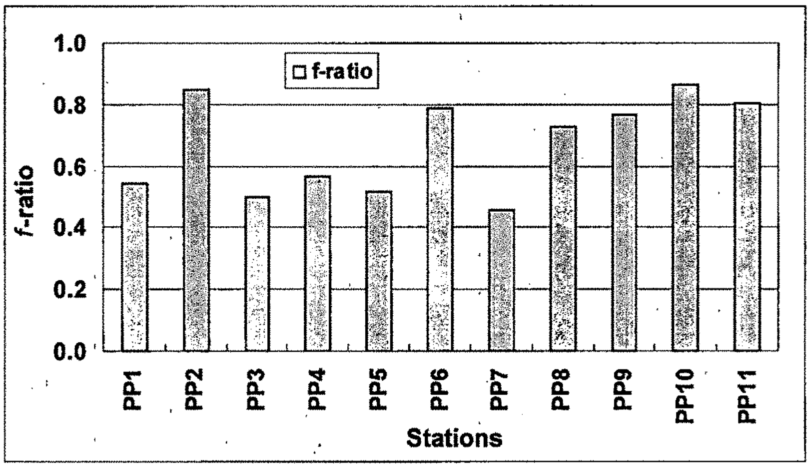


Fig 3.30 *f*-ratio at different stations in the eastern Arabian Sea during the early winter monsoon.

Stations	New Production	Regenerated Production		Total* Production	f-ratio
	ρNO_3*	ρNH_4*	ρNH_2*		
PP 1	5.70	2.79	2.02	10.51	0.54
PP 2	19.70	2.36	1.25	23.31	0.85
PP 3	3.25	2.14	1.11	6.51	0.50
PP 4	3.21	1.70	0.76	5.68	0.57
PP 5	2.68	2.04	0.49	5.21	0.51
PP 6	9.02	1.82	0.57	11.40	0.79
PP 7	1.95	2.03	0.29	4.27	0.46
PP 8	8.69	2.25	1.01	11.95	0.73
PP 9	4.70	1.13	0.32	6.15	0.76
PP 10	3.52	0.47	0.08	4.07	0.87
PP 11	4.91	1.18	ND	6.09	0.81

* all uptake rates are in $mmolNm^{-2}d^{-1}$

Table 3.2 ^{15}N based productivity and *f*-ratios during December 2004 (early winter monsoon) in the eastern Arabian Sea

3.7 Effect of winter cooling on the *f*-ratio

Madhupratap et al., (1996) suggested that northeast trade wind, which is dry and has low temperature, causes increase in evaporation over precipitation in the northern Arabian Sea. Increase in evaporation leads to cooling of the surface layer which makes the surface water denser. Increase in evaporation over precipitation also causes densification of the surface water which sinks resulting in convective mixing. This causes deepening of the mixed layer and consequent transport of nutrient rich deeper water to the surface. During the present study also decrease in sea surface temperature (SST) and an increase in the salinity is observed on a south-north transect. SST decreased from 28.8°C in the south to 25.2°C in the north during Feb-March 2004 and from 28.6 to 26.3 during Dec-2004 (Table 3.3). Salinity increased from 33.8 in the south to 36.1 in the north and from 35.1 to 36.2 during Feb-March and Dec-2004 respectively. This significant change in SST and salinity is due to the winter cooling effect. The phenomenon of winter cooling was more intense in the Feb-March than Dec and the same was more intense in the north as compared to the South; SST decreased from 28.2°C at PP6 to 25.2°C at PP10. It decreased by more than 3°C over 4.5° latitudinal difference. Salinity also showed a sudden increase from 34.8 at PP6 to 36.6 at PP10 during the late winter.

a).

Stations	SST (°C)	Salinity
PP 1	28.8	33.8
PP 2	28.9	33.9
PP 3	28.2	35.0
PP 4	28.1	34.6
PP 5	28.6	34.7
PP 6	28.2	34.8
PP 7	27.3	35.2
PP 8	26.8	35.2
PP 9	25.2	36.4
PP 10	25.2	36.6
PP 11	25.9	36.1

b).

