Nitrogen uptake rates and *f*-ratios in the Equatorial and Southern Indian Ocean

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We report data on nitrate, ammonium and urea uptake rates from the Equatorial and Southern Indian Oceans. Productivity (0.81–2.23 mmol N m^{-2} d^{-1}) over the Equatorial Indian Ocean was low, but the *f*-ratio (0.13–0.45) was relatively high. In the Southern Indian Ocean total N-uptake rate varied from 1.7 to 12.3 mmol Nm^{-2} d^{-1}; it was higher in the Antarctic coast (69°S) and lower over most of the Southern Ocean, the lowest being at 58°S. The *f*-ratio also showed significant spatial variation, but was higher compared to values at the Equatorial Indian Ocean. The mean *f*-ratio in the Southern Indian Ocean was 0.50. The nitrate-specific uptake rates and *f*-ratios appear to have increased significantly in the recent past relative to earlier estimates. While productivity in the Southern Ocean is comparable to that in the Equatorial Indian Ocean, higher *f*-ratios in the former underscore its importance in the uptake of CO_2.

Keywords: Carbon sequestration, *f*-ratio, nitrogen-uptake, primary productivity, Southern Ocean.

Introduction

THE Indian Ocean, landlocked in the north and influenced by seasonally reversing monsoon, has received much attention from oceanographers. The northern Indian Ocean, comprising the Arabian Sea and Bay of Bengal, has been studied in some detail[1–4], but its equatorial and the southern regions are yet to be studied in detail. There are very few studies aimed at understanding the upper ocean variability of these parts of the Indian Ocean and its relation to primary/new productivity[5–8].

The Equatorial Indian Ocean (EIO), unlike its counterparts in the Pacific and Atlantic, does not possess an upwelling regime[9]. This is because the driving wind field is different in the Indian Ocean: at EIO the annual mean winds on the equator are eastwards causing convergence, whereas in the Pacific and Atlantic Oceans the southeast trades do not cross the equator, which causes an equatorial divergence and hence upwelling. Upwelling in the Indian Ocean occurs in the north, along Somalian and Omani coasts and also along the west coast of India, mostly during the summer monsoon. Therefore, biological productivity in the Equatorial Atlantic and Pacific is usually higher than that in the EIO. Productivity studies in EIO are limited in space and time[6,10]: the surface chlorophyll *a* is low (0–0.19 mg m^{-3}) with perennial subsurface maxima at 60–80 m and low primary productivity[6] (5–40 mg Cm^{-2} d^{-1}). Satellite-derived data also show persistence of low surface chlorophyll in the EIO surface waters all round the year. However, small-scale phytoplankton bloom (chlorophyll > 1 mg m^{-3}) has been observed in the latitudinal band of 5–10°N in the central and western Indian Ocean[5], reportedly caused by vertical displacement of the thermocline due to local wind stress. Episodic events such as weather disturbances caused by storms/cyclones[11,12] and remote forcing such as upwelling Rossby waves[13] are also known to trigger high surface productivity in adjoining regions.

The Southern Ocean (SO), on the other hand, is a net sink for atmospheric CO_2 via the solubility and biological pumps[14] and, therefore plays an important role in the global carbon cycle and climate regulation[15]. In this 'high nutrient low chlorophyll (HNLC)' area[16], the surface waters harbour significant amounts of unused macronutrients such as nitrate and phosphate. It has been reported that only half the available nutrients are consumed by the subantarctic phytoplankton, the rest being sent back into the deep sea via formation of Antarctic intermediate (AAIW) and bottom waters (AABW)[17]; the global and low-latitude export production is controlled by the amount of nutrients received through intermediate and deep waters from the subantarctic[18,19]. Despite its potential major role in global climate change, SO, particularly the Indian sector is one of the least studied regions of the world oceans. During the last decade, a concerted effort was made, through both natural[20,21] and man-made fertilization experiments[22], to understand the factors controlling the biogeochemistry of this region, mostly to test the

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hypothesis of Fe limitation. As in the case of the EIO, primary productivity (PP) measurements in the Indian sector of SO are limited both in space and time as well. In the Southern Indian Ocean (SIO, which encompasses the region between SO and EIO), PP measurements are even sparser.

