Chapter 5
Summary and
Scope for future work

5.1 Important findings of this study

The present study has added new data that can lead to better understanding of carbon fixing potential of the northern Indian Ocean. **For the first time**, new production and natural isotopic variability of nitrogen have been measured in the Bay of Bengal and the northeastern Arabian Sea. In addition, some uptake experiments and the estimation of primary productivity using IRSP4 data has provided insights into the experimental procedure and parameters to be adopted for the region. The important results that have emerged from this study and their implications are summarized below:

5.5.1 New production in the Bay of Bengal

The results obtained from the estimation of new production in the Bay of Bengal during the present study have emphasized the role of moderately productive oceans in the global carbon and nitrogen cycles. An ocean basin, such as the Bay of Bengal, is capable of high new production, and thus can be efficient in removing the atmospheric CO_2 on longer time scales. The results obtained so far have the following possible implications:

Reason for comparable organic carbon flux observed in sediment traps

The average rate of photosynthetic fixation of carbon by marine phytoplankton is more than a factor of two higher in the Arabian Sea than in the Bay of Bengal. 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 mg C m^{-2} d^{-1} (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 Bay of Bengal, except for the upwelling region in the north-west. The experiments done in two different seasons discussed earlier consistently show relatively higher new production (averaging around 2.6 mmolN m^{-2} d^{-1} during postmonsoon and 5.4 mmol N m^{-2} d^{-1} during premonsoon) and could be one of the reasons for relatively higher downward organic carbon flux in the moderately productive Bay. One explanation for 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, independent estimates of new production based on nitrogen uptake during present study have helped to understand this in a better way, because, new production and particle sinking are coupled over longer time scales (Eppley et al. 1983). Consistent higher new production observed during two different seasons in the Bay indicates its role in the observed organic carbon flux on the time scales of sediment traps data. Hence, such oceanic regions may play a more significant role in removing the excess anthropogenic CO_2 from the atmosphere, than believed so far.

Reasons for reduced pCO_2 in surface Bay of Bengal

Limited earlier data regarding the air-sea exchange of CO_2 for the northern Indian Ocean in general, and Bay of Bengal in particular 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) predicted that cause for the low pCO_2 in the Bay could be physical as well as biological processes. One such important physical parameter known to decrease the pCO_2 level is salinity, however, Kumar et al, (1996) have shown that the salinity can lower the pCO_2 by a maximum of ~30 μatm, which was about 25% of the highest recorded pCO_2 drawdown, and therefore predicted that biological activity should account for most of the observed pCO_2 decrease by sustaining moderately high new production. New production during April-May 2003 (overall average~ 433 with shelf region average of 552 and offshore average of 284 mg C m^{-2} d^{-1}) and September-October 2002 (overall average~ 207 with shelf stations averaging around 180 and offshore region around 243 mgC m^{-2} d^{-1}) observed during present study in the Bay of Bengal is indeed higher and comparable to the new production off India, 400±160 mg C m^{-2} d^{-1} reported for the Arabian Sea. Therefore, the present study successfully verifies the earlier conjecture put forward to explain the low pCO_2 in the surface Bay.

Contributing to development of Oxygen Minimum Zone in the Bay

Presence of OMZ in ocean is usually explained by the utilization of oxygen due to decomposition of organic matter brought into the deeper water from surface that holds good for the productive Arabian Sea. But the existence of OMZ in the Bay of Bengal, where the overhead productivity is moderate, is puzzling. The present study provides one possible explanation. Due to the observed high new production in the Bay the flux of material going to the deeper waters could be more than that previously believed and this higher flux could be responsible for consuming the available dissolved oxygen for the decomposition, leading to the formation of OMZ.

5.5.2 Results from uptake experiment

The mechanism through which nutrients are supplied and the kinetics of dissolved inorganic nitrogen utilization play a critical role in determining the productivity, size structure, and species succession of phytoplankton in the world ocean. During the present study, experiments were performed to examine the effect of concentration and time on the uptake rate of different nitrogenous species, which lead to the following results.

New production may be underestimated if the incubation time is less than four hours. Incubation done for different time periods (one to four hours) after adding the enriched tracers for nitrate, ammonium and urea revealed that the uptake rate for nitrate remained the same for the first two hours but increased after the end of fourth hour (from 0.92 to 1.5μmol $m^{-3}h^{-1}$). However, for ammonium, it decreased after one hour and remained the same for higher incubation times (0.74 to 0.38 μmol N $m^{-3}h^{-1}$). The urea uptake declined after the third hour (2.48 to 1.56 μmol N $m^{-3}h^{-1}$). These variations in uptake rates of different N-species lead to change in the f-ratio from 0.29 (after two hours) to 0.42 (after four hours).

