A Summary of the thesis on "Role of the Ocean in the Global Carbon Cycle"

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Chapter 1. INTRODUCTION

Biogeochemical processes including the marine carbon cycle are the key factors in global change. During the last 150 years the concentration of CO_2 in the atmosphere has increased by 35% compared to the pre-industrial level (from 280ppm in pre-industrial era to 379ppm in 2005) (IPCC AR IV-2007) and is projected to double in the coming century, mainly due to anthropogenic activity such as fossil fuel burning, deforestation and change in the land use pattern. This has lead to an increase in the global temperature by 0.74±0.18°C during the last century (IPCC AR IV-2007). The observed growth rate of CO_2 in the atmosphere is less than that expected. This is because a major part, approximately 104.9 Gt/yr, of this is taken up by the terrestrial and oceanic biota. In the oceanic photic zone, microscopic plants (phytoplankton) convert inorganic carbon through photosynthesis into particulate organic carbon. When these plankton die, they tend to sink to the deep and thus a large part of biologically fixed carbon gets exported to the deep. This is known as the "Biological Pump" and it plays an important role in the ocean's ability to absorb atmospheric carbon. In this way the ocean works as a net sink for this greenhouse gas. The rate at which inorganic CO_2 is converted into organic carbon by phytoplankton is called primary productivity, measured in units of $mgCm^{-2}d^{-1}$ or $mgCm^{-2}y^{-1}$.

Nitrogen plays a key role in oceanic productivity and its unavailability can be a limiting factor. On the basis of the source of nitrogen into the euphotic zone, primary productivity can be subdivided into two: new productivity and regenerated productivity (Dugdale and Goering 1967). New productivity is defined as a fraction of primary productivity supported by the newly borne nitrate into the euphotic zone and regenerated productivity as that supported by the recycled nutrients within the same zone. The ratio of the new productivity to the total productivity is called the *f*-ratio (Eppley and Peterson 1979). Integrated over an annual time scale, new productivity approximates the exportable productivity and thus, measuring new productivity allows us to quantify the amount of atmospheric carbon being removed by different regions of the ocean i.e., the strength and efficiency of the oceans biological pump.

As oceans play a major role in the global carbon cycle, it is required to quantify the amount of inorganic carbon taken up by the individual ocean basins. Also the assessment of different ocean basins as source/sink of carbon is important. The present study was carried out using the ^{15}N tracer technique (Dugdale and Wilkerson 1986) which gives total production as a sum of new production (nitrate uptake) and regenerated production (ammonium and urea uptakes). The advantage of this technique lies in the quantification of new productivity which is a measure of carbon removed from the surface for significantly longer time periods (>1000yrs). The present work is a comprehensive study of primary productivity in different regions of the Indian Ocean such as the Arabian Sea, equatorial Indian Ocean and Southern Indian Ocean. Though some study has been carried out previously in some selected parts of the Arabian Sea, most of them are concentrated on the north-western and central Arabian Sea. No study has been done in the equatorial Indian Ocean and Southern Indian Ocean. The present study concentrates on the north-eastern Arabian Sea and is the *first* to measure primary productivity in the *equatorial Indian* and *Southern Indian Oceans*.

Chapter 2: Sampling Locations, Seasons and Experimental Techniques

The main aim of this thesis is to characterize the Indian Ocean on the basis of new production and *f*-ratio and to evaluate its role in the Global Carbon Cycle. To achieve this goal, three different methods are used:

1. Ocean color studies of northeastern Arabian Sea
2. ^{15}N based measurements in the some region of the Arabian Sea. Measurements were also done in the equatorial and the southern Indian Ocean
3. Small scale iron enrichment experiment in the southern Indian Ocean

Recent observations based on ocean colour show that the summer productivity in the western Arabian Sea has been increasing during the last seven years, reportedly due to the warming of the Eurasian landmass (Goes et al., 2005). Ocean color data from SeaWiFS (Sea-viewing Wide Field of view Sensor) for the eastern Arabian Sea were analyzed by me to asses the role of global climate change on the productivity of the eastern Arabian Sea.

For ^{15}N based measurements four cruises were undertaken: two cruises in the eastern Arabian Sea and one each in the equatorial Indian Ocean and the Southern Indian Ocean.

The details of the cruises with the region of study, cruise number and duration are described in detail in this chapter.

