Chapter Four

The Equatorial and Southern Indian Ocean

4.1 Introduction

The equatorial region of the Indian Ocean is distinctly different from the other two major oceans in the sense that it lacks equatorial upwelling unlike the Pacific and Atlantic. This is because the driving wind field is different in the Indian Ocean: in the Pacific and Atlantic oceans the southeast trades do not cross the equator and hence causes an equatorial divergence whereas in the Indian Ocean the annual-mean wind on the equator is eastwards causing convergence on the equator. The near-equatorial winds in the Indian Ocean are weak throughout the year and change directions four times a year (Fig. 4.1). Consequently the associated surface currents also change direction four times a year; it flows westward during the winter, weakly westward during the summer and strongly eastward during the spring and fall inter-monsoons. In the north, along Somalia and Oman coasts and also along the western Indian coast upwelling takes place only during the summer monsoon.

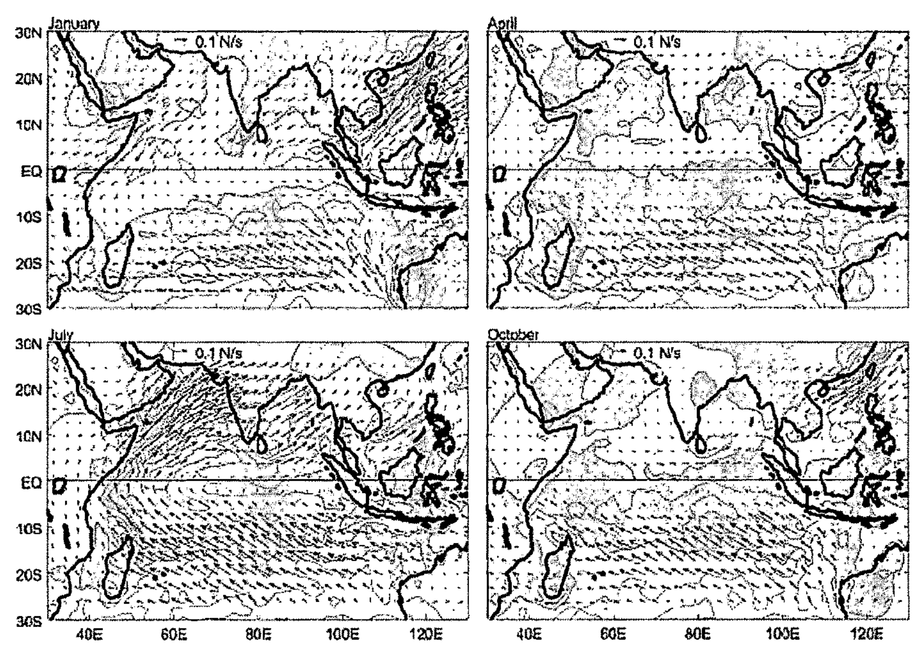


Fig. 4.1 Figure showing wind stress field for the Indian Ocean during January, April, July and October (Source: Miyama et al., 2003). The contour interval for wind curl is 10^7 Nm^{-3}, and negative values are shaded. After Hellerman and Rosenstein (1983).

The upwelled water can come from depths of 200–300 m, occasionally with temperatures colder than 15°C and densities in excess of 26.5 kgm^{-3} (Schott and McCreary, 2001). These temperatures and densities correspond to those in southern mid-latitudes near 40°S. Waters upwelled off Somalia, having low salinities, also clearly suggest southern-hemispheric origin (Fischer et al., 1996). All these suggest that the Indian Ocean meridional circulation has a shallow overturning cell where a northward subsurface branch supplies water for the northern hemisphere upwelling and a southward branch returns the same to the southern Indian Ocean (Miyama et al., 2003). There is also a net heat transport towards the south associated with this flow since the subsurface branch imports cooler water into the northern hemisphere and the surface branch exports warmer water to the south. This circulation is referred as the cross-equatorial cell (CEC). Two other cells, namely sub tropical cell (STC) and the eastern limb of sub tropical cell (Eastern STC), are also found in the equatorial region of the Indian Ocean. These are shallow overturning cells causing upwelling in the southern region of the Indian Ocean. The subtropical cell causes upwelling in a band of 5°S to 10°S in the central and western Indian Ocean and is driven by negative wind stress curl in this region associated with equatorward weakening of the southeast trades. Observational evidences, such as rise in pycnocline to the surface, are well documented but the same has not been recorded in terms of SST (Wyrtki 1988; Levitus et al., 1994). Ocean colour satellite data also indicates presence of phytoplankton bloom (Murtugudde et al., 1999) in this band attributable to the upwelling caused by overturning cells. The other cell, known as eastern limb of subtropical cell, causes upwelling in the eastern equatorial Indian Ocean *i.e.*, along Java and Sumatra coast, occasionally it also causes upwelling along the equator. It is now reasonably established, though dependent on season and direction of trade winds, that equatorial upwelling does take place in the Indian Ocean, no data exists on the phytoplankton productivity. The equatorial Indian Ocean is still a virgin area and the present data set is the first of its kind from this important basin.

4.2 Physical parameters, chlorophyll-*a* and nutrients in the equatorial Indian Ocean during pre-monsoon season 2005

4.2.1 Hydrographic conditions:

During the present study sampling was done along two different transects, namely along 77°E and 83°E. Five stations were taken along each transect at every 2.5° latitude starting from 5°N to 5°S: PP1 to PP5 along 77°E and PP6 to PP10 along 83°E. Latitude-wise variation in sea surface temperature (Fig 4.2) along 77°E and 83°E transects are shown in Fig 4.2. SST at 5°N (PP1) was 30.2°C which decreased towards the equator to 29.7°C and 29.4°C respectively at 2.5°N (PP2) and equator (PP3). It again increased slightly to the south of equator, from 29.4 to 29.7°C at 2.5°S (PP4) and remained the same at 5°S (PP5). The minimum SST was recorded at the equator and the maximum was at 5°N.

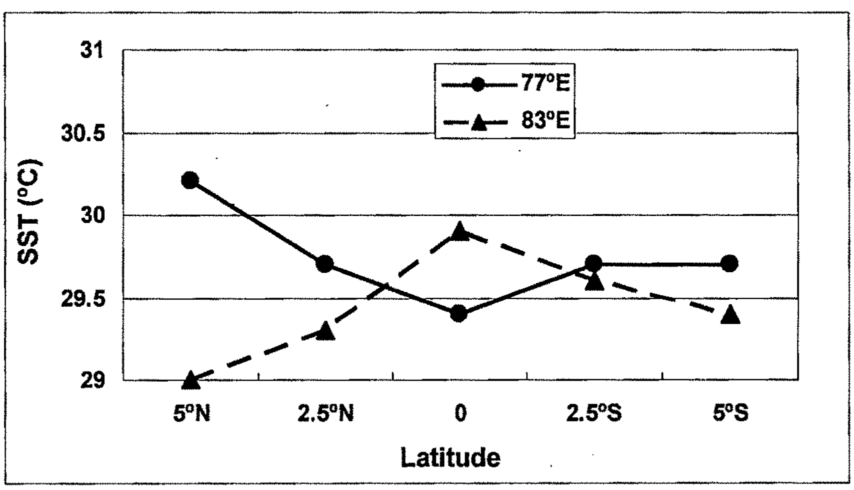


Fig 4.2 SST (°C) at all stations along 77°E and 83°E transects

Along 83°E transect SST increased towards the equator, from 29.0°C at 5°N (PP6) to 29.9°C at equator but again decreased south of equator to 29.4°C at 5°S (PP6). Unlike 77°E transect where a general decrease in SST was observed from 5°N to equator, an increase was observed between the same latitude along 83°E.

Sea Surface salinity increased from 5°N to the equator along 77°E (Fig 4.3), from 33.3 to 35.2 but decreased south of equator to 33.8 at 5°S; surface water at equator had the maximum salinity. Along 83°E, though a similar increasing trend in salinity was there from 5°N to the equator (Fig 4.3), the magnitude of change was relatively smaller; it increased from 34.0 at 5°N to 34.7 at equator. Also unlike at 77°E where it decreased south of equator, salinity increased till 2.5°S and started decreasing only after that.

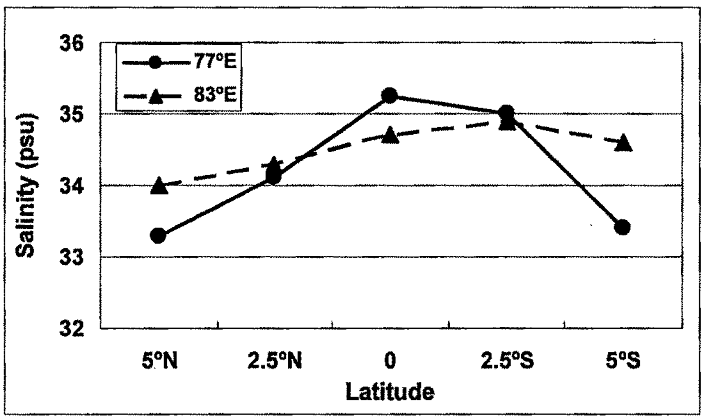


Fig 4.3 Salinity at all stations along 77°E and 83°E transects

4.2.2 Nutrients

Among nutrients only nitrate could be measured during the present study in the equatorial Indian Ocean during the pre-monsoon season. Photic zone integrated nitrate concentration varied from 370.7 mmol m^{-2} to 1665.4 mmol m^{-2} over the study region (Fig 4.4); it varied from 397.8 mmol m^{-2} to 1665.4 mmol m^{-2} along 77°E transect and 370.7 mmol m^{-2} to 1294.1 mmol m^{-2} along 83°E transect. A comparison of the integrated nitrate concentrations at stations along the two transect suggests that at stations north of the equator nitrate concentration was more at stations along 77°E as compared to those along 83°E. Among equatorial stations, station along 77°E had nitrate one fourth of those along 83°E. Among the stations south of equator, stations along 83°E again had more nitrate compared to the stations along 83°E at 2.5°S whereas at 5°S nitrate concentration was almost the same at both the stations.

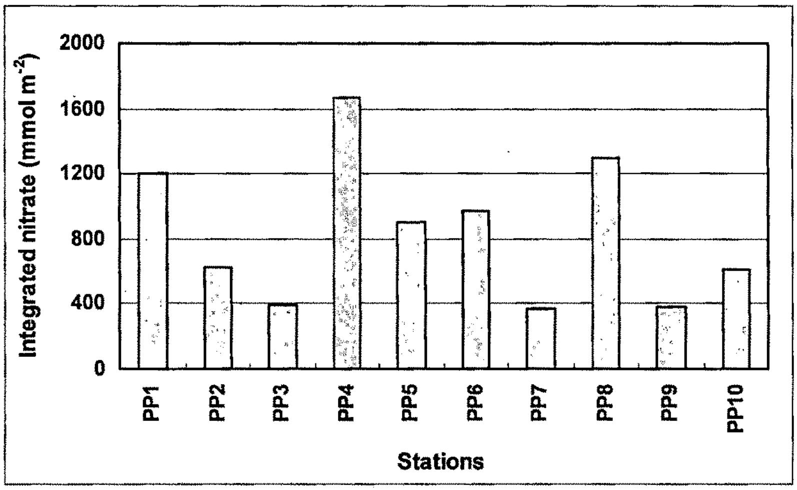


Fig 4.4 Photic zone integrated nitrate at different stations in the equatorial Indian Ocean The maximum nitrate was measured at PP3 and a minimum was measured at PP7.