Nitrogen isotopes are important tools to estimate marine production. On the basis of the source of nitrogen to the euphotic zone, primary production can be subdivided into 'new' and 'regenerated' production[23], routinely measured using ^{15}N. New production is defined as a fraction of primary production supported by the newly injected nitrogen (such as nitrate) and regenerated production as that supported by recycled nutrients (such as ammonium and urea) in the euphotic zone. Integrated over an annual timescale and under steady-state condition, new production approximates export production (amount of photosynthetically fixed carbon exported out of the surface ocean via the biological pump). A ratio of new to total production is the *f*-ratio; it is an important parameter which helps estimate new production using PP map produced from satellite-derived surface chlorophyll images[24]. However, in oligotrophic areas where the rate of nitrification (particularly when incubation is done for sufficiently longer duration, e.g. ~12 h) or nitrogen fixation is significant, the *f*-ratio may not provide an estimate of the new/export production[25]. In HNLC areas such as SO, *f*-ratio is also an important tool to assess the strength of export fluxes in the basin[25]. Compared to the Pacific and the Atlantic, N-uptake studies are quite limited in SO[26–31] and our knowledge about the temporal variation of N-uptake and the *f*-ratio characteristics of this region is meagre. Here we report ^{15}N-based productivity measurement of N-uptake and *f*-ratios in EIO and SIO. The present study is also among a few which report primary productivity and also reports on nitrogen uptake rates from the EIO region.

Material and methods

Water sampling was carried out in the pre-monsoon season (May–June 2005) on-board *ORV Sagar Kanya* (SK-220) along two transects, 77°E and 83°E with five stations along each transect (Figure 1). In SO, sampling was done in late austral summer (February–March 2006), on-board *Akademik Boris Petrov* (ABP-15) at six different stations in SIO (often the weather and sea state preclude closer sampling) and at two stations in the EIO. Water samples were collected just before the start of the experiment, using pre-cleaned 30 l Nansen bottles attached to a CTD rosette, from six different depths, corresponding to light levels of 100%, 80%, 64%, 20%, 5% and 1% of the surface value, to cover the entire photic zone. Water samples were immediately transferred to polycarbonate Nalgene bottles; individual samples were taken, in duplicate, for measurement of nitrate (2 l volume), ammonium (2 l) and urea (1 l) uptake rates. Next, 250 ml of samples from each depth was separately collected for nutrient measurements using a SKALAR autoanalyser. ^{15}N-enriched (99 atom% ^{15}N) $Na^{15}NO_3$, $^{15}NH_4Cl$, $CO(^{15}NH_2)_2$ (procured from Sigma-Aldrich, USA) tracers were added to individual samples taken for the measurement of their respective uptake rates. In EIO, the nitrate concentration in the upper layer was below the detection limit. Therefore, an effort was made to add a minimum amount of nitrate tracer (~0.01 μM). In SIO, the amount of nitrate tracer added corresponded to less than 10% of the ambient concentration. Ambient ammonium and urea could not be measured due to logistic reasons during the cruises; so for the EIO stations a small and constant (~0.01 μM) amount of ammonium and urea tracers was added, following Watts and Owens[32]. For the SIO stations, 1 μM of ammonium following Reay *et al.*[33] and urea tracers were added. Addition of high concentration of ammonium, however, may lead to overestimation of ammonium uptake and hence underestimation of the *f*-ratio[34,35].

Addition of tracers was followed by covering the sample bottles with appropriate neutral density filters to mimic the light condition at the depths from which they were taken. Samples were then incubated for 4–6 h (6 h incubation for stations close to Antarctica, i.e. station SP1–SP4 and 4 h incubation for the rest), symmetrical to the local noon, on deck under simulated *in situ* conditions. Sea water, pumped from a depth of 4 m, was continuously circulated to maintain a constant temperature. All samples were filtered in dark through precombusted (4 h at 400°C) 47 mm diameter and 0.7 μm pore size Whatman GF/F filters. Filtration was done using a

