Chapter One

Introduction

One of the major roles of contemporary oceanographers is to understand the role of ocean in the carbon cycle and thus in Global Change. According to an estimate, the concentration of CO_2 in the atmosphere has increased by 35% during the last 150 years compared to the pre-industrial level (from 280 ppm in pre-industrial era to 379 ppm in 2005) (IPCC AR IV-2007) and it is projected to double in the coming century. Carbon dioxide is a greenhouse gas which can trap the longer wave radiation emitted by the earth and hence causes increase in the earth's temperature; the global temperature has increased by 0.74±0.18°C during the last century (IPCC AR IV-2007). One of the main causes of increase in concentration of CO_2 is the increased human activities like fossil fuel burning, change in agricultural patterns, deforestation etc. However, its growth rate, at present, is less than half of the expected if all the CO_2 released by fossil fuel burning and land-use pattern change had remained in the atmosphere. This is because the growth rate of atmospheric CO_2 depends not only on the human activities but also on the different biogeochemical and climatological processes which lead to its drawdown from the atmosphere to different earth reservoirs (Falkowaski et al., 2000). A rapid and continuous exchange of CO_2 takes place between atmosphere and the ocean and terrestrial ecosystems. Oceans, in particular, take up considerable amount of CO_2 through physico-chemical and biological processes and acts as a "sink" of atmospheric CO_2 (Sarmiento and Gruber, 2002) but the complex processes affecting it are still poorly understood (Ittekkot 1991). A major part of the atmospheric CO_2 is also taken up by the terrestrial and oceanic biota; it has been estimated that a total of 104.9 Gt of carbon is fixed per year by the terrestrial and oceanic biota, out of which about 46.2% (48.5 Gt) is taken up by ocean (Field et al., 1998).

1.1 Marine primary production

Ocean biota mainly consist of single celled micro-organisms called phytoplankton. They are the first link in ocean food-web and have the same mode of nutrition as terrestrial plants, but are short-lived, free floating and have no supporting structure to maintain unlike terrestrial plants. They are present in the upper sunlit layer of the ocean called the photic zone i.e., the depth at which the ambient light intensity becomes 1% of that the ocean surface. In the presence of sunlight phytoplankton convert atmospheric inorganic CO_2 into organic carbon through photosynthesis.

$$nCO_2 + nH_2O + \text{Sunlight} \longrightarrow (CH_2O)_n + nO_2$$

The amount of carbon thus fixed by these phytoplankton through synthesis of organic carbon, measured in units of 'amount of carbon per volume of water per unit time (mgC l^{-1} hr^{-1} or mgC m^{-3} d^{-1})' is called primary production. A major part of this primary production is recycled in the photic zone itself, through microbial decay or is eaten by zooplankton, and thus enters the food web but still some part of newly synthesized organic matter is also transported to the deep via sinking. They escape from the upper ocean to the thermocline and below and thus get removed from the atmosphere for longer times. This is termed as 'export production' and the process is known as the "biological pump".

Availability of sunlight is one of the major limiting factors of primary productivity, as light intensity decreases with depth. The general limit of light penetration, even in open ocean waters, is approximately 100-150 m (1% of surface intensity). Since photosynthesis depends on light, primary production takes place within this zone. Apart from sunlight, CO_2 and H_2O, some elements such as N, P, Fe, Si etc are also essential for phytoplankton growth (Toggweiller 1999), absence of which limits photosynthesis and primary production. These are called nutrients. All these nutrients occur in small amounts.

Among all the other nutrients supply of nitrogenous nutrients is considered as a major limiting factor that regulates the oceanic primary production (Harrison et al., 1987). On the basis of the source of nitrogen, primary production can be divided into two: New Production and regenerated production (Dugdale and Goering 1967). New production is fuelled by newly-borne nitrogen, mainly in the form of nitrate, into the photic zone. The main sources of this nitrogen are upwelling of nitrate rich deep waters, aeolian deposit and through lateral advection. Regenerated production is supported by nitrogen derived from recycling of organic matter in the photic zone itself (Fig 1.1). This nitrogen is mainly in the form of ammonium or urea.