2.1 Ocean colour studies

The only possible way to monitor the variation in the biological properties of the ocean on a larger spatial scale is by remote sensing. Chlorophyll-a, which is the main photosynthetic constituent in the phytoplankton, absorbs more in blue than in green; as the concentration of phytoplankton increases, the backscattered light progressively shifts towards the green. This property is successfully used to derive the Chl-*a* concentration with the help of a sensor in a satellite. In the tropics, where variation in sunlight is not significant on an interannual scale, variation in chlorophyll concentration can indicate the variation in primary production. Satellite ocean colour data provides the spatial and temporal variations in phytoplankton biomass and hence in the primary production on a larger scale. Since the launch of SeaWiFS (Sea-viewing Wide Field of view Sensor) in August 1997, global ocean colour data are available to the science community on a regular basis. For present study, monthly composites Level-3 Version 4 9-km resolution mapped SeaWiFS chlorophyll images were taken. From these images chlorophyll values were obtained using SEADAS software (provided by NASA for ocean colour image processing).

The seasonality of the north-east Arabian Sea SST (Sea Surface Temperature) is also inspected over the same region for the same time period in order to analyse the effect of sea surface cooling due to upwelling on the chlorophyll-*a* concentration. Monthly composite SST data are taken from AVHRR (Advanced Very High Resolution Radiometer) pathfinder version 5 (June-1997 to Dec-2004) and MODIS (Moderate Resolution Imaging Spectro-radiometer) data (Jan-2005 to June-2005). We also analyzed version-3 QuickScat data in order to monitor change, if any, in wind speed over past 6 years (1999-2005).

The remote sensing studies were done for the eastern Arabian Sea. We have divided the eastern Arabian Sea into two zones: Zone 1 extends from 20°N to 25°N and 62°E to 75°E and zone 2 extends from 20°N to 10°N and 62°E to 75°E. This division (into two different zones) is based on the observed physical forcing responsible for the high production in each zone.

2.2 Primary Production

Joint Global Ocean Flux Study (JGOFS) protocol was followed for the estimation of total primary production which is the sum of new and regenerated production. For the present study nitrate uptake rate is considered as new production and a sum of ammonium and urea uptake rates as regenerated production. New production is measured as the uptake rate of ^{15}N-labelled nitrate by the phytoplankton during deck incubation and regenerated production as a sum of ^{15}N-labelled ammonium and urea uptake rates.

Experimental Procedures

The depth of the photic zone i.e., the depth at which light falls to 1% of the surface level, was estimated using an underwater radiometer (Satlantic Inc.). Based on these light measurements six different depths were chosen for collecting water samples for ^{15}N and chlorophyll measurements. These, six depths, correspond to light levels 100, 80, 64, 20, 5 and 1% of the surface value, cover the entire photic zone (except at two stations: PP 5 and PP 6). Water samples were collected using clean Go-Flo bottles (General Oceanic, Miami, Florida, USA) attached to a CTD rosette. 100 ml of each sample was separately collected for nutrient measurement using a SKALAR autoanalyzer. 1 L of water sample from each depth was also collected for chlorophyll measurement and filtered on 47 mm GF/F 0.7 μm pore size filter under low vacuum. Chlorophyll was then extracted using 10ml of 90% acetone (AR) grade and was measured using Turner Design fluorometer. Individual seawater samples were taken in duplicates in polycarbonate Nalgene bottles, for measurement of nitrate (2L), ammonium (2L) and urea (1L) uptakes rates. Appropriate neutral density filter were put on the bottles, immediately after the collection of samples, to simulate the same light condition that was present at the corresponding depths. This was followed by the addition of ^{15}N enriched (99 atom% ^{15}N) $Na^{15}NO_3$, $^{15}NH_4Cl$, and $CO(^{15}NH_2)_2$ (obtained from SIGMA ALDRICH USA) tracers to the individual samples taken for the measurement of nitrate, ammonium and urea uptake rates. The amount of nutrient tracer added corresponded to less then 10% of the ambient nutrient concentration. After the addition of tracers, the samples were incubated for 4 hrs symmetrical to the local noon on the deck. Sea water, pumped from a depth of 4 m was continuously circulated to maintain the temperature during incubation. Subsequently all samples were filtered subsequently under low pressure (<100mm Hg) through precombusted (4 hrs at 400°C) 47mm diameter and 0.7μm pore size Whatman GF/F filter, then dried in oven at 60°C overnight and brought to the shore for mass-spectrometric analysis. The samples were analysed using a *CarloErba* elemental analyser interfaced via conflo III to a *Finnigan Delta Plus* mass spectrometer, using a technique for sub-microgram level ^{15}N determination (Owens and Rees, 1989).

