Chapter 4
The Bay of Bengal

4.1 Introduction

The Bay of Bengal (BOB) is a semi enclosed tropical basin located in the northeastern part of the Indian Ocean touching the eastern boundary of the Indian Subcontinent. BOB is also partially connected to the Pacific through the Australasian seaways, thus exchanging physical, chemical and biological properties. BOB covers an area of $2.2x10^6$ km^2 and constitutes 0.6% of the world ocean (LaFond 1966). Like the extensively studied Arabian Sea, BOB also experiences seasonal changes in climate and surface circulation due to the Asian monsoon system, resulting in heavy rainfall during the SW monsoon in the Indian Subcontinent (Ramage 1971). On an average, the annual rainfall over the BOB is in excess of 2m (Gill 1982) and precipitation has been reported in excess of evaporation (Venkateswaran 1956). The fresh water discharge into BOB due to all major Indian rivers, particularly the Ganges-Brahmaputra system, reaches a maximum during SW monsoon (Figure 4.1). BOB receives fairly large quantities of fresh water from the Indian rivers ($1.6x\ 10^{12}$ m^3 yr^{-1} compared to $0.3\ x10^{12}$ m^3 yr^{-1} to the Arabian Sea, Subramanian 1993) exerting a strong influence on the surface water circulation and stratification of the sea surface (Shetye et al. 1991; Shetye et al. 1996). This riverine input of freshwater in BOB also causes significant variations in the salinity, which varies from 35 psu in the open Bay to as low as 20 psu in the coastal regions during the SW monsoon (La Violette 1967; Prasanna Kumar et al. 2002). The river water also brings a lot of nutrients and thus, is a major source of nutrients such as SiO_2, nitrate and phosphate. The supply of SiO_2 by major Indian rivers like Ganga and Brahmaputra to the Bay has been estimated to be 1.5% ($133\ x10^9$ mol yr^{-1}) of the total annual riverine input of SiO_2 to the world ocean (Sarin et al. 1989). BOB receives 10% of the total dissolved phosphorus flux of the world ocean by the Ganga-Brahmaputra-Meghna river system (Datta 1999). However, the reported nitrate concentration is not as high as that of silica in the Bay (DeSousa et al. 1981). Also, the Ganga-Brahmaputra river system alone supplies a significant part of its average annual sediment load of $1.1x\ 10^9$ tonnes (Milliman and Syvitski 1992), and forms the largest deep sea fan of the world. In general, the circulation pattern in BOB is controlled by the equatorial Indian Ocean effects, atmospheric forcings and fresh water inputs (Schott and McCreary 2001). During premonsoon, BOB circulation is characterized by a well developed anticyclonic gyre and a poleward western boundary current known as the East India Coastal Current (EICC, Shetye et al. 1993). During the

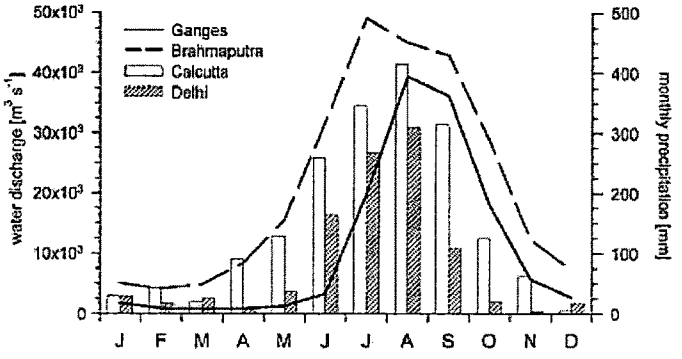


Figure 4.1 Mean monthly water discharge of Ganges (averaged over 1985-1992) and Brahmaputra (averaged over 1969-1975) and mean monthly precipitation at Delhi and Calcutta (averaged over 1994-1997). Source: Unger et al. (2003).

summer monsoon, there is a reversal of the circulation pattern with a southward current along the coast (Shetye et al. 1996). Coastal upwelling has also been reported in BOB, but much less in intensity than in the Arabian Sea (Shetye et al. 1991, 1993), and is known to be hampered due to surface stratification (Shetye at al. 1991). Overall, BOB represents a magnificent natural laboratory to study the effect of freshwater fluxes due to seasonally changing and interacting continental and oceanic processes on the marine ecosystem and material cycling.

The present study in the Bay of Bengal concentrates mainly on the ^{15}N based new production measurements, *which is the first of its kind in the BOB*. It also concentrates on the natural nitrogen isotopic variability in suspended matter. The discussion on BOB in the subsequent sections will be in the following sequence:

- Experiments related to the effect of concentration and incubation time on the uptake rate of nutrients.
- ^{15}N based new and total production during the postmonsoon.
- ^{15}N based new and total production during the premonsoon.
- Natural isotopic composition of suspended matter.
- Productivity estimates using remotely sensed data.

4.2 Effect of tracer concentration and incubation time on the uptake rate of nutrients

The mechanism by which the nutrient is supplied and the kinetics of the utilization of the dissolved inorganic nitrogen play a critical role in determining the productivity, size

structure, and species succession of phytoplankton in the world ocean (Harrison et al. 1996). Dugdale (1967) proposed a theoretical framework for nitrogen uptake by phytoplankton at steady state. Generally, uptakes of both nitrate and ammonium follow the Michaelis-Menten expression for enzyme kinetics. Michaelis-Menten expression is concentration dependent and a hyperbola describes the relationship between the concentration of nitrate (or ammonium) and its uptake; however, exceptions to this exist (MacIsaac and Dugdale 1969). Nitrate uptake estimates have been made in different regions of the world ocean (Dugdale et al. 1992; McCarthy et al. 1999; Watts and Owens 1999; Sambrotto 2001; L'Helguen et al. 2002; Rees et al. 2002). These are based on the incorporation of 'trace' addition of ^{15}N-labelled NO_3 into phytoplankton during incubation experiments. The details of the experimental procedure followed in these studies are somewhat variable; e.g. time of incubation could vary between 2 and 24 hours (the latter, when dark incubation is included). Though in general, the JGOFS protocol (JGOFS 1996) is followed, a number of questions arise regarding these procedures for uptake at low-level concentrations. These are: (a) what is the effect of duration of the incubation on the uptake rate of nutrients by the phytoplankton? Are there significant variations within the time of 2-4 hours as recommended by the JGOFS protocol? (b) What is the effect on the uptake rate of the substrate concentration added? (c) f-ratio, the ratio of new to total production (Eppley and Peterson 1979), has been calculated by different workers (Wafar et al. 1995; Watts and Owens 1999) for different oceans but what happens to the f-ratio in cases (a) and (b)? (d) The JGOFS protocol suggests simulated *in-situ* incubation for ^{15}N uptake experiments for durations of 2 to 4 hours. Longer incubation times could lead to problems such as increased regeneration of ammonium and urea, which will also be taken up along with nitrate. However, primary productivity (PP) experiments using ^{14}C are preferably done *in-situ* for 12 hours (e.g., Madhupratap et al. 2003). To facilitate comparison of PP measured and new production estimated from ^{15}N experiments, it is essential to know whether the results of *in situ* and simulated *in-situ* incubation experiments (using ^{15}N) from dawn to dusk are comparable.

The intention of the present study was to investigate the above questions based on ^{15}N uptake experiments performed for very low concentration of nutrients in the surface waters of the Bay of Bengal (BOB). Although the number of experiments during this study is limited, the idea was to have a first hand investigation of the NO_3 and NH_4 uptake behaviour and to explore the possible signature of inhibitory effects of

NH_4 on NO_3 uptake in the natural plankton assemblages of the Bay of Bengal. Our objective was also to investigate if N uptake in very small concentration can be expressed by traditional saturation kinetics. Sampling was done during Sep-Oct 2002 onboard ORV Sagar Kanya. The tracers used for experiments were 99 atom% ^{15}N enriched sodium nitrate, ammonium chloride and urea procured from SIGMA-ALDRICH. Details of the individual experiments are discussed below.

4.2.1 Material and Methods

Experiment 1

The aim of this experiment was to observe the variations in the uptake rates of different N-species due to varying durations of incubation. The JGOFS protocol was followed: surface water samples were collected (at 17° 56' 33.1" N, 87° 54' 38.6" E) in one litre Polycarbonate NALGENE bottles, pre-washed to avoid contamination. Samples were divided into three sets of four bottles each for nitrate, ammonium and urea tracers. In each bottle, a constant amount of 0.01 μM of the respective tracer was added. After the tracer addition, samples were kept for incubation at 10.00 Hrs, in a deck incubator with flowing surface seawater (from 5m depth). No neutral density filters were used as the samples were from the sea surface. Every hour one bottle from each set was taken out of the incubator and filtered on precombusted (4hr @ 400°C) Whatman GF/F filters under low vacuum. The samples were dried and kept for further mass spectrometric analysis.

Experiment 2

This experiment was intended to determine uptake rate variations of different nitrogenous species by the phytoplankton due to varying concentrations of the substrates. For this experiment too, surface water samples were collected (at 20° 0' 15.0" N, 87° 59' 36.4" E) in one litre bottles and divided into three sets of four each. But the concentration added in different bottles of each set was different. The concentrations added were 0.01, 0.02, 0.03 and 0.04 μM of the respective tracers in different bottles of the respective sets. These amount to 9%, 18%, 27% and 36% respectively of the nitrate concentration in the surface waters. For ammonium and urea, these are much in excess of the ambient concentrations (see section 2.4). Incubation was done on deck for four hours symmetrical to local noon i.e., from 10.00 to 14.00

Hrs. Running seawater maintained the temperature during incubation. Neutral density filters were not used, as in experiment 1. After incubation, the samples were filtered and preserved for analysis as described earlier.

Experiment 3

To estimate the differences in the uptake rates due to deck and in-situ incubations, samples were collected (at 14° 0' 17.2" N, 80° 59' 54.9" E) from surface, 20, 40 and 60 metres depth and transferred to six one litre bottles from each depth. Three bottles were used for in-situ and the other three for deck experiments for each of the three different tracers. In the case of urea and ammonium, the ambient concentration measurements could not be performed due to logistic problems; however they were estimated indirectly using zooplankton biomass. The euphotic zone in the Bay of Bengal is well oxygenated; the expected ambient ammonium and urea concentrations here are low, hence, a constant concentration of 0.01μM for ammonium and 0.03μM for urea was added for all the four depths. No literature exists for the relationship between oxygen and ammonium concentration for the Bay of Bengal. However, US JGOFS data for Arabian Sea suggests absence of ammonium in surface layers where water is well oxygenated as in the Bay of Bengal. An attempt to add less than 10 % of ambient concentrations was made in the case of nitrate, which lead to the addition of 0.03, 0.02, 0.03 and 0.6 μM for surface, 20, 40 and 60 m samples. A secchi disk was used to measure the light attenuation with depth. It was found that light was less than 1% of the surface value at ~60 m depth. Further, Chl *a* concentrations were near zero below this depth. The light conditions for the deck incubation were simulated using well calibrated neutral density filters and also the continuous flow of seawater from 5m depth was maintained in order to maintain the temperature. The neutral density filters used were such that equivalent depths were 4, 41, 55 and 77m. The incubation was done for 12 hours (from dawn to dusk) in both cases and subsequently, the samples were filtered and preserved for analysis.

In all three experiments above duplicate analysis was made wherever possible

4.2.2 Physical conditions and nutrients at the experimental stations

The salinities at the stations of experiment 1 and 2 were 29.2 and 28.1 psu and are

affected by fresh water influx. However at the site of experiment 3 surface salinity was 33.4 psu. The riverine inputs are a potential source of nutrients, such as phosphate and silica to the Bay. Also, BOB is a cyclone-prone region and these events churn up the sea, injecting nutrients into the surface layer especially during the post monsoon season. Sea surface temperature (SST) varied from 28.2 to 30.1°C. SST along with other meteorological and hydrodynamic parameters at the experimental stations is listed in Table 4.1. The ambient nitrate concentration required for the uptake calculation was measured by column reduction technique (Strickland and Parson, 1972). These values are also listed in Table 4.1. Ammonium and urea concentrations have been calculated as follows: The regeneration of ammonium and urea by zooplankton is well known (Mullin et al. 1975; Jawed 1973). Mesozooplankton biomass in this season in BOB ranged from 0.1 to 1.1 $ml.m^{-3}$.

Table 4.1 Physical parameters at the experimental stations.

Parameter	Experiment 1	Experiment 2	Experiment 3
Latitude (°N)	~18	~20	~14
Longitude (°E)	~88	~88	~81
Wind speed (m/s)	6	4	4
Pressure (mbar)	1008	1008	1010
Air Temperature (°C)	>31	29	27.5
SST (°C)	29	28.9	30
surface Salinity (PSU)	29.2	28.1	33.4
MLD (m)	3	6	24
Chlorophyll-a (mg/m^2)	15	13	15
surface Nitrate(μM)	0.07	0.11	0.16
PON (μM)	1.04	1.2	1.08

Based on the equations given by Wiebe et al. (1975) the zooplankton biomass was converted into dry weight and using the average ammonium and urea excretion rates of 0.59 and 0.32 mg at-N $(g\ dry\ wt)^{-1}\ d^{-1}$, the release rates were calculated for 12 hour residence time of zooplankton in mixed layer (Wafar et al. 1986). According to this calculation, the ammonium and urea concentrations near the station of experiment-3 were found to be 0.014 and 0.004μM respectively. Considering the uncertainties involved in the equations used for the calculation, the above values could well be near zero.

4.2.3 Results and Discussion

Experiment 1

UREA: Results from experiment 1 suggest that both specific uptake rate and the uptake rate are the highest for N-uptake from urea (Figure. 4.2) in the nutrient poor waters of the Bay. This observation is similar to that of Rees et al. (2002), who observed urea to be the most preferred substrate in the oligotrophic North Sea. However our value for the average uptake rate from urea is only one third of the value obtained by Rees et al. (2002) for a similar concentration of the substrate added. The specific uptake rate for urea increases for incubation times more than 2 hours, but declines for incubation times greater than 3 hours. This significant decline is also exhibited by the uptake rate for urea. Uptake rates range from a maximum of 2.48 μmol N $m^{-3}h^{-1}$ to a minimum of 1.56 μmol N $m^{-3}h^{-1}$. These values are comparable in magnitude with values obtained by others elsewhere (McCarthy et al. 1999; Cochlan and Bronk 2001).

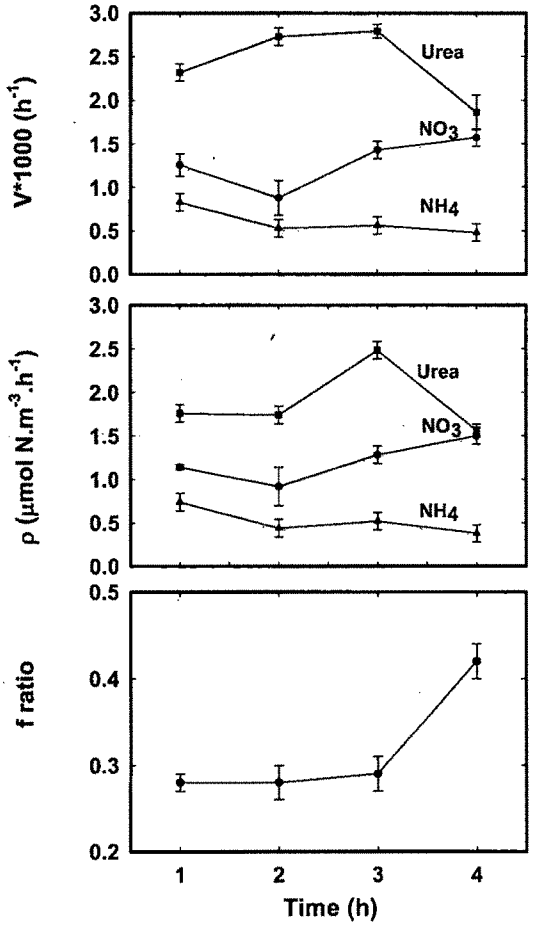


Figure 4.2 The result of experiment 1 showing variation in specific uptake rate (top panel), uptake rate (middle panel) and f-ratio (bottom panel) with increase in the duration of incubation from 1 to 4h.

AMMONIUM: In the case of ammonium, where constant addition of 0.01 μM was made, both specific uptake rate and uptake rate decreased slightly for incubation time more than 1 hour, and remained constant for higher incubation times (Figure 4.2). The uptake rate for ammonium showed a maximum of nearly 0.74 μmolN $m^{-3}h^{-1}$ and a minimum of 0.38μmolN $m^{-3}h^{-1}$. These values are comparable to those reported by Rees et al. (2002) for ammonium uptake rate in the oligotrophic North Sea, extrapolated to the same substrate concentration. It is known that in ammonium poor waters, ammonium is taken up as soon as it becomes available (Glibert et al. 1982b). For example phytoplankton growing in ammonium deprived cultures can assimilate ammonium at a much faster rate compared to their growth rate (McCarthy and Goldman 1979).

NITRATE: The specific uptake rates and uptake rates for nitrate lie between those of urea and ammonium. The uptake rate remains nearly the same for incubation times upto 2 hours, but for 3 and 4 hour incubations, it is slightly higher (Figure 4.2). The uptake rate varies within a narrow range of 0.92 to 1.5 μmol N $m^{-3}h^{-1}$, values comparable to those obtained by Rees et al. (2002) for North Sea waters.

These changes in the uptake rates of different N-species as a function of time are reflected in the f-ratio as well. The f-ratio [defined as the ratio of the uptake rate of NO_3^- and uptake rates of (NO_3 + NH_4 + Urea)] almost follows the pattern of NO_3 uptake rate. There is a significant increase in the f-ratio for incubation times greater than 3 hours, from 0.29 to 0.42. This is partly due to the significant decrease (2.48 to 1.56 μmol $m^{-3}h^{-1}$) of the urea uptake rate.

The change in uptake rates of individual N-species within four hours of incubation indicates the high demand for ammonium in the initial hours so that ammonium may become limited in the third and fourth hours due to a rapid initial uptake. In contrast, the uptake of nitrate is less prominent in first two hours but rises in the third and fourth hours. This may be because unlike reduced species such as urea and ammonium, nitrate has to be reduced in the cells before uptake, which therefore has a larger time constant. The effect of these variations on f-ratio is notable. It appears that f-ratio may be underestimated if incubation is done only for two hours, f-ratio at this stage in this water was found to be 0.28. However the result after four hours of incubation shows an f-ratio of 0.42. This may be because of the higher uptake rate for

nitrate in later hours of incubation. The f-ratio after four hours of incubation is one and a half times more than that observed after two hours. Harrison et al. (1996) have reported a linear tracer uptake over a 3 hour incubation period during time-course experiment performed in the Canary Basin. However, Goldman and Glibert (1983) suggested that the estimates of parameters could change with incubation time reflecting different biogeochemical processes: short term incubations (minutes) assess membrane transport processes, whereas long incubations (hours) assess macromolecular synthesis (Wheeler et al. 1982).

Experiment 2

As seen in the case of experiment 1, urea seems to be the most preferred substrate in this water, in general. When concentration added is 0.01μM for all the three tracers, the rate of uptake after four hours of incubation is the highest for nitrate followed by urea (Figure.4.3). But when the concentration of substrate added is increased, the specific uptake as well as uptake rate for urea becomes higher.

There is a significant increase in sp. uptake rate from 0.0024 to 0.0062 h^{-1} when the concentration of urea added increased from 0.01 to 0.04 μM. The uptake rate of urea also increased from 2.3 to 7.3 μmolN $m^{-3}h^{-1}$. There is a significant linear correlation between the urea-N uptake rate (y_u) and the substrate concentration (x_u): $y_u = 1.88x_u + 0.004$ ($r^2 = 0.88$).

Ammonium closely follows the pattern exhibited by the urea; however, the sp. uptake rate and uptake rate values are less than that for urea. The sp. uptake rate varies from 0.0014 to 0.0044 h^{-1} when ammonium concentration added increased from 0.01 to 0.04 μM. Uptake rate varies from 1.3 to 5.6 μmolN $m^{-3}h^{-1}$. There exists a significant linear correlation between the ammonium-N uptake rate (y_a) and the substrate concentration (x_a): $y_a = 2.07x_a - 0.002$ ($r^2 = 0.55$). Similar linear correlations for ammonium and urea uptakes have been reported by Rees et al. (2002). The slopes reported by them are lower possibly because their experiments pertain to a plankton bloom, whereas ours do not.

Nitrate shows a completely opposite trend of what has been observed in the cases of ammonium and urea. The specific uptake rate and uptake rate for nitrate decreases with increase in concentration. It shows maximum values when nitrate addition was 0.01μM. It shows a marginal change in uptake rate when concentration

changed from 0.02 to 0.03 μM, however it drops down when concentration added is increased to 0.04μM. There is a significant negative correlation between the nitrate-N uptake rate (y_n) and the substrate concentration (x_n): $y_n = -0.76x_n + 0.05$ ($r^2 = 0.86$).

The f-ratio almost reflects the change in nitrate uptake rate. It shows maximum value of 0.47 when nitrate uptake rate is maximum i.e., when concentration added to the sample is 0.01μM. It shows minimum value of nearly 0.10 for 0.04 μM addition, because at this concentration the nitrate uptake rate drops down.

