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Nitrogen uptake rates and new production in the northern Indian Ocean

Naveen Gandhi[1], Satya Prakash[1,2], R. Ramesh[1]* and Sanjeev Kumar[1,3]

[1]Physical Research Laboratory, Navrangpura, Ahmedabad – 380 009 India

[2]Present address: Indian National Centre for Ocean Information Services, Hyderabad-500 055, India.

[3]Present address: Faculty of Natural Resources Management, Lakehead University, Thunder Bay, ON, Canada P7B 5E1

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Nitrogen-15 based new production measurements initiated during the last decade in the northern Indian Ocean are summarized. Two different biogeochemical provinces in eastern Arabian Sea have been recognized during the late winter monsoon: less productive southern (non-bloom) and more productive northern (Noctiluca scintillans bloom) regions. The southern sector is characterized by low column N-uptake and very low f-ratio (~5.5 mmol N $m^{-2}d^{-1}$ and 0.4 respectively). The f ratio, although low, increased progressively towards north. This increase may be the effect of more intense winter cooling towards the north. The northern part is a highly productive zone, with very high N-uptake and significantly high f ratio (~19 mmol N $m^{-2}d^{-1}$ and 0.8 respectively). New production during the pre-monsoon in the Bay of Bengal is higher than that in the post-monsoon. New production for the region during the pre-monsoon averages around 5 (±4) mmol N $m^{-2}d^{-1}$, almost twice the average value observed during the post-monsoon (2.6 mmol N $m^{-2}d^{-1}$). Average f ratio for the entire region increases to 0.70 (±0.1) during pre-monsoon from 0.5 during the post-monsoon.

[**Keywords**: New productivity; *f* ratio; ^{15}N tracer technique; northern Indian Ocean.]

Introduction

Nitrogenous nutrients are considered to be the major limiting factor of oceanic primary production in many regions[1]. Primary production is partitioned on the basis of the nitrogen source: 'new' production[2] supported by the N-sources, principally, nitrate brought into the euphotic zone from the deep, and secondarily, N_2-fixation, riverine and atmospheric inputs; 'regenerated' production[2] supported by ammonium and urea, derived from biological processes occurring within the euphotic zone.

The ratio of new to total production is called the *f* ratio[3]. It represents the probability that a nitrogen atom is assimilated by phytoplankton due to new production; likewise (1-*f*) is the probability of assimilation by regenerated production. Thus, (1-*f*)/*f* provides a measure of number of times nitrogen recycles in the euphotic zone before sinking out of the system as particulate matter[3]. The *f* ratio also defines the strength of the biological pump, the magnitude of the rate of export of organic matter. Theoretically, *f* can vary between 0 and 1. The calculation of regenerated production[2], as proposed originally, did not include the uptake of urea-N. They defined the primary production associated with ammonium alone as regenerated production and those associated with NO_3^- and NO_2^- as new production. Eppley and Peterson[3] qualitatively showed that in some cases the uptake of urea and other organic-N contributes up to ~30% of the total nitrogen uptake and therefore non-inclusion of urea uptake overestimates the *f* ratio. Available data for the northern Indian Ocean[4] was used to check the effect of non inclusion of urea uptake on the *f* ratio (Fig. 1). In general *f* ratio appears to be overestimated by up to 20% (i.e. 40% is estimated as 60%).

The total and new productions are often linearly correlated and the relation can be expressed in terms of a straight line[5].

$$\rho_N = \rho_T \left(f_M \right) + \rho_M$$

where ρ_N and ρ_T are the new and total production, the intercept, ρ_M, is the minimum possible regenerated production in the absence of extraneous nitrate supply and the slope, f_M, gives the upper bound of the *f* ratio for a particular region. The significance of this linear relationship lies in the quantification of new production from satellite data on total production[5] (e.g. derived from ocean color monitor).