Ammonium and urea can circulate indefinitely under a quasi-steady state condition or an ideal closed system if there is no loss from the phytoplankton population. But there are losses through the sinking of particulate matter, mixing and by predation by zooplankton in the real ocean and in such cases other sources of nitrogen is necessary to maintain the system. The sum of the losses, in the form of export production, is balanced by nitrate uptake, by nitrogen fixation or by any other possible source of non-regenerated nitrogen. Therefore on a longer timescale export production is equal to new production under steady state condition (Eppley and Peterson, 1979).

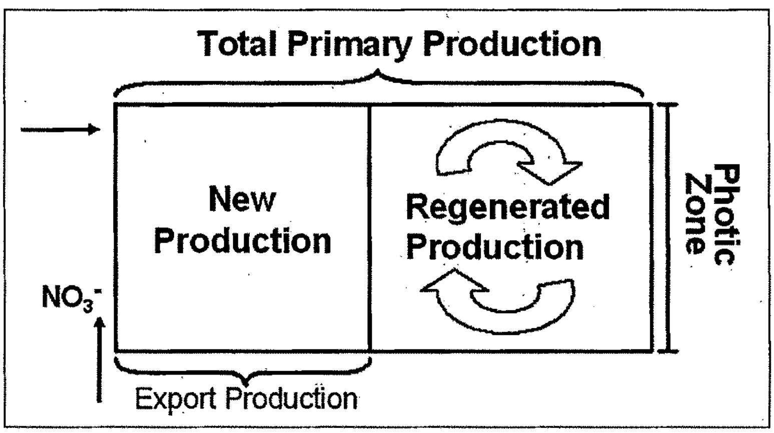

Figure 1.1. Schematic representation of primary production, new production and regenerated production in the photic zone.

The ratio of new to total production is called the *f*-ratio (Eppley and Peterson 1979). It represents the probability that a nitrogen atom is assimilated by phytoplankton due to new production; likewise (1-*f*) is the probability of assimilation by regenerated production. (1-*f*)/*f* provides a measure of number of times nitrogen recycles in the photic zone before sinking out of the system as particulate matter (Eppley and Peterson, 1979).

Phosphorus is another element the availability of which is believed to limit primary production especially in the open ocean (Tyrell and Law 1997, Tyrell 1999). It is present in seawater in the form of dissolved phosphate (PO_4^{3-}), enters the ocean through rivers as a product of continental weathering (Toggweiler 1999) and is removed from ocean waters through sedimentation. Geochemists argue (Broecker 1982) that since its only source is through river discharge; its concentration in open ocean waters is low and limits productivity. This is very unlikely because the residence time of PO_4^{3-} in the ocean is around 50,000 years (Van Cappelan and Ingall 1994). Also PO_4^{3-} is unique in a sense that it escapes burial in sediments: only 1% of the phosphorous taken up by phytoplankton is trapped in sediments (Brocker and Peng 1982). High residence time and low burial rate implies a high standing stock of phosphorus in the oceanic water.

The traditional stoichiometric formula for the composition of marine phytoplankton organic matter:

$106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122H_2O = (CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\ O_2$

Phytoplankton take up C, N and P in a fixed ratio of 106:16:1 known as the Redfield ratio (Redfield 1934). It is the molecular ratio of carbon, nitrogen and phosphorus in marine organic matter (Falkowaski et al., 1998) and it is remarkably close to ratio of these elements in the seawater. Any variation that exists in the natural environment are likely to be small, under the normal marine pH condition.