PP1 and PP9, the surface nitrate concentrations were 0.3 and 0.85 μM and at rest of the stations nitrate concentration was below the detection limit in the surface waters. Depth profiles of the nitrate at different stations are shown in Fig 4.5. At most of the PP stations, surface waters till a depth of 30-40 m the nitrate concentration was below the detection limit. Nitrate concentration increased dramatically to higher concentration at relatively deeper depths at most of the stations of the equatorial Indian Ocean. At most of the stations it increased to more than 5 μM at a depth of 40-60 m and was more in the range of 10-15 μM below 80 m depth. Higher concentrations at the deeper layers coupled with photic depth in this region during the sampling season resulted in higher values of photic zone integrated column nitrate values.

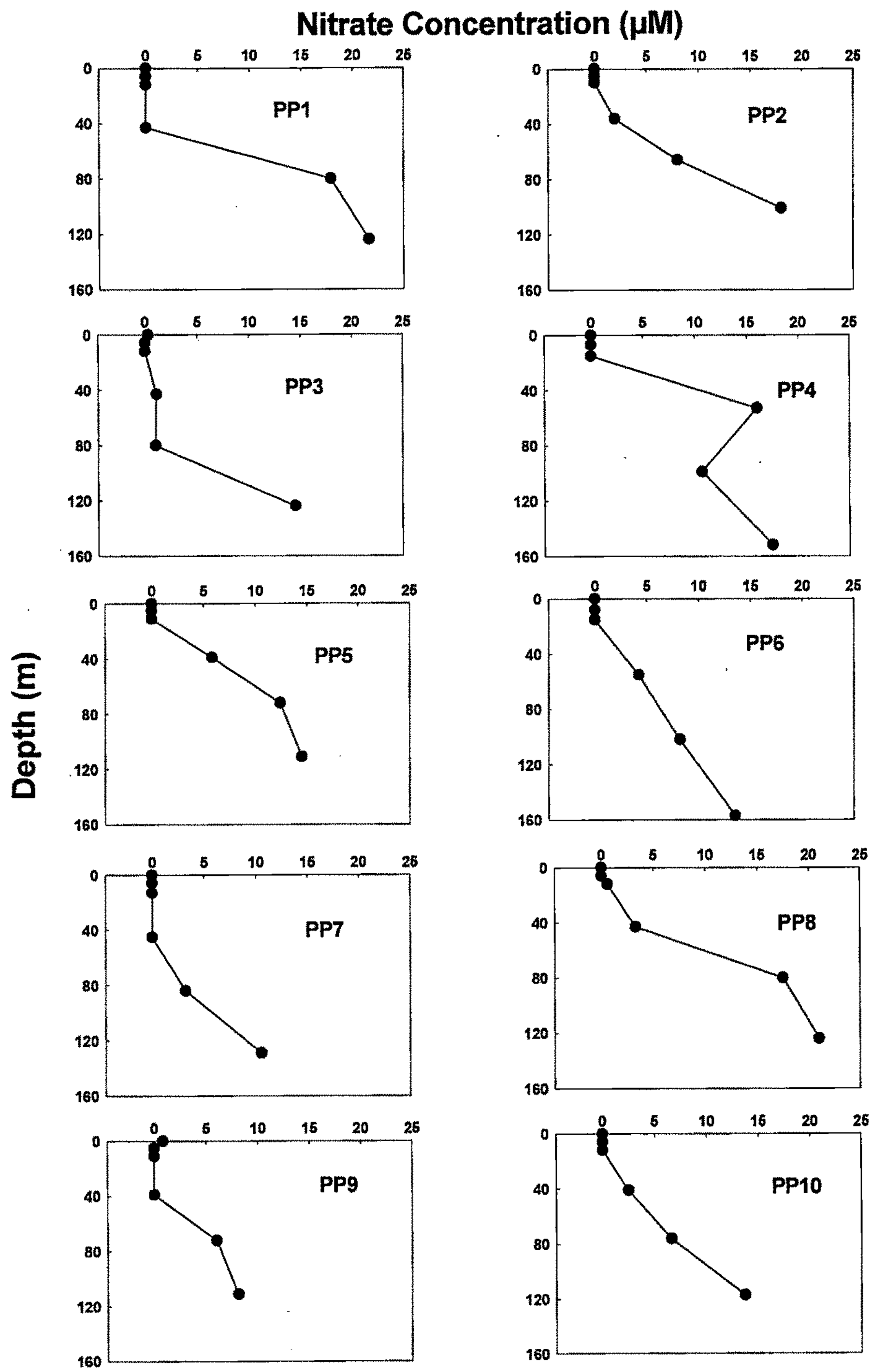


Fig 4.5 Depth profiles of nitrate at different stations in the equatorial Indian Ocean during pre-monsoon 2005

4.3 ^{15}N based productivity studies in the equatorial Indian Ocean during pre-monsoon 2005

4.3.1 Total Production

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 $mmolNm^{-2}d^{-1}$ (Fig 4.6). N-uptake rates were abnormally high at PP5 (5°S; 77°E) and PP8 (0°; 83°E). Excluding these two stations, N-uptake rates varied from 19.1 $mmolNm^{-2}d^{-1}$ to 78.3 $mmolNm^{-2}d^{-1}$. 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 nutrients. But below the mixed layer, where the concentration of ambient nitrate increased dramatically, nitrate uptake also increased.

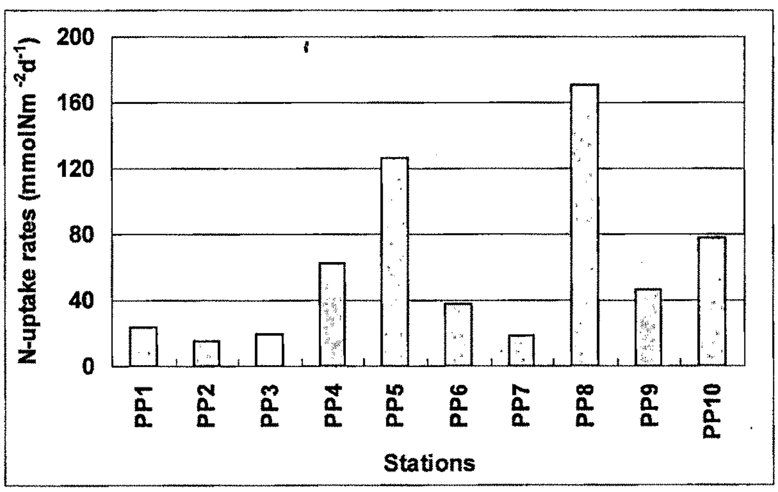


Fig 4.6 Total N-uptake rates at different stations in the equatorial Indian Ocean during pre-monsoon 2005

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 (Fig 4.7). The mean N-uptake rate over the study area was 1.32 $mmolNm^{-2}d^{-1}$ and along 77°E and 83°E it was 1.22 $mmolNm^{-2}d^{-1}$ and 1.43 $mmolNm^{-2}d^{-1}$ respectively. N-uptake rates were higher along 83°E transect compared to 77°E transect at all the stations except at the equator where rate was higher at 77°E than 83°E. No meridional difference could be seen in total N uptake rates at 5°N and 5°S; it was almost the same at both the stations (1.17 mmolNm^{-2}d^{-1} and 1.40 mmolNm^{-2}d^{-1} respectively). At 2.5°N there was a two-fold increase in total N-uptake rate at 83°E compared to 77°E whereas at 2.5°S this increase was more than two-fold. Among the stations at the equator total N-uptake rate was almost 4-fold higher at 77°E compared to 83°E. This difference at the equator is because of the difference in the mixed layer depth at 77°E and 83°E; at 77°E the mixed layer depth was 35 m whereas at 83°E it was only 15 m. The change in MLD may be because of the presence of high wind speed (>15 m/s) at equator at 83°E during sampling and may be just a transient event and may not be generalized. Excluding this extreme equatorial event, at all the other stations productivity along 83°E was more than the productivity along 77°E.

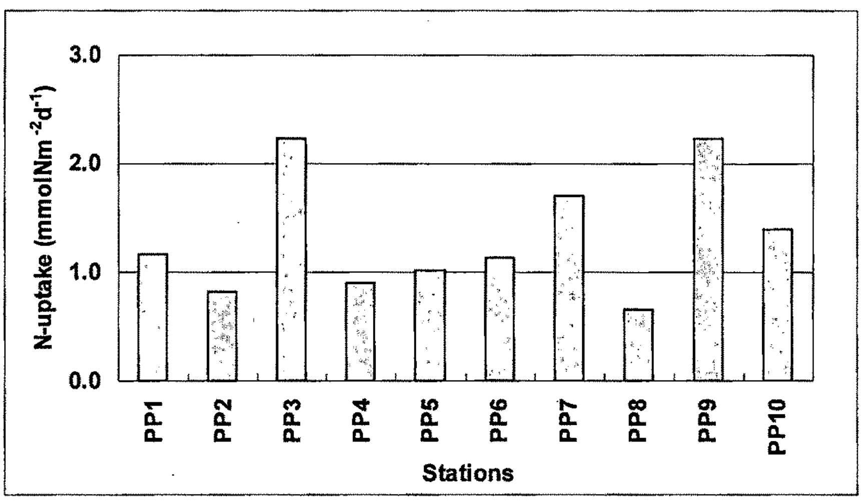


Fig 4.7 Mixed layer depth integrated total N-uptake rates at different stations in the equatorial Indian Ocean during pre-monsoon 2005

One of the main reasons may be the influx of pacific water through the Indonesian throughflow (Gordon and Fine 1996). Though it is well established that it plays a major role in ocean circulation and heat exchange (Godfrey 1996), its effect on the productivity is still not known. It is still not known that whether it carries only heat or it carries nutrients as well and hence more such studies in this region are required to ascertain the effect of the Indonesian throughflow on the biogeochemistry of the Indian Ocean and on the biological productivity of this basin.

4.3.2 New Production:

In the equatorial Indian Ocean photic zone integrated column nitrate uptake rates were significantly high and showed lots of heterogeneity in space during the pre-monsoon season; it varied from 12.84 mmolNm^{-2}d^{-1} to 167.17 mmolNm^{-2}d^{-1} over the study region. It varied from 12.84 mmolNm^{-2}d^{-1} to 123.71 mmolNm^{-2}d^{-1} with a mean of 45.85 mmolNm^{-2}d^{-1} along 77°E transect and from 14.90 mmolNm^{-2}d^{-1} to 167.17 mmolNm^{-2}d^{-1} with a mean of 66.65 mmolNm^{-2}d^{-1} along 83°E transect (Fig 4.8). In general nitrate uptake rates were higher along 83°E transect at the stations north of the equator but were higher along 77°E transect at stations south of the equator. The most dramatic increase was observed at the equator where column integrated nitrate uptake rates increased more than order of magnitude at 83°E as compared to the same on 77°E. A significant part of nitrate uptake rate was confined in layers below the photic zone. This, again, may be because of the presence of high ambient nitrate concentrations below the mixed layer.