*Author for correspondence
Email : rramesh@prl.res.in

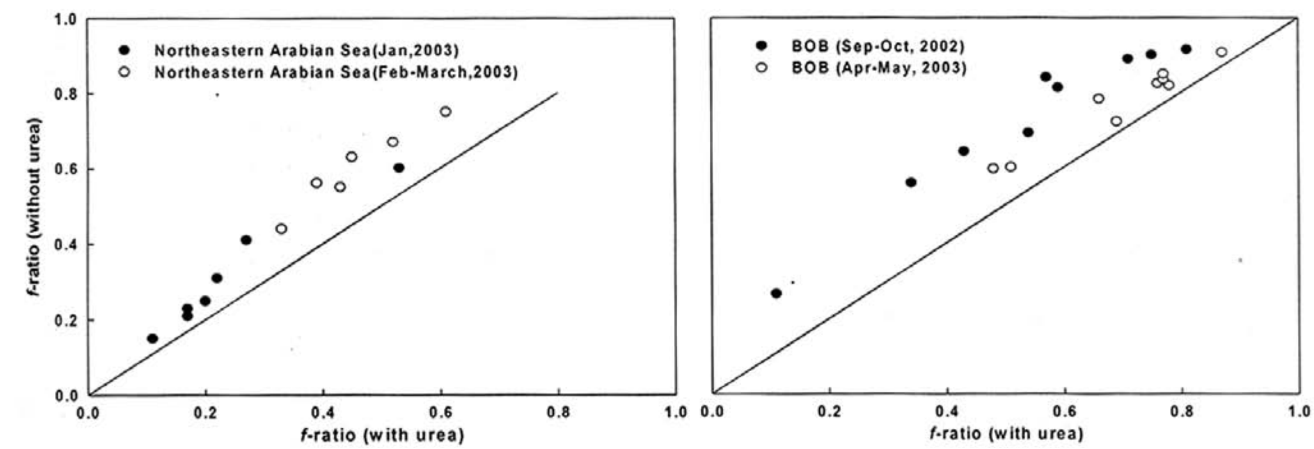

Fig 1—Comparison of *f* ratios calculated by including and excluding urea uptake rates in the total nitrogen fixation in the northeastern Arabian Sea and the BOB in various seasons[4]. 1:1 lines are also shown in above plots.

The Indian Ocean has been identified as a net sink[6] for atmospheric CO_2. It takes up ~330-430 Tg C yr^{-1} by solubility pump, accounting for nearly 20% of the global oceanic uptake of CO_2. Biological uptake of CO_2 by the Indian Ocean has been estimated[7] to be ~750-1320 Tg C yr^{-1}. The Indian peninsula divides the northern Indian Ocean into the Bay of Bengal (BOB) and the Arabian Sea. Although situated at the same latitude, they are significantly different in oceanographic properties such as sea surface temperature (SST), emission of biogenic gases, vertical mixing in the upper layers, mixed layer depth (MLD), nutrients, and productivity[8]. The Indian Ocean is warming faster than any other ocean basin[9]. This makes the northern Indian Ocean important for the oceanographers to study. Some major international scientific programmes such as JGOFS (Joint Global Ocean Flux Studies) aimed at assessing the role of global ocean in the carbon cycle. India also actively participated in this programme and a number of studies were carried out during the Indian JGOFS in the eastern Arabian Sea to assess its role in the global carbon cycle. The BOB is less sampled and studied compared to its western counterpart, the Arabian Sea, particularly for its biogeochemical aspects. However, some recent programs such as the BOBMEX (Bay of Bengal Monsoon Experiment), MLR (Marine Living Resources) and BOBPS (Bay of Bengal Process Studies) have focused on various oceanographic processes occurring in the Bay. Nitrogen uptake rates and new production measurements have been initiated recently under the BOBPS program[5]. In this paper we discuss the ^{15}N based marine productivity and new production measurements in the northern Indian Ocean.

Materials and Methods

Experimental Method

The ^{15}N tracer technique is used to measure new and regenerated productivity[2,10]. In this, new production is measured as the uptake rate of ^{15}N-labelled nitrate by the phytoplankton during deck incubation and regenerated production as a sum of ^{15}N-labelled ammonium and urea uptake rates.