1.2 Estimation of new and regenerated productivity

1.2.1 Different methods for measuring new and export production

New and regenerated productivity are measured using the ^{15}N tracer technique, originally proposed by Dugdale and Goering (1967), modified by the JGOFS (1996). Uptake rates of ^{15}N labeled nitrate, ammonium and urea are measured in the post-incubated samples; nitrate uptake rate gives an estimate of new production whereas a sum of ammonium and urea uptake rates gives a measure of regenerated production. New production is also measured from rate of change of nitrate concentration in the upper water column (Allen et al., 1996). Nitrogen-fixation also provides new nitrogen to the water column (Capone et al., 1997; Karl et al., 1997) and hence is referred as new production. Nitrification of regenerated nutrients such as ammonium and urea, taking place generally below (Dore and Karl 1996) and within the photic zone (Fernandez et al., 2005; Rees et al., 2006), is also a source of new nitrogen. On the other hand release of $DO^{15}N$, and reduced forms of nitrogen such as ammonium from cells during incubation results in an underestimation (Bronk et al. 1994) but it is significant only when samples are incubated for longer durations (~12 hrs) (Glibert et al., 1982). For the present study, the ^{15}N tracer technique is used to estimate new and regenerated productivity; experimental details are given in Chapter 2. Export production is measured using sediment traps (Nair et al., 1989) and ^{243}Th deficiency in the water column (Buesseler 1991, 1998; Ramaswamy et al., 2005). Sediment traps are generally deployed in the open ocean, at a depth ranging from 200 m to more than 1000 m where they collect particulate matter exported to the deep, the major limitation being export flux severely overestimated in the coastal region, where the sediment flux is high. Particulate organic matter sticks to these sediments while settling down, which tends to overestimate it. In the ^{234}Th technique downward flux of organic matter is estimated using the ratio of carbon to ^{234}Th and this does not take care of advection of DOM and the vertical migration of zooplankton. It has been found that trap-derived and ^{234}Th derived export flux differ by a factor of 3-10 (Buesseler 1991) which suggests that these methods may be of limited significance to accurate measure of particle flux to the deep.

1.2.2 Merits of using nitrogen as a tracer for estimating new and regenerated productivity

Nitrogen is one of the essential elements for the growth of phytoplankton. It is a major structural component of their body cells. It is present in oceanic waters in various forms which allows us to distinguish it on the basis of its source and thus provides a tool to measure different components of productivity i.e., new and regenerated productivity. In other words, use of nitrogen as a tool to measure productivity gives a better insight of the biogeochemistry of ocean.

1.3 N-uptake rates and *f*-ratios in different parts of the world's ocean

Since the formulation of concept of new and regenerated productivity by Dugdale and Goering (1967) and use of new productivity as a measure of export production (Eppley and Peterson, 1979), ^{15}N tracer technique has been extensively used to characterize the biogeochemistry of the surface ocean and to asses the ocean's role in carbon sequestration. Global scientific programmes have been carried out in the past to estimate the relationship between new and export productivity. Some of the major programmes are: VERTEX (Vertical exchange processes) in the north Pacific, WECOMA in the equatorial Pacific (Barber 1992), ANTARKTIS in the Atlantic and Indian Sector of the Southern ocean (Semeneh et al., 1998), Research on Antarctic Coastal Ecosystem Rates (RACER; Huntley et al., 1991), Subarctic Pacific Ecosystem research (SUPER) in the north Pacific (Miller et al., 1991; Miller 1993), time series experiments at Bermuda (BATS) and Hawaii (HOT) (Lohrenz et al., 1992; Malone et al., 1993; Roman et al., 1993), 1988 Black Sea Expedition (Murray 1991), POMME in the Atlantic ocean (Fernandez et al., 2005) and BOBPS (Bay of Bengal Processes Studies) in the Bay of Bengal (Sanjeev Kumar et al., 2004; Sanjeev Kumar and Ramesh, 2005).

Region/season	Nitrate uptake	*f*-Ratio	Reference
HOT	0.6	*0.10*	Michaels et al. (1994)
BATS	*0.9*	*0.15*	Emerson et al. (1997)
NABE	7.0	0.51	Bender et al. (1992); McCarthy et al. (1996)
Equatorial Pacific (150°W)			
November	0.5-2.7	0.08-0.21	Raimbault et al.(1999)
August	0.5-4.8	0.05-0.2	McCarthy et al. (1996)
Sub-Arctic Pacific			
Station-P winter	1.0-4.5		Varela and Harrison (1999)
Station-P summer	0.8-4.0		Wheeler and Kokkinakis (1990)
Peru	18.3-24.2	0.30-0.42	Wilkerson et al., (1987)
Sub-Arctic Atlantic			
Iceland Basin-July	0.9-5.8		Sambrotto et al. (1993)
North Atlantic	3-9	0.25-0.56	Fernandez et al., (2005)
Greenland polynya	2.5	0.56	Smith et al., (1997)
Southern Ocean			
170°W /summer	0.9-12.5	0.05-0.48	Sambrotto and Mace (2000)
Ross Sea			
Arabian Sea			
Spring Intermonsoon	0.1-3.0	0.04-0.35	Sambrotto (2001)
Southwest Monsoon	3.0-9.0	0.05-0.42	Sambrotto (2001)
Early NE Monsoon	0.8-6.0	0.15	McCarthy et al.(1999)
Late NE Monsoon	0.7-3.0	0.13	McCarthy et al.(1999)
Bay of Bengal			
Late SW Monsoon	0.4-8.8	0.34-0.81	Sanjeev Kumar et al., (2004)
Early SW Monsoon	1.0-3.3	0.48-0.78	Sanjeev Kumar et al., (2004)