Analysis was done using a Finnigan Delta Plus stable isotope ratio mass spectrometer. The aim was to measure the total organic nitrogen content of natural and enriched samples and the atom% ^{15}N. For this, the mass spec is calibrated using some standard material, inorganic as well as organic, of known nitrogen content. Main standards used are: Potassium nitrate, ammonium sulphate, acetylene, Casein and BSA (an organic compound) which contains 13.8, 21.2, 10.3 and 17.8% nitrogen respectively. ^{15}N atom % estimation has an error of less then 0.5%. .Uptake rates were calculated using the equation given by Dugdale and Wilkerson (1986).

Quality Control

Special care was taken during experiments to avoid any contamination. For collection of samples Teflon coated Go-Flo bottles were used to avoid any trace metal contamination. These bottles were rinsed thoroughly before using them for sample collection. Samples were directly transferred from Go-Flo bottles to polycarbonate Nalgene bottles. No other plastic cans or pipes were used as a precautionary measure to avoid contamination. Always new and separate pipette tips were used for adding different tracers. Continuous running seawater was maintained during incubation to maintain the temperature. Samples were immediately transferred to the ship-board laboratory after incubation and kept covered under dark clothes till the filtration was over. Filtration cups were thoroughly washed with milliQ water before the filtration and were rinsed properly once the filtration of each sample was over. This was done to restrict cross contamination. Filter papers were handled using well cleaned and separate forceps for each tracer. After filtration each bottles were washed thoroughly using 10% HCl for the next experiment. For the mass spectrometric analysis samples were packed in clean silver foils. Blanks with silver foils were run in the mass spectrometer during every batch.

Chapter 3. The Northeastern Arabian Sea

The northern Indian Ocean is divided into two major ocean basins by the Indian Peninsula: The Arabian Sea in the west and the Bay of Bengal in the east. The Arabian Sea has a unique geographical setting: it is surrounded by the Arabian and African continents on its north and west and by the Indian peninsula on its east. The Arabian Sea is one of the most biologically productive region of the world ocean (Madhupratap et al., 1996; Smith, 2001) and is characterized by a range of biogeochemical provinces, based on atmospheric forcing due to the seasonally reversing southwest (summer) and northeast (winter) monsoons (Bange et al., 2000: Wiggert et al., 2000: Kumar et al., 2001a). Both trigger high biological production, but have different underlying mechanisms. During the winter monsoon, cool dry air from the Himalaya enhances evaporation in the northern Arabian Sea causing convective mixing. This deepens the upper mixed layer causing entrainment of nutrients from the deeper to the upper layers and triggers high primary production (Kumar et al., 2001b), sometimes leading to the initiation of phytoplankton bloom. The total production during this period can reach up to ~ 3 $gCm^{-2}d^{-1}$ (Sanjeev Kumar et al., 2007). The bloom during the late winter monsoon is dominated by *Noctiluca scintillans*, a large and conspicuous dinoflagellate, commonly found in coastal areas worldwide. Its most widely spread form is completely heterotrophic and is red in colour, survives on a wide range of pray such as phytoplankton and micro-zooplankton (Hansen et al., 2004). Heterotrophic *Noctiluca scintillans* had been reported from the eastern Arabian in the month of September i.e., during the late summer monsoon (Sahayak et al., 2005). In the tropical and subtropical areas of the Southeast Asia, particularly in the northeastern Arabian Sea during late winter monsoon, a green form of *Noctiluca scintillans* is also found which can do photosynthesis and survive on itself under light for at least a month (c.f Sweeney 1971). The appearance of *Noctiluca* bloom in the northeast Arabian Sea is well documented in the literature (Dwivedi et. al., 2006, Parab et al., 2006) but data available on the nitrogen uptake and *f*-ratios is limited (Sanjeev Kumar et al., 2008).

The rates of nitrogen uptake, integrated over euphotic zone, varied from 2.7 mmolNm^{-2}d^{-1} to 23.0 mmolNm^{-2}d^{-1} over the study area. The higher rates were measured at the stations in the north (PP9, 10 and 11), whilst the lower rates were associated with the southern stations. The same spatial variability in the nitrogen uptake was also reported by Owens et al., (1993) *i.e*, the lower uptake in the south and the higher in the north with an overall increasing trend from south to north. Euphotic zone integrated nitrate uptake rate or new production during the late winter monsoon in the eastern Arabian Sea showed significant variation in new production; it varied from 0.63 mmolNm^{-2}d^{-1} to 20.91 mmolNm^{-2}d^{-1}. It was low in the southern sector of the sampling area but was significantly higher in the northern sector. The mean new production in the southern sector or the non bloom area was 2.1 mmolNm^{-2}d^{-1} whereas in the bloom area it was 15.7 mmolNm^{-2}d^{-1}, almost eight fold higher than the non-bloom area. The present study indicates the presence of two different biogeochemical provinces in the eastern Arabian Sea during the late winter monsoon: less productive southern and more productive northern regions. The southern sector was characterized by low column N-uptake and low new production. The column integrated total N-uptake rates, although low, increased progressively towards north. This increase may be the effect of more intense winter cooling towards the north. The northern part was a highly productive zone, with very high N-uptake and new production.