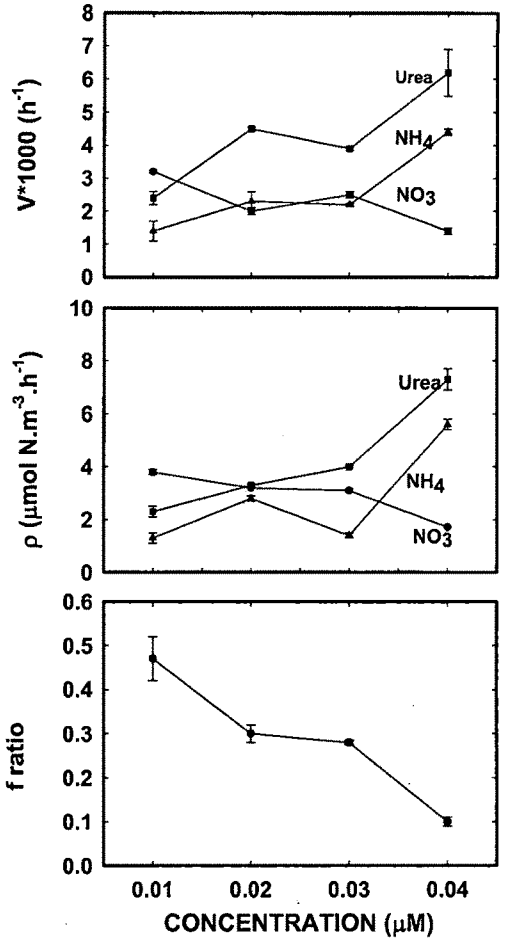


Figure 4.3 The result of experiment 2 showing variation in the specific uptake rate (top), uptake rate (middle) and f-ratio (bottom) with increase in the substrate concentration.

The results of the present study were examined to determine whether the traditional saturation kinetics model (Michaelis-Menten equation) was followed or not at present nanomolar level experiment. Ammonium and urea uptakes, in general, were found to have a positive correlation with the concentration but could not be represented by a

typical hyperbolic function as in Harrison et al. (1996). The main reason could be the range up to which experiment was done. During present study, the maximum addition of tracer was done up to 40nM whereas Harrison et al. (1996) have gone upto substrate levels of 2000nM. Since, the required hyperbolic curve could not be traced because of the above reasons, the half saturation constant could not be determined reliably during present study.

At lower concentration level (with an incubation time of four hours), the uptake rate for nitrate is more but as the concentration of substrate increases, the uptake rates for ammonium and urea are higher. The reason for the decrease in the nitrate uptake for a higher concentration may be the build up of ammonium due to its regeneration in the bottle (Glibert et al. 1982b). This ammonium might be preferred for uptake leading to an increase in the concentration of glutamine on reduction, known to suppress the synthesis of the enzyme needed for reduction of nitrate and hence suppression of its uptake (Dortch 1990; Flynn et al. 1997; Flynn 1998). Suppression of nitrate uptake in the presence of ammonium has been observed earlier in the Arabian Sea (McCarthy et al. 1999). Wheeler and Kokkinakis (1990) have shown that an extremely low level of NH_4 is capable of significant inhibition of NO_3 uptake (50% reduction of nitrate uptake at NH_4 concentrations of 50-200nM). However, contradictory reports do exist: Wheeler and Kokkinakis (1990) have observed almost complete NO_3 inhibition at NH_4 concentrations of 100-300nM, whereas Harrison et al. (1996) have rarely observed a complete inhibition even at NH_4 concentrations of 2000nM. Harrison et al. (1996) in the experiment where $^{14}NH_4$ was added to bottles containing $^{15}NO_3$ found that the simultaneous uptake of unlabelled nitrogen ($^{14}NH_4$) during incubation dilutes the isotope ratio in the PON and results in an underestimate of nitrate uptake rate (Collos 1987) and consequently the overestimation of NO_3 uptake inhibition. It is not very clear why the effect of the nitrate suppression should be more at a relatively higher NO_3 concentration than at a lower concentration during present study. However, Conway (1977) suggested inhibition to be the greatest under nutrient replete conditions and the least when phytoplankton are N-starved. The present nutrient level, however, cannot be classified as nutrient replete; but there may be a relative increase in the suppression effect with increased concentration. Price et al. (1994) have found that in the NO_3 rich equatorial pacific ambient ammonium level (150nM) alone may have reduced nitrate uptake by half. Harrison et al. (1996) have suggested that if NH_4 level were ~10nM (likely in the Bay of Bengal) inhibition of nitrate uptake by ambient ammonium levels

would have averaged 15-20% at oceanic stations. The f-ratio during the present study decreases drastically with increase in the substrate concentration. To circumvent this effect it is important to add tracers in a level less than 10% of the ambient concentration to get a reasonably correct estimate of the f ratio.

If the above results are extrapolated to in-situ conditions, as long as the surface nutrients are close to zero as observed, a small amount of extraneous input can increase the new production. If the extraneous input is used up quickly enough, then the conditions are restored for further uptake as and when nutrient pulses are introduced. On the other and, if the extraneous input is relatively large, the initial surge in new production may not be sustained at a high level for prolonged periods. This is in contrast to the observation of Rees et al. (2002), who observed a linear increase in the nitrate uptake rate with substrate concentration. However, it is worth noting that their experiments were conducted on a coccolith bloom, whereas the waters of the Bengal seldom known to support a bloom.

It is interesting to compare the uptake and specific uptake rates of the 4 hour incubations at 0.01 μM nitrate addition from the two experiments above (see Table 4.2). Values obtained in the second station (experiment 2) are significantly larger than those from the first (experiment 1). However it is to be noted that there is no significant difference in the f-ratios. Table 4.1 shows that the environmental conditions are more or less same on both the days. The reason for the difference in uptake rates, therefore, may be attributed to the difference in available light levels on these two days. On the day of the first experiment, the sky was intermittently overcast (during the incubation period), whereas on the day of the second experiment, it was bright and sunny. Day to day variations in uptake rates can be quite significant depending on cloudiness, in the Bay of Bengal. Gomes et al. (2000) have observed column productivity significantly affected by cloudiness in the Bay.

Table 4.2 Comparison of specific uptake and uptake rates at two different stations for 4 h incubation at 0.01μM concentration. Uncertainty based on duplicate measurements given in parentheses.

	Experiment 1		Experiment 2	
Tracer	Sp. Uptake rate *1000 (h^{-1})	Uptake rate μmol N m^{-3} h^{-1}	Sp. Uptake rate *1000 (h^{-1})	Uptake rate μmol N m^{-3} h^{-1}
Nitrate	1.57(0.1)	1.5(0.1)	3.2(0.05)	3.8(0.1)
Ammonia	0.48(0.1)	0.38(0.1)	1.4(0.3)	1.3(0.2)
Urea	1.86(0.2)	1.56(.07)	2.4(0.3)	2.3(0.2)

Experiment 3

The nitrogen uptake rates from ammonium (triangle), urea (square) and nitrate (circle) are plotted as a function of depth in Figure 4.4 both for deck (filled symbols) and in-situ (open symbols) incubations. Results of the deck experiments are plotted such that the depths correspond to the light levels provided, rather than the actual depths from which the water samples were taken. The analytical uncertainties in the calculated uptake rates are shown as error bars corresponding to one standard deviation. It is seen that the surface values (2 to 4 m depth) are the same for in situ and deck incubations, within errors. Ammonium uptake rates are the lowest and do not vary much with depth in both in-situ and deck experiments. Urea uptake rates are also in agreement within two standard deviation for the in-situ and interpolated deck values for corresponding depths. Only at 20 and 40 m depths the nitrate uptake rates are significantly higher in the in-situ case relative to the interpolated deck values. In region such as the Bay of Bengal one would expect a subsurface maximum in the nitrate uptake rate, which is seen in the in-situ experiment, but is absent in deck experiment. Two possible reasons for this discrepancy could be (a) The deck incubation were probably carried out at a higher temperature (of water at 5m depth) than the actual temperature at 20, 40 and 60m depths (the mixed layer was only 5m, Table 4.1); (b) Sample heterogeneity and (c) The light cut off was more than that required for the depths of incubation of the in-situ experiment.

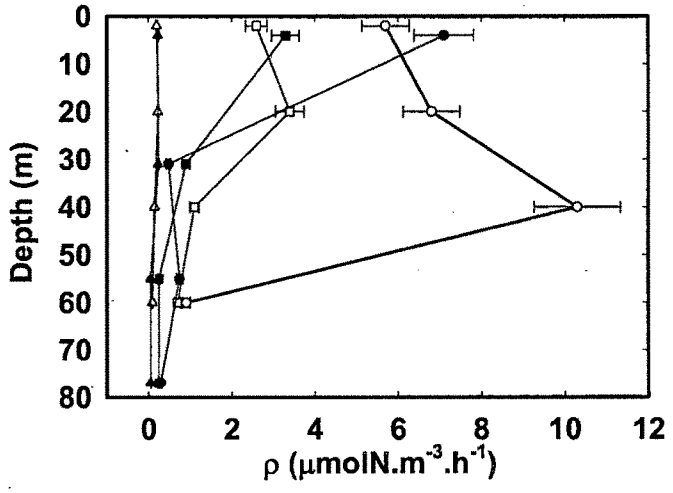


Figure 4.4 Comparison of uptake results obtained from in-situ and simulated in-situ experiments. In situ nitrate, ammonium and urea uptake are indicated by open circle, triangle and square respectively. Simulated in-situ nitrate, ammonium and urea uptake are indicated by filled symbols.

The column-integrated values for the productivity (taking C/N Redfield ratio as 6.6) obtained by us were 519 mg C m^{-2} d^{-1} and 251 mg C m^{-2} d^{-1} respectively for in-situ and deck incubations. In the same location primary production was measured using ^{14}C method for the same depths during the previous day (same mean solar radiation ~100mW/cm^2 on both days). This value ~218 mgC m^{-2} d^{-1}, is closer to our deck incubation value. Use of 6.6 for C/N ratio might be questionable as variations have been reported (Rees et al. 2002) for C: N consumption rates. However, here we use statistical average of 6.6 observed for organic matter in this region.

Another experiment to check the effect of incubation during different intervals in a day was performed during premonsoon cruise (SK-191) at two different locations- PP2 and PP7. At both the stations the surface water samples were collected early in the morning (before sun rise) in 9 one litre NALGENE bottles. The three bottles were incubated from 600 to 1000 Hrs. after adding 0.01μM of each tracer (nitrate, ammonium and urea). The rest six were kept in dark. At 1000 Hrs., another three were incubated till 1400 Hrs. followed by next three from 1400 to 1800 Hrs. The samples were filtered and dried as soon as incubation was over. The results obtained from this study show a similar trend at both the stations. The specific uptake rate during morning (600 to 1000 Hrs) is higher for all the tracers (except urea at PP7) and remain same for noon (1000 to 1400 Hrs) and evening (1400 to 1800 Hrs) intervals (Figure 4.5). The most striking is the very high specific uptake rate for nitrate during morning interval at both the stations, which decreases drastically at noon and evening intervals. One possible reason for reduction in specific uptake rate during noon and evening intervals may be the storage of phytoplankton for a longer time in the bottles. However, these are preliminary results, which need to be repeated in future cruises.

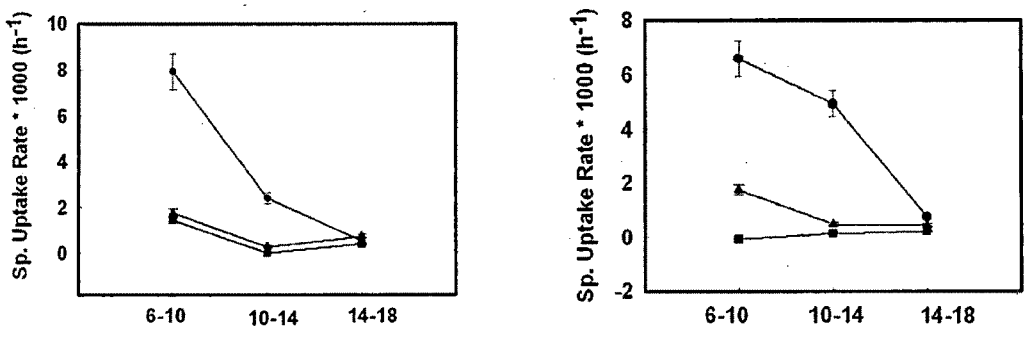


Figure 4.5 The specific uptake rate at PP2 (left) and PP7 (right) for the incubation at different intervals during a day. The x-axis denotes the different intervals.

4.3 Earlier measurements of ^{14}C based Productivity and Chl *a* in the Bay of Bengal

As mentioned earlier, the Bay of Bengal has not received much scientific attention compared to the Arabian Sea. The ongoing Bay of Bengal process studies (BOBPS) is an attempt to evaluate the biogeochemical characteristics of the Bay. A few measurements exist regarding the total primary productivity, which show a random distribution over space and time. Qasim (1977) observed that surface production in the Bay is higher than Arabian Sea due to low light intensities whereas column production is higher in the Arabian Sea. Nair et al. (1973) have reported primary productivity values varying from 3.0-8.7g Cm^{-2} d^{-1} for inshore waters of the east coast of India during the SW monsoon. Radhakrishna et al. (1978) have reported the variability in the primary productivity (PP) values for the off shore regions from 129.99 to 329.45 mgC m^{-2} d^{-1} (av. 219 mgC m^{-2} d^{-1}) and 49.66 to 606.37 mgC m^{-2} d^{-1} (av. 315.43 mgC m^{-2} d^{-1}) for the slope region along the western margin of the Bay during August-September 1976. Bhattathiri et al (1980) have reported 180-2200 mgC m^{-2} d^{-1} (av. 740 mgC m^{-2} d^{-1}) for offshore and 120- 3410 mgC m^{-2} d^{-1} (av. 1280 mgC m^{-2} d^{-1}) for the slope region along the Indian side for August-September 1978 and concluded that primary production of the Bay is not less than that reported for the Arabian Sea. Most recently Gomes et al. (2000) have studied the productivity and Chl *a* concentration for the three seasons in the BOB for both off shore and inshore regions. Average depth integrated Chl *a* values for inshore stations have been reported to be 30.4, 165 and 26.2 mg m^{-2} while for offshore stations it was found to be 18.8, 97.0, 27.6 mg m^{-2} for presouthwest, southwest and northeast monsoon respectively. Whereas the average depth integrated primary productivity for the above mentioned three seasons were 1.05, 0.55 and 0.44 $gCm^{-2}d^{-1}$ for inshore waters, for the offshore waters these values were found to be less, averaging around 0.16, 0.30 and 0.30 $gCm^{-2}d^{-1}$. Apart from the above mentioned average values Gomes et al. (2000) have also reported Chl *a* and production rates as high as 53 mg m^{-2} and 4.5 gC $m^{-2}d^{-1}$ for presouthwest monsoon (March-April), which they attribute to nutrient laden cooler waters brought to the surface by poleward flowing east India coastal current. The high Chl *a* but low productivity value reported for summer monsoon has been attributed to light limitation due to intense cloud cover over BOB during this season. Madhupratap et al. (2003) have reported poor surface Chl *a* in open ocean (0.06-0.28 mg m^{-3}) and in the coastal region (0.06-0.16 mg m^{-3}) of

BOB during the summer monsoon 2001. Column integrated PP has been reported between 90-220 mgC m^{-2} d^{-1} in the off shore stations, which lie along 88°E. Relatively higher values have been reported along shelf stations that fall in the range of 328-520 mgC m^{-2} d^{-1}.

4.4 Chlorophyll *a*, nitrate and physical parameters during the postmonsoon (September-October) 2002

4.4.1 Chlorophyll *a*

NIO colleagues (Dr. N. Ramaiah and others) measured the Chl *a* concentration during the cruise up to 120m, regardless of the euphotic depth, which averaged around 60m. The Chl *a* integrated over 120m water column varied from a maximum of 23.3 mg m^{-2} at PP1 to a minimum of 8.65mg m^{-2} at PP9 (Figure 4.6-left panel). No significant difference has been observed when Chl *a* was integrated up to euphotic depth (20.9mg m^{-2} at PP1 and remains the same at PP9), implying the presence of significant portion of Chl *a* within the euphotic zone. Overall the average Chl *a* is 15.2(± 4.3) mg m^{-2} for the region during the study period that reduces to 13(±3.5) mg m^{-2} when integrated only over the euphotic depth. There is no significant difference between offshore (PP1-PP4) and shelf (PP5-PP9) stations and average around 16.7(±4.4) and 14(±4.4) mgm^{-2} and reduce to 14.1(±4.6) and 12.1(±2.7) mg m^{-2} respectively after column integration only upto the euphotic depth. The depth profiles of Chl *a* (Figure 4.6-right panel) at different stations show typical subsurface Chl *a* maxima varying between 10 and 60m. Chl *a* profile at PP1 suggests two subsurface Chl *a* maxima at 10 and 40m with a value 0.42 mg m^{-3} that decreases to less than 0.08mg m^{-3} below 60m. PP2 shows Chl *a* maxima at 60m with value half that of maximum at PP1 (0.21mg m^{-3}), it decreases to less than 0.1mg m^{-3} after 80m. PP3 shows a broad peak between 10 and 20m whereas PP4 has peak at 40m. The maximum Chl *a* at these two stations are the same (0.28mg m^{-3}), that drops to less than 0.1mg m^{-3} after 60m. PP5, PP7 and PP8 show Chl *a* maxima at 40m with increasing concentrations of 0.24, 0.35 and 0.43 mg m^{-3} respectively. PP5 and PP7 show a drastic decrease in the concentration from 40 to 60m (<0.04mg m^{-3}) whereas PP8 shows a concentration less than 0.1 mg m^{-3} only after 80m. PP6 is the only station that has a maximum Chl *a* at surface (0.77mg m^{-3}) with maximum concentration observed for any depth during study period. It could be visually observed that at this station the surface water was green, unlike other stations.

However, the concentration decreases sharply at 10m (0.25 mg m^{-3}) and reaches less than 0.1 mg m^{-3} at 60m.

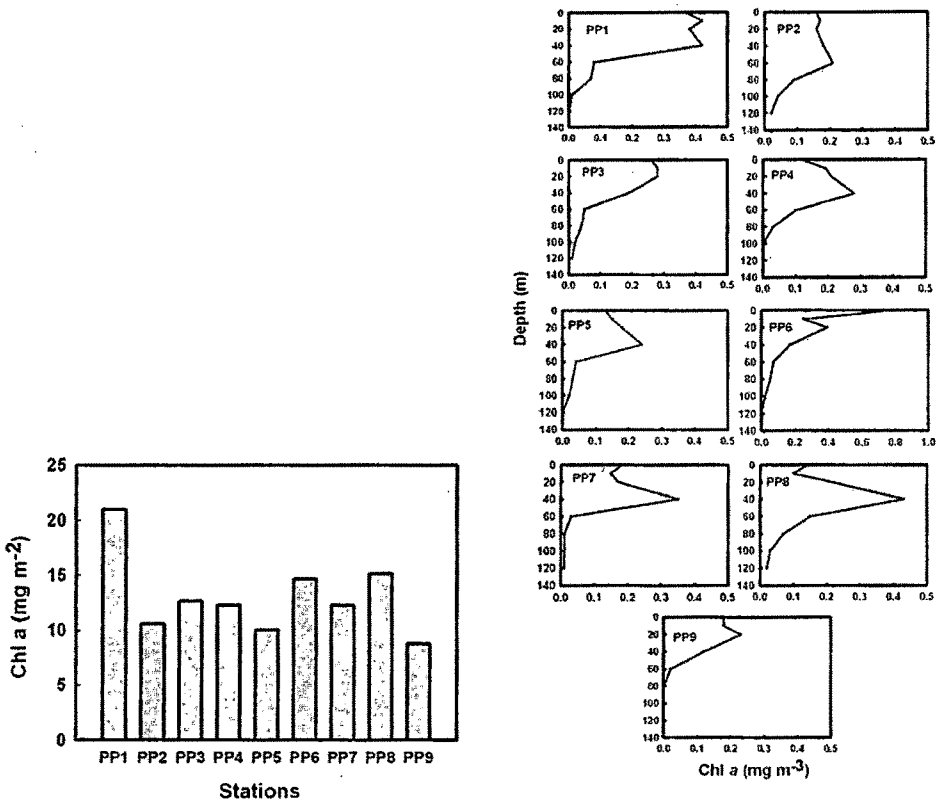


Figure 4.6 Euphotic zone integrated (left) and vertical profiles of Chl *a* at different productivity stations (right) in the Bay of Bengal during postmonsoon (SK-182).

4.4.2.Nitrate

Euphotic zone integrated nitrate concentration (Figure 4.7-left panel) during the study period for the region averaged around 340mmol m^{-2} with a wide variation from minimum of ~46 mmol m^{-2} at PP6 to maximum of ~625 mmol m^{-2} at PP9, both shelf stations. The average euphotic zone nitrate concentrations at offshore and shelf stations are 261 and 402mmol m^{-2} respectively. However, the variations within the offshore (60mmol m^{-2} at PP3 to 572 mmol m^{-2} at PP4) and shelf stations (46mmol m^{-2} at PP6 to 625mmol m^{-2} at PP9) are quite large. Depth profiles of nitrate (Figure 4.7-right panel) at different stations suggest the top 20m to be almost devoid of nitrate. However, the nitrate concentration increases drastically between 20 and 60m depending upon the location. PP1 shows <0.2μM for top 20m but increases to 9.61μM at 40m and 13.86μM at 60m. The nitrate concentrations at PP2 and PP3 are below detection limit for the top 10m and 40m respectively, and increase gradually at PP2 (0.2 and 1.27μM

at 20 and 40m respectively) and drastically at PP3 (5.58μM at 60m). Again at PP4 nitrate is below detection limit in the top 10m but increases to 5.89 and 21.16μM at 20 and 60m. The nitrate at shelf locations (PP5 to PP9) is always more than detection limit even in the surface waters. Interestingly, at all shelf locations (except at PP6) the nitrate in the top 20m is always less than 1.13μM but increases sharply from 20 to 40m (14.82, 16.73, 5.36 and 21.09μM at PP5, PP7, PP8 and PP9 respectively). These increased concentrations at depths lead to a higher column nitrate in the euphotic zone. At PP6 the increase in nitrate concentration is gradual to reach to 7.35μM at 60m.