Water samples were collected by a CTD rosette fitted with Niskin/Go-Flo bottles taking care to avoid trace metal contamination. Six sampling depths, 100, 80, 64, 20, 5 and 1% of surface irradiance measured using a hyperspectral radiometer (Hyperpro-II; Satlantic Inc.), were chosen to cover the euphotic zone. Individual water samples were collected for nitrate (2L volume), ammonium (2L) and urea (1L) tracer experiments. Prior to incubation at 10.00 Hrs. local time, tracers containing 99 atom% ^{15}N (sodium nitrate, ammonium chloride and urea, obtained form SIGMA-ALDRICH, USA) were added to the bottles. After the addition of tracer the samples were incubated for 4 hrs on deck under light conditions similar to their depths of origin and filtered through pre-combusted (12 hrs at 400-450°C) 47mm diameter and 0.7µm pore size GF/F filters under a low vacuum (<70 mm Hg), dried in oven overnight at 50°C and brought to the laboratory for mass spectrometric analysis.

A CarloErba elemental analyser interfaced via conflo III to a Finnigan Delta Plus mass spectrometer was used to analyse all the samples, using a technique for sub-microgram level ^{15}N determination[11]. The mass spectrometer was calibrated using international standards such as IAEA-NO_3 (KNO_3, #213) and IAEA-N-2($(NH_4)_2SO_4$, #342) along with some laboratory standards (Bovine serum albumin and Casein). Suitable and rigorous calibration steps were carried out and used to calculate the atom% ^{15}N and organic nitrogen content of the sample. A good agreement has been found between the atom% of ^{15}N measured on duplicate sets of water samples processed (Fig. 2).

Results and Discussion

^{15}N based studies in different parts of the northern Indian Ocean

Since the formulation of the concept of new and regenerated productivity[2] and the use of new productivity as a measure of export production[3], the ^{15}N tracer technique has been extensively used to characterize the biogeochemistry of the surface ocean and to assess the ocean's role in carbon sequestration. Global scientific programmes have been carried out in the past to estimate the relationship between new and export productivity. The nitrate uptake rates (new production) and *f* ratios obtained from different programmes/areas using different methods are listed in Table 1. A large spatial-temporal variation in the new productivity and *f* ratios are observed in the different part of the world's ocean. To assess the new productivity and *f* ratios in the northern Indian Ocean ^{15}N based new productivity measurements were carried out in the western and central Arabian Sea under US JGOFS programme. Since 2003 our group is involved in the eastern part of the Arabian Sea to carry out such measurements. In addition, we have also initiated new production measurements[5] in the Bay of Bengal (BOB) under BOBPS. New production and *f*-ratio data from the Arabian Sea and the BOB are listed in the Table 2.

Significant seasonal and geographical variations in the new production and *f*-ratios are observed in the Arabian Sea. Owens *et al*[25] reported a large variation in the nitrate uptake rates, from 2.7 mmol N $m^{-2}d^{-1}$ in the central Arabian Sea to 88.9 mmol N $m^{-2}d^{-1}$ in the coastal upwelling region during Autumn, 1986. The *f* ratio varied from a low of 0.09 at an open ocean station to as high as 0.92 at a coastal station. N-uptake rates varied from 9.2 mmol N $m^{-2}d^{-1}$ to 40 mmol N $m^{-2}d^{-1}$ during winter monsoon and from 3.9 mmol N $m^{-2}d^{-1}$to 24 mmol N $m^{-2}d^{-1}$ during the late summer/early winter monsoon for the central