Table 1.1 New or export production (mmol $Nm^{-2}d^{-1}$) and *f*-ratio in different regions (Source: Falkowski et al. 2003 and Sambrotto and Mace 2000); NABE = North Atlantic Bloom Experiment.

During JGOFS (Joint Global Ocean Flux Studies), different parts of the worlds ocean e.g., the equatorial Pacific (Barber et al., 1994), the Arabian Sea (Smith 2001;

Sambrotto 2001), the Southern ocean (Sambrotto and Mace 2000), the North Atlantic (Ducklow and Harris 1993) were studied in detail to get a better estimate of carbon fluxes in these oceans. The nitrate uptake rate (new production) and *f*-ratio obtained from different programmes/areas using different methods is listed in Table 1.1.

The global ocean can be subdivided into three main categories on the basis of new production (Ducklow 1995): (i) regions where nitrate is depleted in spring but is again renewed in winter every year and (ii) regions where surface water contains high concentrations of nitrate throughout year (iii) regions where nitrate is permanently depleted in the surface waters. In some part of the world ocean nitrate is transported to the upper layer due to vertical mixing during the winter; this increases productivity of the basin, sometimes leading to initiation of phytoplankton bloom. Such regions are coastal and shelf regions (Townsend et al., 1992; Hansell et al., 1993); Southern Ocean (Holm-Hansen and Mitchell 1991; Sullivan et al., 1993), northern Arabian Sea (Dwivedi et al., 2006) and North Atlantic (Sambrotto et al., 1993). Occurrence of bloom in such regions leads to episodic increase in the export of biomass (Honjo and Manganini 1993). There are regions such as the subarctic north Pacific, central equatorial Pacific and the Southern Ocean where surface nitrate is high yet the productivity is low. Because of this property these are described as a "High Nutrient Low Chlorophyll" or HNLC regions (Minas et. al., 1986). In general new production has been reported to be low in HNLC (Dugdale et al., 1992). 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 the "HNLC" condition. In the oligotrophic gyres, the surface ocean is almost devoid of nitrate, but is known to maintain a significant new production even in the absence of new nitrate from deeper layers. The other sources suggested for such significant new production are nitrate enriched buoyant mats of diatoms (Villareal et al., 1993) or atmospheric inputs of nitrogen species. However, the latter causes only 1-2% of global new production. Sometimes the atmospheric inputs of nutrients can drive local blooms (Michaels et al. 1993) or can stimulate new production in nutrient poor waters (DiTullio and Laws 1991).

Some major international scientific programmes such as JGOFS aimed at assessing the role of global ocean in the carbon cycle. India also actively participated in this programme and a number of studies were carried out during the Indian JGOFS in the eastern Arabian Sea to assess its role in the global carbon cycle and to determine whether it is a "source" or "sink" of CO_2. A large part of the Indian Ocean such as the equatorial and the Southern Indian Ocean still remains unexplored from this point of view.

1.4 Indian Ocean and its biogeochemical properties

The Indian Ocean, the third largest ocean, caters to the large population of the southern and eastern Asia. It plays an important role in the global ocean system as a modulator of heat and salinity transport (Bates et al., 2006a). As a large population inhabits the coasts of the Indian Ocean, it is more likely to be affected by human impacts and other anthropogenic causes. Most of this population survives on resources derived from this ocean such as fishing and trade. Ever increasing population, different types of chemicals dumped by them into the coastal areas and also changes in the riverine discharge and composition due to human activities may affect the chemistry of the Indian Ocean. According to a study Indian Ocean is warming faster than any other ocean basin (Levitus et al., 2000). This makes the northern Indian Ocean an important region of the world ocean for the oceanographic studies to study and understand the effect of human activities on ocean biogeochemistry.