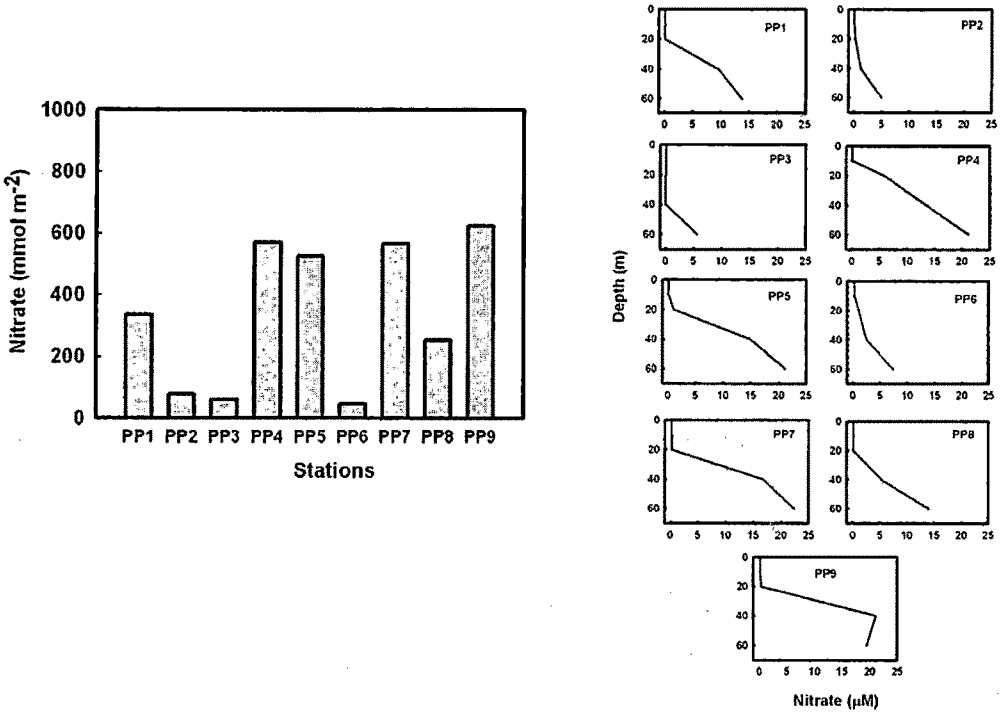


Figure 4.7 Euphotic zone integrated (left) and vertical profiles of nitrate at different productivity stations (right) in the Bay of Bengal during postmonsoon (SK-182).

4.4.3 Hydrographic and meteorological conditions

As mentioned earlier, freshwater input causes a significant spatial variation in the salinity of the surface Bay during and after the monsoon (Figure 4.8-top left). The salinity during the study period varies from 20.92 psu at PP7 (Stn.18, a shelf station) to 34.59 psu at PP1 (Stn. 3, an offshore station). The salinity for the offshore locations decreases from south to north from a maximum of 34.59 psu at PP1 (Stn.3) to a minimum of 28.40 psu at the northern Stn. 13. Shelf stations show wide variation from a maximum of 33.92 psu at the southern part (Stn. 23) to a minimum of 20.92 at PP7

(Stn. 18). The salinity structure of the Bay during the study period clearly indicates the terrestrial influence (i.e., fresh water) on shelf stations and the northernmost offshore stations. Sea surface temperature (Figure 4.8-top right) along the offshore varies marginally from 28.2 (Stn. 2 and Stn. 3) to 29°C (Stn. 12) from the south to the north, whereas for shelf locations it does not show any trend and varies from 28.9 (Stn. 14) to 30.1°C (Stn. 19). The mixed layer depths (MLD) for the study period show a wide variation from a maximum of 64m at Stn.5 to a minimum of 2m at Stn. 17 (Figure 4.8-bottom left). Freshwater stratifies the surface layer leading to low MLD at stations

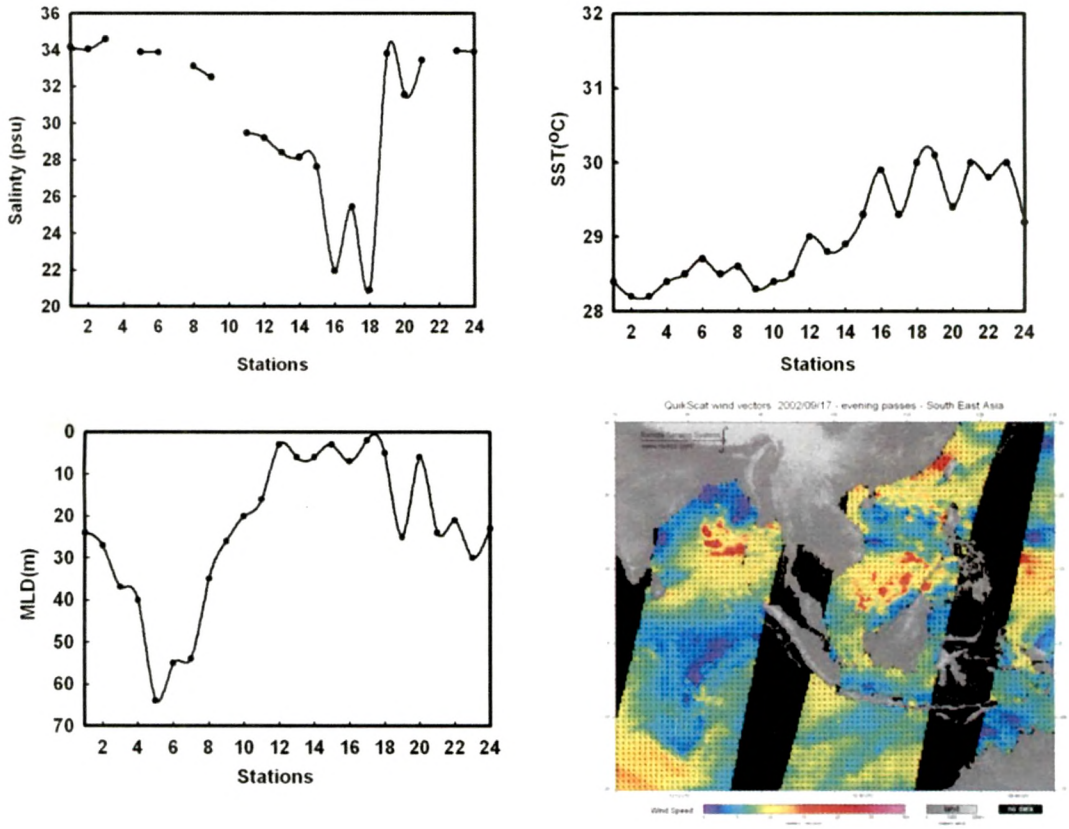


Figure 4.8 The spatial distribution of salinity (top left), SST (top right), MLD (bottom left) and typical wind speed (17th Sep 2002, bottom right) during (SK-182).

with low salinity. The MLD for offshore stations increases from Stn.1 (24m) to Stn 5 (64m) but starts decreasing further northward and shoals up to 3 and 6m at Stn. 12. and Stn.13 respectively. MLD at the northern shelf stations (Stn. 14 to Stn. 20) is less than 10m except at Stn. 19 (25m) and increases southward to reach between 20 and 30m. Bay of Bengal is known for frequent cyclonic activity during the postmonsoon season (Sep-Dec.) that is understood to be one of the predominant factors that bring nutrients from deeper to the surface Bay by churning the ocean. Data from Indian

Meteorological department shows that 25 and 15% of the total cyclones in the BOB occur during September-October and April-May respectively (Das 1995). However, no specific cyclone was encountered during the study period but wind with relatively higher speed was prevalent in the area during the beginning of the study (Figure 4.8-bottom right).

4.5 ^{15}N based productivity study during postmonsoon 2002

4.5.1 Total Production

Total productivity during the present study has been estimated as the sum of nitrate uptake rate and conservative estimates of ammonium and urea uptake rates. Overall, the total productivity varies almost an order of magnitude with a maximum value of 10.99mmolN $m^{-2}d^{-1}$ (~ 873 mgC $m^{-2}d^{-1}$) at PP2, an offshore station to 1.17mmolN $m^{-2}d^{-1}$ (~93 mgC $m^{-2}d^{-1}$) at the southernmost shelf station, PP9 (Figure 4.9-left panel). The average total production for the study region is 4 (±3.14)mmolN$m^{-2}d^{-1}$ (~318 mgC $m^{-2}d^{-1}$). The total production based on ^{14}C technique observed during the same cruise had a similar average value of around 300mgC m^{-2} d^{-1}. However, these values are greater than the average values reported for the summer monsoon 2001 (Madhupratap

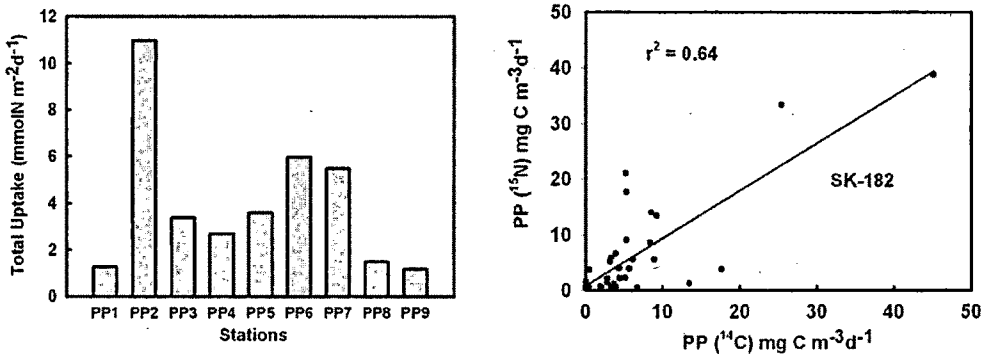


Figure 4.9 The euphotic zone integrated total column productivity (left) and relationship with ^{14}C based productivity (right), during postmonsoon 2002 (SK-182).

et al. 2003). The offshore locations average around 4.58 (±4.36) mmolN m^{-2} d^{-1} (~364 mgC $m^{-2}d^{-1}$) whereas shelf locations average around 3.54 (±2.21) mmolN m^{-2} d^{-1} (~280 mgC $m^{-2}d^{-1}$). The biomass-normalised productivity (P/B) has been obtained by dividing the productivity (mgC $m^{-3}h^{-1}$) with the measured Chl (mg m^{-3}) at discrete depths at all the stations and it averages around 2.4 (±3.3) h^{-1}. A similar exercise performed with simultaneous ^{14}C based productivity measurements by NIO scientists yields an average

value quite similar (2.2±2.3 h^{-1}) to the ^{15}N based measurements. The maximum value in both the cases has been found at the surface of PP7, where it is 15.2 and 11.8h^{-1} using the ^{15}N and ^{14}C methods respectively. The depth wise ^{14}C (denoted by x) and ^{15}N (denoted by y) based total productivity values are well correlated: y = 0.85x + 0.82, with linear correlation coefficient of 0.80, significant at 0.005 level (n = 34) (Figure 4.9-right panel). The slope of 0.85 implies that on an average the ^{15}N based total productivity is less than that based on ^{14}C by ~15%. However, this could be due to the analytical uncertainties associated with both the methods and therefore the two methods during study period appear to yield consistent results.

4.5.2 New Production

New production (the nitrate uptake rate) in the region during the study period averages around 2.61(±2.77)mmolN m^{-2} d^{-1} (~207 mgC m^{-2} d^{-1}). It varies from a maximum of 8.85mmolN m^{-2} d^{-1} (~703 mgC $m^{-2}d^{-1}$) at the offshore station, PP2, to a minimum of 0.17mmolN m^{-2} d^{-1} (~13 mgCm^{-2} d^{-1}) at a southern shelf station, PP8 (Figure 4.10-left panel). The average new production for offshore stations is 3.06(±3.89) mmolN m^{-2} d^{-1} (~243 mgC $m^{-2}d^{-1}$) mainly because of very high new production observed at PP2. The average new production reduces to 1.13mmolN m^{-2} d^{-1} when PP2 is omitted. The variation in the new production at shelf locations is from 0.17 at PP8 to 4.48mmolN m^{-2} d^{-1} at PP6. The new production averages around 2.26(±1.91) mmolN m^{-2} d^{-1} (~180 mgC $m^{-2}d^{-1}$), similar to the offshore stations. Depth profiles of nitrate uptake at various locations during the study period suggest the general absence of subsurface maxima except at PP2 and PP4 where an uptake maximum has been observed at 20m (Figure 4.10-right panel). Based on the maximum uptake observed at any depth, stations may be divided into two categories: first where the maximum uptake rate is less than or equal to 0.1mmolN $m^{-3}d^{-1}$ and second, greater than that value. Except PP2, PP6 and PP7, all the rest fall in the first category. At PP1 the maximum uptake is at surface (0.01mmolN m^{-3} d^{-1}) and decreases with depth to reach almost one tenth of the surface value at 60m. PP2 shows a maximum uptake of 0.22mmolN m^{-3} d^{-1} at 20m that remains almost the same at 40m, to decrease sharply at 60m (0.008 mmolN m^{-3} d^{-1}). PP3 and PP5 have maximum uptake at the surface (~0.10 mmolN m^{-3} d^{-1}) that decreases with depth to reach almost 0.001 mmolN m^{-3} d^{-1} at 40m. PP4 shows a maximum at 20m (0.05 mmolN m^{-3} d^{-1}) and decreases at 40m and peaks up again at 60m. PP6 and PP7 show maximum uptake values of 0.40 and 0.33 mmolN m^{-3} d^{-1} respectively at the

surface, which decreases sharply at 15 and 20m respectively. The uptake rate at the surface at PP6 is the highest for any depth during the study period. The maximum uptake at PP8 (0.008 mmolN m^{-3} d^{-1}), which is at surface, is the lowest of all maximum values during the study period. Again, PP9 shows a maximum uptake at the surface, and decreases sharply with depth.

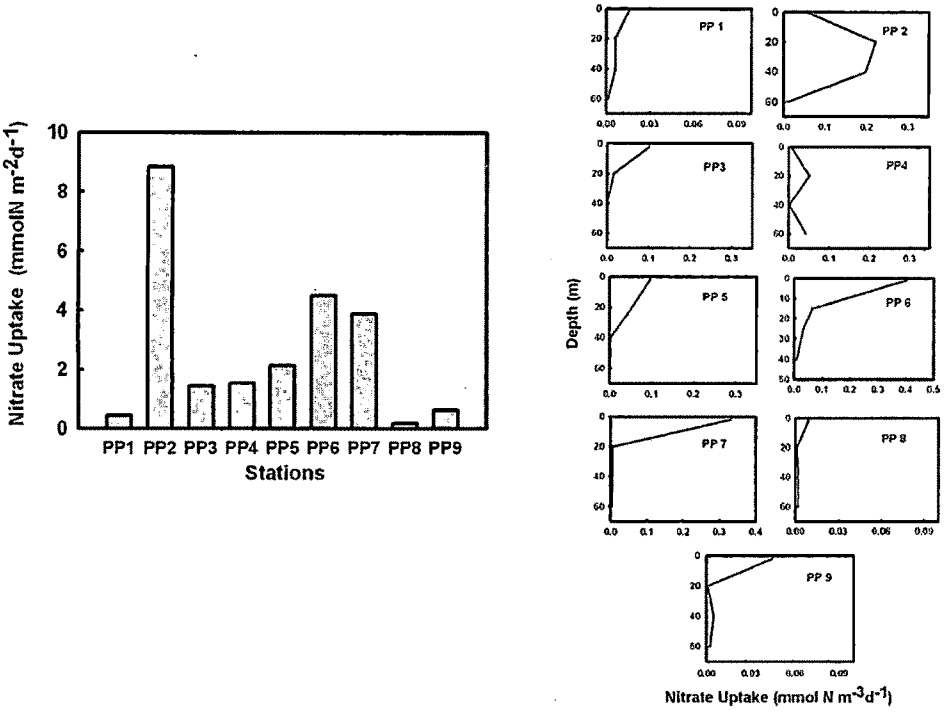


Figure 4.10 The euphotic zone column integrated nitrate uptake (left panel) and depth profile of nitrate uptake at different stations (right panel) in the Bay of Bengal (SK-182).

The maximum uptake observed at the surface during present study agrees with the observations by Qasim (1977) and Radhakrishna (1978), that the surface productivity (1m depth) in the Bay of Bengal (4.9 tonnes carbon km^{-2} yr^{-1}) is greater than the Arabian Sea (3.9 tonnes carbon km^{-2} yr^{-1}), but reverse is the case for column productivity. The reason offered for this difference is the greater cloud cover over Bay of Bengal (Annual range ~ 4.1-5.1 oktas) compared to the Arabian Sea (Annual range ~ 1.5-3.7 oktas). They argue that the cloud cover present over the Bay attenuates the excess light intensity that would otherwise reach the sea surface and result in photoinhibition of plankton in surface water as in the Arabian Sea. Another reason cited for the higher surface production in the Bay of Bengal is significant nitrogen and phosphorus brought by runoff and rainfall into the Bay of Bengal; the runoff can dilute

the upper 25m of the Bay by 5% (Qasim 1977) without influencing the waters below this depth.

4.5.3 Regenerated Production

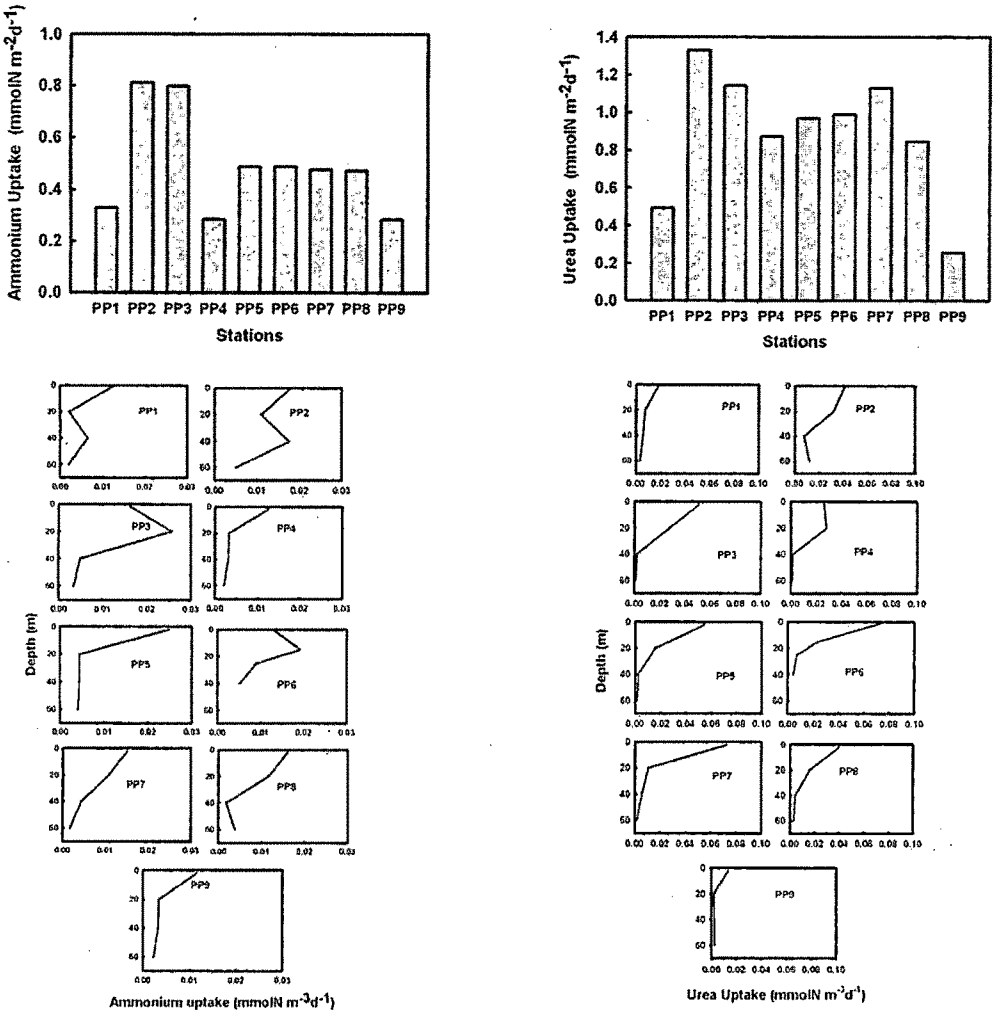


Figure 4.11 Euphotic zone integrated column uptake of ammonium (top left) and urea (top right). Depth profiles of ammonium uptake (bottom left) and urea uptake (bottom right) are also shown for Bay of Bengal (SK-182).

As mentioned earlier the regenerated production during present study has been estimated as sum of conservative estimates of ammonium and urea uptake. This provides the lower limit of regenerated production, and can help in estimating the relative potential of ammonium and urea uptakes at different stations. Ammonium uptake during the study period is less than 1 mmolN $m^{-2}d^{-1}$ and varies from 0.28 mmol N m^{-2} d^{-1} (~23 mgC $m^{-2}d^{-1}$) at southern shelf station PP9 to a maximum of 0.81mmol N $m^{-2}d^{-1}$ (~ 64 mgC$m^{-2}d^{-1}$) at the offshore station PP2 (Figure 4.11-top left). The overall

average for the study region is 0.49(±0.20) mmolNm^{-2}d^{-1} (~40 mgCm^{-2}d^{-1}) with an offshore average of 0.56(±0.29) mmolN m^{-2} d^{-1} (~ 44mgCm^{-2}d^{-1}) and shelf average of 0.44(±0.09) mmolNm^{-2}d^{-1} (~35mgCm^{-2}d^{-1}). Depth profiles of ammonium uptake (Figure 4.11-bottom left) at a majority of stations (except PP3 and PP6) show a maximum uptake at the surface with the majority of values less than 0.018mmolN m^{-3}d^{-1} except at PP5, where it is the maximum (0.024 mmolN m^{-3}d^{-1}). PP3 and PP6 are the two stations showing subsurface ammonium uptake maxima of 0.025 and 0.02mmolN m^{-3}d^{-1} at 20 and 15m depths respectively. Urea uptake for the study period ranges from a minimum of 0.26mmol m^{-2}d^{-1} at PP9 to a maximum of 1.33 mmolN m^{-2}d^{-1} at PP2 with an overall average of 0.89 (±0.33) mmol N m^{-2} d^{-1} (~71mgCm^{-2} d^{-1}), almost twice the average ammonium uptake (Figure 4.11-top right). The offshore region averages around 0.96 (±0.36) mmolN m^{-2} d^{-1} whereas shelf locations average around 0.84(±0.34) mmol N m^{-2} d^{-1}. Depth profiles of urea uptake (Figure 4.11-bottom right) show a maximum at the surface at all stations unlike ammonium and nitrate where a few stations show a subsurface maximum. The maximum surface uptake ranged from 0.07mmolN m^{-3}d^{-1} at PP6 and PP7 to 0.01mmolN m^{-3}d^{-1} at PP9.