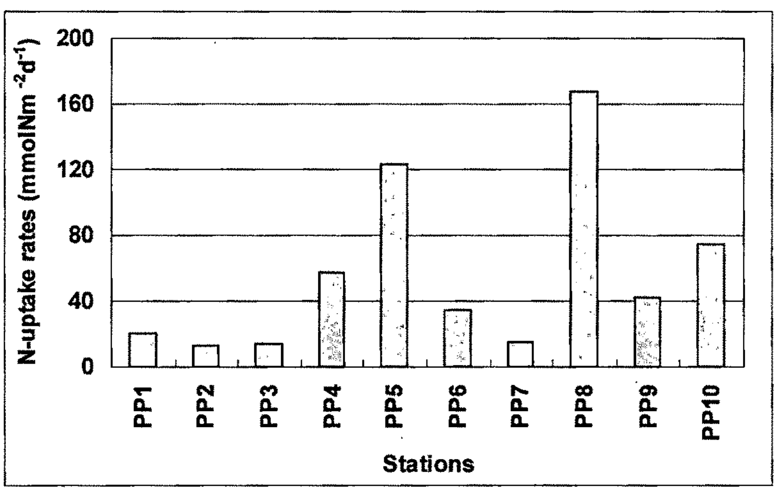


Fig 4.8 Photic zone integrated total nitrate uptake rates (new production) at different stations in the equatorial Indian Ocean during pre-monsoon 2005

The mixed layer integrated nitrate uptake rates were very low during the pre-monsoon 2005. 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. New production varied over a small range along 77°E; it varied from a low of 0.12 $mmolNm^{-2}d^{-1}$ to a high of 0.30 $mmolNm^{-2}d^{-1}$ and along 83°E transect the variation was quite large, from a low of 0.21 $mmolNm^{-2}d^{-1}$ to a high of 0.84 $mmolNm^{-2}d^{-1}$. New production or nitrate uptake rate was low at station along 77°E transect than those along 83°E at all the stations except the equator where new production was higher at 83°E compared to 77°E (Fig 4.9). There was a significant variation in the nitrate uptake rates at stations south of the equator. It was 0.18 $mmolNm^{-2}d^{-1}$ at 5°N, 77°E which increased 3-fold to 0.55 $mmolNm^{-2}d^{-1}$ at 5°N, 83°E. At 2.5°N 7-fold increased was observed in the nitrate uptake rate from 77°E to 83°E; it increased from 0.12 $mmolNm^{-2}d^{-1}$ to 0.84$mmolNm^{-2}d^{-1}$ (Fig 4.9). At the stations south of the equator i.e,. at 2.5°S and 5°S nitrate uptake rates were almost similar at 77°E and 83°E.

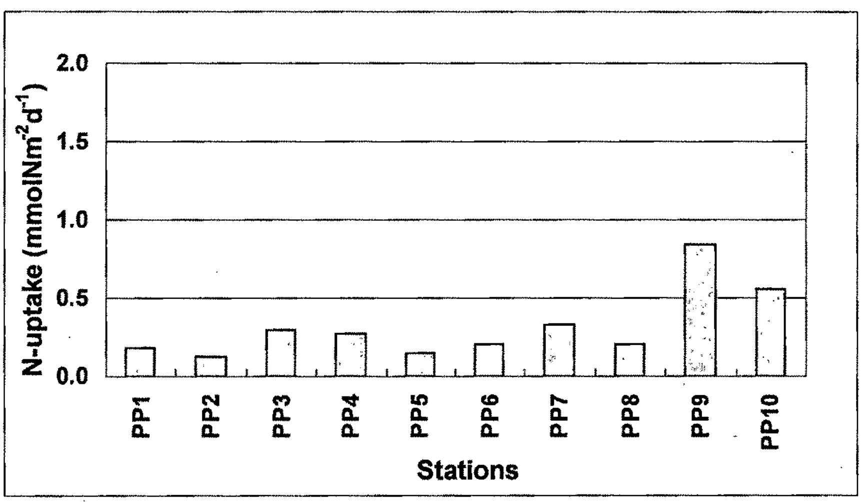
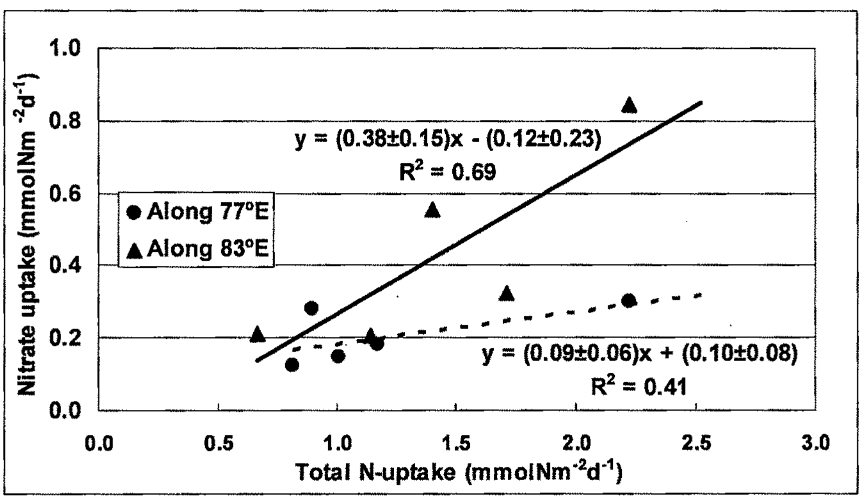


Fig 4.9 Station-wise mixed layer depth integrated nitrate uptake rates (new production) at different stations in the equatorial Indian Ocean during pre-monsoon 2005

Relation between mixed layer integrated nitrate uptake rates (new production) and total uptake rates (total production) suggests two different slopes for the two transects (Fig 4.10). Along 77°E the correlation was weak (correlation coefficient = 0.41) with a lower slope {New Production = (0.09±0.06) Total production + (0.10±0.08)} where as along 83°E correlation was more significant (correlation coefficient = 0.69) with relatively higher slope {New Production = (0.38±0.15) Total production - (0.12±0.23)}. Different slopes along different transects suggests presence of two different biogeochemical provinces in the equatorial Indian Ocean with significantly different potential of export production. Capability of the equatorial ocean for export production is low as compared to that of the 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 higher, of the mixed layer integrated total production.



4.10 Relation between mixed layer integrated total N-uptake rate and nitrate uptake rate in the equatorial Indian Ocean during pre-monsoon 2005

4.3.3 Regenerated production

Ambient ammonium and urea concentrations could not be measured during the present study. For the calculation of regenerated production it was assumed that the tracer added was the only source of nutrient for the plankton and the uptake rates given here are potential uptake rates for ammonium and urea. Ammonium uptake rate varied from 1.14 $mmolNm^{-2}d^{-1}$ to 2.17 $mmolNm^{-2}d^{-1}$ along 77°E transect in the equatorial Indian Ocean. At 5°N (PP1) ammonium uptake rate was 2.17 $mmolNm^{-2}d^{-1}$ which decreased to 1.15 $mmolNm^{-2}d^{-1}$ at 2.5°N (PP2). At the equatorial station (PP3) it again increased to 1.44 $mmolNm^{-2}d^{-1}$. At a station south of the equator, i.e., 2.5°S (PP4) it further increased to 2.17 $mmolNm^{-2}d^{-1}$ but again decreased to 1.14 $mmolNm^{-2}d^{-1}$ at 5°S (PP5). Along 83°E transect ammonium uptake rate varied from 1.26 $mmolNm^{-2}d^{-1}$ to 2.44 $mmolNm^{-2}d^{-1}$. Stations south of equator had more ammonium uptake rates as compared to stations north of the equator. At 5°N (PP10), along 83°E transect, ammonium uptake rate was 2.35 $mmolNm^{-2}d^{-1}$. It increased slightly to reach a maximum of 2.44 $mmolNm^{-2}d^{-1}$ at 2.5°N (PP9) but again decreased to 2.13 $mmolNm^{-2}d^{-1}$ at a station at equator (PP8). At stations south of equator ammonium uptake rate was comparatively less; it was 1.26 $mmolNm^{-2}d^{-1}$ and 1.33 $mmolNm^{-2}d^{-1}$ at 2.5°S (PP7) and 5°S (PP6) respectively. The mean ammonium uptake rate along 77°E transect was less than those along 83°E transect: it was 1.61 $mmolNm^{-2}d^{-1}$ and 1.90 $mmolNm^{-2}d^{-1}$ along 77°E and 83°E transect respectively.

Ammonium uptake rates at different stations are shown in Fig 4.11. At 5°N ammonium uptake rate was slightly more at 83°E but at 2.5°N it was more than twice compared to that at 77°E. Ammonium uptake was also more at 83°E than at 77°E at the equator. At 2.5°S it was more at 77°E than 83°E and at 5°S it was almost the same at both the longitudes. Urea uptake rates varied from 1.19 $mmolNm^{-2}d^{-1}$ to 2.53 $mmolNm^{-2}d^{-1}$ along 77°E transect and from 1.14 $mmolNm^{-2}d^{-1}$ to 2.52 $mmolNm^{-2}d^{-1}$ along the 83°E transect (Fig 4.12). Along the 77°E, urea uptake rate was 1.56 $mmolNm^{-2}d^{-1}$ at 5°N. It decreased to 1.19 $mmolNm^{-2}d^{-1}$ at 2.5°N but increased more than twice to reach a maximum of 3.13 $mmolNm^{-2}d^{-1}$ at a station at the equator. The equatorial station at 77°E had maximum urea uptake rate measured during the present study. At a station south of the equator i.e. at 2.5°S, urea uptake rate again decreased to 2.59 $mmolNm^{-2}d^{-1}$. It further decreased to 1.67 $mmolNm^{-2}d^{-1}$at 5°S. Along 83°E urea uptake rate was 1.55 $mmolNm^{-2}d^{-1}$ at 5°N. At 2.5°N and the equator it was 1.14 $mmolNm^{-2}d^{-1}$ and 1.77 $mmolNm^{-2}d^{-1}$ respectively. Urea uptake rate again increased south of the equator, i.e., at 2.5°S to 2.52 mmolNm^{-2}d^{-1} but decreased to 1.96 mmolNm^{-2}d^{-1} at 5°S. In contrast to ammonium uptake rate, the mean urea uptake rate was more along the 77°E transect than the 83°E transect: it was 2.03 mmolNm^{-2}d^{-1} along 77°E and 1.79 mmolNm^{-2}d^{-1} along 83°E transects respectively. A comparison of urea uptake rates at stations having different longitudes but same latitude is shown in Fig 4.12. At 5°N, 2.5°N and 2.5°S urea uptake rate remained almost the same at both 77°E and 83°E, but at 0° latitude, urea uptake at 77°E was almost twice that at 83°E. Along both transects ammonium uptake was more than the urea uptake at stations north of the equator and the equator, and was less than urea uptake at stations south of the equator.