During the early winter monsoon (i.e., in the month of December) the rates of nitrogen uptake varied from 4.07 mmolNm^{-2}d^{-1} to 23.31 mmolNm^{-2}d^{-1}. Unlike the late winter monsoon when higher uptake rates were measured at stations in the southern part of the eastern Arabian Sea, during the early winter monsoon no such pattern was seen in N-uptake rates at different stations in the same region. New production during early winter monsoon 2004 varied from 1.95 mmolNm^{-2}d^{-1} to 19.70 mmolNm^{-2}d^{-1}. In comparison to the rates of nitrate uptake measured during the late winter monsoon, new production during December month is thrice that of the same in a non-bloom (2.1 mmolNm^{-2}d^{-1}) region but is less than half of that (15.7 mmolNm^{-2}d^{-1}) in the bloom area. These clearly suggests that the productivity pattern has lots of heterogeneity over space and time in the eastern Arabian Sea but still this part of the world ocean has a potential of high new productivity.

Chapter 4. The Equatorial and Southern Indian Ocean

The equatorial region of the Indian Ocean is distinctly different from the other two major oceans in a sense that it does not posses equatorial upwelling regimes like the Pacific and Atlantic. Ocean upwelling does not occur along the equator as it occurs in the Pacific and the Atlantic ocean but in the north, along Somalia and Oman coast and also along western Indian coast, and this upwelling takes place only during the summer monsoon. Though it is now reasonably established, though dependent of season and direction of trade winds, that equatorial upwelling does take place in the Indian Ocean, yet no data exists on the productivity of this important basin. The equatorial Indian Ocean is still a virgin area and the present data set is the first set of data from this important basin. The rates of nitrogen uptake, integrated over the photic zone, span more than an order of magnitude over the study area and it varied from 19.1 mmolNm^{-2}d^{-1} to 171.1 mmolNm^{-2}d^{-1}. Though higher uptake rates were measured at almost all the stations, the N-uptake rates were low in the upper mixed layer and increased tremendously below mixed layer. Most of the productivity was confined below the mixed layer. This was mainly because nitrate concentration was below detection limit in the mixed layer, and in the absence of nitrate ammonium and urea were the preferred nutrient. But below the mixed layer, where the concentration of ambient nitrate increased dramatically, nitrate uptake also increased. The mixed layer integrated N-uptake rates were very low and were similar to the rates reported form the other oligotrophic regions around the world ocean. It varied from 0.81 mmolNm^{-2}d^{-1} to 2.23 mmolNm^{-2}d^{-1} over the study area. The mixed layer integrated nitrate uptake rates were very low: it varied from a minimum of 0.12 mmolNm^{-2}d^{-1} to a maximum of 0.84 mmolNm^{-2}d^{-1}. The mean new production over the study area was 0.32 mmolNm^{-2}d^{-1}. It was very low (0.20 mmolNm^{-2}d^{-1}) along 77°E transect but was more the twice (0.43 mmolNm^{-2}d^{-1}) along 83°E transect. Capability of the equatorial ocean for export production is low as compared to that of Arabian Sea (present study), Bay of Bengal (Sanjeev Kumar et al., 2004) and the Southern Ocean (present study). The slope of the regression equation between new and total production suggests that along 77°E transect only 9% of the total mixed layer production can be exported to the deep where the export production along 83°E transect may be as high as 38%, almost 4-fold more, of the mixed layer integrated total production.