4.5.4 f-ratio

f-ratio, estimated as the ratio of integrated nitrate uptake to total integrated uptake, provides an upper bound of f-ratio in the region. It varies from minimum of 0.11 at PP8 to maximum of 0.81 at PP2 with an overall average of 0.54(±0.22) (Figure 4.12-left

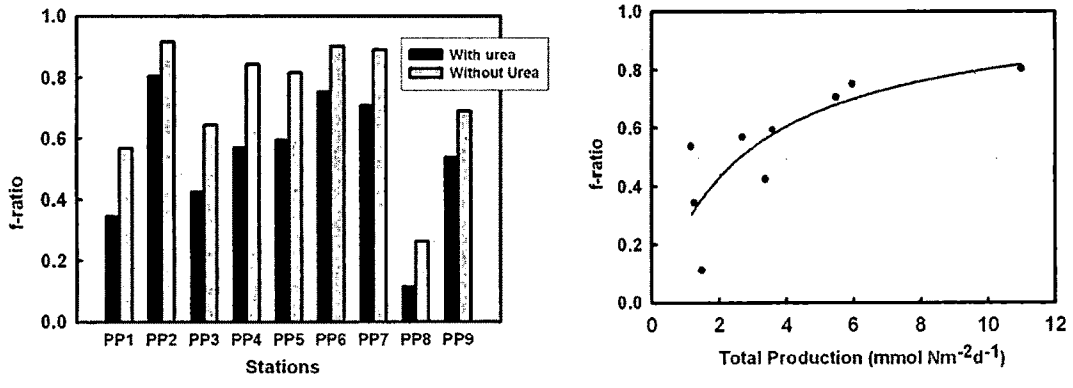


Figure 4.12 The upper bound of f-ratio (left) and relationship between f-ratio and total production during post monsoon in the Bay of Bengal.

panel). Interestingly, the f-ratio in both the offshore and shelf locations averages around 0.54 implying that the Bay of Bengal can at best transfer about half the total production to the deep during the postmonsoon season. Exclusion of urea from the calculation of f-ratio (for the sake of comparison with some Arabian Sea estimates, where urea uptake was not measured by earlier workers) shows an average increase in f-ratio by ~ 47%. The relationship between total production and f-ratio during the study period is best represented by a hyperbola (f-ratio = [1.02(±0.24) *total production] / [2.78(±1.59) + total production]) indicating a higher f-ratio for a higher total production emphasizing the substantial role played by nitrate in the total production (Figure 4.12-right panel).

4.6 Chlorophyll *a*, nitrate and physical parameters during the premonsoon (April-May 2003)

4.6.1 Chlorophyll *a*

The euphotic zone integrated Chl *a* concentration during the premonsoon in the Bay of Bengal varies from 8.65 mg m^{-2} at the offshore station PP1, to 42.35mg m^{-2} at a shelf station PP7 (Figure 4.13-left panel). Locations on the offshore transect show increasing integrated Chl *a* from the south to the north with maximum concentration at

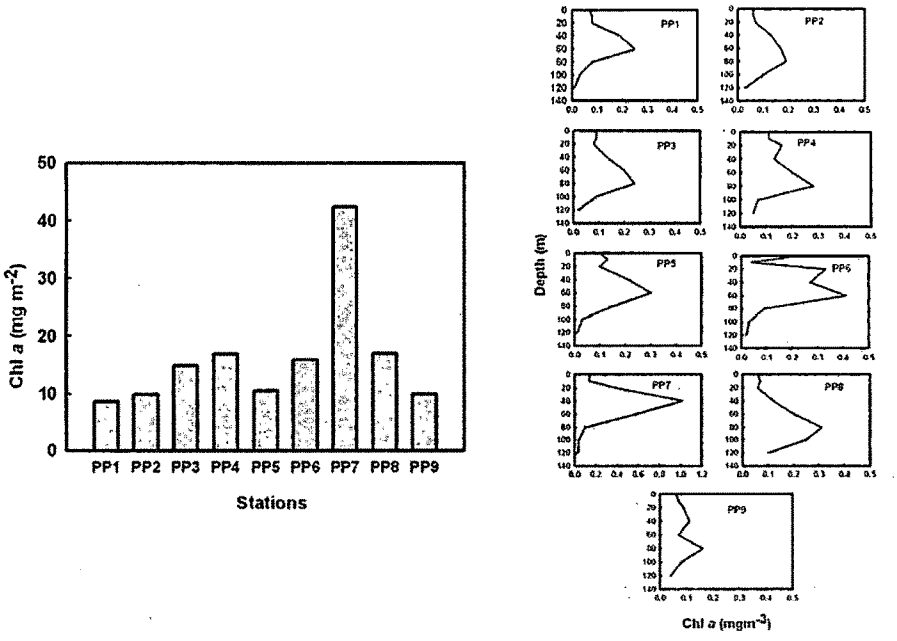


Figure 4.13 Euphotic zone integrated (left) and vertical profiles of Chl *a* at different productivity stations during premonsoon (right) in the Bay of Bengal (SK-191).

northernmost station PP4 (16.95mg m^{-2}). There has been a significant decrease in Chl *a* concentration at PP1 compared to the postmonsoon season (20.95 mg m^{-2}) whereas Chl *a* at PP3, PP4 and PP5 increased during the premonsoon. Among the shelf locations the variations in Chl *a* is more than four fold with a minimum at the southernmost station, PP9 (9.95mg m^{-2}), and a maximum at PP7. The integrated Chl *a* at PP7 is the highest observed during the study period. Almost all shelf stations show an increase in the euphotic zone integrated Chl *a* compared to the postmonsoon. Depth profiles of Chl *a* at all stations show subsurface Chl *a* maxima varying between 40 and 80m that is deeper than subsurface Chl *a* maxima observed during post monsoon (20-60m) (Figure 4.13-right panel). This may be due to relatively deeper euphotic depth (~60-100m) during premonsoon compared to postmonsoon (~60m). PP1 and PP5 show maximum Chl *a* of 0.25 and 0.30 mg m^{-3} respectively at 60m, to decrease to 0.01 mgm^{-3} at 120m. Majority of stations (PP2, PP3, PP4, PP8 and PP9) show Chl *a* maxima at 80m with values varying between 0.31mg m^{-3} (PP8) and 0.16mg m^{-3} (PP9). PP6 shows two subsurface Chl *a* peaks at 20 and 60m with values 0.33 and 0.41mg m^{-3} respectively. PP7 shows peak at 40m with maximum Chl *a* for any depth during present study (1.02mg m^{-3}).

4.6.2 Nitrate

The euphotic zone integrated nitrate concentration during the premonsoon for the region shows wide variations from a minimum of 78mmol m^{-2} at PP5 to maximum of 1622 mmol m^{-2} at PP7, both being shelf stations. PP6 and PP8 show relatively moderate concentrations of 153 and 113 mmol m^{-2} whereas PP9 has nitrate concentration as high as 490mmol m^{-2} (Figure 4.14-left panel). Among the offshore stations, PP3 shows the highest nitrate concentration of 625.5 mmol m^{-2} whereas PP1 has the minimum concentration of 189 mmol m^{-2}. Comparison with the postmonsoon data indicates a decrease in the euphotic zone integrated nitrate at two offshore locations (PP1 and PP4), and increase at another two (PP2 and PP3). Nitrate concentrations at shelf locations, except PP7, normally show a decrease compared to postmonsoon. Depth profiles of nitrate during premonsoon suggest that the nitrate level has never declined below the detection limit in the surface layer, a case which was frequent at offshore locations during postmonsoon (Figure 4.14-right panel). The

nitrate concentration, in general, has always been more than 0.2μM in the top 40m at any location in the study region and starts increasing thereafter. Another difference

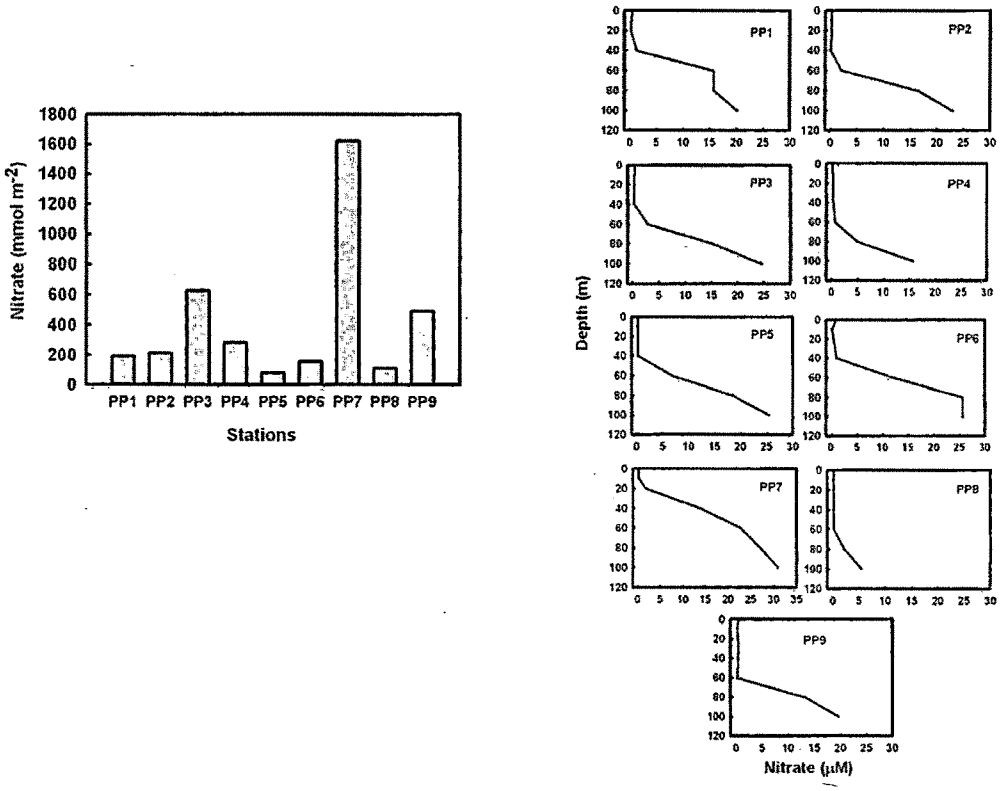


Figure 4.14 Euphotic zone integrated (left) and vertical profiles of nitrate at different productivity stations (right) during premonsoon in the Bay of Bengal (SK-191).

between post and premonsoon nitrate profile is the change in nitrate concentration with depth. During postmonsoon nitrate shows a sharp increase between 10 and 40m (actual depth varying with location) whereas during the premonsoon it seems to occur between 40 and 60m, except at PP7 where it shows an increase after 10m only. The reason for relatively higher euphotic zone integrated nitrate at most of the stations during postmonsoon is the higher concentration at 40 and 60m depth despite the absence or less concentration at the top. However, during premonsoon nitrate is present throughout the euphotic zone but not as high as postmonsoon values at 40 and 60m.

4.6.3 Hydrographic and meteorological Conditions

The hydrographic and meteorological conditions of the Bay of Bengal during premonsoon are different from those during postmonsoon. The main difference is in terms of reduced freshwater influx from the rivers and is evident from the difference in

the observed surface salinity variation during the two seasons. Overall, salinity varies in a narrow range of 34.23 psu at Stn. 21 to 32.47 psu at Stn. 10 compared to wide variation of 34.59 to 20.92 psu during postmonsoon (Figure 4.15-top left). The northern offshore locations (Stn.11 to Stn.13) where salinity was less than 30psu (28.40-29.47psu) during postmonsoon has reached more than 32.89psu (32.89-33.33psu) during premonsoon. The shelf stations (Stn.14 to Stn.18) showing very low salinity during the postmonsoon (28.15-20.92 psu) exhibit salinity as high as 32.94-33.84 psu. However, the southern shelf (Stn19-Stn.23) as well as offshore stations (Stn1-Stn.9) do not show much change in salinity. In fact, the southernmost offshore stations are more saline (by up to 1.6 psu) during postmonsoon than premonsoon.

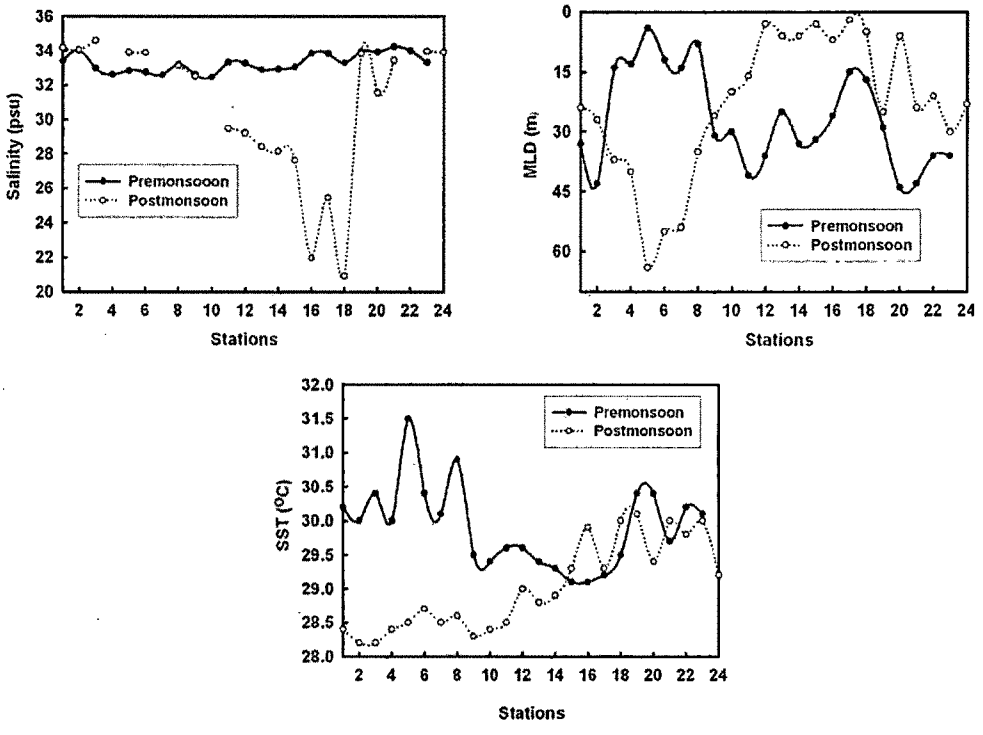


Figure 4.15 Comparison of Salinity (top left), MLD (top right) and SST (bottom) during pre and postmonsoon in the Bay of Bengal.

The rise in salinity from postmonsoon to premonsoon is a direct manifestation of the decrease in river runoff and hence the terrestrial influence. This rise in salinity (~ density) leads to a reduction in the stratification of the surface, evident from the increased mixed layer depths (MLD) at stations normally influenced by riverine discharge. MLD of 2-7m (Stn.12-Stn.18) during postmonsoon deepened to more than 25m (Stn. 12-Stn.16) and 15m (Stn.17 and Stn.18) during the premonsoon (Figure

4.15-top right). Overall, MLD during the premonsoon varies from 4m at the offshore stn. 5 to 44m at the shelf Stn. 20. The first two offshore stations show relatively deeper MLD of 33 and 43m respectively to shoal up to 4m at Stn.5. This deepens northward to reach 8m at Stn.8. From Stn. 9 onwards MLD is always more than 25m except at Stn 17 and Stn. 18 where it shoals up to nearly 15m. However, the comparison of MLD for the two seasons shows the reversal of pattern for offshore and shelf locations. In general, the MLD during postmonsoon was deeper for offshore ocean and shallower for shelf locations that has reversed during premonsoon. Overall the variation in SST during premonsoon is from 31.5°C at Stn.5 to 29.1°C at Stn. 15 and 16 (Figure 4.15-bottom). SST during premonsoon is more by 1-3°C than postmonsoon at offshore locations whereas shelf locations fall in a similar range during both the seasons (within ±1°C).

4.7 ^{15}N based productivity study during premonsoon 2003

4.7.1 Total Production

In general, total productivity during the premonsoon is higher than the postmonsoon. It varies from 1.93mmolNm^{-2}d^{-1} (~154 mgC m^{-2}d^{-1}) at an offshore station PP1 to 12.27 mmolNm^{-2}d^{-1} (~975 mgCm^{-2}d^{-1}) at the shelf station PP6 (Figure 4.16-left panel). Overall, it averages around 7.23(±4.17)mmolNm^{-2}d^{-1} (~575 mgC m^{-2}d^{-1}) for the study region against the 4mmolNm^{-2} d^{-1} during the postmonsoon. The total productivity for both the offshore and shelf transects have increased from the post to the premonsoon. In the offshore transect total productivity varies from a minimum at PP1 to a maximum of 11.17mmolNm^{-2} d^{-1} at PP4 with an average of 5.33(±4.08) mmolNm^{-2} d^{-1} (~424 mgC m^{-2}d^{-1}). Shelf locations show variations from 3.56 mmolNm^{-2}d^{-1} at PP5 to a maximum at PP6 averaging around 8.75(±3.97) mmolNm^{-2}d^{-1} (696 mgCm^{-2}d^{-1}). One important difference between the post and the premonsoon is the higher average productivity for the offshore transect than the shelf transect observed during postmonsoon has reversed during premonsoon, probably indicating the shift in the availability of nutrients. Productivity measurements performed using the ^{14}C technique during the same cruise yields an average value around 300mgC m^{-2}d^{-1}, significantly less than that obtained using ^{15}N technique. The main difference between results obtained using two techniques during present study has been found at one offshore location (PP4) and two shelf locations (PP8 and PP9) where total productivity obtained

by ^{14}C is significantly lower than that by the ^{15}N technique. Significant differences in the results obtained using the two techniques has also been observed in the Arabian Sea (Watts and Owens 1999). The productivity normalised to biomass (P/B) obtained during present study is higher than that for the postmonsoon possibly due to optimum light conditions. The average value during present study is $4.5h^{-1}$ compared to $2.4h^{-1}$ during postmonsoon with maximum value of $13.7h^{-1}$ in the subsurface waters of PP9. The relationship of the productivity values observed at discrete depths using ^{14}C (x) and ^{15}N (y) techniques (y = 0.94x + 3.64) has deteriorated (n= 54; linear correlation coefficient r=0.36) compared to the postmonsoon (Figure 4.16-right panel). The ^{14}C based results are preliminary and need to be re-checked.

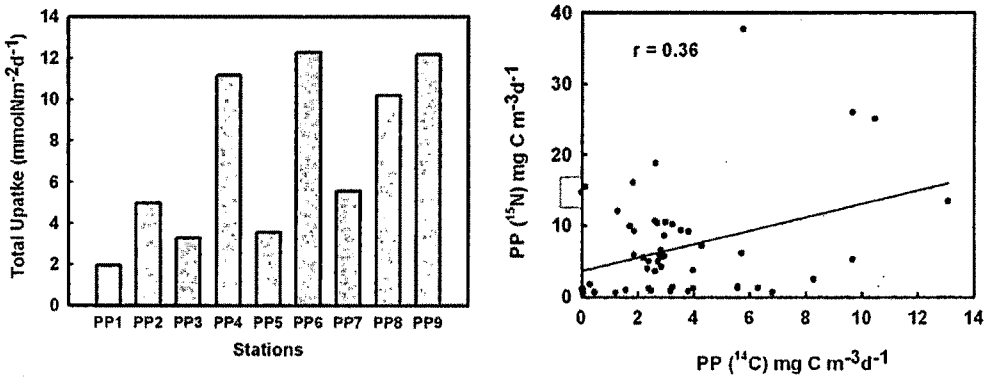


Figure 4.16 The euphotic zone integrated total column productivity (left) and relationship with ^{14}C based productivity (right) during the premonsoon.