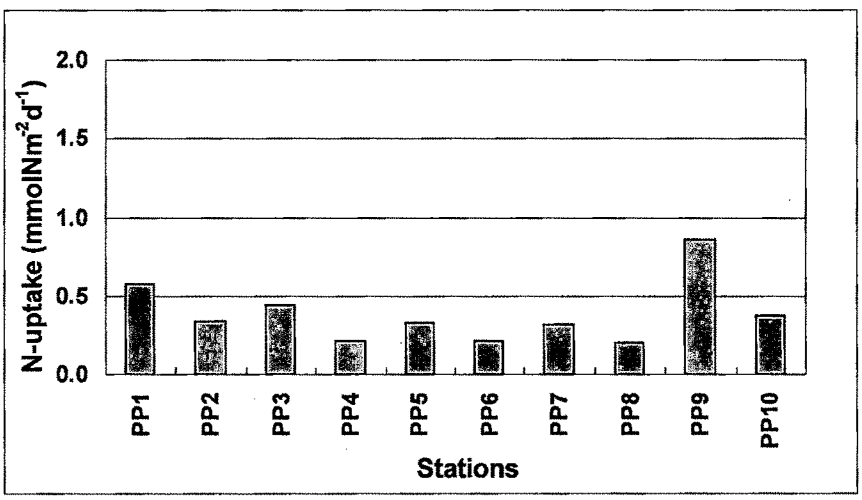


Fig. 4.11 Mixed layer depth integrated ammonium uptake rates at different stations in the equatorial Indian Ocean during pre-monsoon 2005

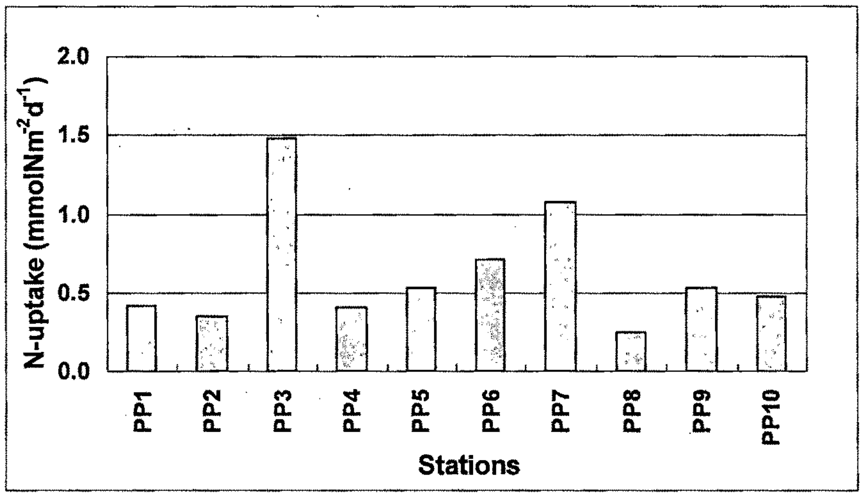


Fig. 4.12 Mixed layer depth integrated urea uptake rates at different stations in the equatorial Indian Ocean during pre-monsoon 2005

4.3.4 *f*-ratios in the equatorial Indian Ocean

The column integrated *f*-ratio was very high in the equatorial Indian Ocean; it varied from 0.85 to 0.98 over the entire region (Fig 4.13). Along 77°E transect *f*-ratio varied from 0.85 to 0.98 whereas along 83°E transect it varied from 0.80 to 0.98. The mean *f*-ratio along 77°E and 83°E were 0.87 and 0.91 respectively. These values are comparable to *f*-ratios reported from upwelling regions of the northwestern Arabian Sea during the summer monsoon; Watts and Owens (1999) has reported *f*-ratios as high as 0.92 from the upwelling regions of the Arabian Sea. The *f*-ratio found during the present study in the equatorial region of the Indian Ocean is significantly higher than that at the other parts of the Indian Ocean. This is again due to availability of huge amount of nitrate in the water column below the mixed layer and thus may have been somewhat overestimated. Mixed layer integrated *f*-ratio were very low compared to the column integrated *f*-ratios; they varied from 0.16 to 0.40 over the entire region. The *f*-ratios were low along 77°E transect; it varied from 0.16 to 0.31 with a mean of 0.18. The maximum *f*-ratio of 0.31 along this transect was found at PP4. Excluding PP4 the *f*-ratio varied from a low of 0.13 to a high of 0.18. Along 83°E, the *f*-ratio varied from 0.18 to 0.40 with a progressively increasing trend. The mean along this transect was 0.29.

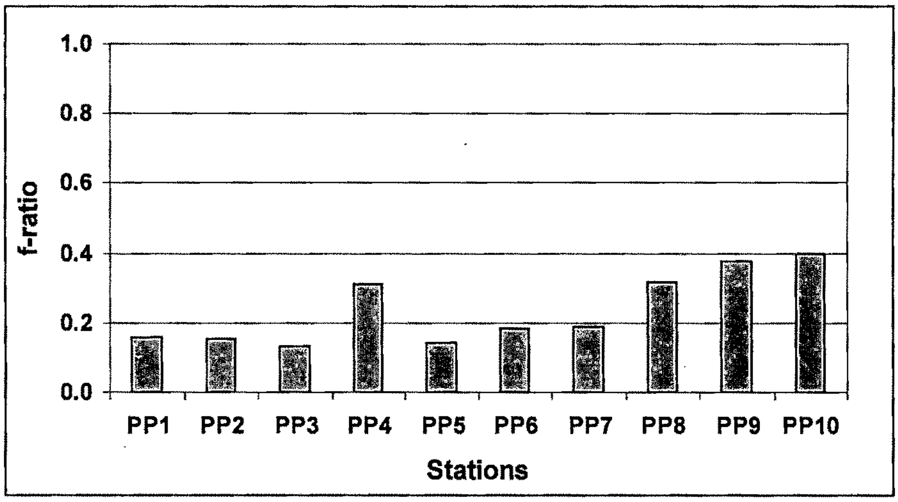


Fig. 4.13 *f*-ratios at different stations in the equatorial Indian Ocean.

4.4 SOUTHERN OCEAN

The Southern Ocean is now delimited as the world's fifth ocean by the International Hydrographic Organization (IHO). It comprises of the southern portions of the Pacific, Atlantic and the Indian Oceans (Fig.4.14) and it constitutes approximately 10% of the world's oceans. The Southern Ocean plays an important role in the global carbon cycle and climate regulation by acting as a net sink, *via* solubility and biological pumps, for the atmospheric CO_2 (Chisholm et al., 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 and Nicol 2003). The Antarctic Circumpolar Current (ACC), the only current that flows completely around the globe, is the strongest current in the world ocean and the most important current in the Southern Ocean. The ACC, as it encircles the Antarctic continent, flows eastward through the southern portions of the Atlantic, Indian, and Pacific Oceans. 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). Some of the areas of the world's ocean such as the Southern Ocean, the equatorial and the North Pacific Ocean contain huge amounts of unused macro-nutrients such as nitrate in their surface waters. Despite this, the productivity in these areas is low (column integrated primary productivity varies between 130-220 $mgCm^{-2}d^{-1}$; Gervais and Reibesell 2002). The growth of phytoplankton and uptake of nutrients, during their growth, causes depletion of major nutrients in the surface layer. The persistence of these nutrients in the surface waters of the Southern Ocean suggests retardation of plankton growth due to some reason. Because of this property these regions are described as "High Nutrient Low Chlorophyll" or HNLC regions (Minas et. al., 1986; Dugdale and Wilkerson, 1986; Martin et. al., 1991; Mitchell et. al., 1991). The Southern Ocean is unique in the sense that it is the largest HNLC region in the world oceans; its surface water also contains significant amounts of macronutrients such as nitrate, silicate and phosphate to support high primary production and yet the productivity in this region is quite low.

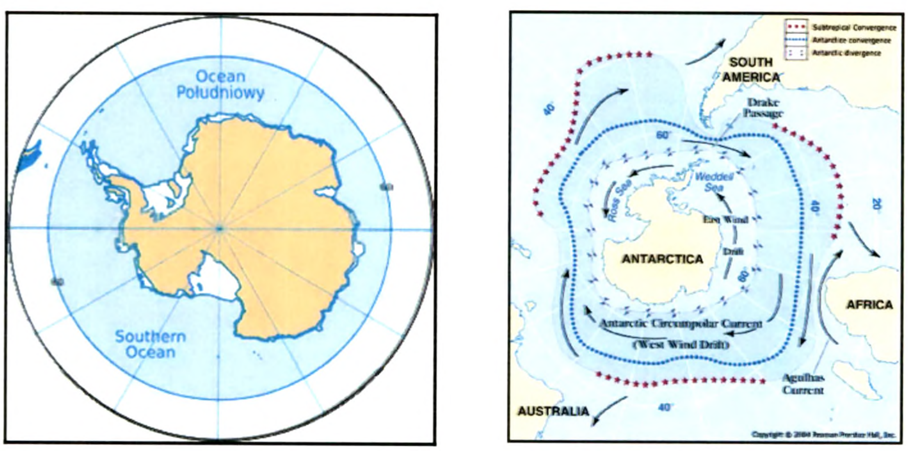


Fig 4.14. The aerial extent of the Southern Ocean (left) and the cartoon of the Antarctic Circumpolar Current (ACC; right).

Several causes have been proposed in the past to explain the existence of the HNLC condition particularly in the Southern Ocean. The important ones are: presence of deep mixed layer, low sea surface temperature, low specific growth rate, grazing control, sun-light limitation, trace metal toxicity and Fe-limitation. The insufficient availability of micronutrients such as iron (Fe) ($<10^{-12}$ M in the open ocean) appears to be the main cause for observed low productivity in such regions (Martin et al., 1991). The role of iron in controlling the productivity in the open ocean and, consequently the climate is called the "Iron Hypothesis".

Martin and his colleagues (Martin and Fitzwater 1988) were the first to measure the concentration of iron in the waters of the Gerlache strait (Antarctic coast) and the Drake Passage (offshore). They concluded that the offshore locations were less productive (~100 $mgCm^{-2}d^{-1}$) because of lack of iron (<0.16 nM). They also proposed that the coastal stations received iron (~7.4 nM) from the continental margins and so the productivity was very high (3 $gCm^{-2}d^{-1}$) and therefore the supplied iron did not get transported to the open ocean (Martin et al., 1990). Iron can limit productivity in the open ocean because (i) it is required for the synthesis of chlorophyll and it helps in plant metabolism (Geider and LaRoche 1994) and (ii) lack of iron may also cause decline in the photosynthetic electron transfer (Geider and LaRoche 1994; Hutchins 1995) which in turn may lead to low photosynthetic efficiency (*i.e.*, production per unit chlorophyll). The idea of iron limitation got momentum when it was shown, through bottle scale experiments carried out for the first time at station PAPA (50°N, 145°W) in the sub-arctic north Pacific by Martin and his colleagues, that there is a rapid increase in the chlorophyll concentration and nitrate was totally consumed after 4 days since the iron enrichment (Martin and Fitzwater 1988). This was followed by a number of large-scale Fe-enrichment experiments carried out to test the hypothesis of Fe-limitation in different HNLC regions (Hutchins 1995).

In the Southern Ocean four large scale iron enrichment experiments have been done, two each in the Pacific sector (SOIREE and SOFeX) and the Atlantic (EisenEx and EiFex) (Martin et al. 1991; Coale et. al., 1996; Gervais and Riebesell 2002; Coale et. al., 2004); the Indian sector of the Southern Ocean still remains unexplored. The first large scale iron enrichment experiment in the Southern Ocean was done in February 1999 in the Australian (Pacific) sector (Boyd and Law, 2001). The iron enrichment site was observed for 13 days on-board and an increase of more than 10-fold was measured in column primary production (~1.3 $gCm^{-2}d^{-1}$) (Gall et al., 2001). Chlorophyll increased markedly (~2 μgl^{-1}), nitrate and silicate concentration in the surface waters decreased during these 13 days but export flux measured for "IN" and "OUT" patches were not significantly different.

SOIREE was followed by EisenEx, another large scale iron fertilization experiment, in Atlantic during austral spring, 2000. Primary production during EisenEx increased from 130-220 $mgCm^{-2}d^{-1}$ at an "OUT" patch station to ~800 $mgCm^{-2}d^{-1}$ after 16 days. Chl-a increased from 48-56 mgm^{-2} to 231 mgm^{-2} after 21 days of enrichment. Another enrichment experiment SOFeX was carried out in the Pacific sector of the southern Ocean. During this experiment two patches were fertilized, each having different silica concentration; the northern and southern patches had Si concentrations of <5 μM and >60 μM respectively. The northern patch witnessed almost a 10-fold increase in Chl-a and a 4-fold increase in the carbon biomass, whereas in the southern patch Chl-a increased almost 8-fold and productivity increased from ~3.5 $mgCm^{-3}d^{-1}$ to ~55 $mgCm^{-3}d^{-1}$ (Coale et al., 2004). Absolute nitrate uptake rate also increased by factors of 15 and 25 respectively in the northern and southern patches compared to control regions (Coale et al., 2004). *f*-ratio increased from 0.1-0.2 to 0.5-0.6 in the southern patch (silica rich) and from 0.3 to 0.4 in the northern patch (silica depleted) which suggested that availability of iron increases nitrate uptake by marine plankton (Coale et al., 1996).