The Indian Ocean has got a unique geographical setting; it is landlocked on its northern side and is connected to the Southern Ocean and Antarctica on the south. The winds over the northern Indian Ocean *i.e.*, north of 10°S, reverse direction twice a year; it blows from the southwest during May–September (known as summer monsoon) and from the northeast during November–February (known as winter monsoon) (see Fig 1.2). During March–April and October winds are generally weak and are in transition phase. The winds during the summer monsoon are much stronger than the winter monsoon.

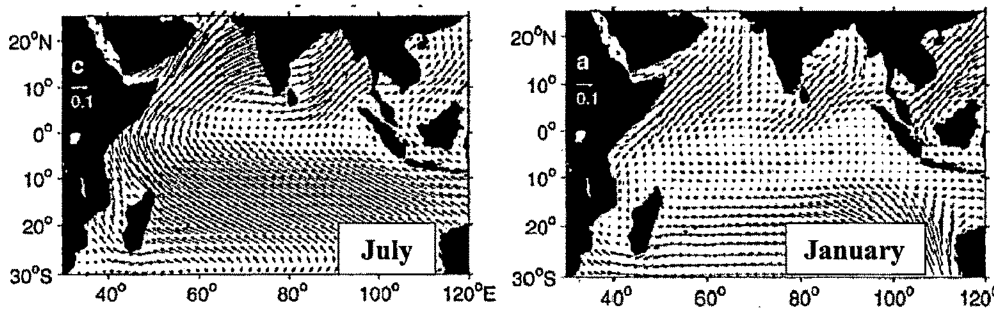

Fig 1.2 Monsoon wind-stress filed over the northern Indian Ocean for July (summer monsoon) and January (winter monsoon) (Source Shankar et al., 2002).

The seasonally reversing monsoon winds over the northern Indian Ocean forces a seasonally reversing circulation in the upper ocean (Shankar et al., 2002) which is mainly controlled by the land-sea temperature contrast between the Eurasia and the northern Indian Ocean. Change in wind direction and reversal of upper ocean circulation patterns makes the Indian Ocean a unique basin and also different from the other two major ocean basins i.e., the Pacific and Atlantic basins. The Indian peninsula divides the northern Indian Ocean into two: the Bay of Bengal and Arabian Sea. Though they are situated at the same latitude they are entirely different in oceanographic properties such as sea surface temperature (SST), mixed layer depth (MLD), nutrients, productivity etc. The Bay of Bengal receives a large quantity of fresh water through the rivers and experiences more precipitation than evaporation. This leads to formation of less saline water on the surface causing a strong vertical stratification. This inhibits the transport of nutrients from the deeper layer to the surface, which in turn, decreases the productivity of this basin. The Arabian Sea, on the other hand, receives significantly less amount of fresh water through rivers. Also, evaporation exceeds precipitation in the Arabian Sea resulting in the formation of high saline water known as Arabian Sea High Salinity Water (ASHSW) and spreads as salinity maximum just beneath the upper mixed layer (Schott and Fischer 2000). The equatorial Indian Ocean is characterized by semiannual strong eastward surface wind (Wyrtki 1973), known as Wyrtki jets, during the transition seasons between the monsoons i.e., April to June (spring intermonsoon or SIM) and October to December (fall intermonsoon or FIM) (Schott and McCreary 2001). The Wyrtki jet carries equatorial warm surface water towards the east causing a decrease in the mixed layer depth in the west but an increase in the east (Rao et al., 1989).

The Arabian Sea is one of the most productive regions in the world oceans (Banse 1987; Nair et al., 1989; Madhupratap et al., 1996; Smith 2001) and is characterized by strong, seasonal oscillations in the biological production (Burkill et al., 1993) which is attributed to the strong seasonal oscillation in the oceanic circulation forced by the monsoons. In summer, the strong southwest monsoon causes intense upwelling in the western Arabian Sea along the Somalia and Oman coasts and also along the western Indian coast. Increase in the mixed layer due to strong winds during the southwest monsoon brings ample nutrients into the surface layer and causes phytoplankton blooms. During the winter monsoon, cool dry air from Himalaya causes enhanced evaporation which results in the deepening of mixed layer due to convective mixing. This again brings nutrients into the surface layer and trigger blooms during the later phase. The spring and fall inter-monsoons are characterised by well stratified surface water with shallow mixed layer devoid of nutrients and low productivity in the Arabian Sea. The southwest monsoon current advects to the southern Bay of Bengal through the south of Sri Lanka and triggers high biological productivity in the Bay (Vinaychandran et al., 2004).