4.7.2 New Production

As in the case of total productivity, new production during the premonsoon was also higher than that in the postmonsoon and ranged from a minimum of 0.98mmolN$m^{-2}d^{-1}$ (~78mgC$m^{-2}d^{-1}$) at an offshore station PP1 to 10.67 mmolN $m^{-2}d^{-1}$ (~ 849mgC$m^{-2}d^{-1}$) at PP6, a shelf station. Overall, new production for the region during the premonsoon averages around 5.44(±3.66)mmolN $m^{-2}d^{-1}$ (~ 433mgC$m^{-2}d^{-1}$), that is almost twice the average value observed during the postmonsoon (2.61mmol N $m^{-2}d^{-1}$) (Figure 4.17-left panel). The variation at offshore locations is from as low as 0.98 mmolN $m^{-2}d^{-1}$ at the southernmost PP1 to 8.46mmolN $m^{-2}d^{-1}$ at the northernmost PP4 with an average of 3.57(±3.39)mmolN $m^{-2}d^{-1}$ (~284 mgC$m^{-2}d^{-1}$). The difference between the average new production for the offshore transects during the two seasons is not significant (premonsoon higher only by 0.5mmolN $m^{-2}d^{-1}$). The shelf locations show variations

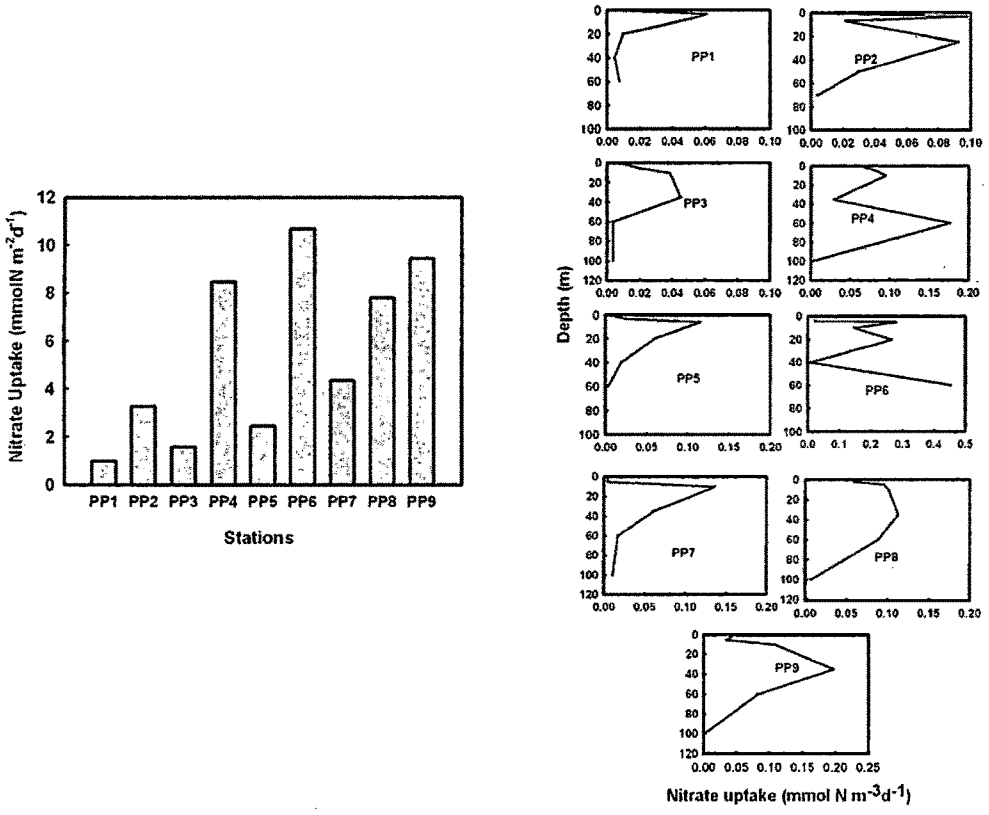


Figure 4.17 The euphotic zone column integrated nitrate uptake (left panel) and depth profiles of nitrate uptake at different stations (right panel) during premonsoon in the Bay of Bengal (SK-191).

from 2.46 mmolN $m^{-2}d^{-1}$ at PP5 to 10.67 mmolN $m^{-2}d^{-1}$ at PP6 with an average of 6.94 mmolN $m^{-2}d^{-1}$ (~ 552mgC$m^{-2}d^{-1}$). Average values of the shelf transect exhibit new production during the premonsoon to be thrice that of the postmonsoon indicating an increased rate of supply and more efficient use of nitrate during the premonsoon season. The presence of nitrate throughout the water column and increased P/B during premonsoon may be the reasons for this increased new production. In general, the depth profiles of nitrate uptake for the premonsoon is also different from those of postmonsoon, where the maximum uptake was at the surface. The nitrate uptake profiles during the premonsoon show subsurface uptake maxima at all the stations indicating the photoinhibition at surface Bay as suggested by Qasim (1977) and Radhakrishna et al. (1978) for the surface Arabian Sea (Figure 4.17-right panel). Although the euphotic depth during the study was between 60-100m the subsurface uptake maxima occur between 3 and 60m. Three out of four offshore stations (except PP4) fall in the category where maximum uptake is less than 0.10mmolN $m^{-3}d^{-1}$. All

shelf stations have uptake maxima of more than 0.10 mmolN $m^{-3}d^{-1}$. PP1, PP5 and PP7 are the stations where uptake maxima lie in the top 10m (3, 6 and 10m, respectively) with values 0.06, 0.11, and 0.13 mmolN $m^{-3}d^{-1}$ respectively, and the uptake does not cease completely at the euphotic depth. PP2, PP4 and PP6 are the stations that show more than one subsurface maximum. PP2 shows uptake maxima at 3 and 25m with values 0.09mmolN $m^{-3}d^{-1}$. PP4 shows uptake maxima at 10 and 60m with values 0.09 and 0.17mmolN $m^{-3}d^{-1}$ and decreases sharply to cease at 100m. PP6 shows the maximum value at the base of the euphotic zone (0.45mmolN $m^{-3}d^{-1}$), that is the maximum for any depth during the study period. The Chl *a* concentration at that depth is also maximum (0.41mgm^{-3}). Apart from this, PP6 also has two peaks at 5 and 20m (0.28mmol N $m^{-3}d^{-1}$). PP3, PP8 and PP9 show uptake maxima at 35m with values 0.04, 0.11 and 0.19mmolN $m^{-3}d^{-1}$. The uptake during postmonsoon was almost negligible below 40m (20m at some) at most of the stations whereas significant uptake was observed between 40 and 100m at most of the stations during premonsoon. This might be one of the reasons for higher column new production during the postmonsoon.

4.7.3 Regenerated Production

Sum of the conservative estimates of ammonium and urea uptake rates has been considered as regenerated production, as during the postmonsoon. Compared to the postmonsoon, there is an increase in the ammonium component of the regenerated production whereas the urea component has decreased slightly. Ammonium uptake varies from a minimum of 0.67mmolN $m^{-2}d^{-1}$ at PP1 to a maximum of 1.80mmolN $m^{-2}d^{-1}$ at PP4, both offshore stations (Figure 4.18-top left). Overall, the ammonium uptake averages around 1.18(±0.39) mmolN $m^{-2}d^{-1}$ (~94mgC $m^{-2}d^{-1}$) compared to 0.49(±0.20) mmolN $m^{-2}d^{-1}$ during the postmonsoon. The offshore stations average around 1.11(±0.48) mmolN $m^{-2}d^{-1}$ (~88 mgC$m^{-2}d^{-1}$) whereas shelf locations average around 1.24(±0.34) mmolN $m^{-2}d^{-1}$ (~99mgC$m^{-2}d^{-1}$). Depth profiles of ammonium uptake are similar to those of nitrate uptake (Figure 4.18-bottom left). They also show a subsurface uptake maximum that shifts between 3 and 35m depending on the location. However, the uptake rate never exceeds 0.034mmol $Nm^{-3}d^{-1}$ for any depth at any station. PP1 shows maximum at 20m (0.025mmol $Nm^{-3}d^{-1}$), to drop sharply at 40m. PP5 also has a maximum at 20m (0.027mmol $Nm^{-3}d^{-1}$) but also shows another similar peak at 3m. PP3, PP4 and PP7 have maximum uptakes at 10m (0.022,0.028 and 0.021

mmol $Nm^{-3}d^{-1}$ respectively) and decrease downwards. However, the uptake rates at these stations do not cease completely even at the bottom of euphotic zone. PP2 has a prominent peak at 25m (0.022 $mmolNm^{-3}d^{-1}$). Both PP8 and PP9 have a maximum uptake rate of ~0.025 mmol $Nm^{-3}d^{-1}$ at 35m. Urea uptake during the study period for the region averages around 0.60(±0.32) mmolN $m^{-2}d^{-1}$ that is slightly less than the premonsoon value of 0.89 mmolN $m^{-2}d^{-1}$ (Figure 4.18- top right). The offshore

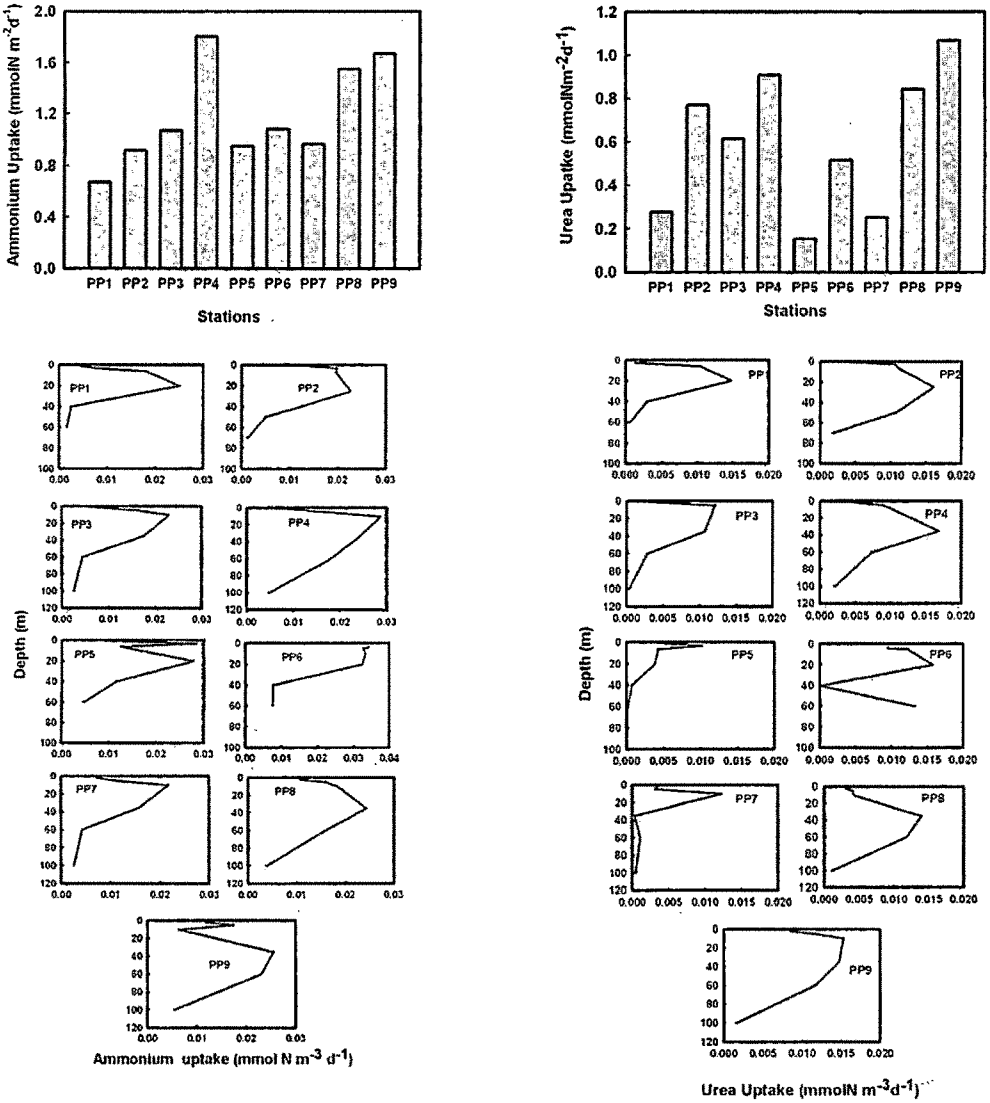


Figure 4.18 Euphotic zone integrated column uptake of ammonium (top left) and urea (top right) during premonsoon. Depth profiles of ammonium uptake (bottom left) and urea uptake (bottom right) during same season are also shown.

transect averages around 0.64 (±0.27) mmolN $m^{-2}d^{-1}$ whereas shelf transect averages 0.56(±0.38) mmolN $m^{-2}d^{-1}$. Depth profiles of urea uptake also follow the pattern shown by nitrate and ammonium uptake (Figure 4.18-bottom right). At all the stations

subsurface uptake maxima exist between 3 and 35m and uptake rate never exceeds 0.016mmolN $m^{-3}d^{-1}$. PP6 exhibits the pattern observed during nitrate uptake where the uptake rate peaks at the base of euphotic zone (~60m) where Chl *a* concentration is also maximum.

4.7.4 f-ratio

The f-ratio during premonsoon has also been calculated as described earlier (nitrate uptake/total uptake) and hence provides the upper bound of the f-ratio at the respective stations. The estimated f-ratio during premonsoon varies from a minimum of 0.50 at PP1 to maximum of 0.87 at PP6 implying that at best 50 to 87% of the total productivity can be exported to deeper layers under steady state (Figure 4.19-left panel). However, the average f-ratio estimated for the entire region has increased to 0.70(±0.12) during premonsoon as compared to 0.54 during the postmonsoon. The f-ratio for offshore transect averages around 0.60(±0.12) whereas for the shelf transect it averages 0.77(±0.06). During postmonsoon the average f-ratio for both shelf and offshore stations was same (0.54) whereas during premonsoon shelf stations have

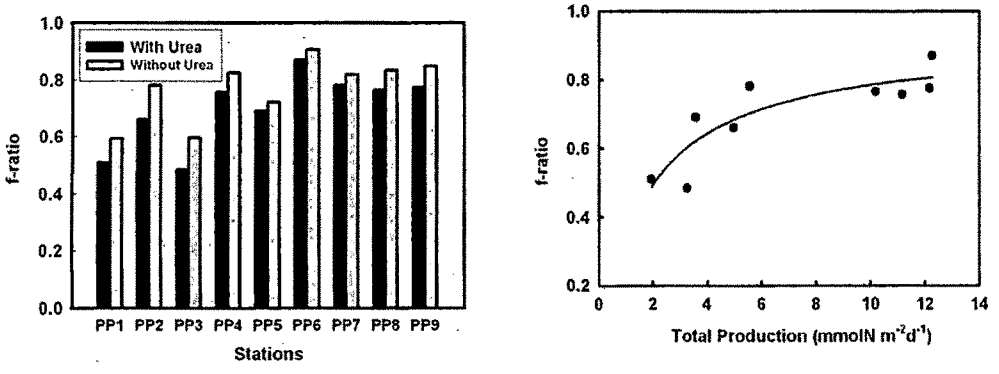


Figure 4.19 The upper bound of f-ratio (left) and relationship between f-ratio and total production during pre monsoon in the Bay of Bengal (SK-191).

significantly higher f ratios than the offshore stations. This is mainly due to the increased column new production in the offshore transect due to the reasons discussed earlier. One important difference observed during pre and postmonsoon is the change in f-ratio when urea is excluded from the calculation. During the postmonsoon the exclusion of urea lead to an average increase in f-ratio by 47% whereas this increase was only around 11% during premonsoon. The relationship between total production

and f-ratio can be represented by hyperbola as during postmonsoon (Figure 4.19-right panel): f-ratio= [0.91(±0.06)*total production] / [1.7(±0.55)+total production]. This is indistinguishable from the postmonsoon relationship within the associated uncertainties. The observed hyperbolic relationship between f-ratio and total production in the Bay of Bengal can be used for estimating the fraction of total production, which has potential to sink down to the deeper layers.

4.8 Implications of the new production measurements in the Bay of Bengal

The average rate of photosynthetic fixation of carbon by marine phytoplankton (primary productivity) is more than a factor of two higher in the Arabian Sea than in the Bay of Bengal (Madhupratap et al. 2003). However, the time averaged sediment trap data indicate that on the basin scale, the downward flux of organic carbon in the Arabian Sea is not proportionately higher than that of the Bay of Bengal, except for the upwelling region in the northwestern Arabian Sea. Our experiments done in two different seasons consistently show a high new production (averaging around 2.6 mmolN m^{-2} d^{-1} during postmonsoon and 5.4mmolN m^{-2} d^{-1} during premonsoon) and a linear relationship with total production (Figure 4.20); which could be one of the reasons for relatively higher downward organic carbon flux in the moderately productive Bay. Hence, such oceanic regions may play a more significant role in removing the excess anthropogenic CO_2 from the atmosphere, than considered so far. The new production measurements in the Bay of Bengal during present study have helped to understand a few long standing paradoxes related to the Bay on basin scale. The following are the most important:

Reason for comparable downward organic carbon fluxes in the Arabian Sea and the Bay of Bengal:

Major international scientific programmes such as JGOFS (Joint Global Ocean Fluxes Study), aimed at assessing the role of oceans as source/sink of atmospheric carbon dioxide, concentrated mostly on highly productive regions of the oceans, e.g., Arabian Sea (Smith 2001). Intense upwelling during summer and convective mixing due to surface cooling in winter enhance the productivity of the Arabian Sea (Madhupratap et al. 1996). In contrast, the limited studies carried out for the adjacent Bay of Bengal

suggest it to be less productive because of the cloud cover and stratification of the surface layers by copious freshwater discharge from rivers draining the Indian sub-continent, inhibiting vertical mixing and the supply of nutrients from below (Prasanna Kumar et al. 2002). Although there is some seasonal and geographical variability, the typical average ^{14}C based productivity in the Arabian Sea is around 1200 mgC m^{-2} d^{-1}, (Barber et al. 2001), whereas in the Bay it is about 300 mgC m^{-2} d^{-1} (Madhupratap et al. 2003), despite comparable numerical abundances of phytoplankton (Sawant and Madhupratap 1996). In contrast, sediment trap data from both these regions (Table 4.3) show that on an average, the annual downward flux of organic carbon in the Bay of Bengal is not significantly less than that of the Arabian Sea (Ittekkot 1991; Haake et al. 1993; Unger et al. 2003). Exceptions do exist; e.g., sediment traps placed near

Table 4.3 Time-averaged fluxes of organic carbon ($gC.m^{-2}yr^{-1}$) in sediment traps, 1000 m above sea floor (values in parentheses are from the shallow trap, 1000 m below the sea surface). Traps were distributed east-west in the Arabian Sea and north-south in the Bay of Bengal (Ittekkot 1991; Haake et al. 1993; Unger et al. 2003; Honjo et al. 1999; Lee et al. 1998).

ARABIAN SEA				
Stations	**Latitude (°N)**	**Longitude (°E)**	**Flux (gC $m^{-2}y^{-1}$)**	**Data averaged over (yrs)**
WAST	16° 20'	60° 30'	3.2	4
CAST	14° 31'	64° 46'	1.9	3
EAST	15° 31'	68° 43'	2.1	4
MS1	17° 41'	58° 51'	3.8	1
MS2	17° 24'	58° 48'	5.6	1
MS3	17° 12'	59° 36'	5.3	1
MS4	15° 20'	61° 30'	3.6	1
MS5	10° 00'	65° 00'	1.3	1
BAY OF BENGAL				
NBBT-N	17° 27'	89° 36'	2.86(3.11)	10
NBBT-S	15° 32'	89° 13'	2.38 (2.38)	10
CBBT	13° 09'	84° 22'	2.7 (2.6)	10
SBBT	04° 28'	87° 19'	2.27(2.5)	10

the upwelling sites by US JGOFS (particularly traps MS2 and MS3) have observed higher organic carbon fluxes (Honjo et al. 1999; Lee et al. 1998)]. The most important question was to understand the possible reasons for the comparable downward organic carbon fluxes in highly productive Arabian Sea and moderately productive Bay of Bengal. One possible explanation to this observation is the ballast hypothesis whereby

organic carbon is ballasted into the deep by the high lithogenic flux from rivers, which form aggregates with the former (Ittekkot 1991). However, the annual lithogenic flux in the Bay decreases sharply from the north to the central shallow trap (21.89 g m^{-2} to 9.37g m^{-2}, by 57%), whereas the organic carbon flux (3.59 g m^{-2} to 2.6 g m^{-2}) does not show a corresponding reduction. It decreases only by 26%. (Ittekkot et al. 1991). Further, time series data from two shallow traps in the north (17° 27' N and 15° 32' N) show that the annual lithogenic flux decreased from 14.5 to 8.7g m^{-2} (by 40%), while organic matter flux decreases from 5.6 to 4.3 g m^{-2} (by 23%; Unger et al. 2003). However, the annual carbonate flux increases from north to south (12.5 to 13 g m^{-2}), probably compensating for decrease in lithogenic fluxes, as the possibility of other mineral matters acting as ballast have been reported (Hedges et al. 2001). However, apart from the efficient transfer mechanism there has to be the availability of organic matter to form the aggregate, particularly for southern region in the Bay, which is far from the influence of possible organic matter contribution by rivers. Independent estimates of new production based on nitrogen uptake performed during present study has helped to understand this in a better way, because, under steady state, new production is considered theoretically equal to the export production (Eppley and Peterson 1979). Eppley et al. (1983) have suggested that new production and particle sinking are coupled over longer (annual) time scales. Consistent higher new production of 4mmol N $m^{-2}d^{-1}$ (~318mgC $m^{-2}d^{-1}$) observed during two different seasons in the Bay of Bengal indicates its significant role in the observed organic carbon flux on the time scales of sediment traps data. The higher new production observed may be responsible for the higher downward flux of organic carbon in the Bay of Bengal despite moderate overhead productivity.

Reason for reduced pCO_2 in surface Bay of Bengal:

Despite having some seasonal sinks, the oceanic region between 10 and 25°N, in general, is considered to be a source of atmospheric CO_2 (Broecker et al. 1986; Takahashi 1989). However, data on the air-sea exchange of CO_2 for the northern Indian Ocean in general, and Bay of Bengal in particular, are not adequate in space and time. So far, very little data exists for the Bay (Kumar et al. 1992; George et al. 1994). The study carried out by Kumar et al. (1996) during the presouthwest monsoon and the northeast monsoon of 1991 reveals that a large area of the Bay is characterized by pCO_2 levels far below the atmospheric value (~350 μatm). This effect was found to be

more prominent during northeast monsoon when air-sea pCO_2 gradient sometimes exceeds 100 μatm. Kumar et al. (1996) guessed that the cause for the low pCO_2 in the Bay could be physical as well as biological processes. One important physical parameter known to decrease the pCO_2 level is salinity due to its effect on solubility of CO_2, dissociation constants for carbonic, boric and other weak acids and the concentration of boric acid in seawater (Takahashi et al. 1993). However, Kumar et al (1996) have shown that the salinity can lower the pCO_2 to a maximum of only ~30 μatm which was about 25% of the highest recorded pCO_2 drawdown and therefore surmised that biological activity should account for the rest of the observed pCO_2 decrease i.e., due to moderately high new production sustained by external nutrients brought in by rivers and/or atmospheric deposition. The higher new production estimates during present study has proved the conjecture of Kumar et al. (1996) for low pCO_2 in surface Bay. However, the nutrient source is probably not exactly as predicted.