More recently it has been proposed that natural iron fertilization due to upwelling of nutrient rich water from deep leads to development of bloom in 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. Even though most the Fe-enrichment experiments have seen a significant increase in the chlorophyll, studies pertaining to the nitrogen biogeochemistry are limited. The Indian Sector of the Southern Ocean constitutes ~39% ($13.1 x 10^6$ sq. km) by area (deBaar et al., 2005)and is the least explored area (Slawyk 1979: Probyn and Painting 1985: Collos and Slawyk 1986: Mengesha et. al., 1998: Semeneh et al., 1998: Savoye et. al., 2004), compared to the Pacific and Atlantic oceans, in terms of N-uptake studies. Our knowledge about the

N uptake and the *f*-ratio characteristics of this region is rather limited. The present study highlights new results of N-uptake and *f*-ratios from the Indian sector of the Southern Ocean, though only based on bottle-scale experiments.

4.5 Summary of the earlier work

Slawyk (1979) was the first to study nitrate uptake rates from the Kerguelen Island area of the Southern Ocean. He described the Southern Ocean water as transparent water with relatively high photic depth, varying between 50 to 100 m. He reported very low nitrate uptake rates, varying 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 of the coastal regions between Cape Ann and Mawson in the Southern Indian Ocean. The N-uptake rate reported by them was significantly high; it 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; the mean *f*-ratio was 0.42. They also studied the nitrate uptake according to the size class and found that the phytoplankton of size <200 μm contributed the maximum to nitrate uptake; nanoplankton (size < 15 μm) and picoplankton (size < 1μm) contributed mostly to regenerated production. Mengesha et al., (1998) studied N-uptake characteristics of the Southern Ocean waters over two different seasons, austral spring and summer 1994, for a small area near Kerguelen Island. They found a pronounced seasonal variation in the nitrogen uptake in the Indian sector of the Southern Ocean. During spring the 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, from 0.0015 hr^{-1} in spring to 0.0018 hr^{-1} in the summer. The *f*-ratio also decreased in the summer but showed considerable variation; it varied from 0.68 to 0.85 in spring and from 0.17 to 0.63 in summer. They observed a transition from nitrate based autotrophic community in spring to regenerated nitrogen based community in summer. Specific nitrate and ammonium uptake rates reported for the surface waters by Semeneh et al., (1998) were lower than the 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. Though the specific nitrate uptake rate was more in the open ocean zone relative to coastal zone (the mean specific uptake rate in coastal zone was 0.5 hr^{-1} whereas in the open ocean zone it was 1.0 hr^{-1}), specific total N-uptake rate (a sum of specific nitrate and ammonium uptake rates) was almost the same. The same trend was seen in the *f*-ratio as well; the mean *f*-ratio in coastal zone was 0.42 whereas in the open ocean zone it was 0.68. The absolute total N-uptake rate in the coastal zone was more than three fold higher than the rate in the open ocean zone; the absolute N-uptake rate was 147.2 ± 71.9 $\mu molNm^{-3}d^{-1}$ in the coastal zone and was 38.9 ± 24.7 $\mu molNm^{-3}d^{-1}$ in the open ocean zone. They 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 that at the open ocean zone of the Prydz Bay but the *f*-ratio was low (0.034).

Savoye et al., (2004) studied N-uptake and *f*-ratio characteristics of the Australian sector of the Southern Ocean. They reported a continuous increase in total N-uptake and nitrate uptake rates on a north-south transect. Nitrate uptake rate increased from a low of 1.4 $mmolN/m^2/d$ at 48.8°S to a high of 8.8 $mmolNm^{-2}d^{-1}$ at 64.9°S, total N-uptake rate increased from 4.9±0.7 to 9.2±2.2 $mmolNm^{-2}d^{-1}$. Ammonium and urea uptake rates remained almost constant (2.3±0.5 $mmolNm^{-2}d^{-1}$ and 0.5±0.1 $mmolNm^{-2}d^{-1}$ respectively). The *f*-ratio also increased southwards, from 0.33 in the north to 0.69 in the south.

Sambrotto and Mace (2000) reported N-uptake rates and *f*-ratios from the western Pacific sector of the Southern Ocean along 170°W. Like Semeneh et al., (1998), they also reported high N-uptake rates for the late austral spring/ early summer (December); the column integrated nitrate and total N-uptake rates were as high as 10 $mmolNm^{-2}d^{-1}$ and 30 $mmolNm^{-2}d^{-1}$. He also found that a significant part of the N-uptake was from the surface waters and subsurface contribution was very less. During summer, new production reduced by an order of magnitude in the same area. The *f*-ratio varied from 0.04 to 0.5; high *f*-ratios were measured at the ice edge during spring and lower *f*-ratios were measured during summer.

4.6 Chlorophyll a, nutrients and physical parameters during Feb-March 2006 in the Southern Indian Ocean

4.6.1 Chlorophyll-a

Chlorophyll was measured at all the stations in the Southern Ocean using a submersible fluorescence probe. The Southern Ocean showed significant variations in chlorophyll concentration. During the study period the maximum column integrated (integrated up to photic zone) chlorophyll concentration of 155 mgm^{-2} was found at the Antarctic coastal station. Integrated chlorophyll concentration decreased significantly towards the north and varied between 46 to 99 mgm^{-2} (Fig. 4.15 left panel), except at station PP4 where it was 144 mgm^{-2}. Chlorophyll profiles at different stations are shown in Fig 4.15-right panel.

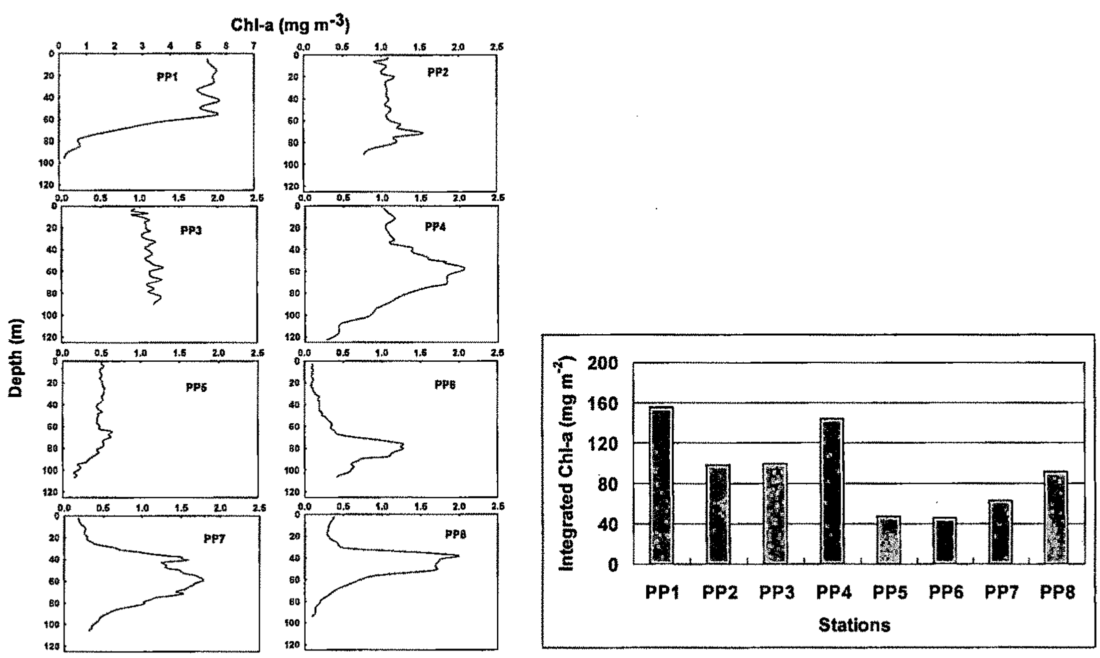


Fig. 4.15 Vertical profiles of Chl-a (left panel) and column integrated Chl-*a* (right panel) at different stations in the Southern Indian Ocean

In the Coastal zone of Antarctica (PP1) the chlorophyll was high; it varied between 2-6 mgm^{-3} in the adjoining areas. Though both green algae and diatoms were present, the latter dominated as they contributed to more than 65% of the total Chl-*a*. Though Chl varied between 4.97 to 5.74 mgm^{-3} in the upper layer, it was almost constant up to 55m. It decreased below, to a minimum of 0.2 at 96 m. Away from the coast, at PP2, surface Chl-a decreased significantly to 1.09 mgm^{-3}. Here also it was almost constant up to 60m, increased downward to reach a maximum of 1.55 mgm^{-3} at a depth of 71 m but again decreased downwards. Green algae dominated over diatoms at this station; green algae contributed more than 70% to the total Chl-*a*.

At PP3, Chl-*a* varied between 0.94 to 1.27 mgm^{-3} throughout the photic zone; green algae and diatoms contributed 60 and 40% of the total Chl concentration. Surface Chl at PP4 was similar to PP3 i.e, 1.02 mgm^{-3} but unlike PP3 it had a marked deep chlorophyll maximum (2.04 mgm^{-3}) at 56 m. Chlorophyll decreased to 0.28 mgm^{-3} at 123 m. Here also the green algae (>70%) dominated over the diatoms. Chlorophyll concentration decreased significantly to 0.49 mgm^{-3} in the surface waters of station PP5 and remained almost the same up to a depth of 63 m. It increased slightly to 0.63 mgm^{-3}at a depth of 65 m but again decreased to 0.15 mgm^{-3} at 107 m. A marked deep chlorophyll maximum was not present at this station. The concentration of diatoms reduced significantly at this station, green algae contributed more than 85% to the total Chl. Chlorophyll further decreased to 0.1 mgm^{-3} at PP6. A marked deep chlorophyll maximum was at a depth of 76 m where the chlorophyll concentration was 1.28 mgm^{-3}. Only green algae were present in upper water column; diatoms were not there in the water column up to a depth of 70 m.

The equatorial station (PP7 and PP8) exhibited similar characteristics in terms of chlorophyll in the water column. Both the stations had marked deep chlorophyll maximum at depths of 62 and 41 m respectively. Surface waters were devoid of diatoms, though they were present in the deeper waters.

4.6.2 Nutrients

Samples from all the stations and all corresponding depths were analysed for ambient nitrate concentrations. During the present study the nitrate concentrations found for the surface waters of the Southern Ocean were typical of that area. Vertical profiles of ambient nitrate at different stations in the Southern Ocean are shown in Fig 4.16. All stations had high nitrate concentrations (~20 μM) in the surface and they remained high throughout the column. At PP6, the northernmost station in the Indian sector of the Southern Ocean, the ambient nitrate concentration was significantly less compared to other southern Ocean stations, 5.65 μM.