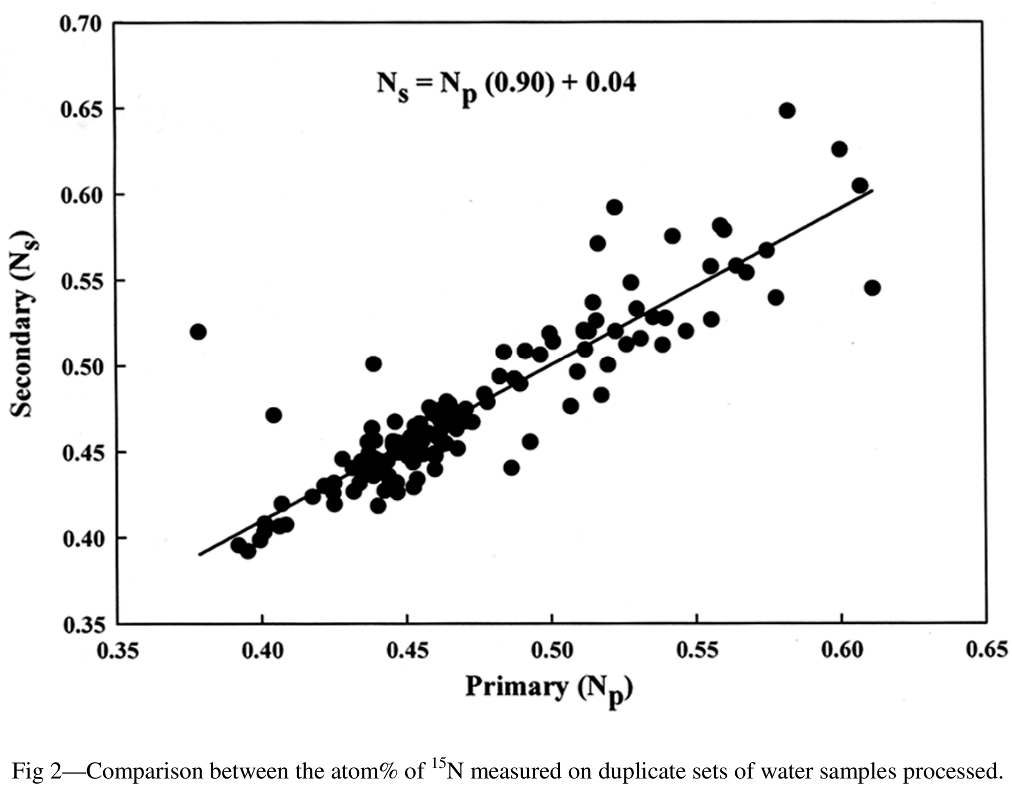

Fig 2—Comparison between the atom% of ^{15}N measured on duplicate sets of water samples processed.

Table 1—New or export production and *f* ratios in different regions[12,13].

Region/season	New productivity (mmol N $m^{-2}d^{-1}$)	*f* ratio
Hawaii Ocean Time-series (HOT)[14]	0.6	0.10
Bermuda Atlantic Time-series Study (BATS)[15]	0.9	0.15
North Atlantic Bloom Experiment (NABE)[16,17]	7.0	0.51
Equatorial Pacific (150ºW)[18,19]		
November	0.5-2.7	0.08-0.21
August	0.5-4.8	0.05-0.2
Sub-Arctic Pacific[19-21]		
Station-P winter	1.0-4.5	
Station-P summer	0.8-4.0	
Peru	18.3-24.2	0.30-0.42
Sub-Arctic Atlantic[22-24]		
Iceland Basin-July	0.9-5.8	
North Atlantic	3-9	0.25-0.56
Greenland polynya	2.5	0.56
Southern Ocean[12]		
170ºW/summer Ross Sea	0.9-12.5	0.05-0.48

Arabian Sea[28]. Here the N-uptake rate is significantly higher in the winter (~26 mmol N $m^{-2}d^{-1}$) than late summer (11 mmol N $m^{-2}d^{-1}$). The *f* ratio varied from 0.03 to 0.31 and from 0.04 to 0.29 during winter and the late summer monsoons, respectively. Large variations in the N-uptake rate from 1.1 mmol N $m^{-2}d^{-1}$ to 23.6 mmol N $m^{-2}d^{-1}$ have also been found[27] for the north-western Arabian Sea during an inter-monsoon period. It is found that the *f* ratios varied from a low of 0.07 in the open ocean region to a high of 0.52 at a coastal station. A large variation in the N-uptake rate, ranging from 0.1 to 13 mmol N $m^{-2}d^{-1}$ has also been reported[26] during the spring inter-monsoon and the summer monsoon for the northern Arabian Sea.