Contribution to the development of Oxygen Minimum Zone in the Bay:

Oxygen Minimum Zone (OMZ) has been observed between 100-500 m in the Bay of Bengal. Its presence in ocean is usually explained by the utilization of oxygen due to decomposition of organic matter brought into the deeper water from the surface. This explanation holds good for the Arabian Sea where the overhead productivity is high and the degradation of organic matter settling down consumes dissolved oxygen, leading to the existence of OMZ and denitrification zones (Olson et al. 1993). But the existence of OMZ in the Bay of Bengal, where the overhead productivity is less is indeed puzzling. There may be two possible reasons for this. First, higher residence time of the deeper waters of the Bay due to lack of ventilation caused by presence of low density waters on the top (ventilation is also limited due to the closure of the basis by the continent in the north), leading to the constant use of sub surface oxygen by the organic matter, even if it is small in magnitude. Secondly, higher f-ratio i.e., high new production may be responsible as the fraction of organic matter going to deeper waters is more than that previously believed and the available oxygen is getting consumed in decomposition of these organic matter leading to formation of OMZ.

4.9 Relationship between new and total production: possible implication

Results of nitrate, ammonium and urea uptakes for both the seasons at nine stations discussed earlier are shown in Table 4.4. The nitrate uptake (new production) has been estimated after consideration of ambient concentration, whereas the ammonium and urea uptakes are conservative estimates. From Table 4.4 it is seen that the f-ratio (calculated here as nitrate uptake / total uptake) is in general very high (mean upper bound ~0.65), regardless of season and the proximity to the coast. Since f-ratio has been calculated using conservative ammonium and urea uptakes, it provides the upper limit of the f-ratio for the region. This is significantly higher than the values (mean < 0.3) reported for the highly productive northwestern Arabian Sea for intermonsoon season (Watts and Owens 1999). However, the data of Watts and Owens (1999) take into account the ambient ammonium concentration and may go up when conservative estimates are taken. Using the average Redfield ratio (C/N) of 6.6, we convert the total nitrogen uptake to carbon uptake; the total productivity in the Bay of Bengal was found to vary from 90 to 870 mgC m^{-2} d^{-1} during September-October 2002, with an average value of 318 mgC m^{-2} d^{-1}. The total productivity during April-May 2003 varied from 154 to 975 mgC m^{-2} d^{-1} with an average of 575mgC m^{-2} d^{-1}. Also, the new production during April-May 2003 (overall average~ 433 with shelf region average of 552 and offshore average of 284 mgC m^{-2} d^{-1}) is higher than that of September-October 2002 (overall average~ 207 with shelf region averaging around 180 and offshore around 243 mgC m^{-2} d^{-1}). These values are comparable to the new production off India, 400±160 mgC m^{-2} d^{-1} reported for the Arabian Sea (Sambrotto 2001). However, these values reported here are somewhat higher than the productivity (^{14}C tracer method) reported for this region (40 to 502 mgC m^{-2} d^{-1}) during the peak summer monsoon (July, 2001; Madhupratap et al. 2003). The reason for this discrepancy could be two fold: first, the increase in mean cloudiness during the summer monsoon season over the BOB (i.e., less light available for photosynthesis), which is known to affect the productivity in this region (Gomes et al. 2000). Second reason could be the cyclones, which are very frequent in the Bay during the postmonsoon season (September-December) and can bring nutrients to the surface by churning up the ocean and hence increase the productivity.

Table 4.4 The nitrate, ammonium and urea uptake rates in the Bay of Bengal during post and premonsoon

	Stations	Nitrate ($mmolN\ m^{-2}d^{-1}$)	Nitrate ($mgC\ m^{-2}d^{-1}$)	Ammonium ($mmolN\ m^{-2}d^{-1}$)	Ammonium ($mgC\ m^{-2}d^{-1}$)	Urea ($mmolN\ m^{-2}d^{-1}$)	Urea ($mgC\ m^{-2}d^{-1}$)	Total ($mmolN\ m^{-2}d^{-1}$)	Total ($mgC\ m^{-2}d^{-1}$)	f-ratio
Post	PP1	0.43	34.40	0.33	26.21	0.49	39.22	1.26	99.82	0.34
monsoon	PP2	8.85	703.32	0.81	64.47	1.33	105.64	10.99	873.44	0.81
	PP3	1.44	114.35	0.80	63.48	1.14	90.82	3.38	268.65	0.43
	PP4	1.53	121.77	0.28	22.51	0.87	69.45	2.69	213.73	0.57
	PP5	2.13	169.61	0.49	38.74	0.97	76.96	3.59	285.32	0.59
	PP6	4.48	356.45	0.49	38.70	0.99	78.62	5.96	473.77	0.75
	PP7	3.87	307.81	0.48	37.84	1.13	89.81	5.48	435.45	0.71
	PP8	0.17	13.33	0.47	37.47	0.85	67.35	1.49	118.15	0.11
	PP9	0.63	49.87	0.28	22.56	0.26	20.40	1.17	92.83	0.54
Average										
Overall		2.61	207.88	0.49	39.11	0.89	70.92	4.00	317.91	0.54
Offshore		3.06	243.46	0.56	44.17	0.96	76.28	4.58	363.91	0.54
Shelf		2.26	179.41	0.44	35.06	0.84	66.63	3.54	281.10	0.54
Pre	PP1	0.99	78.37	0.67	53.38	0.28	22.03	1.93	153.78	0.51
monsoon	PP2	3.28	260.67	0.91	72.68	0.77	61.22	4.96	394.57	0.66
	PP3	1.58	125.64	1.07	84.94	0.61	48.72	3.26	259.30	0.48
	PP4	8.46	672.85	1.80	143.29	0.91	72.12	11.17	888.26	0.76
	PP5	2.47	195.99	0.95	75.45	0.15	12.19	3.57	283.63	0.69
	PP6	10.68	848.98	1.08	86.02	0.51	40.80	12.27	975.80	0.87
	PP7	4.35	345.57	0.96	76.69	0.25	19.98	5.56	442.25	0.78
	PP8	7.80	619.78	1.55	123.31	0.84	66.91	10.19	809.99	0.77
	PP9	9.44	750.13	1.67	133.01	1.07	85.03	12.18	968.17	0.77
Average										
Overall		5.45	433.11	1.19	94.31	0.60	47.67	7.23	575.08	0.70
Offshore		3.58	284.38	1.11	88.57	0.64	51.02	5.33	423.98	0.60
Shelf		6.94	552.09	1.24	98.90	0.57	44.98	8.75	695.97	0.78

There is a very significant correlation between new (y) and total production (x): $y = 0.88\ x - 0.89$ (coefficient of determination, $r^2 = 0.99$) in the Bay of Bengal. The relationship remains significant (r^2=0.96) but with a small decrease in the slope,

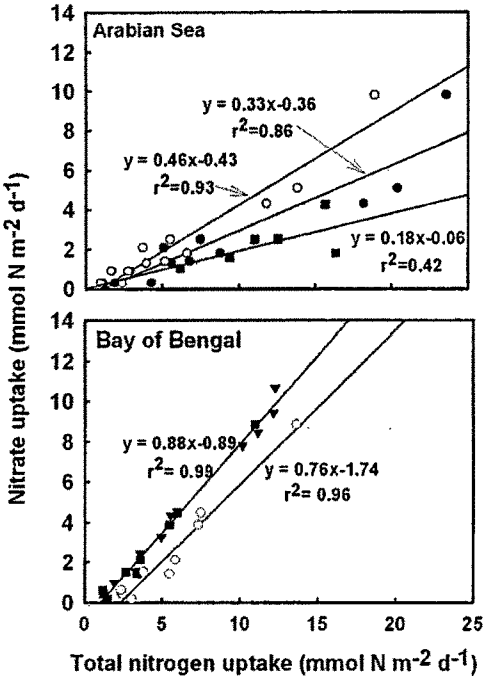


Figure 4.20 Relationship between total and new production. Top panel represents the Arabian Sea data from Watts and Owens (1999) where filled circles are the original data, open circles are the recalculated conservative estimates and squares are Arabian Sea data of the present study (SK-186). In the bottom panel, rectangles are for Sep-Oct 2002, triangles for Apr-May 2003 and circles are for Sep-Oct 2002 after taking into account the ambient ammonium estimated from zooplankton biomass.

when ammonium concentration from zooplankton regeneration is considered for September-October 2002 (Figure 4.20). Data for the Arabian Sea (Watts and Owens 1999) also show such a correlation, but with some scatter: $y = 0.33\ x - 0.36$ (r^2 =0.86). However, this relationship improves ($y = 0.46\ x - 0.43$; $r^2 = 0.93$) when the conservative estimates (i.e., no ambient ammonium) were considered. During this calculation the average ammonium concentration was taken as 0.13μM (Woodward et al. 1999; where the nutrient data of their study are presented). Interestingly, in both the seas, the x-intercept, i.e. minimum amount of regenerated production in the total absence of extraneous nitrate supply is ~1 mmolN m^{-2} d^{-1} (equivalently ~80 mgC m^{-2} d^{-1}). Based on the regression of Watts and Owens (1999) data and present data for the Bay of Bengal, the f-ratio (= y/x) can be expressed as α (1-1/x) (as the slope and intercept being roughly equal numerically, in both cases), where x is the total

production and α is the slope of the straight-line in (x, y) plot. It is apparent that when x tends to large values, there is a limit to the f-ratio, given by the slope, α. Thus, available limited data suggest that in the Bay of Bengal, the f-ratio can be as high as 0.88 while in the Arabian Sea it can be at best ~0.46 during intermonsoon. The Arabian Sea data of the present study during NE monsoon (January) also agrees with the above argument where the f ratio in general is less than 0.41 except at PP2 where it is anomalously high (0.60). However, the upper bound of f-ratio estimated for early March could go as high as 0.61 at the bloom station PP4.

4.10 Possible nutrient sources to the Bay of Bengal

Different sources and mechanisms of nutrients supply to the Bay of Bengal and their effect on productivity have not been thoroughly investigated as in the case of the Arabian Sea and the situation here is partly speculative. The present section discusses the different possible sources of nutrient supply to the Bay of Bengal required to sustain the observed new production.

Terrestrial Sources

One important source of nutrients to the Bay of Bengal is the adjacent land, particularly due to the river water discharge, which has been speculated to have an enormous influence on biogeochemical processes in the Bay of Bengal (Ittekkot 1991). However, no systematic data exists to quantify the riverine contribution to the nutrient pool of the Bay despite the fact that almost all the major rivers of the Indian subcontinent, except the Indus and the Narmada, drain into the Bay of Bengal. These rivers are expected to bring a large pool of nutrients with them. Curiously, actual measurements from the shelf to offshore in the surface Bay does not show significant presence of nitrate (De Sousa et al. 1981). The nitrogen flux into the Bay was indirectly calculated by Kumar et al. (1996) using the global flux of water ($37.4*10^{12} m^3\ yr^{-1}$; Martin and Whitfield 1983) and nitrogen ($50*10^{12}$ gN yr^{-1}; Duce et al. 1991) in world rivers to the ocean assuming the Indian rivers deliver nitrate in the same proportion to the total water flux. It was found to be $2.17*10^{12}$ gN yr^{-1}. If the fresh water is assumed to spread over a total area of the Bay ($2.2*10^{12}$ m^2; LaFond 1966), the above calculated influx works out to be 2.68mgN m^{-2} d^{-1}. Another possible contribution to the nitrate pool of the Bay is by atmospheric deposition, which has been proposed to play a crucial role in regulating

the productivity of ocean (Jickells 1998). The contribution to the nitrogen pool of the Bay through atmospheric wet deposition has been reported to be around 1.53mgN m^{-2} d^{-1} (Kumar et al. 1996) using an annual precipitation rate of 2m over BOB (Tomczak and Godfrey 1994) and an average combined nitrogen concentration of 20μM in rainwater. This calculation shows total external input of nitrogen to the Bay as 4.21mgN m^{-2} d^{-1}. However, another estimate for the external nitrogenous inputs to the Bay has been given by Schafer et al. (1993) and is on the relatively higher side. According to them, the fluvial input (particulate and dissolved) has been estimated to be 5.2 *10^{12} gN yr^{-1}, which amounts to 6.36 mgN m^{-2} d^{-1} after taking into account the areal extent of the Bay. The atmospheric input values are based on the cruises carried out during spring and autumn 1988 and have been divided into nitrogen inputs in the form of ammonium and nitrate compounds (dry and wet deposition). Total nitrogen input from the atmosphere in the form of ammonium compounds has been reported to be around 3.74mgN m^{-2} d^{-1} (3.70 mgN m^{-2} d^{-1} as wet deposition and 0.04 as dry deposition) whereas in the form of nitrate deposition to be 2.5*10^{12} gN yr^{-1} (~ 3.09mgN$m^{-2}d^{-1}$). These values are the upper estimates provided by Schafer et al. (1993). Therefore, the total maximum atmospheric nitrogen input works out to be 6.83mgN m^{-2} d^{-1}, which is of the same order of magnitude as the fluvial input; thus the total extraneous nitrogen (fluvial + atmospheric) to the Bay is around 13.19mgN m^{-2} d^{-1} (~0.94mmol N m^{-2} d^{-1}). However, all may not be in bioavailable form, particularly the particulate component contributed by rivers. Our results for the two seasons show average new production of 4mmolN m^{-2} d^{-1}; therefore, estimated nitrogen inputs from rivers and atmosphere can at best supply only around 20% of the total required nitrogenous inputs (<10% by the estimates of Kumar et al. 1996). The rest 80% of the required nitrogen has to come from the supply of nitrate from the deeper waters.

Cyclonic Churning

The shallow nitracline in the Bay of Bengal (Madhupratap et al. 2003) might have allowed the nitrate to come up to the surface, especially when aided by churning due to cyclonic winds in the postmonsoon season. These cyclones stir up the surface Bay and thus supply the nutrients from below. The formation of localized intense blooms and also the intensification of bloom generated by anticyclonic gyre are known due to cyclonic activity in this region (Vinaychandran and Mathew 2003). Also, the stratification due to freshwater discharge, which prevents the upwelling of nutrients in

the Bay, reduces towards the south and is not strong enough to prevent nutrients to come up to the surface (Vinaychandran et al. 2002). At the beginning of study period the wind speed more than 20m/s over the Bay had been encountered (Figure 4.8-bottom right; Qscat wind speed data; http://www.ssmi.com/qscat/). Furthermore, in 2002 the monsoon was somewhat weaker (80% of long term mean rainfall over India, see www.tropmet.res.in), leading perhaps to less than normal stratification of the surface Bay. It is seen from Figure 4.8-bottom left that the mixed layer depths are generally higher for the offshore stations than the shelf stations for September-October 2002. As discussed earlier the nitrate concentration in the Bay increases sharply below 40 and 60m, the stations with mixed layer depth more than 40m (average euphotic depth was ~ 60m) shows higher new production (PP2 during September-October 2002 and PP8 during April-May 2003), probably indicating the coupling between surface and subsurface layers.

Surface Currents

The higher new production in the Bay at shelf stations during April-May 2003 may be attributed to the presence of a poleward surface current along the western boundary of the Bay of Bengal. This current, known as EICC is active at north of 10°N that brings cooler, more saline water with nutrients to the surface (Shetye et al. 1993). Shetye et al. (1993) have also proposed that this poleward current is the western boundary current of anticyclonic subtropical gyre which is best developed during March-April, and decays only by June, which includes the study period. Gomes et al. (2000) have also observed the increase in productivity in the coastal region due to EICC.

Moreover, another reason could be the higher uptake rates observed at deeper depths (~ 40m) during premonsoon season where nutrients are available in plenty (average ~7μM) along with the light (euphotic zone ~80m). Since the euphotic zone was more than 80m and mixed layer was thin, as often the case during the intermonsoon period, the upper part of the thermocline with high nutrient levels fell well within the euphotic zone leading to higher uptake rates at depths more than 40m (Figure 4.17). In such a condition photosynthetic rate several fold higher than that at sea surface has been reported earlier (Pollehne et al. 1993).

Upwelling

Another mechanism that can bring nutrients to the surface is upwelling, a major cause of the high biological productivity in the Arabian Sea. The nutrient rich waters upwelled off Somalia and Arabia are advected laterally out of the upwelling region and contribute to productivity in the Central Arabian Sea (Prasanna Kumar et al. 2001). However, Bay of Bengal lacks such intense upwelling except for a 40 km wide band along the western margin that has been found to be the result of local longshore wind stress (Shetye et al. 1991). This upwelling has been observed during southwest monsoon and disappears northward as this phenomenon is overwhelmed by the enormous freshwater influx from Ganga-Brahmaputra rivers. Therefore, upwelling does not seem to be a prominent nutrient source during the study period.

Convective mixing

Cooling of surface waters by the northeasterly winds during the northeast monsoon has been suggested (Shetye et al. 1996). Winter cooling of surface water in the month of January has also been reported (Murty et al. 1998). However, this winter cooling does not lead to convective mixing as in the case of Arabian Sea (Madhupratap et al. 1996). Mixing is again prevented due to the presence of low salinity water in the upper layer.

Eddies

Presence of thermocline oscillations and cold-core eddy signatures during summer 2001 have been reported (Madhupratap et al. 2003). These eddies could pump cold water and nutrients from below to upper subsurface waters. But such eddies are usually capped by surface freshwater layer and are unable to surface, thus perhaps not contributing significantly to the surface nitrate pool.

Submarine ground water discharge

Another potential nutrient supply to the Bay of Bengal may be from submarine groundwater discharge. An annual subsurface discharge from Bengal Basin to the Bay of $1.5\pm0.5*10^{11}$ $m^3 yr^{-1}$, which is ~10% of Ganga-Brahmaputra riverine flux to the Bay, has been reported (Dowling et al. 2003). The depth of discharge is more than 30m. However, the nitrate in groundwater sampled from domestic wells in Bangladesh shows large variations ranging from 1 to 191 μmol/kg, with most of the wells showing

nitrate less than detection limit. Taking a conservative 10 μmol/kg as the mean concentration, this would lead to a total annual nitrogen flux of 1.5 $*10^9$ mol N, ~1% of the surface flux of nitrogen (Kumar et al. 1996) from rivers. Thus, available limited data do not clearly advocate the submarine discharge to be the substantial source of nutrient in the surface Bay of Bengal. Further studies are required for better quantification.

Cyclonic churning, therefore appears to be the best candidate to explain the high new production.

4.11 Natural Nitrogen Isotopic Composition of Suspended Matter

The importance of the study related to the natural isotopic composition of nitrogen in suspended matter has already been discussed in the previous chapter. In the Bay of Bengal the stations studied are divided into two transects: one along the 88°E longitude (Stn.1-Stn.13), defined here as offshore stations (transect) and the other parallel to the Indian coast (Stn. 14 to Stn.24) as the shelf stations (transect).

4.11.1 Surface suspended matter

In the Bay of Bengal, it has been observed that the average surface particulate organic nitrogen (PON) concentration during postmonsoon (~1.41 μM N) is nearly twice that of premonsoon (0.71μM N). During the postmonsoon the difference in average shelf (1.31 μM N) and offshore (1.49 μM N) surface PON is around 0.18μM N, which is significant. The same is not true for the premonsoon season, where it averages 0.74μM N for shelf and 0.69 μM N for offshore locations. During the study period, a maximum surface PON of 2.5μM N has been observed at Stn.15 (postmonsoon), which is the nearest to the coast with the shallowest water column depth of 620m. The $\delta^{15}N$ values of surface PON for both pre and postmonsoon season range from 2 to 7.6 ‰ and fall in the general range of known oceanic $\delta^{15}N$ for PON. The overall $\delta^{15}N$ of surface PON averages around 4.1‰ for postmonsoon and around 4‰ for premonsoon season, which agree within analytical error. There is a significant difference of 1.5‰ between average $\delta^{15}N$ of offshore (4.8‰) and shelf (3.3‰) stations during postmonsoon (Table 4.5). However, no such difference has been observed for the

samples collected during premonsoon, (where both average around 4‰). There is no significant latitudinal variation in $\delta^{15}N$ during either season. There exists a significant

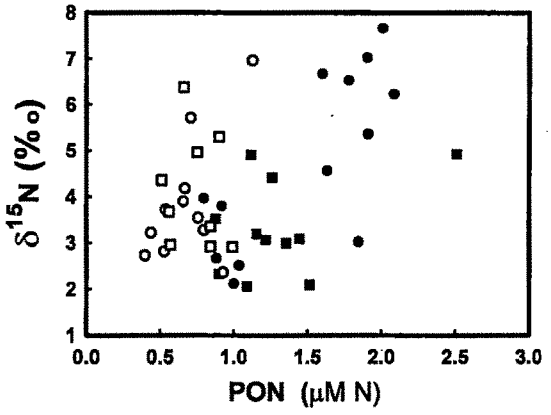


Figure 4.21 The relationship between $\delta^{15}N$ and PON during post (filled circles and squares represent offshore and shelf stations) and premonsoon (open circle and squares represent offshore and shelf stations).

Table 4.5 PON content and $\delta^{15}N$ of surface suspended matter observed during pre and post monsoon in the Bay of Bengal.

Stations	Premonsoon		Postmonsoon	
	$\delta^{15}N$(‰)	PON (μM)	$\delta^{15}N$(‰)	PON (μM)
1	3.2	0.44	6.7	1.60
2	2.8	0.53	5.3	1.91
3	3.9	0.66	7.6	2.01
4	N.A	N.A	2.1	1.00
5	N.A	N.A.	3.8	0.92
6	4.2	0.67	4.0	0.80
7	5.7	0.71	6.5	1.78
8	3.5	0.76	7.0	1.91
9	3.7	0.54	2.7	0.89
10	2.7	0.40	6.2	2.09
11	7.0	1.13	3.0	1.85
12	3.3	0.80	2.5	1.04
13	2.3	0.93	4.6	1.64
14	N.A	N.A	3.1	1.22
15	5.3	0.90	4.9	2.51
16	5.0	0.75	3.0	1.35
17	2.9	0.84	3.1	1.45
18	3.4	0.84	2.1	1.51
19	3.7	0.56	4.9	1.12
20	3.0	0.57	2.3	0.90
21	2.9	0.99	2.1	1.09
22	6.4	0.66	3.2	1.15
23	4.4	0.51	3.5	0.88
24	N.A	N.A.	4.4	1.26

positive linear correlation between PON and $\delta^{15}N$ (Figure 4.21) during the postmonsoon (r^2 = 0.42, n=24, p = 0.005; $\delta^{15}N$ = 2.35*PON + 0.78) and vanishes during premonsoon (r^2 = 0.09; $\delta^{15}N$ = 2.01*PON + 2.52). During the postmonsoon shelf stations show less variability and data points lie in the lower regime i.e., low PON- low $\delta^{15}N$ zone. On the other hand, the offshore stations show two clusters of data points, one with low PON-low $\delta^{15}N$ which averages around 3.0‰ and other with high PON-high $\delta^{15}N$ with an average of 5.8‰. During the premonsoon no clear cut distinction exists between $\delta^{15}N$ of PON in shelf and offshore ocean transects.