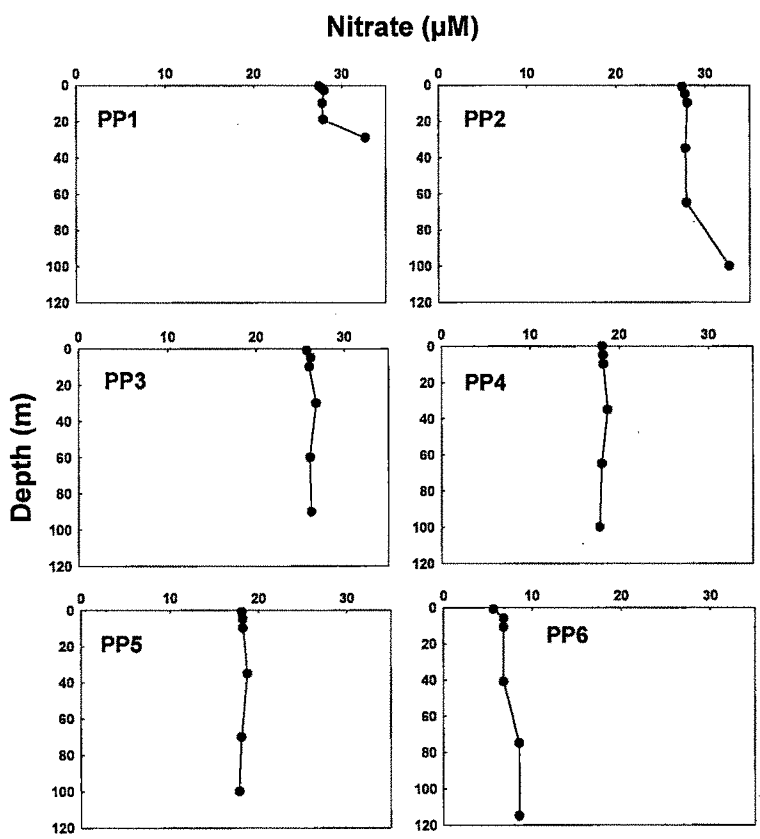


Fig. 4.16 Vertical profiles of ambient nitrate concentrations at different stations in the Southern Indian Ocean.

4.6.3 Hydrographic Conditions

The physical conditions encountered during the present study were typical of that area i.e., low sea surface temperature and deeper mixed layer in the south close to Antarctica and relatively shallow mixed layer in the north. Meridonial variation in SST is shown in Fig. 4.17 where PP1 is the southern most station and PP8, a station in the equatorial Indian Ocean. In the areas adjoining Antarctic coast the SST was very low, lowest SST was -1.7°C. Though it increased slightly to -0.9°C at 65°S the low temperature zone continued up to 58°S where SST was 0.9°C. SST increased northwards to 11°C at PP4, a station south of subtropical front (STF). There was sharp rise in SST from 43°S to 40°S. 40°S marks the presence of STF in the Indian Ocean where the cold sub-antarctic water meets warm subtropical waters. In the equatorial region SST was almost the same. Southern Ocean close to the Antarctic coast is characterized by the presence of deep mixed layer. During the present study temperature based mixed layer depth (MLD) was more than 90 m at the station in the Antarctic waters, i.e., at PP1, PP2 and PP3 (Fig 4.18).

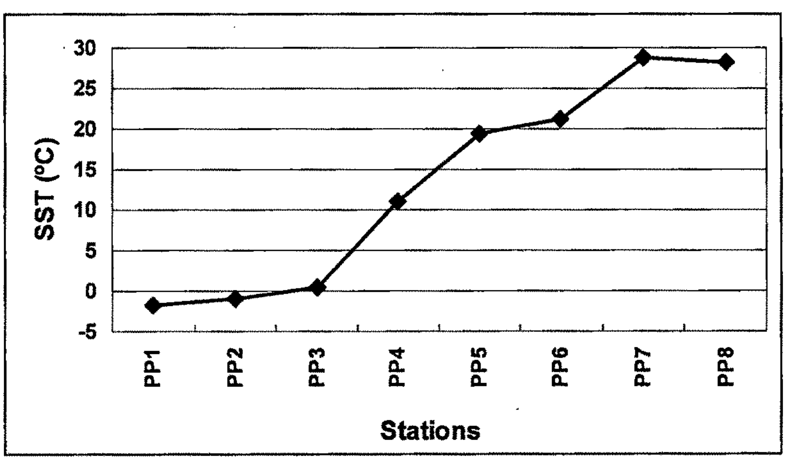


Fig. 4.17 SST (in °C) at different stations in the Southern Indian Ocean

The presence of deep MLD in the Southern Indian Ocean causes entrainment of nutrients, mainly nitrate into the upper layer. Since these newly entrained nitrates are not utilized efficiently by the plankton present there, the upper layer water of this area rich in nutrients (nitrate) throughout a year. Absence of micro-nutrient iron is believed to be responsible for underutilization of these nitrates.

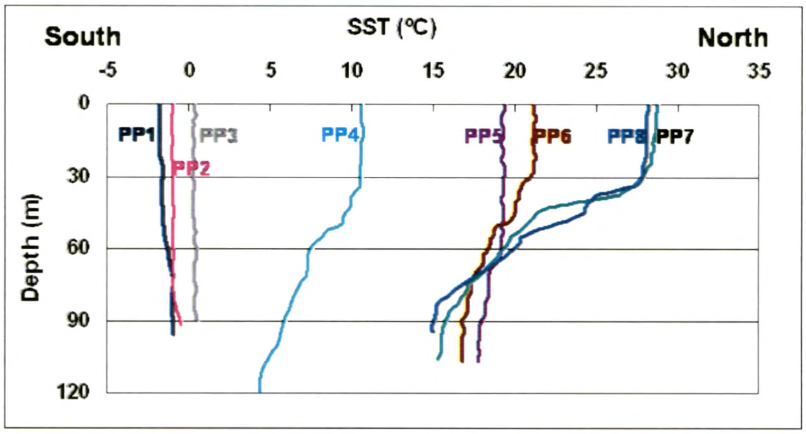


Fig. 4.18 Temperature-depth profiles at different stations in the Southern Indian Ocean. The stations in the south had deeper mixed layers compared to those in the north.

At PP4 at 43°S MLD decreased to 45 m. MLD again deepened to ~72 m at 40°S at STF. Temperature-depth profile of station PP6 (north of STF) was similar to that of PP4 (south of STF) but MLD at PP6 of 39 m was less than that at PP4. The equatorial Indian Ocean had almost similar temperature depth profiles; MLD at both the stations was 30 m.

4.7 ^{15}N based productivity during late austral summer 2006

4.7.1 Total Production

The main aim of the present study was to characterize the Indian sector of the Southern Ocean on the basis of N-uptake rates and *f*-ratios. For the present study ^{15}N measurements were done at six different stations in the Southern Ocean and at two different stations at the equatorial Indian Ocean. 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 (Fig. 4.19).

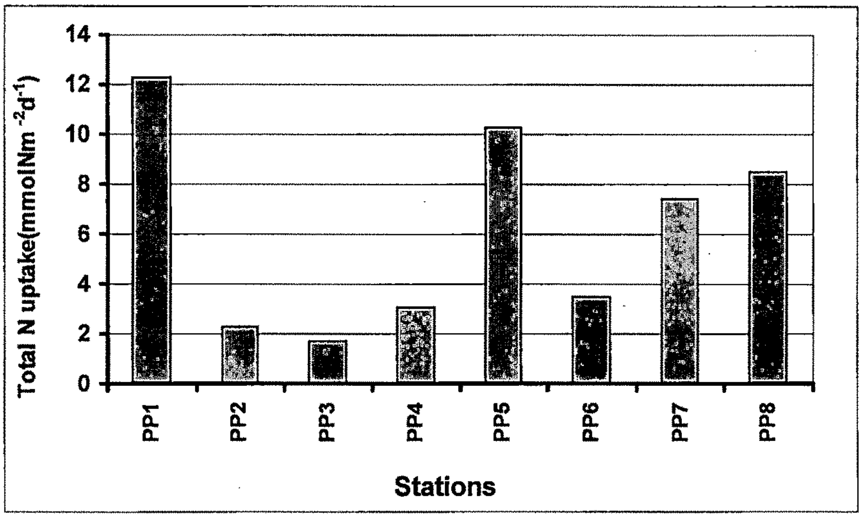


Fig 4.19 Total N-uptake rates at different stations in the Southern Indian Ocean

At station PP 1, which lies in coastal zone of Antarctica (69.18°S, 76°E), the total N uptake rate is very high (~12.3 mmolNm^{-2}d^{-1}), the highest observed during the present study. In terms of carbon, the total carbon uptake during late austral summer in the Antarctic coastal zone is 981.5 mgCm^{-2}d^{-1}. High carbon uptake rate in coastal regions of Antarctica was also reported by other authors (Treguer and Jacques, 1992). Probyn and Painting (1985) reported N-uptake as high as 5.91 mmolNm^{-2}hr^{-1} (mean = 4.74 mmolNm^{-2}hr^{-1}) for a coastal station between the Cape Ann and Mawson. High production in this zone has also been reported by pCO_2 measurements by Poisson et al., (1994). The production here is high, because the coastal region receives ample nutrients from the Antarctic continent. These nutrients are derived through the coastal continental erosion and the run off contains significant amount of iron along with other major nutrients. At PP2, located to the north of PP1, N-uptake decreased drastically to 2.3 mmolNm^{-2}d^{-1} (~183.8 mgCm^{-2}d^{-1}). Though ambient iron measurements were not done, we suspect that iron is not transported up to this station. This is because of the formation of Antarctic bottom water (AABW). During late summer, water near the Antarctic coast starts freezing (Vyas et al., 2004), leaving all the salts behind. This extra input of salt to the remaining water makes it very dense and it sinks to form AABW. The formation of

AABW takes place near the coast and during this process it carries unused nutrients, also the nutrients supplied through coastal erosion, along with it. This results in the absence of iron in the surface waters of the regions to the north of the Antarctic coast and limits the production farther from the coast. Productivity further decreased northwards and this low productivity zone extended up to the Sub-tropical front (STF) i.e., 40°S. The 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 $mmolNm^{-2}d^{-1}$) for the Australian sector of the Southern Ocean at 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). Also, silicon is considered as one of the limiting nutrients in this zone. Since the major species here are diatoms, because of the lack of silicon they are not able to proliferate. We have taken two stations, PP 3 and PP 4, in two different regimes: PP 3 in the zone of high Si concentration (>30 μM) and PP 4 in the zone of low Si concentration (1-3 μM). At PP 3, though the silicon concentration is more than that at PP 4, the productivity is less. Column N-uptake rates at PP 3 and PP 4 are 1.73 $mmolNm^{-2}d^{-1}$ (~138.2 $mgCm^{-2}d^{-1}$) and 3.05 $mmolNm^{-2}d^{-1}$ (~244 $mgCm^{-2}d^{-1}$) respectively. This variation in column production suggests that silicon is not the ultimate limiting nutrient in this area; rather, iron likely acts as a limiting nutrient. This is reflected in the photosynthetic efficiency (mgC/mgChl/hr) of phytoplankton present here. The photosynthetic efficiency of phytoplankton at PP 3 and PP 4 is very low (~0.08 mgC/mgChl/hr and 0.26 mgC/mgChl/hr respectively). This occurs due to the lack of micro nutrient, iron (Coale et. al., 2004: Martin et. al., 1991: Gervais and Riebesill 2002). Iron helps in the plant metabolism (Geider and La Roche 1994), and lack of iron may cause a decline in the photosynthetic electron transfer (Geider and La Roche 1994: Hutchins 1995) and this may decrease the photosynthetic efficiency of phytoplankton present there. There was a sudden increase in productivity at PP5 (40°S). Column N-uptake increased to 10.26 $mmolNm^{-2}d^{-1}$ (~821 $mgCm^{-2}d^{-1}$) but again decreased to 3.49 $mmolNm^{-2}d^{-1}$ (~279 $mgCm^{-2}d^{-1}$) at 35°S. The 40°S marks the presence of STF (sub-tropical front) which defines the northern boundary of the Antarctic Circumpolar Current (ACC) and it separates the subtropical warm waters from sub-Antarctic cold waters (Sparrow and Heywood, 1996). This is marked by the sudden change of surface temperature (upto 4°C) and salinity (Stramma, 1992). Upwelling of the Antarctic intermediate water (AAIW) takes place at STF which triggers high carbon fixation. The upwelled water is carried northward as surface advection (Marinov et al., 2006) but its effect is not reflected on production at station north of STF *i.e.* PP 6 (35°S).