Very high new production has been reported[29] from the north-eastern Arabian Sea during winter ranging from 1 to 4.3 mmol N $m^{-2}d^{-1}$ with a lower *f* ratio, averaging around 0.19. A general trend of spatial increase in the new production from south to north has been observed. During late winter monsoon, new production and *f* ratio were significantly different in bloom (23 mmol N $m^{-2}d^{-1}$, 0.65) and non-bloom

Table 2—Region, period of sampling, new or export production and *f* ratios for the Arabian Sea.

Region	Period	New productivity (mmol N $m^{-2}d^{-1}$)	*f*-ratio
NW and central Arabian Sea	Autumn inter-monsoon[25]	2.7-5.3	0.09-0.14
	Spring inter-monsoon[26]	0.4-5.2	0.05-0.35
	SW monsoon[26]	4.3-6.4	0.05-0.4
	Autumn inter-monsoon[27]	1.3-9.8	0.20-0.41
	NE monsson[28]	0.56-6.8	0.01-0.27
	Autumn inter-monsoon[28]	0.63-2.9	0.14-0.29
Omani coast	Autumn inter-monsoon[25]	4.1-88.9	0.12-0.92
	Spring inter-monsoon[26]	3.1* (n=5)	<0.05
	SW monsoon[26]	4.8* (n=5)	<0.05
	Autumn inter-monsoon[27]	0.3-2.5	0.17-0.52
	NE monsson[28]	0.87-7.2	0.03-0.31
	Autumn inter-monsoon[28]	0.34-4.4	0.06-0.24
Gulf of Oman	Autumn inter-monsoon[27]	0.3-5.1	0.07-0.41
NE Arabian Sea	NE monsoon[29]	1.0-4.3	0.11-0.53
	Late NE monsoon[29]	5.7-23.2	0.33-0.61
	Late NE monsoon[30]	0.63-20.91	0.17-0.91
	NE monsoon[30]	1.95-19.70	0.46-0.87
	Spring inter-monsson	0.35-1.58#	0.51-0.82#
Bay of Bengal	Autumn inter-monsoon[5]	0.17-8.85	0.11-0.81
	Spring inter-monsoon[5]	0.98-10.67	0.50-0.87

*Average values
#unpublished data

(5.7 mmol N $m^{-2}d^{-1}$, 0.54) regions. An increasing trend from south to north in N-uptake rates, 2.7 to 23.0 mmol N $m^{-2}d^{-1}$, also has been observed by Prakash *et al*[30] in the eastern Arabian Sea during late winter monsoon. In addition, they have found the presence of two different biogeochemical provinces in eastern Arabian Sea during the late winter monsoon: less productive southern (non-bloom) and more productive northern (*Noctiluca scintillans* bloom) regions. The southern sector is characterized by low column N-uptake and very low *f*-ratio (~5.5 mmol N $m^{-2}d^{-1}$ and 0.4 respectively). The *f* ratio, although low, increased progressively towards north. This increase may be the effect of more intense winter cooling towards the north[31,32]. The northern part is a highly productive zone, with very high N-uptake and significantly high *f* ratio (~19 mmol N $m^{-2}d^{-1}$ and 0.8 respectively).

New production during the pre-monsoon in the BOB was higher than that in the post-monsoon (Table 2). Overall, new production for the region during the pre-monsoon averaged around 5 (±4) mmol N $m^{-2}d^{-1}$, that was almost twice the average value observed during the post-monsoon (2.6 mmol N $m^{-2}d^{-1}$). However, the average *f* ratio estimated for the entire region increased to 0.70 (±0.1) during pre-monsoon as compared to 0.5 during the post-monsoon[5].