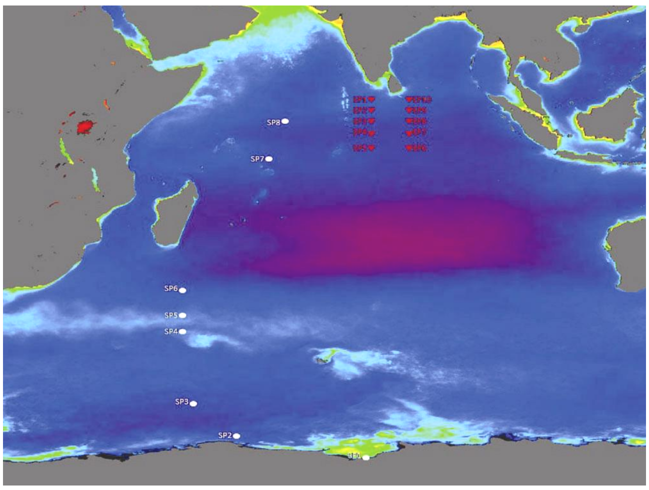

Figure 1. Station locations for cruises SK-220 (red-coloured triangle) and ABP-15 (white circles). EP and SP denoted primary productivity stations in Equatorial and Southern Indian Ocean respectively. Refer to Tables 1 and 2 for actual locations of the stations. The underlying image is annual composite of SeaWiFS for the year 2006 CE.

manifold filtration unit and vacuum pump (procured from Millipore, USA) under low vacuum (<70 mm Hg). After this, filters were dried in an oven at 60°C overnight and brought to the shore for mass-spectrometric analysis. Samples were analysed using a CarloErba elemental analyser interfaced via conflo III to a Finnigan Delta Plus mass spectrometer, using a technique for sub-microgram level ^{15}N determination[36]. Standards such as IAEA–NO_3 (KNO_3, #213), IAEA-N-2 ($[NH_4]_2SO_4$, #342) and other internal laboratory standards containing organic nitrogen such as caseine and BSA (bovine serum albumin) were also used (caseine and BSA are organic compounds which contain 12.7 and 17.8 atom% nitrogen respectively) to check the accuracy of the measurements; the maximum difference in the duplicates of particulate organic nitrogen (PON) and ^{15}N atom percentage was found to be less than 5 and 1 respectively. The specific and absolute uptake rates (h^{-1} and mmol Nm^{-2} d^{-1} respectively) for nitrate, ammonium and urea experiments were calculated using the equation of Dugdale and Wilkerson[37]. The uptake rates calculated here for ammonium and urea are conservative estimates. Total uptake rate is the sum of nitrate, ammonium and urea uptake rates; *f*-ratio is the ratio of nitrate uptake to the total N-uptake.

In situ chlorophyll *a* measurements were carried out using a submersible fluorescence probe (FluoroProbe, bbe-Moldaenke, Kiel, Germany) during the SO cruise. The probe contains five light-emitting diodes (450, 525, 570, 590 and 610 nm) for the excitation of pigments present in the phytoplankton. Chlorophyll fluorescence is measured at 685 nm. The excitation spectrum obtained is compared to standard curves stored in the probe and the amount of chlorophyll is then estimated[38].

Results and discussion

Equatorial Indian Ocean

Here we give a brief description of the hydrographic conditions with a listing some of the physical parameters in Table 1. Along 77°E (83°E) transect, sea-surface temperature (SST) was minimum (maximum) at the equator and increased (decreased) polewards. Surface salinity was also higher at the equator and decreased away from it. Sardessai *et al.*[39] list nutrient data from this cruise and have given a detailed account of nutrient distribution in conjunction with variability of physical parameters. The mixed layer depth (MLD) was maximum (~35 m) at the equator along 77E transect and reduced towards both north and south to ~28 m, whereas the MLD along 83E transect was more than 35 m. The nitrate concentration in the upper layer was below the detection limit at all the stations.

The total N-uptake rates, integrated up to the MLD, were low and similar to the rates reported from the other oligotrophic regions around the world oceans. They varied from 0.66 mmol N m^{-2} d^{-1} to 2.23 mmol N m^{-2} d^{-1} over the study area. The mean N-uptake rate was 1.32 (± 0.56) mmol N m^{-2} d^{-1} and along 77°E and 83°E it was 1.22 (± 0.58) mmol N m^{-2} d^{-1} and 1.43 (± 0.59) mmol N m^{-2} d^{-1} respectively. N-uptake rates were higher along 83°E compared to 77°E transect at all the stations, except at the equator where the rate was higher at 77°E than 83°E. At the equator, the total N-uptake at the stations of 77°E was almost four-fold higher compared to 83°E. This difference is because of the deeper MLD at 77°E (35 m) than at 83°E (15 m). The observed change in MLD was due to a much stronger wind (wind speed ~15 m/s) at the equator at 83°E during sampling, which may be an episodic event and, thus cannot be generalized. Excluding this extreme equatorial event, at all the other stations productivity along 83°E was higher than that along 77°E.