Stations	SST (°C)	Salinity
PP' 1	28.6	35.1
PP' 2	28.5	35.1
PP' 3	27.9	35.6
PP' 4	27.8	35. 7
PP' 5	27.9	35.8
PP' 6	27.5	36.4
PP' 7	27.7	36.1
PP' 8	26.8	36.1
PP' 9	26.3	36.5
PP' 10	26.9	36.2
PP' 11	27.6	35.9

Table 3.3 Sea Surface Temperature (SST) and salinity a) during Feb.-March 2004 (late winter monsoon) b) during Dec-2004 (early winter monsoon) in the eastern Arabian Sea. PP1 to PP 11 represent stations during the late winter monsoon and PP'1 to PP'11 represent station during the early winter monsoon. PP is different from PP'.

The rate of decrease in the SST was more than 0.6°C per degree during Feb-March. Madhupratap et al., (1996) has reported SST decrease at a rate of 0.5°C per degree latitude during winter in this region. This higher rate of decrease in SST per degree latitude suggests more intense winter cooling effect in this region in 2004. Intense cooling effect resulted in transport of nutrients from the deeper layer to the surface and consequently this triggered a bloom, dominated by *Noctiluca scintillans,* in the north. The increase in nitrate uptake, total N-uptake and *f*-ratio over a south-north transect also suggests the influence of more intense winter cooling. The *f*-ratio in the north, *Noctiluca* dominated area, was significantly high; the mean *f*-ratio was 0.86. The *f*-ratio during the present study is significantly higher than those reported by Sanjeev Kumar et al., (2008). They reported an increase from a low of 0.11 in the south to a high of 0.27 in the north. McCarthy et al., (1999) has also reported *f*-ratio varying from 0.03 to 0.31 during winter monsoon for the central Arabian Sea. Bienfang et al., 1990 has suggested nitrate based phytoplankton community during the initial phase of the bloom. High *f*-ratio measured during this study, in accordance with Bienfang et al., 1990, suggests the developing phase of the bloom where nitrate uptake dominates the total nitrogen uptake. Nitrate required by phytoplankton is brought to the photic zone, from the deeper layer, through the convective mixing caused by cool dry air from the Himalaya.

3.8 Export flux in the Arabian Sea during the winter monsoon

Export production in the Arabian Sea also oscillates with the changing atmospheric forcing; export of carbon out of the euphotic zone is usually less than 10% of the primary production during the non-bloom season (Buesseler et al., 1998) but exception to this it increases to more than 75% of the total primary production during the bloom (Ramaswamy et al, 2005). The present study shows that during the late winter monsoon in the southern part of the eastern Arabian Sea the export production is 38% of the total production. The mean export production in this region was 168 $mgCm^{-2}d^{-1}$ which increased to 1256 $mgCm^{-2}d^{-1}$, more than 82% of the total primary production, during the *Noctiluca Scintillans* bloom in the northern part of the eastern Arabian Sea. Average POC (Particulate Organic Carbon) flux of 332

$mgCm^{-2}d^{-1}$, representing 36% of the primary production, has been reported by Ramaswamy et al., (2005) from the eastern Arabian Sea during northeast monsoon (February-2007) using ^{234}Th deficit technique. The amount of carbon export reported by Ramaswamy et al., (2005) is twice of the export estimated using ^{15}N during the present study but the fraction of total primary production getting exported is the same. This difference may be due to the difference in the primary production; Ramaswamy et al., (2005) have reported column daily primary production of ~900 $mgCm^{-2}d^{-1}$ whereas the mean column production during the present study was ~450 $mgCm^{-2}d^{-1}$. Though the present data is in good agreement with those reported by Ramaswamy et al., (2005), discrepancy in the ^{234}Th and sediment trap data has been reported by Sarin et al., 1996 where he found that ^{234}Th derived export flux is higher than those measured using the sediment trap; export flux measured using ^{234}Th was 290 and 251 $mgCm^{-2}d^{-1}$ during Feb-March 1994 and 1995 whereas the same measured using the sediment trap was 371 and 986 $mgCm^{-2}d^{-1}$ for the top 100 m.During the early winter monsoon (Dec-2004), the mean export production was ~490 $mgCm^{-2}d^{-1}$ which is 67% of the total production. ^{210}Pb scavenging technique also does not give accurate estimation of C_{org} flux (Borole 2002).