In oceanic environments, PON is mainly derived from phytoplankton, micro-zooplankton, bacteria and detritus. The nitrogen isotopic signature of PON in suspended matter depends on the isotopic fractionation associated with its formation, and in turn upon the isotopic composition of inorganic form of dissolved nitrogenous sources (such as $NO3^-$, 3-7‰; $NH4^+$, 6-8‰; and atmospheric N_2, 0‰; Miyake and Wada 1967) available for the utilization by phytoplankton. The variation in $\delta^{15}N$ of PON reveals the utilization of different nitrogen sources by phytoplankton as these sources have distinct isotopic compositions. Microscopic study suggested absence of *Trichodesmium* during the postmonsoon, while diatoms were found to be the dominant species. However, there were sporadic occurrences of *Trichodesmium* during the premonsoon but it did not dominate in terms of N contribution to the PON. Our $\delta^{15}N$ data also precludes the possibility of significant N_2 fixation in the Bay of Bengal, as the cyanobacteria *Trichodesmium*; a well-known N_2 fixer, generates PON with a $\delta^{15}N$ value (0.6‰) nearer to the atmospheric N_2 in equilibrium with seawater (Emerson et. al. 1991). $\delta^{15}N$ values around -2 to 0‰ has also been reported for cyanobacteria *Trichodesmium* (Minagawa and Wada 1986). All our $\delta^{15}N$ data are above the required value for an area dominated by N_2 fixers.

For the purpose of discussion, stations in the Bay may be classified into two based on the surface salinity of the stations. The first includes the stations with salinity less than 32psu (the six shelf stations and three offshore stations during postmonsoon; Figure 4.22) and second includes the stations with surface salinity more than 32psu (all the rest). The former are influenced by the riverine discharge whereas the latter are not. The salinity and $\delta^{15}N$ of suspended PON (Figure 4.22) for the two seasons indicate that when salinity is low (<32 psu), the $\delta^{15}N$ is consistently on the

lower side (2-3‰) (except at one location each in shelf and offshore region, which have $\delta^{15}N$ values of 4.9 and 4.6‰ respectively). The rivers draining the BOB bring a lot of terrestrial organic as well as detrital material (Unger et al. 2003). The consistent low

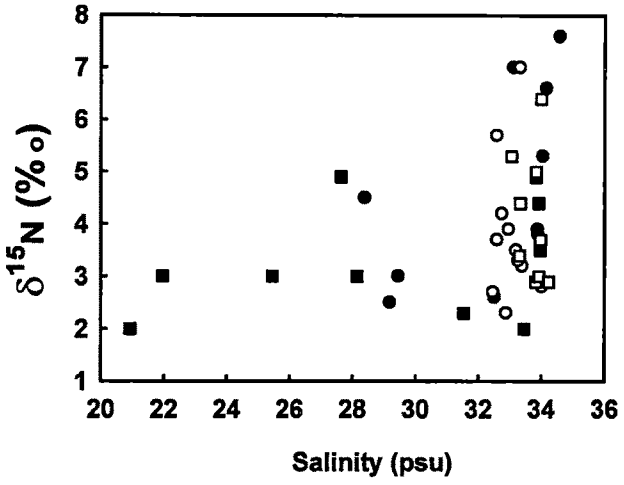


Figure 4.22 The relationship between salinity and $\delta^{15}N$ for post (filled circles and squares represent offshore and shelf stations) and premonsoon (open circle and squares represent offshore and shelf stations).

$\delta^{15}N$ suggests that isotopic signature of PON at these locations have been influenced by terrestrial inputs. Terrestrial particulate matter, brought by major rivers, might have diluted the overall $\delta^{15}N$ signal of PON, although there exists no literature regarding the $\delta^{15}N$ of such particulate matter draining into the Bay. But, the naturally occurring land derived materials are known to have low $\delta^{15}N$ (mean of 2.5‰ for terrestrial organic matter, Sweeney et al. 1978; and 1.5‰ for terrestrial detrital component, Mariotti et al. 1984). Also, the C: N values in suspended matter during postmonsoon at locations under terrestrial influence have been found to be relatively higher (9.5, 9.3 and 8.2 at stations 12, 16 and 18 respectively) compared to stations without influence (5, 3.4, 4.6, 6.2 and 6.4 for stations 3, 6,9,20 and 23 respectively), indicating the contribution of continental inputs at these stations.

The stations, which are not influenced by riverine discharge, show a wide isotopic variability (2-7.6‰). However, high average $\delta^{15}N$ of surface suspended matter (5.3 ‰ for offshore stations during postmonsoon and 4‰ for both offshore and shelf stations during premonsoon) have been observed for these stations. Since these locations are unaffected by the terrestrial influence the variability observed may be

attributed to the two possible reasons: first, uptake of regenerated ammonium (Wada and Hattori 1976); and second, supply of nitrate from deeper waters due to the presence of shallow nitracline, which is between 50-100m (Prasanna Kumar et al. 2002). In the former case, regenerated ammonium produced by excretion of zooplankton and heterotrophs in the surface layer has been considered as a source. In most oceanic regions, ammonium is the preferred substrate and normally does not accumulate in the surface layer (Mino et al. 2002). Soon after regeneration of ammonium, it is rapidly taken up by the algae; there is little time for isotopic fractionation and the $\delta^{15}N$ of ammonium is imprinted in PON without much modification. Unfortunately, $\delta^{15}N$ of ammonium in the BOB has not been measured to directly assess the role of ammonium on $\delta^{15}N$ of PON. Values in the range of 6-8‰ have been reported for ammonium in other oceans (Miyake and Wada 1967). However, indirect estimation of degree of contribution of ammonium in $\delta^{15}N$ of PON may be obtained from the new production (Dugdale and Goering 1967) measurements in the region (Kumar et al. 2004). If the new production is less, there could be a prominent effect of the regenerated ammonium on the $\delta^{15}N$ of PON. But in the Bay of Bengal, in general, high new production has been observed during present study in both post (average ~ 2.6 mmolN m^{-2} d^{-1}) and pre (average ~5.4 mmolN m^{-2} d^{-1}) monsoon. Therefore, regenerated ammonium is likely to have played a limited role in observed $\delta^{15}N$ of PON. However, significant ammonium contributions cannot be ruled out for three locations in the open ocean during postmonsoon and at one location during premonsoon, where values higher than 6‰ have been observed.

The nitrate from deeper water is a known source of nutrients in the Indian Ocean for phytoplankton (Vinaychandran and Mathew 2003); however, its possible imprint on $\delta^{15}N$ of PON and related fractionation mechanism could only be estimated if the nitrate $\delta^{15}N$ is known. But, as in the case of ammonium, nitrate $\delta^{15}N$ has also not been measured in the Bay. $\delta^{15}N$ values of 3-7‰ have been reported for nitrate in deeper waters lacking significant column denitrification as in the Bay (Miyake and Wada 1967; Cline and Kaplan 1975). The average value reported here for $\delta^{15}N$ of PON in offshore waters during both post and premonsoon seasons (5.3 and 4%) are found to be of similar magnitude. However, the observed variability can be explained in two different ways: first, the rapid uptake of the nitrate without fractionation and second, the fractionation of nitrate during uptake by the phytoplankton. In the first scenario, the

consumption of nitrate has to be fast enough for little or no isotopic fractionation and the original $\delta^{15}N$ of nitrate would be reflected in the $\delta^{15}N$ of PON (Altabet and McCarthy 1985; Wada and Hattori 1991). In this case, complete consumption of nitrate from the surface would be expected. The offshore stations during postmonsoon show a virtual absence of nitrate from the surface, implying its complete consumption. However, there is variability (2.1 to 7.6‰) in the $\delta^{15}N$ of PON at these offshore stations despite undetectable ambient nitrate. Out of the thirteen stations, ten have $\delta^{15}N$ ranging from 3 and 7.6‰, falling in the range of $\delta^{15}N$ for oceanic nitrate as mentioned earlier. This variability in $\delta^{15}N$ of PON indicates the possibility of change in isotopic composition of source nitrate. $\delta^{15}N$ for 3 stations falls below 3‰ and cannot be explained by the complete consumption argument, discussed above.

The $\delta^{15}N$ at premonsoon locations varies from 2.7 to 7‰ with relatively higher surface nitrate concentration (0.2 to 1.1μM). This availability of nitrate pool in the surface water suggests that the phytoplankton have the luxury of discriminating in favour of ^{14}N during uptake. The exact mechanism by which these nutrients reach the surface in the open Bay during premonsoon is a subject of speculation. However, nitrate for shelf locations during premonsoon might have been supplied by the EICC acting north of about 10°N. The EICC is best developed during March-April and decays only by June (Shetye et al. 1993).

As mentioned earlier, $\delta^{15}N$ of suspended matter in BOB varies from 2 to 7.6‰, falling in the known oceanic range (-5 to +15‰; Wada and Hattori 1991). However, the latter is known to fall in different ranges depending on the nitrogen source and fractionation by the phytoplankton. Table 4.6 compares a few recent studies of $\delta^{15}N$ in suspended matter of the world ocean. Rau et al. (1998) observed values in the Monterey Bay varying between 1.3 to 7.6‰, similar to the range observed during present study. Mino et al. (2002) have studied near surface waters along 50°N to 50°S in the Atlantic Ocean and the values ranged from -0.8 to 5.4‰. The negative relationship between $\delta^{15}N$ of PON and nitrate concentration as observed by Rau et al. (1998) and Mino et al. (2002) was not observed during present study. Relatively higher values (4-6‰) observed by Mino et al. (2002) have been attributed to the rapid consumption of nitrate from deeper waters as found in a few open ocean stations during the postmonsoon of the present study.

Overall, the $\delta^{15}N$ values of PON in the surface waters observed in the Bay may be explained in terms of mixing between (i) the terrestrial particulate matter with low $\delta^{15}N$, which has mostly influenced the six shelf locations and three offshore locations during postmonsoon, and (ii) marine phytoplankton, which has mainly inherited the $\delta^{15}N$ of nitrate from deeper waters. However, the phytoplankton have a wide spectrum of values because of two extremes: one due to uptake of nitrate without fractionation (highest $\delta^{15}N$) and other with high degree of fractionation (lowest $\delta^{15}N$).

Table 4.6 $\delta^{15}N$ of particulate organic nitrogen in surface suspended matter from different oceanic regions of the world.

Oceanic regions	$\delta^{15}N$ (‰)	References
Southern Ocean		
Subantarctic zone	~1	Lourey et al. (2003)
Polar Frontal zone	0 to -4	Lourey et al. (2003)
Atlantic Ocean	-0.8 to 5.4	Mino et al. (2002)
Monterey Bay	1.3 to 7.6	Rau et al. (1998)
Sargasso Sea (annual Av)	0.2	Altabet (1988)
Northeastern Indian Ocean	2.1 to 10.1	Saino and Hattori (1980)
Bay of Bengal	2 to 7.6	Present Study

4.11.2 Depth profiles of $\delta^{15}N$ of suspended matter

Depth related changes in nitrogen isotopic composition have been used as an indicator of particle transformations in ocean (Altabet 1988). Figure 4.23 presents the vertical profiles of $\delta^{15}N$ and PON for premonsoon season at different locations in the Bay of Bengal. The profile is upto 300m or more, except for Stn.3, where it is only up to 100m. Average $\delta^{15}N$ of PON in the top 60m for all the stations varies between 1.9 (Stn. 14) to 4.9‰ (Stn.16) with an average of around 3.6‰. Below 60m, $\delta^{15}N$ increases with depth and reaches an average value of 5.9 (±1.1)‰ at 300m. For the offshore stations the average top layer (60m) $\delta^{15}N$ shows a decreasing trend from south to north with a maximum of 4.5‰ for southernmost station (Stn. 3) and minimum of 2.9‰ for northern station (Stn.12). $\delta^{15}N$ also shows subsurface minima between 10 to 60 m varying with location. PON, in general, decreases with depth showing subsurface maxima within the euphotic zone. Top layer (60m) average of PON is ~ 0.7μM N that

decreases to ~0.3μM N at 300m. The depth distribution of $\delta^{15}N$ in suspended matter is in agreement with the general pattern observed in the world ocean i.e., it increases with depth and appears to be ubiquitous feature (Saino and Hattori 1980; Altabet and McCarthy 1985; Saino and Hattori 1985; Altabet and McCarthy 1986; Saino and

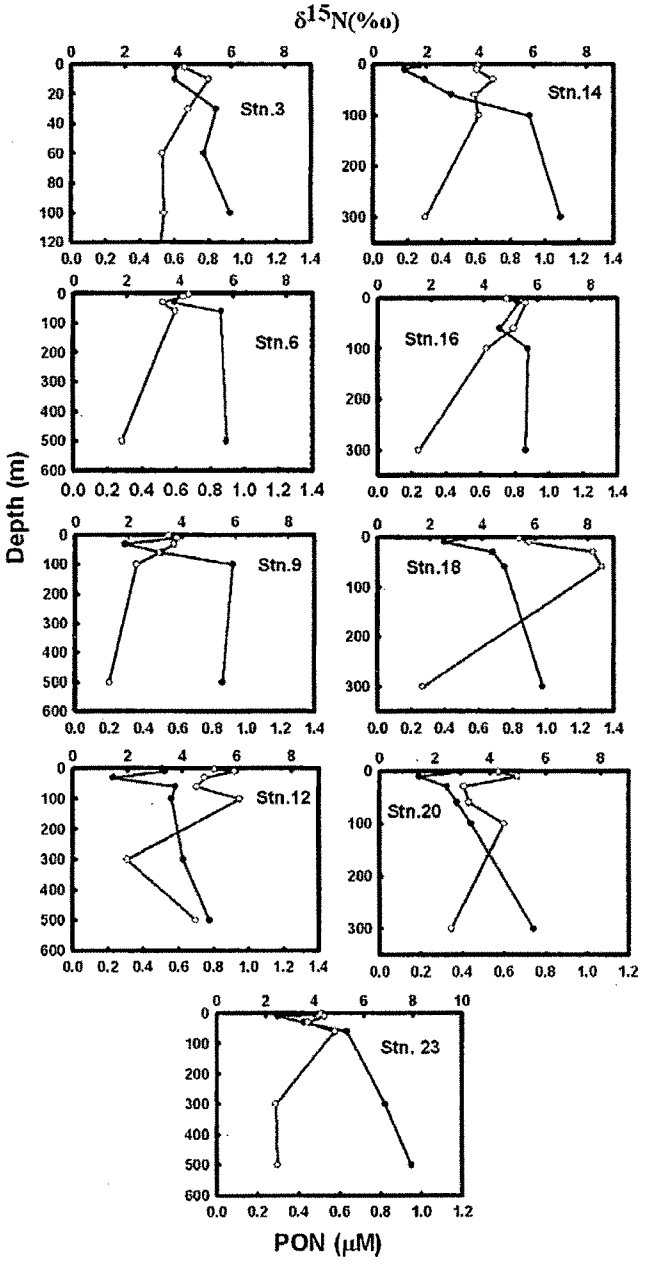


Figure 4.23 The depth profiles of $\delta^{15}N$ and PON during premonsoon in Bay of Bengal at different stations. The filled and unfilled circles indicate $\delta^{15}N$ and PON respectively.

Hattori 1987; Altabet 1988). At most locations there is an increase in $\delta^{15}N$ below 60m. This increase is from 0.21 to around 4‰ between 60 and 300m depending upon the

stations. High $\delta^{15}N$ below euphotic depth has been observed mainly due to two reasons: (1) progressive decomposition of suspended matter itself causing the preferential release of ^{14}N leaving the remaining PON enriched in ^{15}N, in other words, release of dissolved nitrogen depleted in ^{15}N during decomposition. The increased $\delta^{15}N$ below the euphotic depth has been correlated with decreasing concentration and has often been cited as evidence for isotopic fractionation during the destruction of suspended particulate matter (Altabet and McCarthy 1986; Saino and Hattori 1980; Saino and Hattori 1985). This decrease in PON with depth has been observed during present study. (2) Production of suspended matter due to fragmentation of sinking particles below the euphotic depth (Bacon et al. 1985). These sinking particles are enriched in $\delta^{15}N$ by 3-4 ‰ relative to suspended particle in euphotic zone because these particles are formed mainly as a by-product of zooplankton feeding, causing an increase in $\delta^{15}N$ with each trophic step (DeNiro and Epstein 1981). The difference in $\delta^{15}N$ between suspended and sinking PON ($\Delta\delta^{15}N$) has been proposed as a measure of number of trophic steps linking primary production to the export of particulate organic matter from the euphotic zone as sinking particles (Altabet 1988). $\Delta\delta^{15}N$ of 0 has also been observed by Altabet et al. (1991) during bloom conditions where phytoplankton aggregate and sink directly without trophic transfer. However, the variation in isotope ratio in biogeochemical processes are closely related to physico chemical conditions like water circulations, light, salinity and temperature etc. There is no data regarding $\delta^{15}N$ of sinking particles for the Bay of Bengal at 300 or 500m depths. However, $\delta^{15}N$ values for sinking particles are expected to increase with depth but lesser than the suspended particles (Altabet et al. 1991). The sediment traps placed at around 2000m in the Bay show $\delta^{15}N$ variation in the range of 2.2-6.2 ‰ (Schafer and Ittekkot 1995). But $\delta^{15}N$ of deep sinking particles (~2000m) is known to be less as it starts decreasing below 500m (Saino and Hattori 1987; Altabet et al. 1991). Based on this argument the $\delta^{15}N$ of sinking particles around 300m in the present study area should be around 6‰. However, extensive interconversion of sinking and suspended particles through disaggregation and reaggregation also homogenize the $\delta^{15}N$ signal between the two (Bacon et al. 1985); but Altabet et al. (1991) have observed that suspended and sinking particles do not extensively interact in the ocean as proposed earlier. Saino and Hattori (1980) have found $\delta^{15}N$ as high as ~12‰ at 300m depth in the far eastern Indian Ocean. However our data suggest the average value of ~6‰ for the Bay of Bengal at

the same depth. This may be due to the high sinking rate of particles in the Bay allowing it lesser time for degradation. Here, the particle removal to the deep sea occurs in the form of large aggregates formed by the interaction of organic and mineral matter introduced from external sources like rivers and wind. This increases their density and consequently the settling rate in water column (Ittekkot 1991). Minima in the $\delta^{15}N$ of PON within the surface layer as reported by Saino and Hattori (1980), has been observed during present study too, possibly due to the isotopic fractionation during nitrate uptake in light limited conditions.

4.12 Primary productivity estimation using IRS P4 OCM

Due to their broad and synoptic coverage remotely sensed images of ocean colour are considered important for spatial extrapolation of local data collected from ships in ocean biogeochemical studies (Platt and Sathyendranath 1993). These are also the only practical means for monitoring the spatial and seasonal variation of near surface phytoplankton that is essential for studying ocean primary productivity, global carbon and other biogeochemical cycles. During present study an attempt has been made to quantify the primary productivity using IRSP4 OCM (Indian Remote Sensing Satellite P4 Ocean Colour Monitor) data.

The main objective of the ocean colour remote sensing is the quantitative estimation of the oceanic constituents (such as chlorophyll, suspended matter, yellow substances etc.) from the spectral nature of the solar radiation backscattered from the ocean waters. Only the visible portion ($\lambda \sim$ 400-670nm) of the solar spectrum penetrates into the water and undergoes absorption and multiple scattering due to a series of interactions with suspended (phytoplankton, sediment etc.) and dissolved (DOM etc.) matter present. A small portion of this visible radiation is scattered out of the water and is detected by ocean colour sensor. These radiances are detected in a set of suitably selected wavelengths and the concentrations of oceanic constituents are estimated using a variety of empirical, semi-empirical and analytical algorithms.

IRSP4 OCM (Oceansat-1)

IRS P4 (Oceansat-1) was launched by the Indian Space Research Organization (ISRO) on May 26, 1999 with the objectives of gathering systematic data sets for

oceanographic, coastal and atmospheric applications. The satellite is placed in a near circular, sun-synchronous orbit at an altitude of 720km with the local time of equatorial crossing in the descending node at 1200hrs ±10minutes. This satellite carries two oceanographic payloads: the Ocean Colour Monitor (OCM) and Microwave Scanning Multi-frequency Radiometer (MSMR). OCM makes measurement of radiances in different spectral bands that relate to concentrations of phytoplankton pigments, suspended matter and coloured dissolved organic matter in coastal and oceanic waters and also the marine atmospheric aerosol parameters. The technical characteristics of IRS P4 are given in Table 4.7.

Table 4.7 The technical specifications of IRS P4 OCM.