Nitrate uptake rate or new production was low during the pre-monsoon of 2005; it varied from a minimum of 0.12 mmol N m^{-2} d^{-1} to a maximum of 0.84 mmol N m^{-2} d^{-1}. The mean new production over the study area was 0.32 mmol N m^{-2} d^{-1}. It was low (0.20 ± 0.08 mmol N m^{-2} d^{-1}) along the 77°E transect, but was higher (0.43 ± 0.27 mmol N m^{-2} d^{-1}) along the 83°E transect. Ammonium and urea uptake rates were higher compared to nitrate uptake rates in the EIO: these varied

Table 1. Sea surface temperature (SST), mixed layer depth (MLD), N-uptake rates (ρ) and *f*-ratios at different stations in the equatorial Indian Ocean

Station/date	Latitude	Longitude (°E)	SST (°C)	MLD (m)	ρNO_3^*	ρNH_4^*	ρNH_2^*	Total N-uptake rate*	*f*-ratio
EP1 (12/5/2005)	5°N	77	30.18	28	0.18	0.57	0.42	1.17	0.16
EP2 (14/5/2005)	2.5°N	77	29.71	27	0.12	0.34	0.35	0.81	0.15
EP3 (16/5/2005)	0	77	29.42	35	0.30	0.44	1.48	2.22	0.13
EP4 (19/5/2005)	2.5°S	77	29.70	28	0.28	0.21	0.41	0.90	0.31
EP5 (22/5/2005)	5°S	77	29.66	29	0.14	0.33	0.53	1.01	0.14
EP6 (25/5/2005)	5°S	83	29.45	40	0.21	0.22	0.71	1.14	0.18
EP7 (27/5/2005)	2.5°S	83	29.58	40	0.32	0.32	1.07	1.71	0.19
EP8 (31/5/2005)	0	83	29.87	15	0.21	0.21	0.24	0.66	0.32
EP9 (3/6/2005)	3°N	83	29.28	47	0.84	0.86	0.53	2.23	0.38
EP10 (4/6/2005)	5°N	83	29.05	35	0.55	0.37	0.47	1.40	0.40

*All rates are integrated absolute uptake rates and are in units of mmol N m^{-2} d^{-1}.

from 0.21 mmol N m^{-2} d^{-1} to 0.86 mmol N m^{-2} d^{-1} and 0.24 mmol N m^{-2} d^{-1} to 1.48 mmol N m^{-2} d^{-1} respectively. Similar to new production, regenerated production was also higher along 83°E transect relative to that along 77°E. Higher regenerated production compared to the new production resulted in lower *f*-ratios in the EIO, varying from 0.13 to 0.40, with a mean of 0.24 (± 0.10), but was higher along 83°E (0.29 ± 0.10) relative to that along 77°E (0.18 ± 0.07). At the two equatorial stations (SP7 and SP8) sampled during the late austral summer on-board *ABP*-15 the total N-uptake rates were 1.58 and 1.82 mmol N m^{-2} d^{-1} at 7.5°S and equator stations respectively. The *f*-ratios were 0.32 and 0.45. Though the N-uptake rates were again low and typical of EIO, the *f*-ratios were significantly higher than those measured during the pre-monsoon in 2005.

The nitrate concentration in the upper layers EIO was below the detection limit. Productivity was also low: the mean N-uptake rate in EIO was 1.32 (± 0.56) mmol N m^{-2} d^{-1}. During the monsoon season (July–August), however, higher nitrate uptake rates (7.5–14.1 mmol N m^{-2} d^{-1}; mean = 10.8 mmol N m^{-2} d^{-1}) were reported from the thermocline ridge region in the south equatorial region[7]. Although stations SP7 and SP8 were sampled in austral summer, the uptake rates were comparable but the *f*-ratios were relatively higher. This could be seasonal variability and we certainly need more such observations to characterize it. Despite harbouring ample nutrients in the surface waters, new production rates from the Equatorial Pacific[40] (2.07 ± 0.83 mmol N m^{-2} d^{-1}) are comparable with the present value. Variation in the *f*-ratios from the Pacific[40] (mean = 0.17 ± 0.07) and Indian Oceans (mean = 0.24 ± 0.10; present study) is also comparable. Such a large variation in new production and *f*-ratio is usually observed during bloom development phase[24] and is uncommon in oligotrophic (e.g. EIO) and HNLC (e.g. Equatorial Pacific Ocean) regions. Therefore, previous researchers[40,41] found it difficult to explain these variations and cautioned against use of such *f*-ratios for large-scale extrapolation or estimation of new production.