An opposite trend has been observed for the case where tracer addition significantly higher than 10% of the ambient concentration was made. When the concentration of tracer was varied (keeping the incubation time constantly four hours), the uptake rate for both urea [$y = 1.88x + 0.004$ ($r^2 = 0.88$)] and ammonium [$y = 2.07x - 0.002$ ($r^2 = 0.55$)] showed a positive relationship with substrate concentration (x). However, nitrate uptake [$y = -0.76x + 0.05$ ($r^2 = 0.86$)] showed a negative correlation. The f-ratio changed from 0.47 to 0.10 when tracer added was increased from 0.01 to 0.04 μM.

5.5.3 Natural isotopic composition of nitrogen in suspended matter of the Bay of Bengal

The first systematic measurements of $\delta^{15}N$ in surface suspended matter of shelf as well as northern offshore Bay of Bengal shows signatures of mixing between continental inputs and marine sources. Dilution by the organic and detrital continental material brought in by rivers leads to a consistently lower $\delta^{15}N$, evident from the relationship between surface salinity and $\delta^{15}N$. $\delta^{15}N$ values of surface PON of open ocean locations during both seasons, and also at coastal locations during premonsoon suggest nitrate from deeper waters to be a predominant source of nutrients to the phytoplankton. The depth profiles of $\delta^{15}N$ of PON during the premonsoon season at nine different locations are in agreement with the observed trend in the world ocean i.e., they increase with depth. This increase in $\delta^{15}N$ is by maximum around 4‰ between top 60m and 300m, which is lower than that observed in the far eastern Indian Ocean, indicating the role of higher sinking rates of particles ballasted by aggregates of organic and mineral matter in BOB. The particulate organic nitrogen content decreases with depth as expected.

5.5.4 Total productivity comparison with IRSP4 data

Primary productivity was calculated using indigenous satellite data during the present study. However, lack of P-I parameters in the Bay of Bengal and errors in retrieval of oceanic constituents from satellite data led to overestimation of total production. Comparison of the ^{15}N based total production and total production obtained from IRS P4 data reveals the overestimation of satellite based production by more than 40%.

5.5.5 New and regenerated production in the Northeastern Arabian Sea

The new and regenerated production in the northeastern Arabian Sea has been estimated for the first time during present study. At almost all the stations during January NH_4 was assimilated in preference to urea and NO_3. This preference may be because of higher energy requirement during the assimilation of NO_3. Overall variation in the f ratio is from 0.15 to 0.60 and the inclusion of urea uptake rates in the calculation leads to a decrease in the overall average f-ratio by almost 27%.

Effect of winter cooling on new production and f-ratio during January

New production and f- ratio, in general, show increasing trends from the south (off Goa) to the north (off Gujarat), clearly depicting the systematic effect of intensification of winter cooling. Northeast trade winds prevalent in the region during this season bring the cool, dry continental air causing an increase in the evaporation and heat loss from the surface water. This intensified evaporation leads to surface cooling and consequent increase in the density, causing the surface water to sink setting up convective mixing. This whole process leads to a deepening of the MLD and consequent transport of nutrients from the base of the mixed layer and upper thermocline to the surface to increase the new production. The increased MLD also suggests a strong coupling between the surface and subsurface layers.

Negative relationship between f-ratio and integrated nitrate has been observed during the month of January indicating that even at higher column nitrate, the f-ratio can be low, probably due to the inefficient utilization of nitrate. This situation can arise because of suppression of nitrate uptake by the presence of ammonium or because of higher addition of $^{15}NH_4$ tracer. However, during the present study the ammonium addition has not been found to be a possible reason. The third possibility could be the deterioration of light condition due to the deep mixed layer and a relative preference for ammonium in light limited conditions.

Increased new production during late February-early March bloom and nutrients for its sustenance

The average column new production during March has been found to be more than five times the new production observed during January; however, there is no systematic spatial variability in the new production as was the case during January. The f-ratio (upper bound) in the region averages around 0.60 (±0.10) and inclusion of urea uptake rate into the calculation decreases it by almost a similar fraction (25%) as during January. The observed increase in new production may be due to lateral advection of nutrients from the first three stations or it may be sustained by the nutrient that entrained during January. The nitrate residence time for the nitrate entrained during January at most of the stations was more than 50 days suggesting that if the same rate of removal due to nitrate uptake by phytoplankton continues, the nitrate in the water column will remain at least for 50 days. This nitrate might have sustained the bloom during February-March, once the light conditions became optimum due to the waning effect of winter cooling.