Parameters	Specifications	Applications
Spectral Range	404-882nm	
No. of Spectral bands	8	
Wavelength Range	nm	
Channel 1	404-423(414.2)	Yellow substance and turbidity
Channel 2	431-451(441.4)	Chlorophyll absorption maxima
Channel 3	475-495 (485.7)	Chlorophyll and other pigments (< 1.5mg m^{-3})
Channel 4	501-520 (510.6)	Chlorophyll and other pigments (> 1.5mg m^{-3})
Channel 5	547-565(556.4)	Suspended sediments (Away from Chlorophyll and Gelbstoff)
Channel 6	660-677(669.0)	Second Chlorophyll absorption maxima
Channel 7	749-787(768.6)	O_2 absorption R-branch
Channel 8	847-882(865.1)	Aerosol optical thickness
Satellite Altitude	720km	
Spatial Resolution	360 X 236m	
Swath	1420km	
Repetivity	2 days	
Quantisation	12 bits	
Equatorial crossing time	12 noon	
Along track steering	20°	
Camera MTF	> 0.2	
Transmission Frequency	X-Band	
Data rate	20.8 kbps	
SNR	>500	

4.12.1 OCM data processing for Oceanic constituents

OCM data was processed using an in house software package developed at the Space Applications Centre, Ahmedabad (Chauhan et al. 2001). The main steps involved in the processing for the retrieval of oceanic parameters are:

1. Atmospheric correction i.e., retrieval of water leaving radiance in visible bands.
2. Implementation of bio-optical algorithm to normalised water leaving radiance data for estimating the chlorophyll concentration.

Atmospheric correction

The radiation detected by sensor is a mixture of the radiation emerging from water (water leaving radiance) and the solar radiation backscattered by the air molecules (Rayleigh scattering) and the aerosols (Mie scattering) in the atmosphere. The part of the radiation contributed due to the back scattering by air molecule and aerosols is known as atmospheric path radiance and constitutes more than 85% of the radiance at Top of the Atmosphere (TOA). Therefore the radiance detected by ocean colour sensor at TOA in the wavelength λ can be split as (Doerffer 1992): $L_t(\lambda) = L_a(\lambda) + L_r(\lambda) + t_d(\lambda) * L_w(\lambda)$

Where, L_t = Sensor detected radiance

L_a = aerosol path Radiance

L_r = Rayleigh path radiance

L_w = water leaving radiance

t_d = Atmospheric diffuse transmittance

The main idea of the atmospheric correction is to get rid of atmospheric path radiance for which OCM is equipped with two channels in infrared wavelength (channels 7 and 8) where ocean appears dark due to high infrared absorption by water. The radiation detected by OCM in these two bands is mainly due to scattering in the atmosphere and is used for estimating the atmospheric scattering contribution in lower wavelengths ($\lambda <$ 700nm) that is removed from sensor radiances through the atmospheric correction procedure (Gordon and Wang 1994). The atmospherically corrected water leaving radiances are subsequently utilised for the estimation of oceanic constituents using suitable bio-optical algorithms. Cloud screening algorithm is also applied on the OCM data prior to atmospheric correction procedure where albedo in Channel 8 (865nm) is computed and if found > 1.1%, the pixel is masked as cloudy.

Chlorophyll *a* algorithm

A variety of bio-optical algorithms for estimating Chlorophyll (C) and Chlorophyll and Phaeopigments (C+P) from ocean radiance data have been developed and most of them

are empirical equations derived by statistical regression of radiance versus Chlorophyll. During the present study, the empirical algorithm proposed by O'Reilly et al. (1998) known as Ocean Chlorophyll 2 or OC2 for processing SeaWiFS ocean colour data, has been used. O'Reilly et al. (1998) have proposed this algorithm after a comprehensive evaluation of a large number of semi-analytical and empirical bio-optical algorithms for the data collected from different sources and different global locations. OC2 captures the inherent sigmoidal relationship between $R_{rs}490/R_{rs}555$ band ratio and the Chlorophyll concentration (C) Where R_{rs} is remote sensing reflectance. The simple and reversible functional form used by OC2 as well as its statistical and graphical results were superior to other formulations evaluated. The algorithm takes the following mathematical form:

$$C\ (mg\ m^{-3}) = 10^{**}(0.319 - 2.336*R + 0.879*R^2 - 0.135*R^3) - 0.071$$

For $0.01 mg\ m^{-3} \leq C \leq 50\ mg\ m^{-3}$. $R = \log_{10} [R_{rs}490/R_{rs}555]$.

Algorithm for diffused attenuation coefficient (K)

The following algorithm has been used for the calculation of the diffused attenuation coefficient K (490):

$$K(490) = 0.022 + 0.100 * [L_{wn}(443)/L_{wn}(555)]^{-1.30}$$ (Muller and Charles 1994)

Where L_{wn} is the water leaving radiance in the second and the fifth bands. K (490) has been computed by assuming case I waters where changes in phytoplankton biomass is considered to be the most important factor for the changes in optical properties of seawater.

4.12.2 Estimation of Primary production

Models for estimating primary productivity range from relatively simpler (empirical) to complex (spectral). During the present study non-spectral irradiance model proposed by Platt and Sathyendranath (1993) has been used with the following assumptions:

*Biomass is uniform throughout the upper mixed layer depth.

*Ignores spectral structure of irradiance.

*Sinusoidal variation of surface irradiance.

This model takes the mathematical form where water column primary production is proportional to the biomass (B), assimilation number (P^B_m) and day length (D) and

inversely proportional to attenuation coefficient (K) and is also a function of the normalised irradiance.

$$\int_{Z,T} P \sim [(B^* P^B{}_m{}^* D) / K] * f(I_0{}^m * \alpha^B / P^B{}_m)$$

Where, $I_0{}^m$ is noon irradiance at sea surface and α^B is the initial slope of photosynthesis-light curve. $P^B{}_m$ and α^B are called P-I parameters and are characteristic of given water mass.

The solution of the above equation is given in terms of fifth order polynomial and the whole equation is expressed as:

$$P_{Z,T} = [(B^* P^B{}_m{}^* D) / K] * \sum_{x=1}^{5} \Omega_x (I_*{}^m)^x$$

After putting the weights (Ω_x) for x =1 to 5 the equations takes the form:

$$P_{Z,T} = [(B^* P^B{}_m{}^* D) / K] * [0.610305 * I_m - 0.089251 * I_m{}^2 + 0.0081477 * I_m{}^3 - 0.00037427 * I_m{}^4 + 0.0000066103 * I_m{}^5]$$

Where, $I_m = (I_0 * \alpha^B / P^B{}_m) * [e^{-K*Z1} - e^{-K*Z2}]$ and Z1 and Z2 are surface and mixed layer depth.

The parameters required in the model for the calculation and their sources are the following:

- Biomass (**B**) obtained using the OC2 model discussed above.
- Diffused attenuation Coefficient (**K**) obtained using the above model.
- Day Length (**D**) and
- Photosynthetically active Radiation ($\mathbf{I_0}$) for the desired days of year has been estimated using Bird's Clear Sky spectral irradiance model (Bird 1984) with adjustments by Sathyendranath and Platt (1988).
- **Z1** is the surface whereas **Z2** is the mixed layer depth taken from monthly mixed layer depth chart (Hasternath and Greisher 1989).
- The P-I parameters ($\mathbf{P^B{}_m}$ and $\boldsymbol{\alpha^B}$) are characteristics of water types and change over season and phytoplankton species. Assimilation number ($P^B{}_m$) represents a point where photosynthesis becomes independent of light whereas the initial slope of photosynthesis-light curve (α^B) is a measure of the effectiveness of phytoplankton in using the available light for photosynthesis. These two are obtained by generating a curve by a photosynthesis-light experiment, where a

sample of water containing phytoplankton are inoculated with a tracer for oxygen or carbon and incubated in a light gradient for a certain time period. To the best of our knowledge, no measurement of P-I parameter exists for the Bay of Bengal. During the present calculation P^B_m = 3.0 mg C (mg Chl)$^{-1}$h^{-1} and α^B = 0.1 mg C (mg Chl)$^{-1}$h^{-1} (Wm^{-2})$^{-1}$ has been used as in the case of the Arabian Sea (Brock et al. 1994).

4.12.3 Discussion

The primary productivity maps have been generated for the study period (September-October 2002 and April-May 2003) in the Bay of Bengal. The maps obtained for the relatively cloud free days are shown in Plates 1 and 2. In general, the total productivity varied from 100 to 1500mg C m^{-2}d^{-1}. The upper limit of productivity was mainly seen in the coastal waters (red colour). Chauhan et al. (2001) have shown that the OC2 algorithm when applied on OCM data works quite well for open ocean (r^2 = 0.85; rms = 0.175 mg m^{-3}) whereas it was not found satisfactory in the sediment laden case-2 waters (coastal water). This adds to a high level of uncertainty to the primary productivity estimation in coastal waters. However, in general, the error in Chlorophyll determination by OCM data has been around 35% for the range 0.01-10mg m^{-3} (Prakash et al. 2001) and hence this is the minimum error for productivity values also. The productivity maps during September-October show the cloud cover over the Bay that diminishes at the beginning of October. The cloud cover over the Bay seems to be a permanent feature that is evident during April-May 2003 also, particularly in the coastal region. Pixel-wise examination of the productivity values suggests a general overestimation of productivity by remote sensing data compared to insitu values. The overestimation is more during September-October than April-May where insitu values are relatively higher. Figure 4.24 shows the log-log plot of insitu and OCM generated productivity values. When OCM data of same day as insitu experiment is not available due to difference in insitu experiment and OCM pass, the value of last or next OCM pass has been taken. The same exercise has been done for cloudy pixels. The OCM productivity to represent the insitu location has been estimated by taking the average of 3X3 pixels around the exact location. The Figure 4.24 indicates the overestimation of primary productivity by more than 40% at most of the locations by OCM, particularly during September-October. The observed overestimation in productivity is due to the

sum of errors involved in estimation of bio-optical and assumed P-I parameters. The P-I parameter value taken for calculation seems to be higher for the Bay of Bengal. The value taken is actually of summer period for the Arabian Sea and is known to overestimate productivity in the intermonsoons. Changes in P-I parameters (α^B = 0.06 mg C (mg Chl)$^{-1}$h^{-1} (Wm^{-2})$^{-1}$) leads to a significant decrease in productivity value indicating the role of assumed high P-I parameter as one of the reasons for overestimation. The insitu determination of P-I parameters would greatly enhance the accuracy of productivity estimation by OCM data; however, P-I parameters are still scarce in the Arabian Sea and Bay of Bengal leading to significant errors in productivity estimation by algorithms using OCM data. Our measurements of new production and the linear relationship between new and total production can be used with improved algorithms in the Bay of Bengal to generate new production maps in the future.

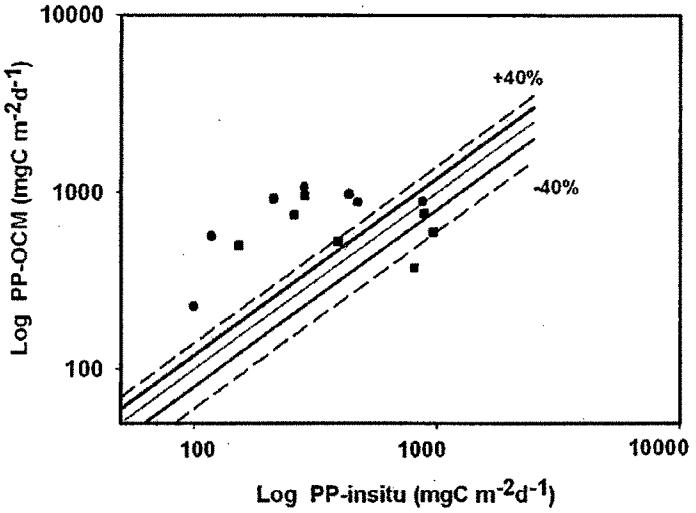
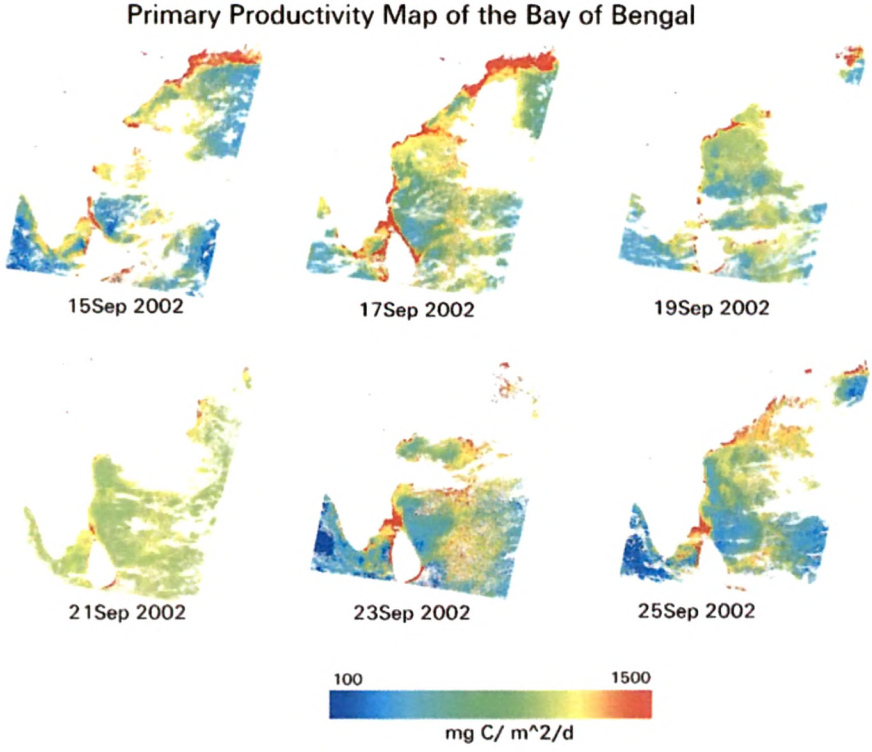


Figure 4.24: The Log-Log plot of euphotic zone integrated insitu primary productivity estimated by ^{15}N technique and corresponding climatological mixed layer integrated OCM values. The circles and squares represent September-October 2002 and March-April 2003 respectively.


Primary Productivity Map of the Bay of Bengal
15Sep 2002
17Sep 2002
19Sep 2002
21Sep 2002
23Sep 2002
25Sep 2002
100
1500
mg C/ m^2/d

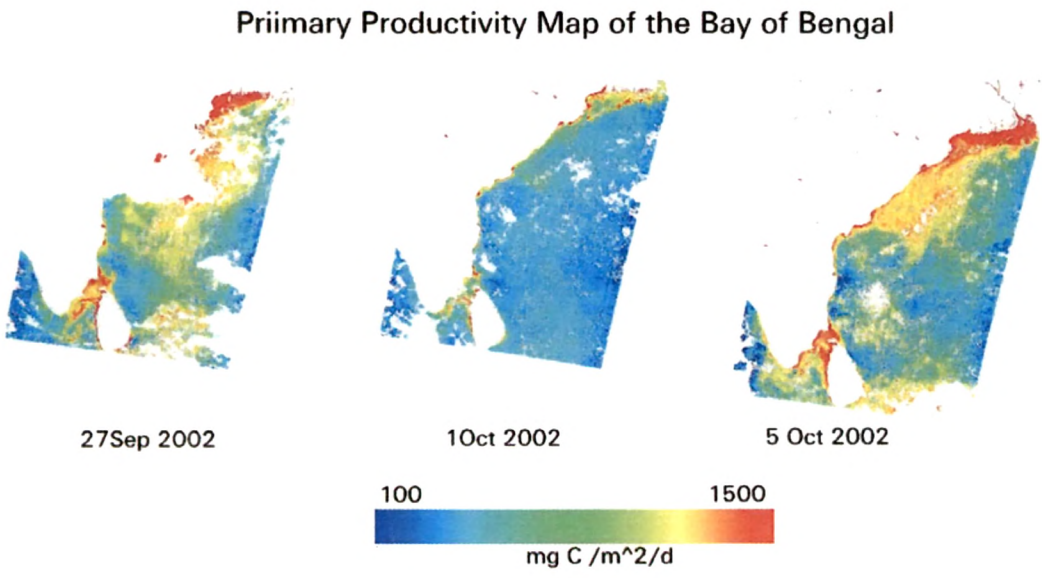
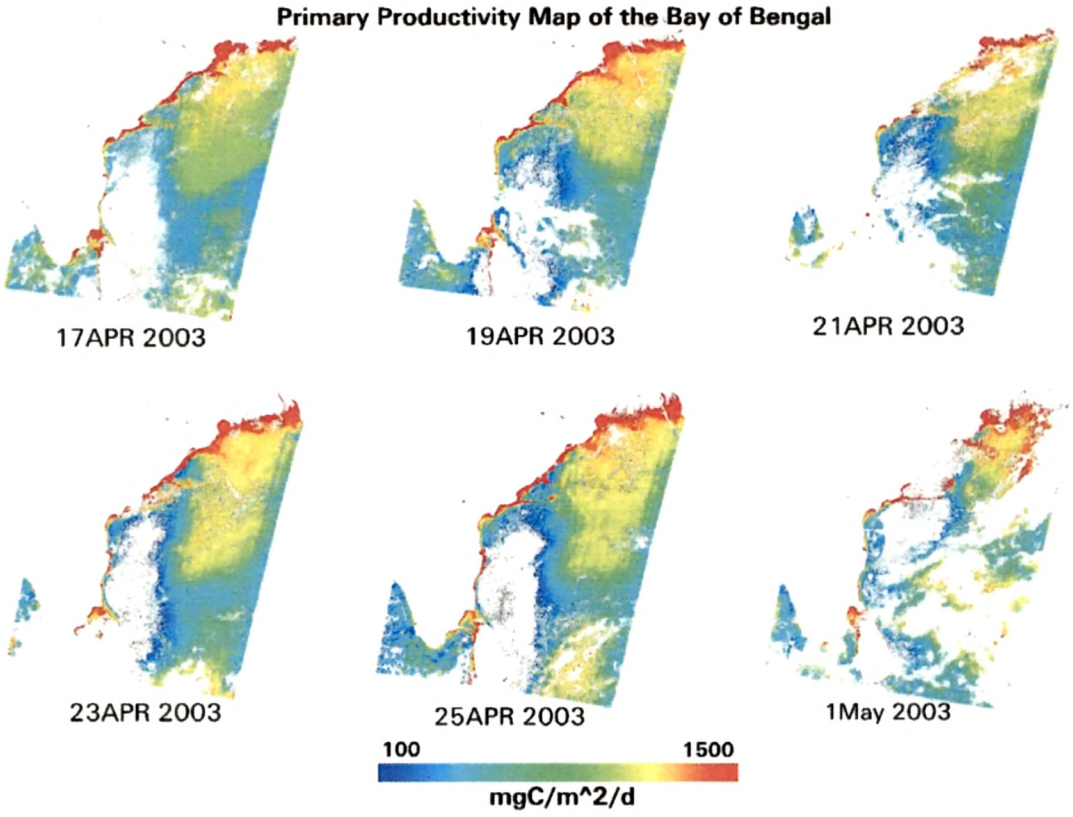
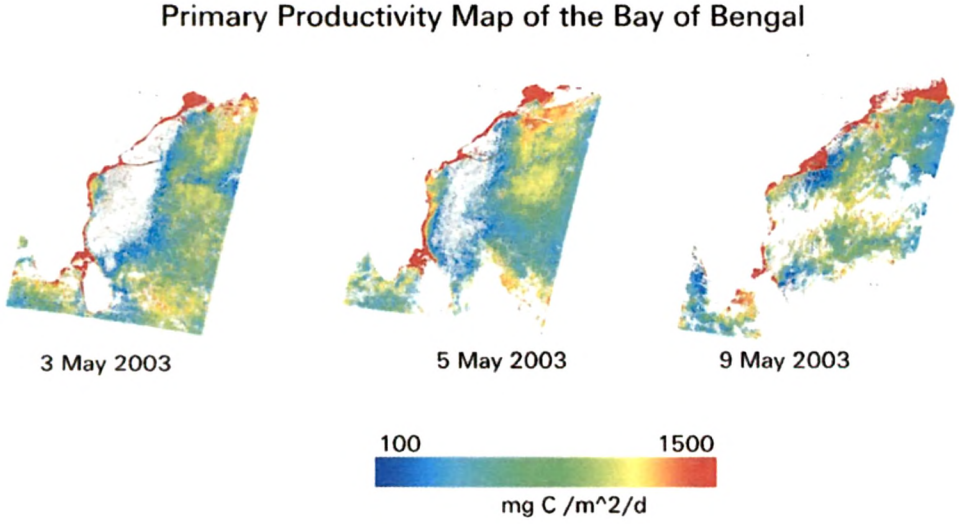

Priimary Productivity Map of the Bay of Bengal
27Sep 2002
1Oct 2002
5 Oct 2002
100
1500
mg C /m^2/d

PLATE 1

PLATE 2


Primary Productivity Map of the Bay of Bengal
17APR 2003
19APR 2003
21APR 2003
23APR 2003
25APR 2003
1May 2003
100
1500
mgC/m^2/d


Primary Productivity Map of the Bay of Bengal
3 May 2003
5 May 2003
9 May 2003
100
1500
mg C /m^2/d

4.13 Conclusions

The main aim of the present study in the Bay of Bengal was to estimate new production in different seasons. The natural nitrogen isotopic variabilities in suspended sediments and its fate at depth along with uptake experiments were also an important part of the work. The main results of the study are as follows:

- The new production measurements in the Bay of Bengal consistently show fairly high values, which average around 2.6mmolN $m^{-2}d^{-1}$ during the postmonsoon and 5.4 mmol N $m^{-2}d^{-1}$ during the premonsoon.

- The average new production during premonsoon is more in the shelf area than in the offshore, contrary to that observed during the postmonsoon, reflecting the shift in the nitrate availability in the Bay.

- The observed higher new production in the Bay could also be one of the reasons for observed high organic carbon fluxes in the sediment trap.

- The observed high new production could be the reason for observed low pCO_2 in the surface Bay of Bengal and OMZ.

- $\delta^{15}N$ of the surface PON in the Bay during postmonsoon shows a signature of mixing between continental and marine inputs.

- $\delta^{15}N$ of PON increases with depth as in the case of other oceans; however, the increase is lower than in the eastern Indian Ocean, indicating the role of high settling rates of sinking particles in the Bay.

- New production, in general, may be underestimated if incubation time is less than four hours.