Southern Indian Ocean

The physical conditions encountered were typical of this region, i.e. low SST and deep mixed layer (~100 m) in the south, close to Antarctica and relatively shallow mixed layer in the north (some physical parameters are listed in Table 2). In the areas adjoining the Antarctic coast, SST was quite low (–1.7°C). The low temperature zone continued up to 58°S where SST was 0.4°C and it increased northwards to 11°C at 43°S. There was a sharp rise in SST from 43°S to 40°S, which marks the presence of subtropical front (STF) in the Indian Ocean, where the subantarctic cold water meets the subtropical warm water. A detailed description of the physical conditions and locations of fronts during the same cruise is given by Srivastava *et al.*[42]. All stations had high surface nitrate concentrations (~20 μM), except SP6, where the ambient nitrate concentration was significantly less than other stations. Results of nitrate, ammonium and urea uptake rates at all eight SP stations, integrated over photic depth are shown in Table 1.

Euphotic zone integrated total N-uptake rate varied from 1.7 mmol N m^{-2} d^{-1} to 12.3 mmol N m^{-2} d^{-1} in SIO the highest uptake rate was in the Antarctic coastal zone (69°S) and the lowest at 58°S (Table 2). Nitrate uptake rate was higher than ammonium and urea uptake rates at all the stations, except SP6; here, north of STF at 35°S, ammonium uptake was higher than nitrate uptake. At station PP 1, which lies in the coastal zone of Antarctica (69.18°S, 76°E), the total N-uptake rate was quite high (12.3 mmol Nm^{-2} d^{-1}) to which nitrate contributed significantly. The *f*-ratio here was 0.6. Chlorophyll *a* at the station near Antarctic coast (SP1) was 3.4 mg m^{-3}, but it varied significantly in the adjoining areas from 2 to 6 mg m^{-3}. At SP2, N-uptake and chlorophyll decreased drastically to 2.3 mmol N m^{-2} d^{-1} and 1.0 mg m^{-3} respectively. The *f*-ratio also decreased to 0.4. Region between 39°S and 43°S in the Indian Ocean has been reported to be highly productive during the austral summer 2004, but is low in the further northward and southward regions[43].

Table 2. SST, photic zone depth, nutrients, integrated chl, N-uptake rates (ρ) and *f*-ratio at different stations in the Southern Indian Ocean

Station/date	Latitude (°S)	Longitude (°E)	SST (°C)	Photic depth (m)	Nitrate# (μM)	Integrated chl (mg m^{-2})	ρNO_3^*	ρNH_4^*	ρNH_2^*	Total N-uptake rate*	*f*-ratio
SP1 (24/2/2006)	69	76	–1.7	29	27.4	155	7.70	3.30	1.27	12.27	0.63
SP2 (3/3/2006)	65	56.3	–0.9	100	27.4	98	1.00	0.54	0.76	2.30	0.44
SP3 (6/3/2006)	58	50	0.4	100	25.7	99	0.92	0.58	0.22	1.72	0.53
SP4 (13/3/2006)	43	48	11	90	18.1	144	1.58	0.99	0.48	3.05	0.52
SP5 (15/3/2006)	40	48	19.5	100	18.1	47	6.05	2.53	1.68	10.26	0.59
SP6 (17/3/2006)	35	48	21.2	115	5.65	46	0.96	1.61	0.91	3.48	0.28
SP7 (2/2/2006)	7.5	61	28.2	124	0	63	3.35	2.79	1.30	7.44	0.45
				(30)			(0.82)	(0.60)	(0.40)	(1.82)	(0.45)
SP8 (30/1/2006)	0	64	28.9	124	0	92	3.89	2.77	1.86	8.52	0.46
				(30)			(0.50)	(0.75)	(0.33)	(1.58)	(0.31)

*All rates are photic zone-integrated absolute uptake rates and are in units of mmol N m^{-2} d^{-1}. Values in the bracket are those integrated up to the mixed layer depth. #Values for surface waters.

