Chapter Five

Conclusions and Scope for Future Work

Biogeochemical processes including the marine carbon cycle are the key factors in global change. The ocean works as a net sink for CO_2, a potential greenhouse gas, through biological pump. The present study brings new data on oceanic productivity using ^{15}N tracer technique which not only gives total productivity but also categorise it into new and regenerated productivity; new productivity indirectly gives an estimation of the export production i.e., amount of carbon that is getting removed from the atmosphere for a sufficiently longer time scale through biological activities. For the first time, ^{15}N based productivity has been measured in the equatorial Indian Ocean. It also provides comprehensive data on new and regenerated productivity and *f*-ratios of the northeastern Arabian Sea and the southern Indian Ocean and has made an effort to asses the role of the Indian Ocean in the Global Carbon Cycle. The important results that have emerged from this study have been summarised below:

5.1 The northeastern Arabian Sea

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

- The Arabian Sea was characterized by the presence of two different biogeochemical provinces during the late winter monsoon: low productive southern province and highly productive northern province with an overall increasing trend from the south to the north.
- Total productivity in the southern region averaged around 5.5 $mmolNm^{-2}d^{-1}$ (440 $mgCm^{-2}d^{-1}$) whereas in the north it was 19 $mmolNm^{-2}d^{-1}$ (1520 $mgCm^{-2}d^{-1}$); increase in productivity from the south to north was more than three fold.
- New productivity also increased on south-north transect, from 2.1$mmolNm^{-2}d^{-1}$ (168 $mgCm^{-2}d^{-1}$) in the south to 15.7 $mmolNm^{-2}d^{-1}$ (1256 $mgCm^{-2}d^{-1}$) in the north. Increase in new productivity was more than 7-fold.
- High nitrate uptake during the *Noctiluca* bloom at the northern stations measured during the present study, in accordance with Bienfang et al.,

(1990), suggests the developing phase of the bloom where nitrate contributed most to the total N-uptake.

- Urea uptake rate was higher than the ammonium uptake rate at all the non-bloom stations but during the *Noctiluca* bloom in the northern stations, ammonium was preferred over urea by the plankton.
- The column integrated total production (x) and new production (y), show a significant correlation (Fig.2): for non-bloom stations: y = (0.44 ± 0.23) x – (0.30 ± 1.38); (coefficient of determination, r^2 = 0.43) and for bloom stations, y = (1.08 ± 0.23) x – (4.68 ± 4.46); (r^2 = 0.91). The slope of regression (i.e., 0.44 and 1.0 for non-bloom and bloom stations respectively) is the maximum possible value of the *f*-ratio.

The results from productivity measurements during early winter monsoon:

- During the early winter monsoon total productivity varied from 4.07 $mmolNm^{-2}d^{-1}$ (326 $mgCm^{-2}d^{-1}$) to 23.31 $mmolNm^{-2}d^{-1}$ (1865 $mgCm^{-2}d^{-1}$) with a mean of 8.65 $mmolNm^{-2}d^{-1}$ (692 $mgCm^{-2}d^{-1}$). Productivity during this season was almost half of that during the bloom but was more than the productivity in the south during the late winter monsoon.
- New productivity showed a large variation; it varied from a low of 1.95 $mmolNm^{-2}d^{-1}$ (156 $mgCm^{-2}d^{-1}$) to a high of 19.70 $mmolNm^{-2}d^{-1}$ (1576 $mgCm^{-2}d^{-1}$).
- Ammonium uptake was more than urea uptake at all the stations unlike those during the late winter monsoon. Also the mean ammonium uptake rate was more than that during the late winter but urea uptake was almost half.
- The *f*-ratio varied from 0.46 to 0.87. This suggests that 46-87% of the total productivity can be exported to the deep under a steady state condition. Relation between total and new productivity yielded a slope of 0.88 which suggests that at the most 88% of the total productivity can be exported.