Other important features of the Indian Ocean are the biogeochemical cycling of carbon and other important elements, its response to natural and anthropogenic changes, geographical constraints on vertical mixing, seasonally reversing monsoon (Hood et al., 2006), globally significant oceanic biological production particularly in the northern Arabian Sea (Madhupratap et al., 1996), intense denitrification as Arabian sea alone contributes ~40% (Bange et al., 2005) of the global denitrification (in this process bacteria begin to utilize NO_3 instead of O_2 as an oxidant for decomposing organic debris when the ambient O_2 concentration is close to zero; Naqvi et al., 1982; Naqvi and Jayakumar 2000), fixation of N_2 by cynobacteria (Capone et al., 1997) and high export production despite low productivity in the Bay of Bengal (Sanjeev Kumar et al., 2004).

1.5 Carbon budget of the Indian Ocean

The Indian Ocean has been identified as a net sink for atmospheric CO_2 (Takahashi et al., 2002). It takes up ~330-430 Tg C yr^{-1}, which accounts for nearly 20% of the global oceanic uptake of CO_2. Most of this air-to-sea CO_2 flux occurs south of 20°S. This is because sea surface temperature decreases drastically south of 20°S, to reach below zero near the Antarctic coast and CO_2 is more soluble in cold water compared to warm water. Contribution of the equatorial and the northern Indian Ocean is yet to be assessed. Bates et al., (2006a) has identified the northern Indian Ocean (north of 35°S) as a net source of CO_2 to the atmosphere. They estimated an annual loss of ~240 Tg C yr^{-1} of CO_2 to the atmosphere from the sea. Subregions of the Indian Ocean affected by seasonally reversing monsoons are perennial sources of CO_2 to the atmosphere (Hood et al., 2006) despite having episodic high biological productivity. Though the surface layer of the Indian Ocean is strongly autotrophic, biological uptake of CO_2 by the Indian Ocean has been estimated to be ~750-1320 Tg C yr^{-1} by Bates et al., (2006b), it can not compensate for the loss of CO_2 to the atmosphere *via* upwelling of deeper cold water. Sabine et al., 2000 and Hall et al., 2004 have proposed an estimate of 150-500 Tg C yr^{-1} of CO_2 loss to the atmosphere by the warm northern Indian Ocean. Table 1.2 summarizes the annual air-sea CO_2 fluxes for the Indian Ocean and its subregions.

Region	CO_2 flux	Net Production	River input	Vertical Diffusion	Upwelling/ Advection
Indian Ocean	-237	-1572 (-802)	+30	+437	+1342 (+572)
Arabian Sea	-64	-150 (-80)	+2	+58	+154 (+84)
Bay of Bengal	-13	-150 (-94)	+25	+25	+113 (+57)
10°N-10°S	-180	-486 (-304)	+1	+178	+ 487 (+304)
10°S-20°S	-110	-349 (-72)	+1	+97	+361 (+84)
20°S-35°S	+130	-437 (-95)	+1	+95	+211 (+26)

Table 1.2. Annual balance of carbon (Tg C yr^{-1}) for the Indian Ocean and sub-regions. "Negative" and "positive" terms are "loss from" and "gain to" the surface layer (0-100 m) respectively. (Source: Hood et al., 2006)