Two stations were sampled at the equatorial region of the Indian Ocean, an oligotrophic region with almost no nitrate in the surface. The equatorial Indian Ocean differs from the other two major oceans as it does not possess a mean equatorial upwelling regime, rather it is characterized by the seasonally reversing circulation pattern, similar to the Arabian Sea: Summer monsoon (Jul/Aug) and winter monsoon (Jan/Feb) (Schott et. al., 2002). Mean Column N-uptake rate at equatorial region was ~8 $mmolNm^{-2}d^{-1}$ (640 $mgCm^{-2}d^{-1}$). Despite being oligotrophic with almost no nutrient in the surface layer the productivity of this region was quite high, in fact higher than most of the stations in the Southern Ocean where the nutrients were present in plenty. This may be because it receives sufficient amount of atmospheric dust, rich in iron, from the Asian and the African continents.

4.7.2 New Production

In late austral summer the whole Southern Indian Ocean is characterized by high nitrate uptake and hence high new production. Euphotic zone integrated nitrate uptake rates or new production during late austral summer in the Indian sector of the Southern Ocean (Fig. 4.20) 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. Nitrate was the main form of nitrogen preferred by plankton at all the stations in the Southern Indian Ocean except at a station north of STF at 35°S where reduced form of nitrogen was preferred. Over a large part of the Southern Ocean i.e from north of Antarctic coastal zone to STF at 40°S, the nitrate uptake was low and varied from 0.92 to 1.58 $mmolNm^{-2}d^{-1}$ with a mean of 1.67 ± 0.36 $mmolNm^{-2}d^{-1}$.

Though low new production (0.64 ± 0.36 $mmolNm^{-2}d^{-1}$) in this region has also been reported earlier (Slawyk 1979), new production during the present study is higher.

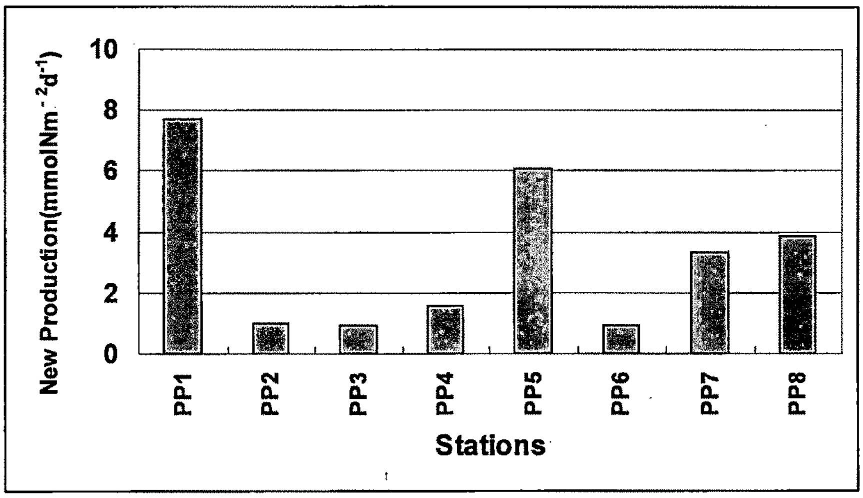


Fig. 4.20 New production at different stations in the Southern Indian Ocean

New production increased at PP5 to 6.05 $mmolNm^{-2}d^{-1}$; it was more than four times the new production at the previous stations but decreased again to 0.96 $mmolNm^{-2}d^{-1}$ at PP6. At the equatorial region new production remained almost the same; mean new production was 3.62 $mmolNm^{-2}d^{-1}$.

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 ± 0.06) x – (0.66 ± 0.42) (coefficient of determination, r^2 = 0.95: Fig. 4.21.). The slope of line of regression suggests the maximum possible value of *f*-ratio (0.63) for this zone. The plot also suggests that the minimum regenerated production for this region is ~1 $mmolNm^{-2}d^{-1}$. This large area is traditionally regarded as a low productive area where 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.

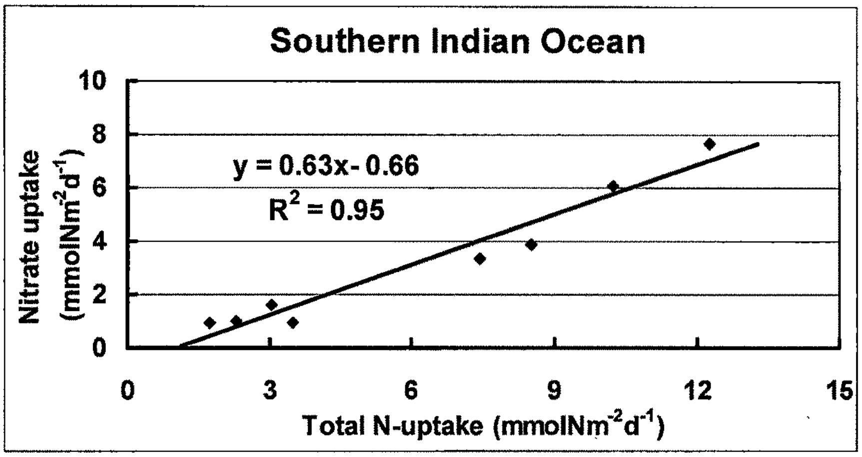


Fig 4.21 Relationship between total N uptake and nitrate uptake in the Southern Indian Ocean

4.7.3 Regenerated production

Ambient ammonium and urea measurements could done be during the present study and hence a conservative estimate of ammonia and urea uptake rates, their sum is regenerated production, was made assuming that water column was devoid of ammonium and urea (Fig 4.22). Ammonium uptake rates varied from 0.54 $mmolNm^{-2}d^{-1}$ at PP2 north of Antarctic Coastal zone to 3.30 $mmolNm^{-2}d^{-1}$ over the study area in the coastal region of Antarctica. At PP1 ammonium uptake rate was almost half of the nitrate uptake rate. Away from the coastal zone ammonium uptake decreased drastically; the mean ammonium uptake rate in the Southern ocean, between north of Antarctic coast up to south of STF (40°S), was 0.70 ± 0.25 $mmolNm^{-2}d^{-1}$. Ammonium uptake increased significantly at STF to 2.53 $mmolNm^{-2}d^{-1}$.

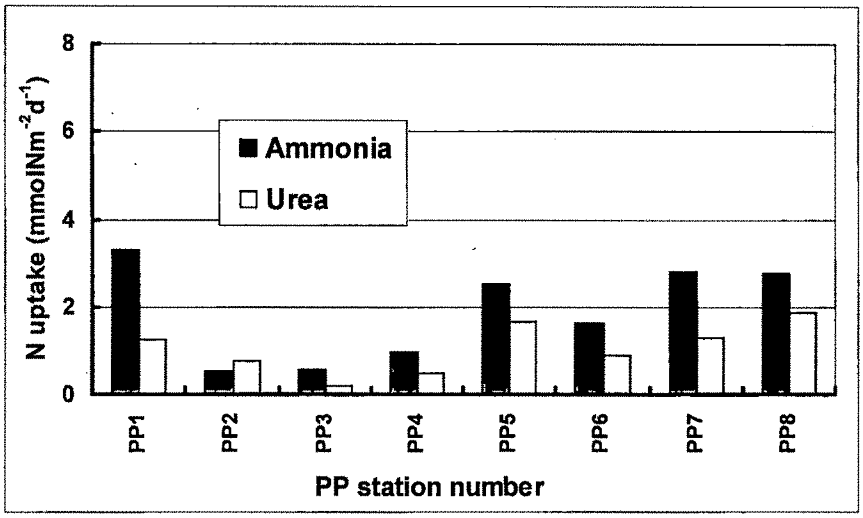


Fig. 4.22 Ammonium and urea uptake rates at different stations in the Southern Indian Ocean. Both the estimates are conservative.

North of STF at PP6 ammonium uptake decreased slightly to 1.61 $mmolNm^{-2}d^{-1}$. This may be the effect of very high production at PP 5, resulting in high regeneration there and some portion of this regenerated nutrients get transported to the north by the northward moving Antarctic intermediate water. The presence of regenerated nutrients such as ammonium inhibits the nitrate uptake (Mengesha et al. 1998). The same seems to hold true at PP 6. In the equatorial region of the Indian Ocean the ammonium uptake at both the stations was almost the same, ~2.78 $mmolNm^{-2}d^{-1}$.

Conservative estimate of ammonium varied from 0.22 to 1.86 $mmolNm^{-2}d^{-1}$ over the study area. At PP1, the coastal station, urea uptake rate was almost one third of the ammonium uptake rate and one sixth of the nitrate uptake rate. Mean urea uptake rate in the Southern Ocean between 65°S to 40°S was 0.49 $mmolNm^{-2}d^{-1}$. At STF i.e, at 40°S (PP5) urea uptake rate was thrice and at 35°S (PP6) it was almost double of that at Southern Ocean. The equatorial Indian Ocean did not show significant variation in the urea uptake rate; it was 1.30 $mmolNm^{-2}d^{-1}$ and 1.86 $mmolNm^{-2}d^{-1}$ at PP7 and PP8 respectively.

4.7.4 *f*-ratios in the Southern Ocean

The *f*-ratios presented here for the Southern Indian Ocean represent the upper bound since they were calculated using the conservative estimates of ammonium and urea uptake rates. The *f*-ratio in the Southern Ocean was moderately high (Fig 4.23); the mean *f*-ratio for the southern ocean stations, i.e., from PP1 to PP6, was 0.50. This was significantly lower than the values reported by Collos and Slawyk (1986) for the Indian Sector waters along 66.5°E transect. They reported *f*-ratios as high as 0.98 from a station at 43°S on the same longitudinal transect. The present study also had a station PP4 on the same latitude but at 48°E. The *f*-ratio here was 0.52, almost half of the value reported by Collos and Slawyk. Savoye et al., 2004 has also reported high *f*-ratio (0.55) from the Australian sector of the Southern Ocean on similar latitudes. Mengesha et al., 1998 has reported *f*-ratio varying from 0.17 to 0.63 with the mean of 0.39 from Kerguelen area in the Indian Ocean. The *f*-ratio of 0.50 indicates that the autotrophic community was based equally on nitrate as well as regenerated nutrients where ammonium and urea contributed to 50% of the total productivity. Mean *f*-ratio of 0.50 has also been reported by others for different sectors of the Southern Ocean; Smith and Nelson (1990) reported mean *f*-ratio of 0.53 during spring for the Weddell Sea. Goeyens et al., (1991) reported a mean *f*-ratio of 0.58 for the same region and the same season. During the present study the highest *f*-ratio was observed at the Antarctic Coast and the lowest at PP6, a station north of STF. The *f*-ratio of 0.63 for the Antarctic coastal water is one and half times of the value (0.42) reported by Probyn and Painting (1985) for the coastal waters. The *f*-ratio was low (0.27) at PP6 a consequence of high production at PP5 which resulted in high regeneration, some portion of which could have been transported to the north by the northward moving Antarctic intermediate water.