In general, results from the present study suggest almost three fold increase in the total productivity during the developing phase of the *Noctiluca* bloom. This increase was more than seven fold in new productivity. During early winter monsoon, total and new productivity was less than those during the bloom but was more compared to non-bloom southern regions. The most important finding of the present study for the eastern Arabian Sea is the identification of two different biogeochemical provinces during the late winter monsoon where the northern province was four times more productive than the southern. Above results from the two seasons suggests that productivity in the Arabian Sea is heterogeneous in space and time but still this basin is capable of high export production, with moderately high *f*-ratio during non-bloom period and very high *f*-ratio during *Noctiluca* bloom period, and thus plays a significant role in global carbon cycle.

5.2 The equatorial Indian Ocean

The results from the equatorial Indian Ocean are:

- Total N-uptake was very less: it varied from 0.66 $mmolNm^{-2}d^{-1}$ to 2.23 $mmolNm^{-2}d^{-1}$. Mean N-uptake was 1.32 $mmolNm^{-2}d^{-1}$ (105.6 $mgCm^{-2}d^{-1}$)
- New production along 77°E transect was 0.20 $mmolNm^{-2}d^{-1}$ (16 $mgCm^{-2}d^{-1}$), almost half of the same 0.43 $mmolNm^{-2}d^{-1}$ (34.4 $mgCm^{-2}d^{-1}$) along 83°E transect.
- The *f*-ratio was low though it showed considerable spatial variation: it varied from 0.14 to 0.40. The f-ratio was low along 77°E (mean = 0.18) transect but was relatively high along 83°E (mean = 0.29).
- Urea was the most preferred form of nitrogen for phytoplankton followed by ammonium. Nitrate was the least preferred.
- Upper mixed had greater control on the productivity of this region. Since this layer was devoid of any nutrients, the productivity was less. Also due to strong stratification the export production was low.

The present study was the first step towards understanding the biogeochemistry of the equatorial Indian Ocean. The results from this region suggest that mixed layer has greater control on the productivity. Total and new production were very less in this layer and so the *f*-ratio. Reduced forms of nitrogen were preferred over nitrate.

5.3 The Southern Indian Ocean

The results from the Southern Indian Ocean are:

- Euphotic zone integrated total uptake rate varied from 1.73 $mmolNm^{-2}d^{-1}$ (138 $mgCm^{-2}d^{-1}$) to 12.26 $mmolNm^{-2}d^{-1}$ (981 $mgCm^{-2}d^{-1}$) in the Southern Indian Ocean; the highest rate was measured in the Antarctic coastal zone (69°S).
- New productivity varied from 0.92 $mmolNm^{-2}d^{-1}$ (73.6 $mgCm^{-2}d^{-1}$) to 7.7 $mmolNm^{-2}d^{-1}$(616 $mgCm^{-2}d^{-1}$). The Antarctic coastal zone, equatorial region and STF had more new production compared to other regions of the Southern Ocean.
- Mean total uptake in a large part of the Southern Ocean was very low. It was 1.73 $mmolNm^{-2}d^{-1}$ (138 $mgCm^{-2}d^{-1}$), almost one-seventh of the Antarctic coastal zone.
- Productivity suddenly increased to 10.26 $mmolNm^{-2}d^{-1}$ (821 $mgCm^{-2}d^{-1}$) at sub-tropical front (STF) where Antarctic cold water and subtropical warm water meet.
- The *f*-ratio varied from 027 to 0.63 in the Southern Ocean with a mean of 0.50 with an upper limit of 0.63.
- Mean Column N-uptake rate at two equatorial stations sampled during this study was ~8 $mmolNm^{-2}d^{-1}$. The *f*-ratio was almost the same (0.45) at both stations.

While a large area of the Southern Indian Ocean is not highly productive, it appears capable of moderate export productivity and thus could be significant in removing atmospheric CO_2 on longer time scales. Relatively high productivity was measured in Antarctic coastal zone, STF and equatorial Indian Ocean. A large part of the Southern Ocean, HNLC region, is less productive but can have high export production, almost 50% of the total. A mean *f*-ratio of 0.50 in the Southern Ocean indicates that the autotrophic community uses nitrate as well as regenerated nutrients equally. Compared to other data from similar regions (Mengesha et al., 1998, Savoye et al., 2004) the present study shows a shift in productivity regime from regenerated nutrient based production to nitrate based production, in the last 12 years, possibly due to global warming. This means a slightly greater export production in this region than before. These results are the first comprehensive estimates of nitrogen based productivity in a large area in the Southern Indian Ocean. Again, a significant correlation between total and new productivity can provide a significant input for the estimation of carbon fluxes over a large region using satellite data.