3.9 Conclusions

The results from the new productivity measurements during the late winter monsoon are:

1. The Arabian Sea was characterized by the presence of two different biogeochemical provinces during the late winter monsoon: low productive southern province and highly productive northern province with an overall increasing trend from the south to the north.
2. Total productivity in the southern region averaged around 5.5 $mmolNm^{-2}d^{-1}$ (440 $mgCm^{-2}d^{-1}$) whereas in the north it was 19 $mmolNm^{-2}d^{-1}$ (1520 $mgCm^{-2}d^{-1}$); increase in productivity from the south to north was more than three fold.

3. New productivity also increased on south-north transect, from 2.1 $mmolNm^{-2}d^{-1}$ (168 $mgCm^{-2}d^{-1}$) in the south to 15.7 $mmolNm^{-2}d^{-1}$ (1256 $mgCm^{-2}d^{-1}$) in the north. Increase in new productivity was more than 7-fold.
4. High nitrate uptake during the *Noctiluca* bloom at the northern stations measured during the present study, in accordance with Bienfang et al., (1990), suggests the developing phase of the bloom where nitrate contributed most to the total N-uptake.
5. Urea uptake rate was higher than the ammonium uptake rate at all the non-bloom stations but during the *Noctiluca* bloom in the northern stations, ammonium was preferred to urea by the plankton.
6. The column integrated total production (x) and new production (y), show a significant correlation (Fig.2): for non-bloom stations: y = (0.44 ± 0.23) x – (0.30 ± 1.38); (coefficient of determination, r^2 = 0.43) and for bloom stations, y = (1.08 ± 0.23) x – (4.68 ± 4.46); (r^2 = 0.91). The slopes of regression (i.e., 0.44 and 1.0 for non-bloom and bloom stations respectively) are the maximum possible values of the *f*-ratio, in the respective seasons.

The results from productivity measurements during early winter monsoon are:

1. During the early winter monsoon total productivity varied from 4.07 $mmolNm^{-2}d^{-1}$ (326 $mgCm^{-2}d^{-1}$) to 23.31 $mmolNm^{-2}d^{-1}$ (1865 $mgCm^{-2}d^{-1}$) with a mean of 8.65 $mmolNm^{-2}d^{-1}$ (692 $mgCm^{-2}d^{-1}$). Productivity during this season was almost half of that during the bloom but was more than the productivity in the south during the late winter monsoon.
2. New productivity showed a large variation; it varied from a low of 1.95 $mmolNm^{-2}d^{-1}$ (156 $mgCm^{-2}d^{-1}$) to a high of 19.70 $mmolNm^{-2}d^{-1}$ (1576 $mgCm^{-2}d^{-1}$).
3. Ammonium uptake was more than urea uptake at all the stations unlike those during the late winter monsoon. Also the mean ammonium uptake rate was more than that during the late winter but urea uptake was almost half.
4. The *f*-ratio varied from 0.46 to 0.87. This suggests that 46-87% of the total productivity can be exported to the deep under a steady state condition.

Relation between total and new productivity yielded a slope of 0.88 which suggests that at most 88% of the total productivity can be exported.

These results indicate almost three fold increase in the total productivity during the developing phase of the *Noctiluca* bloom. This increase was more than seven fold in new productivity. During early winter monsoon total and new productivity was less than those during the bloom but was more compared to non-bloom, southern, regions. Above results from the two seasons suggests that productivity in the Arabian Sea is heterogeneous in space and time but still this basin is capable of high export production during blooms and thus plays a significant role in global carbon cycle.