The Southern Ocean, of which the Indian Sector constitutes ~39% by area (Mengesha et al., 1998), plays an important role in the global carbon cycle and climate regulation by acting as a net sink, *via* solubility and biological pump, for the atmospheric CO_2 (Chisholm, 2001). The biogeochemistry of the Southern Ocean is controlled by two major current systems: the eastward flowing Antarctic Circumpolar Current (ACC) and the westward flowing Antarctic Coastal Current (Constable et al., 2003). The strong westerly wind generates upwelling of nutrient rich deep water in this region. According to an estimate (Anderson, 2003) only half of the upwelled nutrients are consumed by phytoplankton present here and the rest are carried back into the deep sea via formation of Antarctic intermediate water (AAIW) and Antarctic bottom water (AABW). Global and low latitude export production is controlled by the amount of intermediate and deep water formed at subantarctics (Sarmiento et al, 2003; Marinov et al, 2006). The uniqueness of the Southern Ocean is that while its surface water harbors significant amounts of macronutrients e.g., nitrate, silicate and phosphate to support high primary production, yet the productivity in this region is quite low. Because of this property this region is described as a "High Nutrient Low Chlorophyll" or HNLC region (Minas et. al., 1986). Several causes including low temperature, low specific growth rate, grazing control, sun-light limitation, trace metal toxicity and Fe-limitation, have been proposed to explain "HNLC" condition. During the last decade, a number of large scale Fe-enrichment experiments were carried out to test the hypothesis of Fe-limitation in such regions (de Baar et al., 2005). More recently it has been proposed that natural iron fertilization due to upwelling of nutrient rich water, which contains Fe as well, from deep leads to development of bloom near the Kerguelen plateau sector of the Southern Indian Ocean (Blain et al., 2007). As a consequence of these experiments now it is well established that iron addition could cause increased carbon sequestration through enhanced marine productivity but studies pertaining to the nitrogen uptake rates are limited.

The rates of total N-uptake, integrated over the photic zone showed a significant variation in the Southern Indian Ocean. Euphotic zone integrated total N-uptake rate varied from 1.73 $mmolNm^{-2}d^{-1}$ to 12.26 $mmolNm^{-2}d^{-1}$ in the Southern Indian Ocean; highest uptake rate was at a station (PP1) in the Antarctic coastal zone and the lowest at

58°S. Nitrate uptake rate was more than ammonium and urea uptake rates at all the stations except at a station north of STF (sub-tropical front) at 35°S where ammonium uptake was more than nitrate uptake. Our mean column N-uptake rate in this zone (1.17 ± 0.36 $mmolNm^{-2}d^{-1}$) is significantly less than those reported by Savoye et al., (2004) (mean = 5 $mmolNm^{-2}d^{-1}$) from the Australian sector of the Southern Ocean on similar latitudes. The decrease in productivity in this zone has been attributed to the strong stratification due to the melting of sea ice in summer by Treguer and Jacques, (1992). In late austral summer the whole Southern Indian Ocean is characterized by high nitrate uptake and hence high new production: new production during late austral summer in the Indian sector of the Southern Ocean varied from 0.92 $mmolNm^{-2}d^{-1}$ to 7.7 $mmolNm^{-2}d^{-1}$. The highest new production of 616 $mgCm^{-2}d^{-1}$ was observed at the Antarctic coast and lowest of 73.6 $mgCm^{-2}d^{-1}$, the lowest observed during the present study, at a station at 58°S. The plot of total N-uptake (on x-axis) and nitrate uptake (on y-axis) shows very significant correlation between the two: $y = (0.63 \pm 0.06)\, x - (0.66 \pm 0.42)$ (coefficient of determination, $r^2 = 0.95$). The slope of line of regression suggests the maximum possible value of *f*-ratio (0.63) for this zone. This large area is traditionally regarded as a low productive area where for some reason or the other the surface nutrients are not utilized fully. Our measurements show that even though the productivity over a large area of the Southern Ocean is low, the *f*-ratio is moderately high. This signifies that a large part of production could get transported to deeper ocean and thus this area has the potential to play a significant role in atmospheric carbon sequestration.

Chapter 5. 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 are as follows:

- 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.
- During the early winter monsoon total productivity varied from 4.07 $mmolNm^{-2}d^{-1}$ (32 6$mgCm^{-2}d^{-1}$) 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 $mgCm^{-2}d^{-1}$).

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 compare 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.

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. Some important results 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).

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 first comprehensive estimates of nitrogen based productivity in a large area in the Southern Indian Ocean.

- 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.

Scope for the future work

Despite having some major programme such as JGOFS and BOBPS, a large part of Indian Ocean still remains unexplored particularly the Bay of Bengal, equatorial Indian Ocean and the Southern Indian 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 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 and for this we need more such observations pertaining to the estimation of new production and the *f*-ratio.

High productivity events of the Arabian Sea are followed by formation of oxygen minimum zone in sub-surface layer which leads to significant denitrification.

Quantification of denitrification, is important to estimate the carbon and nitrogen budget and hence its needs to be incorporated in the future studies

Quantification of N_2 fixation by these cynobacterium is important to understand marine nitrogen cycle as it is a source of new nitrogen to the marine cycle.

^{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 near future.