5.4 Scope for future work

Even though some major programmes such as JGOFS and BOBPS have been conducted, a large part of the Indian Ocean still lacks good data coverage, especially the equatorial Indian Ocean and the Southern Ocean. Even though the Arabian Sea has received some attention of oceanographers all over the world for being dynamic in space and time, the major emphasis has been given to the central and western Arabian Sea; the northeastern Arabian Sea is relatively less studied. In order to understand the role of the Indian Ocean, as a whole, in the global carbon cycle we need much more comprehensive understanding of the primary and export productions taking place in this part of the world ocean. For this we need more such observations pertaining to the estimation of new production and the *f*-ratio. The following issues can be addressed in future research:

A. The most widely spread form of *Noctiluca scintillans* is completely heterotrophic and is red in colour, survives on a wide range of prey such as phytoplankton and micro-zooplankton [*Hansen et al.*, 2004]. The present study is among the first few works (Sanjeev Kumar et al., 2008) which has highlighted the occurrance of green *Noctiluca* bloom in the northeastern Arabian Sea, enhancing the total as well as new productivity. During this period, the *f*-ratio may be as high as 0.91. Simultaneous measurement of export flux using other techniques such as sediment trap or ^{234}Th along with ^{15}N tracer technique will also be useful in understanding the role of this basin in atmospheric carbon sequestration. More studies during the bloom, using nitrogen isotopes, will give a better insight into the biogeochemical properties of this part of the world ocean. More number of studies will also help in establishing whether the biogeochemical divide of northeastern Arabian Sea during bloom was a separate event or was a regular phenomenon.

B. High productivity events of Arabian Sea is followed by the formation of oxygen minimum zone in sub-surface layer as the concentration of dissolved oxygen with 150-1000 m decreases to less than 0.1 ml/l (Naqvi and Jayakumar 2000). This causes vigorous denitrification, a process through which the ocean looses biologically available nitrogen, where bacteria begin to utilize oxygen derived from NO_3 instead of O_2 for decomposing organic debris. So far, no attempt has been done to study the formation of oxygen minimum zone followed by winter bloom. Quantification of denitrification which follows the bloom of winter monsoon is important to estimate the carbon and nitrogen budget and hence it needs to be corporated in the future studies.

C. Planktonic marine cynobacteria called *Trichodesmium* fixes atmospheric nitrogen during photosynthesis (Capone et al., 1997) and thus they are the source of new nitrogen to the marine cycle (Karl et al., 1997). No direct measurement has been done to quantify N_2 fixation by these cynobacterium in the Arabian Sea. Direct estimation N_2 fixation in future, using $^{15}N_2$ tracer, will help understanding the nitrogen cycle of this basin in a better way.

D. A major limitation of the present study is the unavailability of ambient ammonium and urea concentrations leading to conservative estimate of regenerated production. In the absence of these measurements, regenerated production is often underestimated and thus the *f*-ratio is overestimated. Even though the Arabian Sea is one of the most studied regions of the world ocean data pertaining to the ambient ammonium and urea measurements are limited.

The same holds true for equatorial Indian Ocean and the southern Indian Ocean. A thorough understanding of the nutrient regimes in these basins will provide immense information about the productivity regimes.

E. Unavailability of bio-available iron is believed to limit primary production in a large part of the Southern Ocean. A number of large scale iron enrichment experiments have been done in the recent past in different parts of the Southern Ocean to ascertain the role of iron in limiting marine biological productivity but still no such experiment has been carried out in the Indian sector of the Southern Ocean. A study of effect of iron enrichment on the nitrogen uptake rates will give a better insight into the biogeochemistry of the Southern Ocean.

F. ^{15}N tracer technique can be effectively combined with ^{13}C. A coupled tracer techniques for the estimation of primary and new production may give a better understanding of the productivity regimes and nutrients kinetics and so quantification of new productivity using this technique should be the course of research in the future.