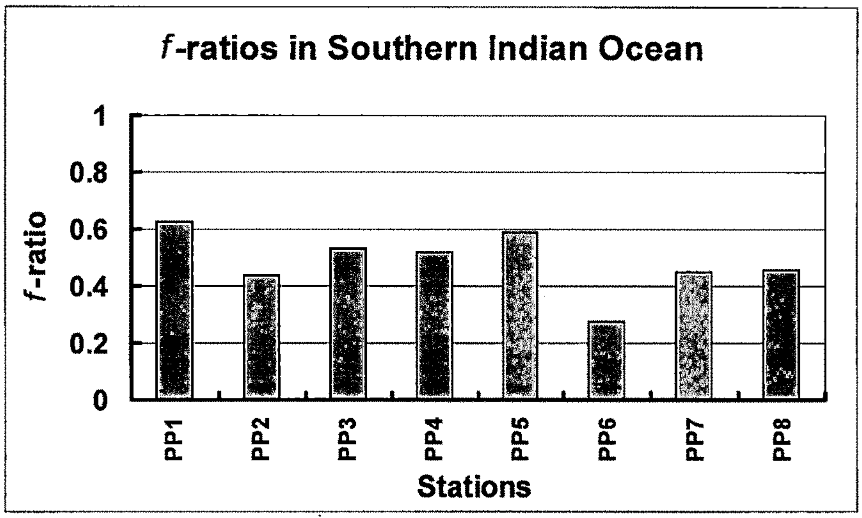


Fig. 4.23 *f*-ratios at different stations in the Southern Indian Ocean.

Previous studies from the Pacific and Atlantic sectors of the Southern Ocean (Probyn and Painting 1985; Smith and Nelson 1990; Smith 1991; Treguer and Jacques 1992) showed that phytoplankton growth in open ocean areas of the Southern Ocean largely depended upon ammonium for its nitrogen need and hence the *f*-ratio was relatively low. Mengesha et al. (1998) reported low mean specific nitrate and ammonium uptake rates during summer (0.0011 hr^{-1} and 0.0018 hr^{-1} respectively; urea was not measured) from transect along 62°E for the austral summer, 1994. The *f*-ratio varied from 0.17 to 0.63 with the mean of 0.39. We observed consistently higher nitrate uptake rates (0.0052 hr^{-1}) during summer 2006, but ammonium specific uptake rate (0.0013 hr^{-1}) was comparable with value reported by Mengesha et al. (1998). Specific urea uptake rate during our study was 0.0011 hr^{-1}. High specific nitrate uptake rate and increased *f*-ratio indicate a probable shift in the regime, from regenerated to new production in the last 12 years but more data are required, on larger temporal and spatial scales, to substantiate this preliminary observation. This signifies also that a large part of surface production could get transported to the deep and thus this area has the potential role in atmospheric carbon sequestration, under a favorable micronutrient regimes.

4.8 Iron experiment

All iron experiments have proved beyond doubt that the Southern Ocean is iron limited and addition of iron enhances productivity. However, the effect of iron on uptake of different N-substrates is still poorly known. Only a few studies (Van Leeuwe et al., 1997; Reay et al., 2001) determined the effect of iron enrichment on the uptake of different substrates such as nitrate, ammonium and urea. The present work is the first such study in the Indian sector of the Southern Ocean. We carried out bottle scale ^{15}N tracer-iron enrichment experiment in the Indian Sector of the Southern Ocean at two different stations to get a preliminary estimate of the role of iron on productivity and on individual nutrient uptake rates and *f*-ratios.

Station IEE1 lay in typical Southern Ocean waters, i.e., south of sub-tropical front, and IEE2 lie north of STF. The 40°-41°S latitude marks the presence of STF (sub-tropical front) in the Indian Ocean which defines the northern boundary of the Antarctic Circumpolar Current (ACC) and it separates the subtropical warm waters from sub-Antarctic cold waters (Sparrow and Heywood 1996). This is marked by the sudden change of surface temperature (upto 9°C) and salinity (Stramma 1992). Upwelling of the Antarctic intermediate water (AAIW) takes place at STF which triggers high carbon uptake. The upwelled water is carried northward as surface advection (Marinov et al., 2006). During the present study STF was located at 41°S and was marked by large temperature gradient (Srivastava et al., 2007). The same is reflected in SST at IEE1 and IEE2 as well; SST at IEE1 & 2 was 11.3°C and 20.3°C respectively. Euphotic zone depth was 100 m and 115 m and temperature-based mixed layer depth was 45 m and 39 m at IEE1 and 2 respectively. The nitrate concentration was 18.1 and 8.6 μM and silicate concentration was 1.66 μM and 0.3 μM respectively at both the stations. The concentration of nitrate and silicate both decreased significantly at IEE2 compared to IEE1. Both these stations lay in a low silicate zone (Coale et al., 1996) where silica concentration in the surface waters is not enough to support large population of diatoms. This was reflected in surface chlorophyll and species composition as well: at IEE1 surface chlorophyll was ~1 $\mu g l^{-1}$ where green algae were the dominant species contributing more than 65% of the total Chl *a*. Euphotic zone integrated Chl *a* was significantly high ~134 mg m^{-2}. At

IEE2 surface chlorophyll was significantly less (0.1 $\mu g l^{-1}$) and euphotic zone integrated chlorophyll was ~49 mgm^{-2}, significantly less compared to IEE1. Diatoms were absent at this station and only green algae contributed to the total chlorophyll.

The results of nitrate, ammonium and urea uptake and the *f*-ratios, from both the stations, under controlled and enriched iron conditions are shown in Table 4.1 and 4.2 respectively.

Duration of Incubation (in hrs)	Nitrate uptake (nM N)		Ammonium uptake (nM N)		Urea uptake (nM N)		Total N-uptake (nM N)		*f*-ratio	
	No Iron	With Iron	No Iron	With Iron	No Iron	With Iron	No Iron	With Iron	No Iron	With Iron
24	29	19	11	6	17	17	58	42	0.50	0.44
48	24	73	12	21	14	41	50	134	0.47	0.54
72	12	36	10	24	11	47	33	107	0.38	0.34

Table 4.1. Nitrate, ammonium and urea uptake and the *f*-ratios at station IEE 1 under controlled and enriched iron conditions

Duration of Incubation (in hrs)	Nitrate uptake (nM N)		Ammonium uptake (nM N)		Urea uptake (nM N)		Total N-uptake (nM N)		*f*-ratio	
	No Iron	With Iron	No Iron	With Iron	No Iron	With Iron	No Iron	With Iron	No Iron	With Iron
24	28	30	39	74	36	31	103	136	0.27	0.22
48	31	31	48	53	72	52	151	135	0.20	0.23
72	37	23	70	5	71	63	178	91	0.21	0.26

Table 4.2. Nitrate, ammonium and urea uptake and the *f*-ratios at station IEE 2 under controlled and enriched iron conditions

At IEE1 the total N-uptake did not show any significant change (within the uncertainty limit) in the 1st 24 hrs. This clearly suggests that even a sudden supply of a large amount of dissolved iron was not able to simulate nitrogen uptake. In other words, usually Fe-starved phytoplankton were not able to respond immediately to this Fe-feast but were responding to the same as the time progressed. This is why N-uptake increased almost thrice under Fe enrichment compared to the control case at the end of 48 hours; nitrate and urea uptake increased more than three-fold and ammonium uptake increased two-fold. An increase in the absolute nitrate uptake by a factor of 15 in another silicon-poor zones in the Pacific sector of the Southern Ocean has been reported earlier (Coale et al., 2004). In HLNC area of the equatorial Pacific Ocean iron enrichment caused 14-fold increase in the nitrate uptake on 6^{th} day (Coale et al., 1996); it increased from <10 $nMhr^{-1}$ to 133 $nMhr^{-1}$; the effect of iron enrichment on ammonium and urea uptake were not studied earlier. An increase in specific nitrate uptake rate, under iron enrichment, has also been reported from the Southern Ocean sector of the Atlantic Ocean (Coale et al., 1996). The same effect of iron enrichment could not be seen at IEE2 on the total N-uptake; within the limit of uncertainty, it remained almost the same in "control" and "enriched" condition. This may be because the water here is not Fe-starved. Station IEE2 lay north of STF, in a zone where upwelled Antarctic intermediate water (AAIW) is getting advected. This water may be transporting macro-nutrients iron with it. As plankton of this station is not Fe-starved, they are not responding to iron enrichment.

The *f*-ratio did not show any significant change due to iron enrichment at IEE1 during the 1^{st} and the 2^{nd} day but it reduced slightly on the 3^{rd} day in both the, "control" as well as "enriched", sets. The *f*-ratio has reported to increase from 0.1-0.2 to 0.3-0.4 on Fe-enrichment in silica depleted zone of the Southern Pacific (Coale et al., 2004). This result was based on nitrate uptake and carbon uptake measurements; ammonium and urea uptake rates were not measured. During the present study Fe-enrichment not only enhanced nitrate uptake but they increased ammonium and urea uptake as well and this is the reason their net effect on *f*-ratio could not be observed at IEE1. The *f*-ratio showed considerable variation; it varied from 0.68 to 0.85 in spring and from 0.17 to 0.63 in summer in Indian sector Southern Ocean waters near Kerguelen Island (Mengesha et al., 1998). A mean *f*-ratio of 0.42 in coastal zone and 0.68 in the open ocean zone has also been reported for the Prydz Bay area (Semeneh et al., 1998). The *f*-ratio from the western Pacific sector of the Southern Ocean along 170°W has been reported to vary from 0.04 to 0.5; high *f*-ratios were measured at the ice edge during spring and lower *f*-ratios were measured during summer (Sambrotto and Mace 2000). At IEE2 also no significant change was observed in the *f*-ratio because of iron enrichment; it remained almost the same in both, "control" and "enriched", conditions.

In summary, preliminary results of ^{15}N tracer-Fe enrichment experiment from IEE1 suggests that addition of iron does not enhance primary productivity during the initial stage of the enrichment but takes some time to increase the uptake. The availability of iron increases uptake of all substrates of nitrogen *i.e*, nitrate, ammonium and urea. This was clearly reflected in enhancement in uptake rates of all substrates at station IEE1 under "enriched condition". This is in contrast to the earlier belief that availability of iron enhances uptake of nitrates only and not of ammonium and urea. As it enhanced uptake of all forms of nitrogen at IEE1, the *f*-ratio remained almost the same under both, "control" and "enriched" conditions. One of the major limitations of the present study is unavailability of ambient iron concentration in the surface waters of the Indian sector of the Southern Ocean and this needs to be incorporated in future investigations to understand the effect of iron on N-uptake rates in a better way.

4.9 Conclusions

The results from the equatorial Indian Ocean are:

1. Total N-uptake was low: 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 $mgCm^{-2}d^{-1}$)
2. New production along the 77°E transect was 0.20 $mmolNm^{-2}d^{-1}$ (16 $mgCm^{-2}d^{-1}$), almost half of that 0.43 $mmolNm^{-2}d^{-1}$ (34.4 $mgCm^{-2}d^{-1}$) along the 83°E transect.
3. 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).
4. Urea was the most preferred from of nitrogen for phytoplankton followed by ammonium. Nitrate was the least preferred.
5. 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 results from the Southern Indian Ocean are:

1. 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).
2. 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.
3. 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.
4. Productivity suddenly increased to 10.26 $mmolNm^{-2}d^{-1}$ (821 $mgCm^{-2}d^{-1}$) at sub-tropical front (STF) where Antarctic cot water and subtropical warm water meets.
5. The *f*-ratio varied from 0.27 to 0.63 in the Southern Ocean with a mean of 0.50 with an upper limit of 0.63.
6. 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.
7. Preliminary results of ^{15}N tracer-Fe enrichment experiment suggests that addition of iron does not enhance primary productivity during the initial stage of the enrichment but takes some time to increase the uptake
8. In contrast to the earlier belief that availability of iron enhances uptake of nitrates only and not of ammonium and urea the present study suggest that it enhances uptake of all forms of nitrogen and hence does not appear to affect the *f*-ratio significantly.

These results are the first comprehensive estimates of nitrogen based productivity in a large area in the Southern Indian Ocean. Relatively higher 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. The *f*-ratio was moderately high here. 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. This means a slightly greater export production in this region than before. 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.