Productivity decreased northwards and this low productivity zone extended up to STF, i.e. 40°S. Here, nitrate uptake varied from 0.9 to 1.6 mmol N m^{-2} d^{-1}, similar to the lower nitrate uptake rate (0.6 ± 0.4 mmol N m^{-2} d^{-1}) reported earlier[26]. The mean column N-uptake rate (1.2 ± 0.4 mmol N m^{-2} d^{-1}) is significantly less than that reported (mean = 5.0 ± 0.7 mmol N m^{-2} d^{-1}) from the Australian sector of SO[31] on similar latitudes but the mean *f*-ratio was almost the same (0.5 ± 0.1). An increased productivity was observed at SP5 (40°S), where the column-integrated N-uptake and *f*-ratio increased to 10.3 mmol N m^{-2} d^{-1} and 0.6 respectively. At SP5 (35°S) N-uptake and *f*-ratio again decreased to 3.5 mmol Nm^{-2} d^{-1} and 0.3 respectively; the *f*-ratio here was the lowest during the expedition. The ammonium uptake rate here was more than the nitrate uptake rate.

Unlike EIO, where the productivity was consistently low, SIO showed significantly large variations; the mean total N-uptake was 5.51 (± 4.54) mmol N m^{-2} d^{-1}. The productivity was considerably high at the Antarctica coast and also at the STF. High carbon uptake rate in the coastal regions of Antarctica was previously reported[44]. Very high N-uptake rates, 5.9 mmol N m^{-2} h^{-1} (mean = 4.7 mmol N m^{-2} h^{-1}) have also been reported for the coastal station between Cape Ann and Mawson[27]. High coastal productivity has been independently confirmed by pCO_2 measurements[45]. Productivity at stations away from the Antarctica coast was considerably low despite having high concentration of nitrate (> 18 μM) in its surface water. Though the dissolved iron concentration was not measured, we suspect unavailability of the same limited productivity over this region. This was also evident from the observed high productivity at the coastal station (SP1) where the iron concentration in the particulate suspended matter was quite high[46] (8.42 mg m^{-3}). The suspended matter was of terrigeneous origin, a product of coastal erosion, which was possibly supplied through melting of ice[46]. The concentration of particulate iron decreased significantly at SP2 (1.66 mg m^{-3}) and other northward stations[46]. It was possibly due to the formation of AABW, which takes place near the coast. During this process, unused nutrients and also those supplied through coastal erosion, are advected down and thus not carried up to SP2 and other northward stations. These advected nutrients control export productivity at low-latitude regions[18,19].

A previous study[29] reported low mean specific nitrate and ammonium uptake rates (0.001 and 0.002 h^{-1} respectively; urea uptake was not reported) from transect along 62°E during the austral summer 1994 (ANTARES II cruise). The *f*-ratio varied from 0.27 to 0.6 with the mean of 0.4 (± 0.1). We observed consistently higher specific nitrate uptake rates (0.005 h^{-1}) during summer 2006, but specific ammonium uptake rate (0.001 h^{-1}) was comparable with the earlier study[29]. Specific urea uptake rate during our study was 0.001 h^{-1}. We found the average *f*-ratio to be 0.50 (± 0.1) (for SO stations, i.e. SP1–SP6), higher than the reported value[29] (Figure 2). Much higher *f*-ratios (0.75 ± 0.08; ANTARES III cruise)[29] were reported during spring when the melting of ice releases nutrients, including iron, into SO[47]. Comparable total N-uptake (5.1 ± 1.7) and *f*-ratios (0.47 ± 0.09) have also been reported from the north of Crozet Island during the early (November–December 2004) austral summer[48]. The *f*-ratio of 0.50 indicates that the nitrate and ammonium/urea have equal contributions to the total productivity and that a large fraction of it may be exported out of the surface layer over a year[8,34]. On the other hand, much lower *f*-ratio (0.09 ± 0.04) has been reported[25] from regions around Prince Edward Island archipelago. The observed variability in specific nitrate uptake rate and *f*-ratio may be due to seasonal or geographical differences[48]. Ecosystem models have also shown a large variation in seasonal *f*-ratio; Kerfix ecosystem model estimated *f*-ratios for the spring, summer and winter are 0.6, 0.23 and 0.1 respectively. Considering the spatial and temporal variability in the SIO, we need more *in situ* measurements, on larger temporal and spatial scales, to understand the biogeochemistry of this part of the world ocean.