1.6 Previous ^{15}N based studies in different parts of Indian Ocean

^{15}N based productivity has been reported for the western and central Arabian sea by a few authors (Owens et al., 1993; McCarthy et al., 1999, Watts and Owens, 1999; Sambrotto, 2001) but only a few results are available from the eastern Arabian Sea (Sanjeev Kumar et al., 2008). Owens et al., (1993) reported a large variation in the total N-uptake rates, from 23.1 $mmolNm^{-2}d^{-1}$ in the central Arabian Sea to 96.7 $mmolNm^{-2}d^{-1}$ in the coastal upwelling region during the late summer monsoon. The *f*-ratio varied from a low of 0.09 at an open ocean station to as high as 0.92 at a coastal station. McCarthy et al., (1999) reported N-uptake rates varying from 9.2 $mmolNm^{-2}d^{-1}$ to 40 $mmolNm^{-2}d^{-1}$ during winter monsoon and from 3.9 $mmolNm^{-2}d^{-1}$ to 24 $mmolNm^{-2}d^{-1}$ during the late summer/early winter monsoon for the central Arabian Sea. Here the N-uptake rate was significantly higher in the winter (~26 $mmolNm^{-2}d^{-1}$) than the late summer (11 $mmolNm^{-2}d^{-1}$). The *f*-ratio varied from 0.03 to 0.31 and from 0.04 to 0.29 during winter and the late summer monsoons respectively. Watts and Owens (1999) also reported large variations in the N-uptake rate; it varied from 1.1 $mmolNm^{-2}d^{-1}$ to 23.6 $mmolNm^{-2}d^{-1}$ for the northwestern Arabian Sea during an intermonsoon period. They found *f*-ratios varying from a low of 0.07 in the open ocean region to a high of 0.92 at a coastal station. A large variation in the N-uptake rate, ranging from 0.1 $mmolNm^{-2}d^{-1}$ to 13 $mmolNm^{-2}d^{-1}$ has also been reported by Sambrotto (2001) during the spring intermonsoon and the summer monsoon for the northern Arabian Sea. Sustained observations over several years are required to get a meaningful average of ^{15}N based export productivity. This thesis is important in this context.

^{15}N based productivity measurements in the Indian sector of the Southern Ocean are limited in time and space. Slawyk (1979) was the first to report nitrate uptake rates from the Kerguelen Island area of the Southern Ocean; nitrate uptake rates were low and varied from 0.03 $mmolNm^{-2}d^{-1}$ to 0.12 $mmolNm^{-2}d^{-1}$ with a mean of 0.06 $mmolNm^{-2}d^{-1}$. Probyn and Painting (1985) reported N-uptake rates for the surface waters from the coastal regions between Cape Ann and Mawson. The N-uptake rates reported by them were significantly high; they varied from 2.16 $mmolNm^{-3}hr^{-1}$ to 5.41 $mmolNm^{-3}hr^{-1}$ with a mean of 4.47 $mmolNm^{-3}hr^{-1}$. They reported a preference for reduced nitrogen (ammonium and urea) over nitrate by the phytoplankton of the Antarctic coastal waters. Mengesha et al., (1998) studied the N-uptake characteristics of the Southern Ocean waters over two seasons, spring and austral summer 1994, for a small area near the Kerguelen Island. During spring specific and absolute nitrate uptake dominated over ammonium and urea uptakes whereas during summer ammonium uptake was more than nitrate uptake. The specific nitrate uptake during spring was 0.0048 hr^{-1} which reduced to 0.0011 hr^{-1} in the summer. Ammonium uptake increased slightly during the summer, from 0.0015 hr^{-1} in spring to 0.0018 hr^{-1} in summer. The *f*-ratio also decreased in the summer but showed considerable variations. It varied from 0.68 to 0.85 in spring and from 0.17 to 0.63 in summer. Specific nitrate and ammonium uptake rates reported for the surface waters by Semeneh et al., (1998) was an order of magnitude lower than the rates earlier reported rates; specific nitrate and ammonium uptake rates were 0.001 hr^{-1} and 0.0004 hr^{-1} respectively in the Prydz Bay area in 1991. The absolute total N-uptake rate and *f*-ratio were 0.038 $mmolNm^{-3}d^{-1}$ and 0.68 respectively. He also reported N-uptake rates from a longitudinal transect along 62°E. The specific nitrate uptake rates from this region was also (0.001 hr^{-1}) low but ammonium uptake rate was high (0.0019 hr^{-1}). The Absolute total N-uptake rate was almost double of the rate from Prydz Bay but the *f*-ratio was low (0.034).

No data exist on the biological productivity of the equatorial Indian ocean except a documentation on the anomalous phytoplankton bloom, using ocean colour data, in eastern part of the Indian Ocean during an Indian Ocean dipole year (Murtugudde et al., 1999).