The maximum uptake observed at the surface reported by Kumar *et al.*[5] (^{15}N tracer method) is in good agreement with that reported by *Qasim*[33] and Radhakrishna[34] (^{14}C method). The surface productivity (1m depth) in the BOB (4.9 tonnes carbon km^{-2} yr^{-1}) is greater than that in the Arabian Sea (3.9 tonnes carbon km^{-2} yr^{-1}), but reverse is the case for column productivity[33]. The reason offered[33] for this difference is the greater cloud cover over BOB (annual range ~ 4.1-5.1 oktas) compared to the Arabian Sea (annual range ~ 1.5-3.7 oktas). It has been argued that the cloud cover present over the Bay attenuates the excess light intensity that would otherwise reach the sea surface and result in photoinhibition of plankton in surface water as in the Arabian Sea[33]. Another reason cited for the higher surface production in the BOB is significant nitrogen and phosphorus brought by large river runoff and rainfall into the BOB[33]. The effect of such supply of nutrients is limited to the surface as the runoff can only dilute the upper 25 m of the Bay by 5% without influencing the waters below this depth[33]. On the other hand, it seems that addition of nutrients through the river runoff and rainfall in the Arabian Sea is not significant in comparison to the Bay[33].

The average rate of photosynthetic fixation of carbon by marine phytoplankton (primary productivity) is more than a factor of two higher in the Arabian Sea than in the BOB[35]. However, the time averaged sediment trap data indicate that on the basin scale, the downward flux of organic carbon in the Arabian Sea is not proportionately higher than that of the BOB, except for the upwelling region in the northwestern Arabian Sea[36-39].

The comparable downward organic carbon fluxes in the highly productive Arabian Sea and the moderately productive BOB can be understood with the help of independent estimates of new production based on nitrogen uptake because, on a longer time scale, new production is considered theoretically equal to the export production[3]. It has been suggested[40] that new production and particle sinking are coupled over longer (annual) time scales. Values reported in two different seasons consistently show a high new production which could be one of the reasons for relatively higher downward organic carbon flux in the moderately/lowly productive BOB[5]. Prasanna Kumar *et al.*[41] proposed eddy pumping by the subsurface cold core eddies as a possible mechanism of nutrient injection to the oligotrophic waters in the Bay of Bengal during summer. It has been found that eddy enhances the biological productivity 2 to 8 times compared to the non-eddy region[41]. Madhu *et al.*[42] observed enhanced primary production along the south-western BOB due to the October 1999 super cyclone. Therefore, such mixing by cyclones or by eddies could be a reason for higher new production in the Bay. Hence, such oceanic regions may play a more significant role in removing the excess anthropogenic CO_2 from the atmosphere, than considered so far. In addition algal blooms could sporadically increase the removal of CO_2 from the atmosphere to the deep ocean[30].

Summary and Conclusions

^{15}N technique has tremendous potential to help understand the marine nitrogen cycle. As nitrogen has a great importance for marine phytoplankton, a large number of studies have focused on elucidating the details of the marine nitrogen cycle. Presently available data show that the marine productivity is highly variable, both temporally and spatially, ranging over several orders of magnitude. The southern sector of eastern Arabian Sea is characterized by low column N-uptake and very low *f*-ratio (~5.5 mmol N $m^{-2}d^{-1}$ and 0.4 respectively). The *f* ratio, although low, increased progressively towards north. This increase may be the effect of more intense winter cooling towards the north. The north-eastern Arabian Sea is a highly productive zone, with very high N-uptake and significantly high *f* ratio (~19 mmol N $m^{-2}d^{-1}$ and 0.8 respectively). New production during the pre-monsoon in the BOB is higher than that in the post-monsoon. Overall, new production for the region during the pre-monsoon averages around 5 (±4) mmol N $m^{-2}d^{-1}$, almost twice the average value observed during the post-monsoon (2.6 mmol N $m^{-2}d^{-1}$). However, the average *f* ratio for the entire region increases to 0.70 (±0.1) during pre-monsoon from 0.5 during the post-monsoon. This is in good agreement with sediment trap based export production. Though some global programs have focused on the northern Indian Ocean, still this region remains inadequately characterized for its biogeochemical aspects, particularly the BOB and north-eastern Arabian Sea. Therefore, to obtain large scale estimations for the carbon export fluxes, sustained observations over several years of ^{15}N based export productivity measurements coupled with biogeochemical models and remote sensing are needed.

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