5.5.6 Natural isotopic composition of nitrogen in the suspended matter of the Arabian Sea

The nitrogen isotopic composition of the surface suspended matter has been estimated during the January and early March in the Arabian Sea. Most noticeable and significant is the overall increase by ~5‰ in $\delta^{15}N$ of the surface suspended matter in the region from January to March. Similarly, a significant increase of 0.7μM N in PON content has also been observed. This increase in the isotopic composition of PON during March is possible due to an overall increase in the nitrogen isotopic composition of source ($\delta^{15}N$) nutrient taken up by the phytoplankton or due to a change in the fractionation behaviour of the phytoplankton, while maintaining the same $\delta^{15}N$ of nitrate during both periods. The analysis of nutrient regime suggests that if the deeper nitrate is the source during both months, the observed increase may be indicative of intensified denitrification leading to an isotopic enrichment of the source nitrate. And if the nitrate entrained during the January is the source, the continuous uptake by the phytoplankton might have led to an isotopic enrichment observed during March.

5.2 Scope for future work

The Arabian Sea and the Bay of Bengal provide magnificent environments to understand the complexity of carbon and nitrogen cycles and their isotopes. These two adjacent basins are endowed with significantly different marine environments. On the one hand, the Bay can be studied for the effect of fresh water input on marine realm, while the Arabian Sea offers highly productive regions and denitrification zones to study the biogeochemistry of nitrogen and its isotopes. An attempt has been made during present study to cover a few biogeochemical aspects of nitrogen and its isotopes, the present study can be improved and new research can be pursued in this field. Based on the limitations faced during present study, the following could be areas of potential future research:

(A) Thorough understanding of nutrient regime in the Arabian Sea and Bay of Bengal.

One of the major limitations of the present work is the non-availability of the ambient ammonium and urea concentrations leading to conservative estimates of regenerated production (except for January in the Arabian Sea). Arabian Sea is one of the most studied basins in the world but the knowledge of ambient ammonium and urea concentrations remains limited, particularly in the northeastern Arabian Sea. There is no data for ammonium and urea in the Bay of Bengal, to best of our knowledge. The thorough understanding of nutrient regime in these two basins, particularly in the Bay of Bengal, can provide immense information about the regenerated production and its seasonal and spatial variability.

(B) Study of nutrient inputs by rivers

The nutrients brought in by rivers are known to affect the ecosystem of coastal waters. Bay of Bengal receives a huge amount of freshwater influx, potentially bringing a lot of nutrients; but a thorough knowledge of the amounts of nutrients such as nitrogen and phosphorus brought in by major rivers to the Bay is lacking, which could have provided important insights into the role these extraneous nutrients play in sustaining new production. Nitrogen and oxygen isotope based studies to infer the source of nutrients, particularly nitrate, for the rivers like Ganga and Brahmaputra during their journey from source to the ocean could be a challenging area of research.

(C) Study of Atmospheric input of nutrients

The dry and wet deposition of nutrients to the ocean and its role in modifying the productivity has gained momentum in recent years due to its significant contribution particularly to the oceanic regime closer to landmass (Kouvarakis et al. 2001). The Arabian Sea and Bay of Bengal have the potential to receive the atmospheric inputs particularly during monsoon periods. The increased frequency of atmospheric sampling in these basins can enhance our present understanding of nutrient inputs by atmospheric deposition.

(D) The isotopic composition of nitrate and ammonium

The knowledge of isotopic composition of seawater nitrate and ammonium is very essential to thoroughly understand the nutrient utilization behaviour in the marine environment. It would help in finding a better explanation of the observed variability in the isotopic composition of suspended matter and related fractionation patterns along with identifying the source of nutrients. Only one vertical profile for the isotopic composition of nitrate exists in the Arabian Sea (Brandes et al. 1998). However, there are no such measurements for ammonium. No such studies have been done in the Bay of Bengal either. The thorough study of nutrient concentrations along with their isotopic compositions would make a challenging and very significant study to take up.

(E) The P-I parameter evaluation

As mentioned in the earlier chapter, knowledge of exact P-I parameters for the Bay of Bengal and the Arabian Sea during different seasons would provide an opportunity to develop the primary and new production maps for the region and would help in estimating the carbon fixing potential of the region on larger temporal and spatial scales with better accuracy using satellite data.