1.7 Scope of the present work

The present work investigates the biological productivity and *f*-ratio characteristics of the Arabian Sea, equatorial Indian Ocean and the Southern Ocean using the ^{15}N tracer technique with following objectives:

1. Estimation of total productivity, new productivity and *f*-ratio characteristics of the northeastern Arabian Sea during winter monsoon and to compare

changes in the N-uptake rate due to occurrence of a phytoplankton bloom dominated by *Noctiluca scintillans* (autotrophic variety).

2. The aim was also to compare the total and new productivity of bloom and non-bloom areas and to know the extent of different biogeochemical provinces, if any, present in this part of the world ocean

3. To know the extent of intra-seasonal variability in the N-uptake rates and *f*-ratio during the winter monsoon and to asses the effect of winter cooling on them.

4. New production estimation in the equatorial Indian Ocean. This would help in assessing the role of this equatorial region in the global carbon cycle. The result will also help in examining it as a possible source/sink for atmospheric CO_2.

5. Productivity measurements in equatorial Indian Ocean have been made along two transects: 77°E and 83°E. This will help understanding latitudinal variation in biological productivity.

6. The estimation of new productivity and *f*-ratio in the Southern Ocean, a globally significant HNLC region. This would help quantify the extent of export production taking place here.

7. The Southern Ocean is characterized by the presence of various current systems which play a major role in its biogeochemistry. The present study covers stations in different current regimes. This will help in ascertaining role of various current systems on the biological and export productivity of the Southern Ocean, especially the Indian Sector.

1.8 Outline of the thesis

This thesis has been divided into five chapters. Their contents are as follows:

Chapter 1 describes the role of the ocean in the global carbon cycle. It also describes, in detail, the concepts of ocean productivity, new and regenerated production and a brief review of literature in the world ocean and study area.

Chapter 2 deals with the sampling details during the cruises and experimental methods followed during present study.

Chapter 3. discusses the results obtained during present study from the Arabian Sea. It discusses the effect of winter cooling on the total and new production and *f*-ratio. It also compares N-uptake rates and *f*-ratios of bloom and non-bloom areas and discusses the effect of occurrence of *Noctiluca* bloom on nitrogen uptake rates.

Chapter 4 deals with the results of present study for the equatorial Indian Ocean and the Southern Indian Ocean. It includes the results of new and regenerated production measurements along two transects in the equatorial Indian Ocean. It also investigates the N-uptake and *f*-ratio characteristics of the Southern Ocean and discusses the effect of the presence of different current systems on the productivity of this basin.

Chapter 5 synthesizes the results obtained in the present study, highlighting the important findings. It also deals with the scope for future work that may further improve our understanding of nitrogen and carbon cycle in this region.

1.9 Scientific questions addressed

The present study has attempted to address the following scientific questions:

The northeastern Arabian Sea:

- Has global warming increased productivity in the northeastern Arabian Sea?
- How much is the total productivity in the northeastern Arabian Sea during the winter monsoon?
- How much is the new and regenerated productivity in this basin during the winter monsoon?
- How does *f*-ratio vary in the northeastern Arabian Sea?
- What is the effect of winter cooling on the total and new productivity and also on the *f*-ratio?
- What is the intra-seasonal variability in productivity in this basin during the winter monsoon?
- How much does the productivity increase because of the occurrence of *Noctiluca* bloom? Does it also affect the *f*-ratio?
- Is there any identifiable productivity based biogeochemical divide in the Arabian Sea during the winter monsoon?

The equatorial and southern Indian Ocean:

- How much is the new and regenerated productivity in the equatorial Indian Ocean?
- What is the magnitude of *f*-ratio in this basin?
- Is there any longitudinal or latitudinal variation in productivity regime of the equatorial Indian Ocean?
- What is the magnitude of export production here? Is it able to export a significant part of productivity despite being an oligotrophic region?
- How much is the primary production in the Southern Indian Ocean which is otherwise considered as iron limited?
- How much is the *f*-ratio and the export production?
- Which is the preferred nutrient in this HNLC area?
- What is the role of different water fronts present in this area on biological productivity?
- Is there is shift in productivity regime due to global warming?
- What is the effect of iron enrichment on N-uptake rates?

In short, this thesis investigates the N-uptake and *f*-ratio characteristics of different parts of the Indian Ocean and evaluates its role in the Global Carbon Cycle.