The plot of total N-uptake (on *x*-axis) and nitrate uptake (on *y*-axis) reveals a significant correlation between the two: $y = 0.63\ (\pm\ 0.06)\ x - 0.66\ (\pm\ 0.42)$ (coefficient of determination, $R^2 = 0.95$, significant at 0.01 level; Figure 3). The slope of line of regression suggests that the maximum possible value of *f*-ratio for this zone is 0.63 in summer, comparable with an earlier estimate[8]. The plot also suggests that the minimum regenerated production for this region is ~1 mmol N m^{-2} d^{-1}. This large region is traditionally regarded as a low productive region

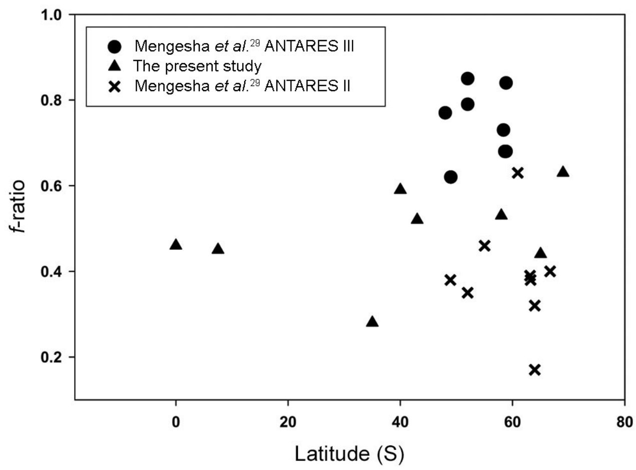

Figure 2. Comparison of *f*-ratios from the present study and previous studies by Mengesha *et al.*[29], in the Indian sector of the Southern Ocean from ANTARES III (•), the present study (▲) and ANTARES II (**x**) data respectively. *f*-ratios obtained during the present study tend to be higher than ANTARES II, conducted during a an earlier austral summer. The *f*-ratios obtained during the ANTARES III cruises are much higher as they were sampled during spring. See text for more details.

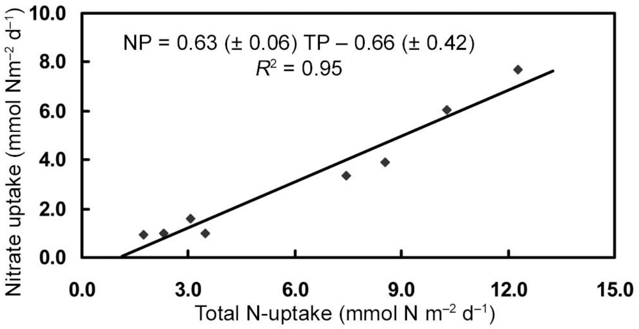

Figure 3. Relationship between total N-uptake and nitrate uptake in the Southern Indian Ocean. NP and TP represent new and total production respectively.

where the surface nutrients are not fully utilized. Our measurements show that although the productivity over a large region of the SO is quite low, the *f*-ratio is moderately high. The present dataset also shows that though the eastern tropical Pacific Ocean and the SIO both harbour ample nitrate in their surface layers, the new production is higher in the Equatorial Pacific relative to SIO; but the *f*-ratio is significantly lower in the Pacific. This suggests that despite low productivity, SIO has the potential to play a significant role in atmospheric carbon sequestration. Also, productivity over a large part of SIO is comparable to that at EIO, but the *f*-ratio is much lower in the latter.

Summary

Data on the N-uptake rates and *f*-ratio characteristics of EIO and SIO confirm that the productivity is low in this part of the world ocean. Capability of the equatorial ocean for export production is lower relative to that of the Northern Indian Ocean and SO. Owing to significantly higher *f*-ratios compared to its equatorial counterpart, SIO has a greater potential in removing CO_2 on longer time-scales. A mean *f*-ratio of 0.50 in SIO indicates that the autotrophic community uses nitrate as well as regenerated nutrients equally. Further studies are needed to explain the seasonal and/or geographical variabilities in the production and *f*-ratio in these two basins.

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